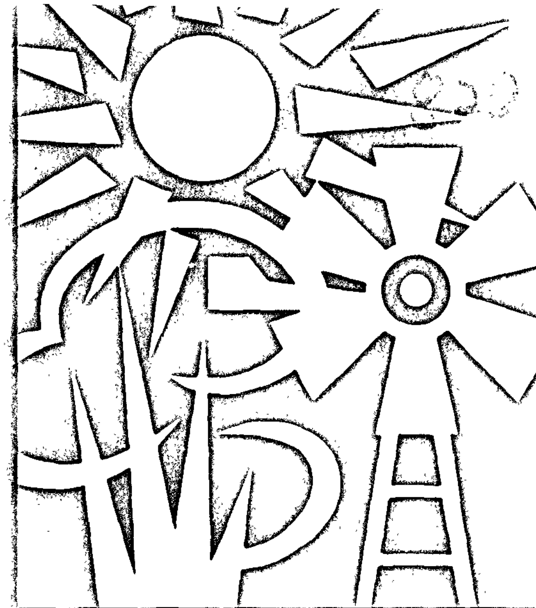

# NEW SOURCES OF ENERGY

## PROCEEDINGS OF THE CONFERENCE

Rome, 21 – 31 August 1961

VOLUME 2

# SOURCES NOUVELLES D'ÉNERGIE

## ACTES OFFICIELS DE LA CONFÉRENCE

Rome, 21 – 31 août 1961

UNITED NATIONS
NATIONS UNIES

# PROCEEDINGS OF THE UNITED NATIONS CONFERENCE ON NEW SOURCES OF ENERGY

SOLAR ENERGY, WIND POWER AND GEOTHERMAL ENERGY
Rome, 21-31 August 1961

## VOLUME 2. GEOTHERMAL ENERGY: I

# ACTES OFFICIELS DE LA CONFÉRENCE DES NATIONS UNIES SUR LES SOURCES NOUVELLES D'ÉNERGIE

ÉNERGIE SOLAIRE, ÉNERGIE ÉOLIENNE ET ÉNERGIE GÉOTHERMIQUE
Rome, 21-31 août 1961

## VOLUME 2. ÉNERGIE GÉOTHERMIQUE : I

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# INTRODUCTION

The United Nations Conference on New Sources of Energy was held in Rome from 21 to 31 August 1961. A brief review of the proceedings, of the papers submitted to the Conference and of the related discussions has been printed in *New Sources of Energy and Energy Development: Report on the United Nations Conference on New Sources of Energy*.[1] That publication also contains the agenda and the lists of participants and conference officers, as well as lists of all the papers and reports.

The Proceedings of the Conference comprise seven volumes as follows:

Volume 1. General sessions.
Volume 2. Geothermal energy: I.
Volume 3. Geothermal energy: II.
Volume 4. Solar energy: I.
Volume 5. Solar energy: II.
Volume 6. Solar energy: III.
Volume 7. Wind power.

The present volume, "Geothermal energy: I", contains the papers and reports relating to agenda item II.A.1, "Prospection of geothermal fields and investigations necessary to evaluate their capacity".

The Rapporteur's general report and his summation of the proceedings in connexion with the agenda item are given in full in both English and French. as are those individual papers that were submitted, to the Conference in both languages. With a few exceptions, all the papers are summarized in both English and French.

The papers are printed in the alphabetical order of the authors' names. References supplied by the authors are listed after the text. As a rule, they are numbered consecutively throughout each paper and are indicated by arabic figures in parentheses.

The reports and papers are printed in the form in which they were presented to the Conference, and the affiliations of the participants are those in effect at that time. Corrections to the papers have been incorporated; some of the figures have been rearranged; and minor editorial changes have been made.

The views and opinions expressed are those of the individual authors and do not imply the expression of any opinion on the part of the Secretariat of the United Nations.

The symbols appearing after the titles of the papers and reports, and in references to them in the text, correspond to the symbols under which they were presented at the Conference. They have here been abbreviated by the elimination of the prefix "E/CONF.35/", which should be included in all full references.

[1] United Nations publication, Sales No. : 62.I.21.

# INTRODUCTION

La Conférence des Nations Unies sur les sources nouvelles d'énergie s'est tenue à Rome du 21 au 31 août 1961. Le document intitulé *Sources nouvelles d'énergie et production d'énergie : Rapport sur les travaux de la Conférence des Nations Unies sur les sources nouvelles d'énergie*[1] donne un aperçu des travaux, des mémoires soumis à la Conférence et des débats dont ceux-ci ont fait l'objet. Il contient en outre l'ordre du jour, la liste des membres du Bureau et des autres personnes ayant pris part à la Conférence, ainsi qu'une liste de tous les mémoires et rapports présentés.

Les Actes officiels de la Conférence comprennent les sept volumes suivants :

Volume 1. Sessions générales
Volume 2. Énergie géothermique : I
Volume 3. Énergie géothermique : II
Volume 4. Énergie solaire : I
Volume 5. Énergie solaire : II
Volume 6. Énergie solaire : III
Volume 7. Énergie éolienne

Le présent volume, « Énergie géothermique : I », groupe les mémoires et rapports ayant trait au point II.A.1 de l'ordre du jour, « Prospection des champs géothermiques et recherches nécessaires pour évaluer la puissance utilisable ».

Le rapport général du Rapporteur et le résumé des débats sur le point de l'ordre du jour établi par le Rapporteur sont donnés intégralement, en anglais et en français, ainsi que les mémoires

[1] Publication des Nations Unies, n° de vente : 62.I.21.

qui ont été soumis à la Conférence dans les deux langues. Sauf quelques exceptions, ils sont tous résumés en anglais et en français.

Les mémoires sont classés dans l'ordre alphabétique des noms d'auteurs. La liste des références fournies par les auteurs figure à la suite du texte. D'une façon générale elles sont numérotées consécutivement pour chaque mémoire et sont indiquées par des chiffres arabes entre parenthèses.

En règle générale, les rapports et mémoires sont publiés sous la forme dans laquelle ils ont été présentés à la Conférence, et les fonctions indiquées pour chaque participant sont celles qu'il occupait à cette époque. Toutefois, les corrections nécessaires ont été apportées et certaines figures ont été remaniées; des modifications de rédaction mineures ont de même été faites.

Les vues exprimées n'engagent que leur auteur et n'impliquent aucune prise de position de la part du Secrétariat de l'Organisation des Nations Unies.

Les cotes indiquées après les titres des mémoires et des rapports et dans les renvois qui y sont faits dans le texte correspondent aux cotes utilisées pour la Conférence. On les a cependant abrégées en éliminant « E/CONF.35 », qui doit être maintenu dans les cas où la référence complète est donnée.

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* The first title refers to the original language; in most cases, it is followed by the translation, in italics.

* Le premier titre est celui de la version originale; il est suivi, dans la plupart des cas, de sa traduction en caractères italiques.

*Agenda item II.A.1*

# PROSPECTION OF GEOTHERMAL FIELDS AND INVESTIGATIONS NECESSARY TO EVALUATE THEIR CAPACITY

*Point II.A.1 de l'ordre du jour*

# PROSPECTION DES CHAMPS GÉOTHERMIQUES ET RECHERCHES NÉCESSAIRES POUR ÉVALUER LA PUISSANCE UTILISABLE

*Chairman — Président*

Frank E. STUDT

*Rapporteur*

Jesús RUIZ ELIZONDO

Original : Spanish

# PROSPECTION OF GEOTHERMAL FIELDS AND INVESTIGATIONS NECESSARY TO EVALUATE THEIR CAPACITY

*Jesús Ruiz Elizondo**

## General survey of geothermal energy

A significant proportion of all countries in the world meet their scheduled requirements for energy by conventional means, burning coal and oil, and harnessing water power. When nuclear energy becomes available on an economic basis, as it promises to be in the near future, the ultimate exhaustion of the existing reserves of fossil fuels will be postponed. The use of these fuels — hydrocarbons and coal — as raw materials in the chemical industries and elsewhere has become important, perhaps even more important than their mere consumption to give heat.

What we call new sources of energy have long been known. History tells us that some of them may even have been utilized by the peoples of antiquity. These new sources are known under the names of wind power, solar energy, tidal energy, thermal energy of the seas, and geothermal energy. In view of the imperative need for greater and greater amounts of energy, to enable man freely to advance along his path of progress and well-being, the new sources of energy must be utilized, wherever they can be, with modern techniques and in the light of scientific progress.

The countries with the greatest natural, technical and economic resources will of course have the brightest economic future. It is logical to include sources of energy among the natural resources; the countries that nature has lavishly endowed with fossil fuel will have little reason for anxiety. But those less abundantly provided with these riches will naturally have to look to other sources of energy to raise the standard of living among their population. Such resources may long have lain dormant and undreamed of, and, when found, still need to be made productive, in order to eliminate the burden to the national economy constituted by imports due ultimately to energy shortage.

The existence of geysers and fumaroles, in many countries and in many parts of the world, has of course played a certain role. Magnificent and curious manifestations have attracted beholders, and led in some places to rudimentary exploitation by those providing tourist and bathing facilities. Many are the places, indeed, where hot springs have been used by the healing art, and, to a lesser extent, for residential heating.

A considerable number of studies lead to the conclusion that geothermal energy is a wasting asset, of uncertain and limited duration. This statement must, however, be related to the average length of human life. Countries like Italy and New Zealand, which have successfully developed their geothermal resources, show such exploitation to be fraught with blessings to population and region alike, and demonstrate that the stores of energy may, in general, last long enough to amortize invested capital, sometimes with a substantial margin of profit, fortifying the economy of village, city and nation.

Geothermal energy utilizes the heat existing in certain parts of the earth's crust near the surface, or at depths not exceeding the limit of economic utilization. This energy is manifested in the form of steam. Valuable chemical by-products may also result, as in Italy. The variation of temperature with depth is known as the geothermal gradient. A geothermal anomaly exists wherever the increase of temperature per metre of depth is greater than normal. Thus the study of geothermal energy for purposes of utilization should be understood in terms of geothermal anomalies.

The prospection of geothermal fields makes it necessary to improve the techniques, to extract the energy available in the thermal regions. The art of geothermal investigation is indeed of recent origin. The great advances registered by prospecting techniques have been due not only to research, but also to practical experiments. The work of prospecting for geothermal fields must rely on method as the key to success, as it is in various branches of economic geology. This has to do with various well-known factors : money, time, knowledge, objectives and profits. No one can doubt that Nature demands risk and investment of all who seek her favours. The risks diminish and security of investment improves only after sound experience has been acquired; but sound experience, in general, comes high.

Various geothermal fields are known in the world today. They confer well-being and blessings on the people of a number of countries. It may be said that all these fields have a common denominator : they represent true persistence and genuine thought, imbued with skill and art. A man whose profession is the search for oil, coal, fissionable materials or dam sites, will realize that the energy obtainable from a geothermal field is recovered more easily, and that with natural steam the recovery by-passes a number of steps necessary to make possible energy generation from other sources. Geothermal energy is therefore one of the cheapest sources of energy. As already noted, it is assuredly not a renewable

* Comisión Nacional de Energía Nuclear, Mexico City, Mexico.

resource; it is by no means easy to predict its life at full-scale production; the only thing that can be said in this respect is that it is indeed transitory.

## Purpose of this report

By invitation of the Secretary-General of the United Nations, the writer is acting as a rapporteur for this conference. At the time of writing, about forty papers have been received from many parts of the world. They evidence enthusiastic interest in this subject, and fundamentally, perhaps, the urgent need of increasing the per capita number of kilowatts generated, which is a justified, natural and inescapable tendency, not only in the developed countries, but also in those termed under-developed. Italy, New Zealand, Iceland, the United States, Mexico, Japan, the Union of Soviet Socialist Republics, El Salvador, France and Belgium are among the countries presenting papers on various aspects of geothermal prospection. This report will attempt to give a very general account of the topic of the prospection of geothermal areas and of the considerations and criteria followed in evaluating their capacity.

## Acknowledgements

The author expresses his sincerest thanks to the Secretariat of the United Nations for giving him the opportunity of collaborating with it on the topic of geothermal energy, and for having continuously assisted him with precise and clear-cut information.

This report could not have been written without the encouragement and aid of Mexican institutions, friends and colleagues. His Excellency, Licenciado José Maria Ortíz Tirado, Chairman of the National Nuclear Energy Commission of Mexico, gave the author permission to undertake this work, and provided the necessary facilities. The Bank of Mexico and the Geothermal Energy Commission have also followed this work with keen interest.

The writer expresses his warmest appreciation to all these persons, as well as to the authors of about forty papers, whose names are listed in the table of contents.

## Description of geothermal fields

This section of the General Report gives a somewhat generalized description of the known geothermal fields. The information has been largely taken from papers reviewed by the author, and also includes data from a number of earlier personal notes.

Tables 1 to 9 have been prepared for the sake of simplicity. They indicate, country by country, the known geothermal fields now in production, together with those now in preliminary development (figure 1).

The tables are divided into three columns. The left-hand column gives the names and locations of the geothermal fields, arranged by countries, and present status, i.e., production, exploration preliminary to production, or merely prospection and survey, in the initial basic stages leading to the discovery of a geothermal field. This column also gives the history of the field and the elevation above sea level, in metres, of the geothermal area, as well as the elevation, if known, of the horizon or deposit from which geothermal energy is extracted in the form of steam. The object is to ascertain statistically the influence of the elevation of geothermal fields on their production.

The central column states, very briefly, the constitution of the geological steam trap in the subsurface, and the formations composing it. Each day sees increasing interest in the origin of the underground steam that yields usable energy at the surface, in its behaviour, and in the subsurface reservoirs in which it is stored.

The right-hand column is used for subjects on which information may or may not be available. They relate to what is known, for these geothermal areas, of the surface heat flux and the flow rate of geothermal fluids, the amount of energy produced by the field, if in production, and the investigations made to estimate this production, where tests have not yet been made. Finally, information has been provided which was considered necessary to supplement the very brief description of the geothermal fields, zones or areas of the country. In some cases it has been considered advisable, in addition to the table, to annex separate statements on topics not previously mentioned.

**Table 1. General features of known steam fields : Italy**

| *Name, location, present stage, history, elevation (metres above sea level)* | *Structural geology of the known or inferred sub-soil zones with steam accumulation* | *Remarks* |
|---|---|---|
| *Larderello*, 17 km S of Volterra. Natural steam vents were known before 1777, but it was then that the presence of boric acid was discovered.<br><br>Count Francesco de Larderel was the founder of the borax industry. The field is named in his honour. Other localities in the neighbourhood of Larderello are Serrazzano, Lagoni Rossi, Lago, Monterotondo, Sasso and Castelnuovo, all in Tuscany. | An impermeable Oligocene-Miocene stratum, locally called "argille scagliose" (schistous clays), discordantly overlies a permeable anhydrite series of the Rhaetic, in which the steam occurs. The fractures emerge through the crystalline basement, and the steam is probably connected with a cooling intrusive body several kilometres below the anhydrite series. | The first geothermal power station, producing 40 hp with natural steam, was installed in 1905.<br><br>The average depth of the wells is 700 m, the maximum 1 600 m.<br><br>A total of 160 wells yield 2 850 000 kg/h of steam, at an average temperature of 200°C and an average pressure of 5 atm abs. |

| Name, location, present stage, history, elevation (metres above sea level) | Structural geology of the known or inferred sub-soil zones with steam accumulation | Remarks |
|---|---|---|
| Larderello is a field in production. The Larderello area covers about 400 sq. km., and includes parts of the provinces of Pisa, Grosseto, Siena and Leghorn. Its maximum elevation is 1 000 m above mean sea level. | | The annual production of energy by the Larderello field is $2 \times 10^9$ kWh. |
| *Monte Amiata,* 70 km SE of the Larderello area, in the provinces of Siena and Grosseto, Tuscany. This field is now in the stage of exploration and of production. Its elevation above mean sea level is 1 738 m. | As at Larderello, the schistous clays are directly in contact with the underlying anhydrite series (which contain the steam), but here the sedimentary deposits are still affected by volcano-plutonic ignimbrites. | The surface temperatures of the thermal springs range from 20 to 50°C. Drilling has reached 400 to 1 100 m depth. A total of 12 wells have been drilled, and 5 of them produce 1 000 kg/h of a fluid containing 30 per cent of gas, at a pressure of 5.5 atm abs and a temperature of 150°C. |
| *Roccastrada,* located 30 km SE of Larderello, in the provinces of Siena and Grosseto, Tuscany. It is now in the stage of exploration and investigation. | Probably similar to those of Mont Amiata. | The average surface temperature of the thermal springs is around 55°C. |
| *Montecatini-Orciatico region,* 25 km N of Larderello, in the province of Pisa, Tuscany. It is in the exploration and investigation stage. | Similar to the above. | Preliminary drilling has commenced. The surface temperatures of the thermal springs are in the neighbourhood of 55°C. |
| *La Tolfa region,* a few kilometres from the Tyrrhenian coast, in the province of Rome. It is now in the exploration and investigation stage. | Similar to the above. | Preliminary drilling has commenced. |
| *Monti Berici region,* in the province of Vicenza, Venetia. It is now in the exploration and investigation stage. | The trap in which the steam has accumulated is probably formed of recent rocks of volcanic origin. | |

In view of the general situation in the Italian geothermal fields, which are unique in their characteristics, not much can be said, without taking a considerable amount of space, as to whether the steam is endogenous or exogenous (that is, whether it comes from magmatic fluids or is formed primarily by meteoric water). It is of major importance, in a region of thermal manifestations, to have sufficient bases to be able to consider a favourable geological trap structure. This is a practical consideration that is borne in mind during exploration in a steam field, and may perhaps be responsible for drilling in some parts of Italy where there are no superficial manifestations. After all, if the heat is at least partially associated with intrusive bodies at a certain depth, it is important to know the existence of successive permeable and impermeable formations capable of forming geologically favourable traps, in order to constitute deposits of heat; the fluids themselves may result either from deep magmatic influence or from shallow meteoric influence. It may be unnecessary to devote practical consideration to the trap, provided an adequate idea of the structural geometry of the formations in depth is obtained. Detailed geological reconnaissance, in addition to gravimetric, electrical and seismic exploration, is therefore recommended in advance of any drilling. Hydrogeological studies are supplementary tools, and isotope geology and geochemistry play the important part of being concerned with the origin and evolution of the elements in the fluids.

In spite of this, and bearing in mind that Italy is the first country to develop geothermal energy, a very broad field for research and production still exists in that country.

**Table 2. General features of known steam fields : New Zealand**

| Name, location, present stage, history, elevation (metres above sea level) | Structural geology of the known or inferred sub-soil zones with steam accumulation | Remarks |
|---|---|---|
| *Wairakei,* about 16.5 km NE of Lake Taupo, in the central volcanic portion, district of North Island, New Zealand. The elevation is about 396 m above sea level. It is now in production. | Volcanic rock is predominant.<br>The Waiora formation, locally intruded by a thick cover of rhyolite, is composed of post-Mesozoic pumiceous breccia, and forms an aquifer constituting the heat | The thermal region of Wairakei consists of both active and extinct thermal areas. The high-pressure steam of Wairakei comes from wells drilled into the principal active faults. |

| *Name, location, present stage, history, elevation (metres above sea level)* | *Structural geology of the known or inferred sub-soil zones with steam accumulation* | *Remarks* |
|---|---|---|
| | deposit, with temperatures up to 260°C. It is covered by impermeable lacustrine mudstones of the Huka formation. The sequence is traversed by sharply dipping fractures of the middle Pleistocene, which cut through the underlying ignimbrites.<br>The fissures at the top of the ignimbrites are large and open. The possible existence of other structural traps below the ignimbrites of Wairakei is under consideration.<br>The probable age of the hydrothermal field is about 500 000 years (Middle Pleistocene, according to G/34). | There are 20 wells in the western region of this field, producing a total of about 480 000 kg/h of high-pressure steam.<br>The eastern part produces about 135 000 kg/h of high-pressure steam from several wells. There are 22 wells producing intermediate-pressure steam. About 10 wells have been declared non-producing. |
| *Waiotapu*, about 48 km NE of Wairakei, North Island, New Zealand. This field is in the stage of investigation. Excepting for well No. 1, all the other wells (6 in number) were started at a surface elevation below 457 m. | There are soft breccias both overlying and underlying the hard ignimbrites. This is called the Waiotapu formation. | Seven wells in all have been drilled to a depth of 1 080 m. The drilling for well No. 8 has been programmed. The total period of this investigation has been 3 years.<br>The deep bores give higher temperatures, up to 295°C, according to G/17.<br>Estimated power is 10 000 kW, using direct steam, with secondary steam from the thermal waters.<br>The estimated theoretical power that could be generated from the geothermal resources of this field is 63 100 kW. |
| *Kawerau*, about 98 km NE of Wairakei, and about 8 km SW of the village of Teteko. | Localized in the principal Quaternary volcanic belt on North Island.<br>The pumiceous breccia forms an aquifer covered by thick rhyolitic effusions. | Twelve bores have been drilled for investigation. The fractured andesite produces high-pressure steam at 270°C |
| The Onepu steam vents are 2.5 km N of Kawerau, which is crossed by the Tarawera River. It is now in the stage of investigation. Its elevation above sea level is over 20 m. | This breccia is underlain by highly fractured andesite, and by ignimbrites.<br>Many active faults cross this field. | The cold water acts unfavourably on the breccia aquifer, cooling the steam wells after they have been 3 years in production.<br>The level of phreatic water has dropped This field differs from those of Wairakei and Waiotapu in that there are rhyolitic effusions instead of ignimbrites. The highest temperature recorded up to now was 253°C at about 500 m depth. An observation reported in *N.Z.J. Geol. Geogr.*, Vol. 1 (1958) is very interesting: from the beginning of this century, up to now, the reaction of the emanations has changed from alkaline to acid. But the acidity is superficial, since the wells gain alkalinity with depth.<br>The chlorine content is 300 to 600 ppm.<br>The heat flux at Onepu is estimated at 25 000 K-cal/s, which would be equivalent to 100 theoretical megawatts. |
| *Orakeikorato*. Present status is one of investigation (?).[a] | | The estimated natural heat flux, relative to 0°C, is 860 × 10⁶ BTU/h. |
| *Tikitere*. Present status is one of investigation (?).[a] | | The natural heat flux estimated at 0°C is 570 × 10⁶ BTU/h. |
| *Tekopia*. Present status is one of investigation (?).[a] | | The natural heat flux estimated relative to 0°C is 430 × 10⁶ BTU/h. |
| *Waikiti*. Present status is one of investigation (?).[a] | | The natural heat flux estimated relative to 0°C is 290 × 10⁶ BTU/h. |

| Name, location, present stage, history, elevation (metres above sea level) | Structural geology of the known or inferred sub-soil zones with steam accumulation | Remarks |
|---|---|---|
| *Taupo,* thermal area adjacent to the township of Taupo. Its present status is one of investigation.[b] | | The estimated heat flux is 35 900 K-cal/s. |
| *Ngatamariki,* in the beds of Orakonui, near the Waikato River. Its present status is one of investigation (?).[b] | | The heat flux has not been estimated. |
| *Rautawiri,* including the thermal areas of Ohaki and Broadland. Its present status is one of investigation (?).[b] | | The estimated heat flux is 23 100 K-cal/s. |
| *Rotokawa area,* crossed by the Parariki River. Its present status is one of investigation.[b] | | The estimated heat flux is 52 100 K-cal/s. |
| *Tauhara,* near the Taupo-Napier road. Its present status is one of investigation (?). | | The heat flux is insignificant. |

[a] J. A. H. Smith, "Production and utilization of geothermal steam", *N.Z. Engineering,* Vol. 13, No. 10 (1958).
[b] D. R. Gregg, *N.Z.J. Geol. Geoph.,* Vol. 1 (Feb., 1958).

The gravimetric survey at Wairakei showed the existence of an anomaly previously attributed to basement uplift, which was found in fact to be due to a thick sequence of over 500 m of rhyolitic rocks. Gravimetric prospection thus has its limitations as far as steam fields are concerned.

The spacing of the wells above the faults is 150 to 300 m; they are occasionally closer together, and the production is not materially affected by the location of other wells on the faults, in the western part of Wairakei.

Knowledge of the stratigraphy and structure is necessary to save time and money, since it has been found that the fissures producing high-pressure steam are large and open, at the crest of the Wairakei ignimbrites. If the well taps the upper parts, one cannot be too sure of getting high-pressure steam; the fissures must consequently be cemented, and this takes time and money. Drilling into the ignimbrite and its fault zones has not shown a substantial increase in production.

The high-pressure producing wells (at over 200 psi) are more affected by temperature and permeability. The temperature falls from the fissure to the aquifer.

The permeability of the aquifer is adversely affected by the hydrothermal alteration of the rocks.

The Wairoa breccia becomes impermeable as a result of deposition of minerals of hydrothermal origin.

Wells drilled near the feed fissures without traversing them are usually non-producing, and therefore the accepted practice is to drill into the fissures themselves.

The flow of the wells is influenced by the deposition of calcium carbonate and silica in the casing (at 300-500 m depth); this deposition reduces the uniform diameter at the wellhead, and also reduces the production, but these phenomena are usually accompanied by a slight increase in enthalpy. In this case, however, there is no mineral deposition in the steam-producing fissures.

The heat flux of the aquifer of Wairakei field is controlled by the same pattern of fault intersection.

The Na/K ratios have been used in a way that might perhaps lead one to think that the steam does not come from a single source, even in the same area.

One method of estimating the heat production in New Zealand considers the chlorine content in the borehold fluids and the chlorine content of the natural steam in order to get an approximate idea.

The gas-water ratio is 30 per cent.

The total productive capacity of the Wairakei field is very difficult to estimate, since the best indication derives from a detailed study of the trends of the natural heat flux and of the behaviour of the individual wells.

The hydrothermal and hydrological studies might lead to the conclusion that the factor limiting the production might be nothing less than the scarcity of meteoric water.

As in Mexico and elsewhere, the steam field of Waiotapu has been studied by means of aerial photography. The calciting of the casing is more rapid than at Wairakei. This causes blocking of the shallow wells, so that they no longer serve for energy production. The deep wells encounter high pressure and temperature without calciting.

In comparison with Wairakei, this field has a high bicarbonate ratio and a low chloride ratio. A low chlorine content is generally considered to indicate that the water of the formation itself has been heated by the steam.

**Table 3. General features of known steam fields : New Britain, Trust Territory of New Guinea**

| *Name, location, present stage, history, elevation (metres above sea level)* | *Structural geology of the known or inferred sub-soil zones with steam accumulation* | *Remarks* |
|---|---|---|
| Area of *Rabalanakaia-Matupi-Vulcan*, near Rabaul, on either side of Blanche Bay and Simpson Harbour. Rabaul township is situated within the subsided caldera. This part of New Britain is served by Diesel generators for the production of electricity.<br>According to G/12, the existence of geothermy in this area has caused belief that it will be possible to obtain 5 megawatts in 8 years, and then reach a total of 20 megawatts, developed in steps or stages of 5 megawatts.<br>The areas with a marked heat flux are located between 50 and 30 m above sea level. The natural thermal emanations are located below high tide mark, and their temperature varies from 40 to 98°C.<br>In 1937 the Matupi volcano erupted, and was active in 1942. The Vulcan volcano erupted in 1878 and 1937. | No structural stratum acting as an impermeable cover is known, but it is possible that the lava effusions from Rabalanakaia could have formed restricted beds.<br>Permeable strata between recent volcanic effusions.<br>It is possible that the lava effusions form impermeable covers above argillaceous and pumiceous sediments. | The heat flux is intimately associated with Matupi and Vulcan volcanoes, and with the Rabalanakaia crater and the eastern wall of the caldera.<br>The quantity of natural heat escaping is not necessarily a measure of the quantity of heat that could be obtained by deep drilling.<br>According to G/12, if the results of the initial investigations show a heat flux of the order of a thousand million BTU/h, investigation of the system will be recommended, for generating 20 megawatts. Drilling deeper than 500 m is recommended, and the possible cost of the proposed investigation would be about £200 000. If these wells were productive, an engine room could be supplied, after adequately cementing the casing liners. |

At Rabaul, in New Britain, if the results of preliminary prospecting are satisfactory, drilling will be undertaken to establish the possibility of production of 20 megawatts by the field.

The latter wells should discharge, for at least a year, at the pressures and flow rates visualized today for the period of approach to the final stage of power production.

During this period, there will be continuous tests of the pressure at well bottom and of the temperatures, as well as of variation in flow rate. The measurements will also include the quantity of steam and water and their chemical composition.

It will cost about £10,000 to measure the natural heat flux and other physical properties.

**Table 4*a*. General features of known steam fields : Iceland**

*High-temperature thermal zones*

| *Name, location, present stage, history, elevation (metres above sea level)* | *Structural geology of the known or inferred sub-soil zones with steam accumulation* | *Remarks* |
|---|---|---|
| *Reykjanes area*, in the Quaternary neovolcanic zone of SW Iceland. The elevation is 15 m above sea level. Its area is 1 square kilometre. | Permeable zones between strata of lava with permeable dikes and faults. | The heat flux has been estimated at 5 to 25 × $10^6$ cal/s. One well 162 m deep has been drilled. |
| *Trölladyngja area*, in the Quaternary neovolcanic zone of SW Iceland. Its elevation is 120 m above sea level and its area is 5 square kilometres. | Permeable zones between strata of basaltic lavas with permeable dikes and faults. | The heat flux is estimated at 5 to 25 × $10^6$ cal/s. |
| *Krysuvik area*, in the Quaternary neovolcanic zone of SW Iceland. It is 150 m above sea level and its area is 10 square kilometres. | Permeable zones between strata of lava with permeable dikes and faults. | The heat production is estimated at 5 to 25 × $10^6$ cal/s. 15 wells have been drilled to a maximum depth of 1 200 m. The base temperature is about 230°C. |
| *Hengill area*, in the Quaternary neovolcanic zone of SW Iceland. Its elevation is 30 to 600 m above sea level, and its area is 50 square kilometres. | Similar to the above. | The heat flux ranges from 25 to 125 × $10^6$ cal/s. The base temperature is 230°C. Numerous shallow wells have been drilled, together with 8 deep wells, to a maximum depth of 1 200 m. |
| *Kerlingafjöll area*, in the Quaternary neovolcanic zone of the eastern central part of the western half of Iceland. Its elevation is 900 m above sea level and its area is 5 square kilometres. | Permeable zones between basaltic formations with dikes and faults. | The heat flux is estimated at 25 to 125 × $10^6$ cal/s. |

| Name, location, present stage, history, elevation (metres above sea level) | Structural geology of the known or inferred sub-soil zones with steam accumulation | Remarks |
|---|---|---|
| *Torfajökull area*, in the southern part of the eastern half of Iceland. It is 900 m above sea level and is 100 square kilometres in area. | Similar to the above. | The heat flux is 125 to 750 × $10^6$ cal/s, with an average of 5 × $10^8$ cal/s. |
| *Vonarskard area*, in the Quaternary neovolcanic zone practically in the eastern half of Iceland. Its elevation is 1 000 m above sea level. | Permeable zone between basaltic formations with dikes and faults. | Heat flux estimated at 5 to 25 × $10^6$ cal/s. |
| *Grimsvötn area*, in the Quaternary neovolcanic zone of the eastern half of Iceland. It is 1 000 m above sea level and 12 square kilometres in area. | Similar to the above. | The heat flux is estimated at 125 to 750 × $10^6$ cal/s. This area is located under the ice cap of Vatnajökull. |
| *Kverkfjöll area*, in the Quaternary neovolcanic zone of the eastern half of Iceland. The elevation is 1 500 m above sea level, and the area is 10 square kilometres. | Permeable zones between basaltic formations with dikes and faults. | Heat flux estimated at 25 to 125 × $10^6$ cal/s. |
| *Askja area*, in the neovolcanic zone of the eastern half of Iceland, at 1 050 m above sea level. | Similar to the above. | Heat flux estimated at 5 to 25 × $10^6$ cal/s. |
| *Namafjall area*, in the neovolcanic zone of the eastern half of Iceland; elevation 350 m above sea level. Area 2.5 square kilometres. | Similar to the above. | Heat flux estimated at 25 to 125 × $10^6$ cal/s. Several shallow wells have been drilled. |
| *Krafla area*, in the neovolcanic region of the eastern half of Iceland. Elevation 450 m above sea level. Area 0.5 square kilometres. | Permeable zone between basaltic formations with dikes and faults. | Heat flux estimated at 5 to 25 × $10^6$ cal/s. |
| *Theistareykir area*, in the neovolcanic zone of the eastern half of Iceland. Elevation 330 m above sea level. Area 2.5 square kilometres. | Similar to the above. | Heat flux estimated at 5 to 25 × $10^6$ cal/s. |

**Table 4*b*. General features of known steam fields : Iceland**

*Low-temperature thermal zones (linear grouping)*

| Name, location, present stage, history, elevation (metres above sea level) | Structural geology of the known or inferred sub-soil zones with steam accumulation | Remarks |
|---|---|---|
| 50 km (?) NW of Torfajökull. | Volcanic strata in Tertiary districts. | Total natural flow 52 litres/s. Maximum surface temperature 100°C. Heat flux 25-125 × $10^6$ cal/s. |
| 50 km (+) NW of Torfajökull. | Same as above. | Total natural flow 140 litres/s. Maximum surface temperature 100°C. Heat flux 5-25 × $10^6$ cal/s. |
| 60 km (+) NW of Torfajökull. Includes the Great Geyser. | Same as above. | Total natural flow 60 litres/s. Maximum surface temperature 100°C. Heat flux 5-25 × $10^6$ cal/s. |
| 40 km E of Krysuvik. | Same as above. | Total natural flow 70 litres/s. Maximum surface temperature 100°C. Heat flux 5-25 × $10^6$ cal/s. |
| Near Trolladyngia. The base temperature at Reykir is 98°C. Seventy wells have been drilled there to a maximum depth of 1 380 m. The production of the wells is 370 litres/s at 87°C. | Same as above. | Total natural flow 120 litres/s. Maximum surface temperature 83°C. Heat flux 5-25 × $10^6$ cal/s. |
| NE of Reykjanes, near Reykjavik. The base temperature at Reykjavik is 146°C. Forty wells have been drilled to a maximum depth of 2 200 m. Their total production is 134 litres/s at a maximum temperature of 138°C. | Same as above. | Total natural flow 10 litres/s. Maximum surface temperature 80°C. Heat flux 5-25 × $10^6$ cal/s. |

| *Name, location, present stage, history, elevation (metres above sea level)* | *Structural geology of the known or inferred sub-soil zones with steam accumulation* | *Remarks* |
|---|---|---|
| In the SW part of Iceland. There is in fact a system of lines including the largest natural manifestation of hot water at Deildartunga. | Volcanic strata in Tertiary districts. | Total natural flow 400 litres/s. Maximum surface temperature 100°C. Heat flux 25-125 × $10^6$ cal/s. |
| W of Akureyri. | Same as above. | Total natural flow 70 litres/s. Maximum surface temperature 89°C. Heat flux 5-25 × $10^6$ cal/s. |

The total potential natural heat resources of Iceland are estimated, in terms of electric power, to be of the order of 500 megawatts.

The thermal areas of Iceland are controlled by permeable contacts between strata of lava, permeable dikes and faults.

"Circulation" may take place at the bottom of the basalts-that is, at a depth of two or three kilometres. Hot volcanic structures of Recent age appear to be supplying the heat to the high-temperature areas. The circulating water is in direct contact with the hot rock. On the other hand, the low-temperature areas appear to draw their natural heat from the heat existing in the lower or deep parts of the basalts. The temperature in the circulation region may be 100-120 °C. There is an excess amount of heat stored in the high-temperature areas, which may be exploited by drilling.

The low-temperature areas are characterized by springs of hot water and underground temperatures below 150 °C. located in Tertiary regions. The high-temperature areas are located in the Quaternary district. The total flux of natural heat in the low-temperature areas is estimated at one hundred million cal/s, while the high-temperature areas appear to have a heat flux of a thousand million cal/s.

About 250 low-temperature thermal areas are known, distributed over the lowlands of the eastern half of Iceland. There are a large number of natural manifestations, about 600, with an estimated total flow of 1 500 litres/s The heat production of the hydrothermal springs is $10^8$ cal/s., at an average temperature of 75 °C.

In his paper presented to this conference, Bodvarsson has fixed a base temperature of 150 °C as the upper limit in the group of low-temperature thermal areas (G/6). From this criterion, he concluded that the subsurface conditions, both chemical and physical, vary considerably as soon as the base temperature exceeds 150 °C.

An approximate total of 70 000 linear metres of wells have been drilled in Iceland to exploit the natural heat resources. The deepest well reached 2 200 m, and is inside the city of Reykjavik. Several tens of thousands of metres are scheduled for drilling during the coming years.

Drilling in the thermal areas of Iceland has shown the important fact that the heat production of the well exceeds the natural production of the area prior to drilling. In one case the increase was twenty-fold.

The continuous and uniform power potential of the thermal areas of Iceland for energy production has been estimated at 300 megawatts, in addition to a recoverable heat of 15 000 megawatts/year.

Heat is used in Iceland today mainly for domestic heating and greenhouses. The total quantity of natural heat utilized corresponds to an annual saving of petroleum fuel of about 60 000 metric tons, or 350 kg/year per capita, from the information given in G/24.

The maximum temperature measured up to now in the thermal regions of Iceland is about 230 °C. The geothermal gradient in nonthermal regions varies from 0.033 to 0.0165 °C/m.

In some cases the geochemical data may indicate the reaction temperatures.

The drilling fluid disturbs stationary temperature conditions by cooling or heating the formation around the drill.

Geochemical methods show a positive correlation between the temperature of the hydrothermal sources and the total content of dissolved solids. For instance, water discharged at 30 °C from hydrothermal sources may contain 150 ppm of solids, while water discharged at 100 °C may contain over 300 ppm.

Combined temperature, gravimetric and magnetometric measurements are being conducted in the thermal area of Reykjavik, and indicate an upward flow of hot water to the west of the intrusive body. During the last six years a total of twenty-five wells have been drilled in this area, on the basis of previous studies. The maximum production temperature is 138 °C, the maximum depth is 2 200 m, and the flow of hot water is 135 litres/s, which is used for domestic heating in the city of Reykjavik. The base temperature of the area is 146 °C. This temperature is prevalent down to 1 000 m depth.

The Reykir thermal area was the first large area to be exploited in Iceland.

Drilling started in 1933. By 1954 there were seventy wells. Maximum depth was 621 m. The production of the wells was 360 litres/s of water at an average temperature of 87 °C. The area is in a block-faulted region with a Tertiary fault striking SW-NE. In 1959, an additional well reached 1 380 m. Only an insignificant production was obtained at depth 670 m. Temperature measurements indicate that after passing a fissure at 670 m, the temperature fell from 98 to 90 °C. The Reykir thermal area is controlled by a porous horizontal stratum, and more than a single fault.

One of the largest geothermal areas of Iceland is the Hengill thermal area, where it is planned to build a power plant based on natural steam.

Large-scale drilling started in 1958, and eight wells have been completed. The depth ranges from 300 to 1 200 m, and the total production is 500 litres/s at 180 to 230 °C.

The area is geologically complex. There is an apparent horizontal stratification of the heat flux. The temperature declines below the permeable horizons.

The decrease of temperature with depth is an interesting phenomenon not fully understood at present. However, the principal practical application is that the area is not one of substantial upward flow.

Iceland possesses Tertiary volcanism, some of it active in several parts of the country.

**Table 5. General features of known steam fields: United States**

| *Name, location, present stage, history, elevation (metres above sea level)* | *Structural geology of the known or inferred sub-soil zones with steam accumulation* | *Remarks* |
|---|---|---|
| *Big Geysers*, California. The first geological observations were made by Brewer in 1861. Geological investigations were privately made for the production of steam to generate electric energy in 1924, first by Decius, and continued in 1955 with the same object. Hyperthermal manifestations occur along a line 8.5 km long in Sonoma County, California. The elevation of Big Geysers is 519 m above sea level. | The results obtained by drilling indicate that the producing zone is a structurally very complex sandstone, which has been fractured and faulted, subjected to intense hydrothermal activity, and undergone alteration as a result. The original rock is a dense grey sandstone with smaller intercalations of lutite; under normal conditions its porosity does not exceed 10 per cent, and its permeability is less than one millidarcy. The relatively high production of the well thus comes from fractures. The sandy formation mentioned is probably of Jurassic age. | Six wells have been drilled in this area first to depths varying between 87 and 121 m, and have later been extended to 226 and 290 m. The temperatures were over 400°F at 280 m during drilling. The previous drilling of 13 wells in this area confirms the above geological situation. |
| *Area of Casa Diablo*, in the south of Mono County, California. Five wells were drilled in 1959 and 1960. | There are considerable volumes of volcanic material at the surface. The producing horizon is probably similar to that of the above zone. Steam production is predicted at a maximum depth of 325 m. | Three of the wells drilled in 1960 over a fault zone, active for over 100 years, reached 192 and 247 m depth respectively. The 3 wells are producers, with a total capacity of 335 000 kg/h of steam at a pressure of 2.37 kg/sq.cm. The exploration is considered to have been only partial. |
| *Area of Calistoga*, Napa County, California. It is located SSE of the Big Geysers zone. It is 29 km from Big Geysers. | Three wells have been drilled in what is called the Franciscan formation of Jurassic sandstones to over 100 m depth. The area is covered by a thick layer of alluvium, making it difficult to determine the structural geology. | |
| *Surprise valley*, California. There was an eruption of mud volcanoes with explosive force in the neighbourhood of this zone in 1951. | The zone is covered by Quaternary sediments and volcanic rock. | Two wells were drilled. One of them was abandoned as non-producing at 652 m in volcanic rock. The other well, 1 029 m to the E of the first one, reached a depth of 357 m, meeting only valley alluvium. |
| *Area of Lakeview*, Oregon. This area was prospected with a well, in view of the existence of thermal manifestations with temperatures up to 180°F. | This area is composed of Tertiary and Quaternary volcanic effusions, with block-faulting. | The well was drilled to 199 m and abandoned as non-producing. |
| *Area of Crump Lake*, Oregon. | | A well was drilled to 512 m, giving a maximum of 170°F. |
| *Area of Wabuska*, Nevada. | There are Tertiary volcanic rocks. There is at least 455 m of alluvial fill. | Three wells have been drilled to over 610 m depth. The hot water obtained was at 140°F, highly charged with sodium sulfate. The project was considered unsuccessful. |

| Name, location, present stage, history, elevation (metres above sea level) | Structural geology of the known or inferred sub-soil zones with steam accumulation | Remarks |
|---|---|---|
| *Area of Steamboat Springs,* Nevada, 16 km S of Reno. | The drilling indicated faulting since Tertiary volcanic rocks appeared at 50 m, while at over 300 m and at the well bottom, there were volcanic rocks and granodiorite. | Four wells were completed, with a maximum depth of 540 m. The first well was abandoned as non-producing. The second well reached 295 m, encountering granodiorite at the bottom. The first tests showed a steam flow of 57 000 kg/h at a production pressure of 2.61 kg/sq.cm. through an 8-inch orifice. The other two wells produced steam, probably from the granodiorite. The probable origin of the heat is a Quaternary rhyolite. |
| *Area of Brady Hot Springs,* Nevada. | This area is an alluvial valley containing Quaternary volcanic effusions. | Three wells were drilled. One of them failed, and two were producers. |
| *Beowawe area,* north central part of Nevada. | Drilling showed andesite, basalt and altered volcanic rock at 50 m depth. At 500 m, traces of slickenside material indicate the presence of faults. | Three wells drilled. The first reached 585 m. The other wells are excellent producers at 152 and 213 m. A fault zone is believed to have been tapped. |
| *Kilauea-Iki volcano,* Hawaii. The eruption of this volcano in 1959 formed a lava lake over 100 m deep in the crater, containing about 100 million metric tons of molten lava. | The heat deposit is the lava stored in the crater. | Drilling and thermal surveys indicate an energy source from which about $2 \times 10^9$ kWh can be recovered. |

In the United States, according to G/48, in the region known as the West, there are about 700 locations of hydrothermal springs, besides the spectacular manifestations in Yellowstone National Park, and about 80 or 90 which can be classified as hyperthermal. The hyperthermal manifestations occur in Oregon, Idaho, California, and Nevada, over about 10 per cent of the total area of the United States. Except for five hyperthermal springs, the others are sufficiently localized around a Pliocene or Quaternary volcanism to conclude that they are directly associated with these phenomena. The intrusive magmas, still retaining much of their initial heat, are believed to be, and possibly are, the only source of the hyperthermal emanations.

The faults and fractures of the overlying rocks provide passage for gases and liquids. The zones of high porosity and permeability in the rock adjoining the heat zones may likewise play an important part in the process.

The prospection of hyperthermal areas may well be confined to surface observations in an area of Recent volcanism, while prospection for production in areas of hyperthermal activity must be by drilling.

Including two wells now being drilled, a total of forty-three wells have been drilled in the western United States for discovery and development of geothermal power. Electric energy is today being produced in one of these areas.

**Table 6. General features of known steam fields: Mexico**

| Name, location, present stage, history, elevation (metres above sea level) | Structural geology of the known or inferred sub-soil zones with steam accumulation | Remarks |
|---|---|---|
| *Pathé field.* Located 7 km W of Tecozautla, in the State of Hidalgo. The present status is exploration and experiment. Elevation 1 550 m above sea level. Drilling started in 1955-1956. | Steam has been obtained at variable depths, due to the fact that the structural control is of faults, which the wells (a total of 12 to date) have intercepted in various zones. The zone that is probably producing consists of a more or less permeable bed of volcanic character of the Upper Tertiary (?), fed through fractures with steam and water. | A turbo-generator produces electric energy from the dry steam of well 2-A. The maximum depth below the surface is 700 m in the other wells. |
| *Valley of Ixtlán.* Situated 22 km NW of Zamora, in the State of Michoacan. Present status : in exploration, with only shallow drilling. | Structural Graben; faulted Tertiary-Quaternary volcanic zone. Alluvium and altered basalts known from two incomplete wells drilled there. | The temperature declines below 150 m. Lake Chapala, 35 km from Ixtlan, influences and will continue to influence the steam production of this field. |
| *Zone of Mexicali.* Situated in Lower California. Elevation 42 m above sea level. Entirely in exploration. | The subsurface structure responsible for the steam production is associated with the San Andres fault zone, whose activity has been manifested in some parts. The affected rocks are Quaternary alluvium and Cenozoic igneous rocks. | Two exploration wells were drilled, meeting a thick cover of alluvium and altered igneous intrusive rock. If the prospecting in this zone is successful, it is hoped to reduce the importation of electric energy. |

**Table 7. General features of known steam fields: Japan**

| *Name, location, present stage, history, elevation (metres above sea level)* | *Structural geology of the known or inferred sub-soil zones with steam accumulation* | *Remarks* |
|---|---|---|
| *Showa-Shinzan area.* Western part of Hokkaido Island. The existence of a subsurface magmatic mass at 800°C was disclosed by geophysical methods. | The zone is composed of Tertiary volcanic rocks. Showa-Shinzan is a volcanic dome parasitically formed almost 16 years ago from the Usu volcano. It is composed of dacitic rock originally at 1 000°C and now at over 800°C. In this locality the igneous masses intrude into deposits of the Pliocene, Pleistocene and Holocene, consisting of lavas, volcanic ash, sand, lapilli, clastic sediments, and pumice rock. The economic and industrial existence of fluids in the permeable rocks overlying the intrusion has not yet been confirmed. | |
| *Matsukawa area.* Northern part of Honshu. This includes a valley in a volcanic district with 3 active volcanoes and other extinct ones, as well as a large number of hot emanations, fumaroles, and sulfur deposits. | Geological work in 1957 has demonstrated that this area consists of a compound and dissected volcano with a central cone, with a collapse caldera structure. The lavas are very compact. The parts lower than the column below 150 m consist of dacite, which is an accumulation of lava and porous tuff containing fragments of pumice. Since 1953 this valley is considered particularly geothermal, probably with an impermeable cover (G/1). | For hot baths, 7 wells were drilled in 1953. Four of them produced steam at a depth of 160 to 300 m. Ten wells in all were drilled to a maximum depth of 450 m, reaching temperatures of 189°C. Production tests indicate that, at diameter 45 mm, the hourly production is one metric ton of steam and 0.3 metric ton of water. |
| *Onikobe area.* Northern part of Honshu. This is an area of elliptic shape, formed by a basin 10 × 1 km. This basin is the result of crustal subsidence in the upper Miocene. | A considerable part of this basin is formed by lacustrine sediments over 300 m thick, which have been penetrated by contemporary dacitic domes. The zone is of Quaternary volcanism, although there are no recent volcanoes. The Onikobe field resembles that of Wairakei, New Zealand, since faults in the basement of very competent rock act as feed ducts for hot fluids ascending from depth to the overlying lacustrine strata, where the heating of the meteoric water in the rock pores, as well as the fractures, initiate a convective geothermal system. | Three wells have been drilled into the lacustrine strata to depths of 255, 250 and 192 m, away from the thermal emanations. Wells 2 and 3 obtained high temperatures of 90 to 130°C at a depth of 110 to 125 m, which depth corresponds to an intercalation of compact andesite in a stratum of tuffaceous breccia. At 255 m the temperature was 185°C. Production tests ran 2 cu. m/h, with steam and water in equal parts. |
| *Beppu area.* North-eastern part of Kyushu. Presents strong surface phenomena comparable to some in New Zealand. | Highly volcanic zone. | Three test wells have been drilled to a depth of 110 m, with a temperature of 145°C. A 75 mm orifice produces 3.4 metric tons/h of steam and water, one-third being steam. Thirty kW of geothermal energy are being generated. |
| *Obama area.* Western part of Kyushu. | Highly volcanic zone. | About 80 wells have been drilled, producing steam and water at 130°C. The total production is 4 200 metric tons/h, which would correspond to 70 000 kW if used to generate electric energy. |
| *Otake area.* Central eastern part of Kyushu. | Highly volcanic zone. | Four exploration wells have been drilled to a maximum depth of 900 m; maximum temperature 185°C. At 150 mm orifice, tests showed 9 metric tons/h, 6 metric tons of which were steam. |
| *Hakone area.* Central eastern part of Honshu. | Highly volcanic zone. | Production 2 metric tons/h, one metric ton being steam. |
| *Noya area.* Northern part of Kyushu. | Highly volcanic zone. | One test well drilled to 200 m; temperature 100°C; the production was one metric ton/h of hot water. |

| *Name, location, present stage, history, elevation (metres above sea level)* | *Structural geology of the known or inferred sub-soil zones with steam accumulation* | *Remarks* |
|---|---|---|
| *Takenoyu area.* Western part of Kyushu. | Highly volcanic zone. | |
| *Unzen area.* W of Takenoyu. Now a tourist centre. | This zone is located in a volcano. | Three wells have been drilled to 30 m depth, giving a temperature of 120°C. The production was one metric ton/h of steam. |
| *Ebino area.* South-western part of Kyushu. | This zone is located in a volcano. | Three wells have been drilled to 75 m, with temperatures 108°C and an hourly production, at 125 mm well diameter, of 12 metric tons of hot water. |
| *Ibusuki area.* S of Tearai. | This zone is located in a volcano. | Tests indicate that 2 metric tons/h of a mixture of steam and water in equal parts can be produced. |
| *Kusatsu area.* Central part of Honshu. | This zone is located in a volcano. | Two wells have been drilled to 200 m, reaching a temperature of 100°C. One metric ton/h of water is produced. |
| *Yamanouchi area.* W of Kusatsu. | This zone is located in a volcano. | A temperature of 100°C has been recorded. Tests indicate that 2 metric tons/h of a mixture of steam and water in equal parts can be produced. |
| *Oshima area.* E of Atagawa. | This zone is located in a volcano. | Three wells have been drilled, temperature 70°C. One metric ton/h of water is being produced. |
| *Atagawa area.* Southern portion of central Honshu. | Area in a volcanic zone. | Tests indicate that 2 metric tons/h of a mixture of steam and water in equal parts can be produced. |
| *Narugo area.* Northern part of Honshu. | Area located in a volcanic zone of the Tertiary. | Twenty-two wells have been drilled to 213 m, reaching a temperature of 175°C. Tests indicate that from 2 to 7 metric tons/h of a mixture of steam and water can be obtained through a 45 mm orifice. The amount of water in this mixture varies from 1 to 6 metric tons/h. |
| *Takinoue area.* Northern part of Honshu. | Area located in Tertiary formations. | |

According to G/1, large areas have been prospected by the Japanese Government since 1947 through its institutions such as the Geological Service, and the electrical companies. The subsoil temperatures measured up to now do not exceed 200°C. Steam is not produced in satisfactory amounts, and is mixed with hot water. Geothermal prospection in Japan is in its initial and preliminary stage.

Intrusive bodies detected in depth by geophysical methods have been studied; and areas have also been studied in which the Tertiary faults break into the granitic basement, transporting high temperature

**Table 8. General features of known steam fields : Soviet Union**

| *Name, location, present stage, history, elevation (metres above sea level)* | *Structural geology of the known or inferred sub-soil zones with steam accumulation* | *Remarks* |
|---|---|---|
| *Area of Pauzhetsk.* This hydrothermal area occurs in the extreme south of Kamchatka, and covers an area of about 400 sq km. Elevation 100 m above sea level (?). In 1958 rotary exploration drilling commenced, and one well reached 800 m depth. | This zone consists of Quaternary volcanic rocks in a tectonic trough, surrounded by volcanic rocks of the Lower Quaternary. These are in turn underlain by a series of Tertiary deposits, consisting of tuffaceous sandstones at 650 m below the surface at Pauzhetsk. An increased production of water and steam is noted on crossing fractures in tuffaceous agglomerates of the Tertiary.<br>The active volcanism of the area is responsible for the accumulation of heat in porous Tertiary formations from which steam and water are drawn by wells. | The flow of thermal water at the surface is estimated at 100 litres/s. Up to 1960 a total of 15 wells were drilled, to 200 to 800 m depth. The maximum temperature reached was 195°C in one well with an enthalpy of 188 K-cal/kg in a mixture of steam and water; the maximum well-mouth pressure was 6.7 atm; the total flow of the field is 150 kg/s, which is considered sufficient to operate a pilot geothermal power station.<br>In the vapour phase, the gas content consists chiefly of $CO_2$, present in quantities over ten times as great as the $H_2S + NH_3$. |

Table 9. General features of known steam fields : El Salvador

| *Name, location, present stage, history, elevation (metres above sea level)* | *Structural geology of the known or inferred sub-soil zones with steam accumulation* | *Remarks* |
|---|---|---|
| *Aguachapan.* Western part of El Salvador. There are two classes of geothermal fluid: water and steam of acid character, and neutral, chlorine-rich, thermal water. This field belongs to the Central Graben, which contains Quaternary volcanism persisting down to historic times. The zone including this field has considerable geothermal activity, and over 40 separate sites are known. Prospection drilling was done from 1956 to 1958, and the deepest reached about 400 m depth. | According to the drilling data, the steam is confined to fissure zones. The geothermal emanations of the country occur in the Quaternary volcanism distributed in two belts 20 km apart. Most of the calorimetric studies in El Salvador have been run in the volcanic belt of the south. The Aguachapan structure has undergone displacements in the Graben up to 1 000 m in the vertical direction; faults at the end of the Pliocene. The Graben has a pyroclastic cover 300 to 500 m thick. The hydrothermal activity is located along the boundary lines of the Graben as well as inside the Graben. The steam is believed to originate in percolating water, fed by hot fluids travelling through fissures in the basement, principally in the region of volcanoes of the Pleistocene. Drilling has shown that the steam is produced from fissures in the Pleistocene cover. | The surface heat losses are : $8 \times 10^4$ K-cal/s, with an average heat flux of about $100 \times 10^{-6}$ cal/sq.cm./s, this figure being comparable with the normal heat flux in El Salvador, which is $2.5 \times 10^{-6}$ cal/sq.cm./s. Sufficient heat to install a plant of 50 to 100 000 kW is expected. The steam produced is low pressure and wet. The hydroelectric potential of El Salvador is $10^6$ kW, of which only about 10 per cent is now being utilized. |

fluids up to the younger overlying sediments with porous rocks. Caldera type volcanic structures have also been identified as well as the associated fractures, in order to learn the geothermal potential when the fluids migrate from depth and are trapped in upper and younger strata of lava.

The first prospecting hole for geothermal power was drilled forty years ago.

The number of steam wells in most of the areas is small. All but a few are shallower than 200 m.

Apparently, from the studies to date, a minimum energy equivalent to 100 000 kW could be recovered from the thermal sources known up to now.

From the analysis, study and comparison in the previous section of the known geothermal zones of the world, we can only repeat that this novel source of energy, geothermal energy, has given good results in the areas exploited in Italy, New Zealand and Iceland, and promises fruitful results in the United States, the Soviet Union, Mexico, Japan and El Salvador. There can be no doubt that, with techniques being improved from day to day, the production of geothermal energy will become economic by comparison with other conventional and non-conventional sources of energy. It is thus essential to devote technique, practice and science to the knowledge that will make it possible to discover new geothermal fields. Prospection techniques will be discussed in the following section.

## Methods and techniques used in geothermal prospection

It now becomes necessary to consider this source of energy as something that is really specialized, although all the methods used to discover, locate or develop thermal zones rely, in one way or another, on the distinctive nature of the zones, that is, they operate with physical, chemical and physico-chemical systems. Water plus heat in the subsoil behave differently from what is observed at the surface, in the form of hydrothermal sources.

Thus, just as oil prospection, in its initial stages, took as points of departure the existence of oil seeps, and wells were sited close to such showings in order to "pinpoint" the deposit in the subsoil; and just as, in many aspects of mining exploration, the existence of gossans, hardpans, etc., was considered as the base for drilling for economic deposits in the subsoil, so, equally, geothermics has had its beginning, in treating of the search for steam deposit in the subsoil, in the existence of hydrothermal sources and steam vents at the surface. But the conclusion was soon reached that the existence of surface manifestations in an area indicates the existence of geothermal energy in the subsoil, but not necessarily the best places for proper siting of wells.

The thermal manifestations are geysers, fumaroles, hot springs, bubbling pools, ponds evolving steam, and mud-pots; likewise the chemical alteration of the rocks, the deposits from hot springs (geyserite, sulfur, alum, etc.) and of products, in general, that could be indications of hydrothermal activity, such as kaolin, pyrite, alunite, chlorites, etc.

Generally, then, it may be said that it is essential to commence by delimiting the thermal area geographically, in accordance with the dictates of observation. Since there is already a certain amount of experience, and certainly bases for comparison with reference to what might be expected to occur in the subsoil, once we know that there is a certain set of conditions at the surface, we must proceed exhaustively and systematically to work directly on the surface.

In this respect, G/54 gives a full treatment, and should be consulted. Under these conditions one must plot surface isotherms, and at 1 metre, at 2 metres, and, in general, at depths not requiring much work, and which can be accomplished with relative ease. From the readings of thermometers and thermocouples, the temperatures over 1°C higher than the average for the formation, and those below an upper limit, for instance 50°C above the average temperature of the formation, are detected. In this way the first thermal anomalies can be located.

The heat flux may next be estimated. By the aid of the following table, we get an idea of this parameter, according to the experience in the New Zealand geothermal fields.

**Table 10. Estimation of heat flux in New Zealand's geothermal fields**

| *Manifestation* | *Heat flux* | *Remarks* |
|---|---|---|
| Abnormally high temperature gradient in the upper strata, unaccompanied by an important amount of steam. | Varies from 1 to 20 gm cal/sq.m./s. | |
| Conductive and convective flux together. | From 4 to 200 gm cal/sq.m./s. | |
| Convective flux. The area is characterized by visible steam, especially at high atmospheric humidity. | From 200 to 2 000 cal/sq.m./s. | The greatest flux comes from light and thermally altered strata, from small fumaroles and, occasionally, from bubbling mud pools. |
| Large fumaroles with discharge vents 15 cm to 1 m in diameter, sometimes yielding slightly superheated steam. | Varies from $10^6$ to $2 \times 10^7$ gm cal/sq.m./s. | |
| Discharge of steam from hot ponds and bubbling mud pools. | Varies from $10^3$ to $1.5 \times 10^4$ gm cal/sq.m./s for calm water up to $1.5 \times 10^6$ gm cal/sq.m./s for ponds in violent ebullition. | The principal discharge is in the form of steam. |
| Steam is discharge from hot springs and geysers. They may be quiet or active. | Of the same order of magnitude as above. | |

The methods of direct measurement in use have adequate instrumentation, such as the Lee disc, the total heat calorimeter, the Venturi collector and tube, the thermocouple and static Pitot tube, according to the nature of the manifestation examined. It is necessary to recognize the superficial conditions of work, and the type of soil in particular, in the zone of heat-flux measurement. In all cases, and for separate areas, one must plot graphs relating the temperature to the heat flux for certain types of material, whether several centimetres below the surface or at a greater depth.

Geological mapping, together with general and detailed reconnaissance, is then pursued in the thermal areas and in the surrounding zones. It is difficult to generalize about the scales used, since the size of the zones for study varies from place to place. It is desirable to convert to a uniform working scale all previous information available, such as geological report, maps of communications, villages, industrial and population centres (the latter is related to adequate utilization if sufficient steam is discovered).

It will not be superfluous to indicate the convenience of having aerial photographs, on the scale of 1 : 10 000, for instance, before starting the geological work on the surface (G/69). The geological work on the field will confirm the findings of the aerial photographs, and one may then proceed to interpret the observations to obtain a structural, stratigraphic and petrological picture as realistic as possible.

As part of the surface reconnaissance, it should not be ignored that vegetation may be an indicator of thermal areas, since a certain type of vegetation is modified in a characteristic way by various temperatures. This indication of the field, aided by aerial photographs, may explain the particular boundaries of thermal areas.

In this state of things, once the list of thermal surface manifestations has been checked, we proceed to chemical analysis, which may be an index and representative of the chemical conditions of the emanations.

Chemical prospection is well situated in this respect within a logical programme of work. G/35 gives ample information, and assigns high importance to the chemical method of prospection.

The chemical analysis will include, with an adequate technique, the sampling and testing of the gas in the steam of the emanations, as well as the condensed steam from the hot waters. It is very useful to know the persistence or variation of the ratios between elements in water from surface sources or from the subsurface of a well in production. G/29 reports, for the case of New Zealand, the costs of a field chemical laboratory, and gives in great detail the methods used in New Zealand for chemical analysis.

The observation of the chemical behaviour of the fluids of a geothermal field in the stage of prospection, and following it, during the production tests, throws light on the possible duration and amount of steam production. G/42 and G/46 separately explain the method of chemical sampling appropriate for geothermal areas.

According to G/35, starting out from the study of active areas, we conclude that a thermal area in detail has characteristic ratios which are constant in this area, but very different from those of other parts. The low gas content of the steam in the fumaroles, and marked variations in the $CO_2/H_2S$ and $CO_2/NH_3$ ratios indicate that the steam is being evolved from boiling water in the subsurface water which, in the case of New Zealand, contains chlorides.

The values of the ratios Cl/As, Na/Li and Na/Ca for all the areas of a region are useful for judging the uniformity of a magma, and for detecting areas belonging to an earlier period of activity, as well as for comparison of the region with others of the world.

The ratios Cl/B, Cl/F and $Cl/SO_4$ are useful to determine the possible suitability of drilling, if the area in question is similar to Wairakei.

As for the sampling of hydrothermal springs, the methods for sampling gas and steam of the fumaroles differ according to whether the gas content of the steam is high or low.

In areas under consideration for drilling, it is essential first to sample the waters of the manifestation with clear water in good flow. The principal manifestation must also be sampled in areas within the entire region of activity, even though many of them are not suitable for drilling, for practical reasons.

It is advisable to determine the following constituents: $Cl/HBO_2$, Cl/F, Cl/As, $Cl/SO_4$, $Cl/NH_4$, Na/K, Na/Li, Na/Ca, Ca/Mg, as well as the silica and bicarbonate (ions), and if possible the ratios Cl/Br, Br/I, As/Sb, Na/Rb, and Na/Ca.

From these ratios, a group characteristic for each area is sought.

At the same time the gas content in the steam of some fumarole in the area should be determined, as well as the ratios $CO_2/H_2S$ and $CO_3/NH$ (G/35).

The conditions indicating the existence in the subsurface of a trap favourable to the commercial accumulation of steam presuppose the use of various physical parameters of the rock. In certain respects, the geophysical exploration here resembles that in prospection for hydrocarbons. One must therefore make use of certain parameters, such as the temperature, the magnetic susceptibility, density, electrical conductivity, velocity of propagation of elastic waves, and the radioactivity.

The temperature gradient is determined by thermometer measurements. Three papers, G/61, G/54 and G/25, give full information on the scope and method of temperature measurements. G/25 mentions temperature measurements on the bottom of wells not over 10 m in depth, and likewise suggests this procedure to avoid the surface fluctuations of temperature. It must also be realized that in the first stage of a thermal survey, not only is the thermal anomaly known geographically, but the incidence of thermal springs is likewise indicated with assurance.

The magnetic properties relate to the intensity of magnetization of a small volume of rocks produced in a unit field. A Schmidt balance is used to determine the variations of the vertical component of the earth's magnetic field. A magnetometer is used only in aerial prospecting. The members of the reservoir rock and of the cover formations are sedimentary strata, in which the magnetic susceptibility is very low. Further than that, the magnetic effect may even be completely masked by volcanic or metamorphic strata, so that in this way one may more or less fail to learn of the possible existence of the cover formation (G/25). It should be noted that, in some places, magnetic prospection has served to focus or locate heat sources, since, owing to the action of $H_2S$, the hydrothermal alteration of the magnetite causes the formation of non-magnetic pyrite. Therefore, when variations in the magnetometric intensity are observed, one must bear in mind that it is of interest to know the decreasing magnetic values of the hydrothermal strata, since they indicate the origin of the hydrothermal activity.

An important parameter is the density, which is used in the gravimetric method of prospection. The variations of the intensity of gravity between the measurement stations and a reference station are measured. The gravimetric method is better adapted than the magnetic method, which has the disadvantage of including all the effects of the surface strata as well as the deep strata in the measured value. Important data on the tectonics are obtained by this method.

The electrical conductivity method is most definitely recommended in geothermal investigation, since the results that can be obtained are the most complete (G/25).

For the general reconnaissance, electric logging is recommended in a network 500 $\times$ 500 m, with four stations to each square kilometre. For semidetail studies, networks 250 $\times$ 250 m are used. The drawing of a resistivity map is suggested for better siting of the initial prospecting wells.

The adaptability of the electric prospecting method to the technical problems that arise is emphasized, as well as the fact that it permits explorations and reconnaissance that are considerably more complete, faster and clearer. The resistivity of a formation depends strictly on its temperature. Thus, if a stratum changes its temperature from 17° to 150°C, its resistivity falls to $\frac{1}{5}$; it falls to $\frac{1}{9}$ if the temperature goes from 17° to 280°C (G/25). Electric prospection permits the drawing of a resistivity map down to depths corresponding to the object of determining whether there are hot zones at the bases of the impermeable formation. It may also be learned whether or not a fracture, that is the cause of the geological structure, is fed by fluids.

The seismic methods are based on measurements of the velocity of propagation of elastic waves, which are proportional to several constants and parameters, such as the modulus of elasticity, the density, and the modulus of incompressibility. The seismic methods include reflection and refraction, depending on whether the energy reflected from the interfaces is utilized, or whether, on the other hand, the wave has passed through formations of different nature, to emerge at the surface after travelling on a certain path. Seismology takes account of the subsurface geological structure on the basis of the velocities of seismic waves.

The radioactive method, which measures the radioactive substances that may be transported by faults and fractures, is also considered. In any case, the results obtained by any single method are fortuitous, and it is of advantage to employ complementary methods. In the last analysis, the drill will speak the last word.

Drilling is considered one of the phases of prospection. During the preliminary development of a geothermal area, it is advisable to drill pilot wells of diameter AX ($2\frac{1}{4}$ inches) with a diamond drill and core sampler, to determine the geological section of the formation in which the steam is accumulated, or down to where it is tapped, in case a fracture is encountered. Smaller diameters are used, in principle, not merely to save money, but also to save time, so as to get a picture of the general geothermal conditions more rapidly. The temperatures, the geothermal alteration of the rock encountered by the test well, the preliminary analysis of the fluids collected, and pressure observation under the conditions so produced, will make the situation clear enough to formulate the drilling programme with greater accuracy and delicacy in siting the larger-diameter wells, which require substantial investment (of the same order of magnitude, for instance, as that required by oil wells).

The purpose of drilling a well with an initial diameter of, say, 20 inches, is not only to site the geological exploration for confirmation. There is always the hope that it may be a producing well. The well spacing will depend on the productive capacity of the field, and on the need of providing the geothermal turbines for electric power with a certain hourly flow of steam, if the energy is to be used to generate electricity. If it is to be used for heating purposes, the arrangements will be different.

Italy is a country where geophysical methods of exploration have been used successfully — the electric method for the most part. The chemical method has been successfully employed in New Zealand, while several geophysical methods have been used on a limited scale in Japan. All these countries have run extensive initial and continuing temperature and heat-flux surveys. In all countries involved, whether they have actual geothermal developments or are merely considering them for the future, it is absolutely essential to start out with the fullest possible geological knowledge about the areas that deserve attention.

## Some views on the origin of the heat and steam in geothermal zones

It is difficult to attribute to any single origin the heat and steam that occur in all areas of the world with geothermal manifestations. In some cases, the evidence will disclose certain causes; in others, the explanations will be different, but in any case one always seeks to adjust them to the actual features of the areas under study.

Isotope studies show that the amount of magmatic steam in all the thermal areas studied up to now is not much more than 5 to 10 per cent of the total amount of hydrothermal fluids. Thus the component of meteoric origin predominates. The increase in temperature rise with depth is due to heat conduction from the magma through the rock, and in reality only a small proportion of the heat is transferred to the magmatic steam itself (G/2).

The high-temperature geothermal areas are due to volcanic heat, and most of the water is of meteoric origin. When the heat supply is great and the permeability of the rock is low, dry steam is formed.

When the fracture system extends to great depth, the meteoric water migrates within a tremendous convection system, and is first heated by conduction through the rock; heating then continues as a result of the condensation of volcanic steam. In the case of New Zealand, the authors suggest that alkali-metal chlorides are continuously transported from the magma. They estimate that a depth of the order of 3 000 m for the zone of steam condensation would be necessary in order to have continuous transport of chlorides.

G/3 states that the water becomes heated in deep circulation as a result of the conduction by hot rock. The largest share is that of primary water released at depth, which arrives at the surface mixed to a greater or lesser degree with meteoric water. This primary water may be either metamorphic connate water or magmatic water.

The isotopic evidence mentioned by G/31 indicates a magmatic contribution of the order of 10 per cent in the thermal fluids of New Zealand.

The normal thermal equilibrium of an area may be affected by: the presence of an intrusive magma rising sufficiently close to the surface to heat the surrounding rock, and, consequently, the interstitial water as well; by extravasation of extrusive igneous rocks, which, owing to their relatively recent activity, still retain a large amount of heat; by heat from volcanoes; by heat from the disintegration of radioactive elements; and possibly from the heat that might be generated by the slip friction of the formation adjoining the faults.

An intrusive body first causes heating at the depth at which it may be in contact with the interstitial water, or may influence that water, so that this heat, transferred by conduction, will be manifested at the surface in the form of steam passing through feed channels, whether these are fractures, discordances, etc. (G/48).

There is an interesting discussion in G/35, according to which an intrusion measuring 7 × 7 × 1 km at depth of 3 km solidified in 40 000 years. During this time the circulating waters entrained the steam, together with the chemical components in the separated magmatic fluid. A deposit 20 × 10 × 1 km was then formed into strata of 5 per cent porosity under an ignimbrite cover at a depth of 3 km. The heat contained in the water and the rock could supply the natural activity of Wairakei for 4 000 years.

Studies based on geochemical prospection show that the heat in chloride water could not all be due to magmatic steam, since in that case the juvenile water content would have to be around 35 per cent. From the chlorine content of this chloride water, its juvenile water content is inferred to be about 8 per cent, and, in agreement with the oxygen isotope evidence, a possible content of 5 per cent is indicated in the thermal water (G/35).

The high lithium and cesium content of the waters of Wairakei or the water of the thermal areas could not have resulted from leaching or entrainment by the magmatic steam, but must have come from a residual aqueous phase of a crystalline magma (G/35).

## Considerations on the evaluation of the capacity of geothermal zones

In zones in the preliminary stage of development, with no steam production as yet, it is customary to proceed on the basis of comparison. In a new zone, with certain characteristics, what can be expected, if we know that other zones have certain other characteristics? No conclusion as to the productive capacity can be formulated without actual drilling. The preliminary tests during the initial drilling of steam wells will throw the first light on this subject.

In an area scheduled for development, with no previous drilling information, or very little of it, the siting of the exploration wells should be based on surface reconnaissance, according to data of geophysics, geology, geochemistry, etc. (G/53). The preliminary objective will be to drill test wells to confirm the inferences from these surveys, and then to supply detailed information about the present formations, including their most important physical properties (porosity, permeability and density) and the existing physical conditions, that is, the temperature and pressure of the fluids, the nature of the percolating fluids, etc. As information from the initial drill holes is obtained, preliminary sections and temperature profiles are drawn as a guide for subsequent siting of discovery wells.

In fields or areas where steam is now being produced or has in the past been produced, evaluation demands more tool and details to meet this requirement. The observations, embodied in the gas-steam and steam-water ratios; the well-bottom and well-mouth temperatures; chemical analyses of the various phases of the fluids; the pressures under various conditions; and the fluid discharge per hour; the corrosion aspects; the deposition of calcite and silica; the meteorological and hydrological features —all these factors, interconnected and interrelated in one way or another, are important elements of any judgement evaluating the capacity of a field in production.

At Wairakei, the data selected have permitted the completion of a schedule of isotherms at a depth of 850 m.

In addition to the above characteristics, the hydrostatic pressure, the heat output, and the heat in the rock, should also be listed in order to evaluate the capacity of the geothermal field.

The total area of the thermal formation, the heat flux and the water flow rate, may be learned and estimated from surface thermal surveys. From this information, preliminary investigations of the power potential may be made in accordance with the graphs (G/53) relating :

1. The available potential of water flow up to 170°C (varying this temperature from 50° to 170°C) to the kW/kg of steam per second, with the depth in metres also entering into the graphs.

2. The enthalpy in cal/gm, at temperatures varying from 50°C to 400°C, plotted against kW/kg/s (between 0 and 700), the depth also being taken into account. This graph indicates the available power potential of hot water flows up to the critical temperature.

3. The storage of energy in water-saturated rock under depth conditions, below the boiling point, may likewise be learned. This graph relates the enthalpy in cal/cm to the energy per unit volume in joules/cc, using the total energy as an additional variable for separate curves of the same graph, expressed in $10^6$ joules/cc; the depth is also introduced as a variable.

4. The power, in megawatts/year, may be estimated from the enthalpy in cal/gm, the depth in km, and the area in sq. km.; curves of depth and area are obtained for a given energy storage in water-saturated rock, which is assumed to yield 25 per cent of the total.

The reader is referred to G/53 for extremely valuable details on these aspects of preliminary evaluation, with special reference to the Wairakei zone.

G/75 sets forth ideas on the evaluation of the fundamental characteristics of a new well in steam production; a logical and rational programme must be carried out, to establish measurements of the steam discharge, based on the relations between discharge pressure and mass flow rate through the surface orifice, for which a calibrated outlet is used.

The gas-steam ratio, or the volume of gas corresponding to a certain weight of condensed steam, is measured by means of specially designed instruments (G/75). Values are found determined from the closed-valve pressure, with pressure readings at regular time intervals. To use the most accurate means of measuring the water-steam mixture in a producing well, the steam and water must be separated, and each phase separately measured. Cyclone and axial separators have been designed for this purpose.

Adequate information is essential to the proper use of the necessary technical and scientific aid assistance in the evaluation of geothermal zones. In this respect, G/76 summarizes the methods and the analyses performed at the Larderello investigation laboratories. In general, the samples of gas or steam are examined after collection and cooling of the natural fluids by water cooling systems. Very interesting conclusions have been obtained in the course of this work, such as the fact that the abundance of $Ar^{40}$ in the so-called endogenous gases is higher than in the atmosphere; the isotopic composition of the $CH_4$ indicates an organic origin; the isotopic composition of the $CO_2$ indicates a contribution of $CO_2$ derived from limestone. The permanent gas phases are collected together or separately, like the residual gases, and the noble gases argon and helium are quantitatively estimated; both these and the residuals ($CH_4$, $N_2$, $H_2$) are recovered after absorption of the principal gaseous constituents in the form of $CO_2$ and $H_2S$.

Where the thermal gradient is normal, the thermal conductivity is 12 000 cal/s/sq.km. The high-intensity thermal areas possess a heat flux at least fifty times as great as the normal. Thus the measurement and estimation of the heat flux in new areas, and in the known areas, are highly necessary and desirable, to be able to know whether or not they are really geothermal resources.

The evaluation of the heat flux, of the steam/water ratio, of the chemical content, and thus of the possible production, requires experience in order to judge and recommend the implementation of specific projects for energy generation or the recovery of valuable salts. It is essential, if this evaluation is to be valid, to sample the well discharges, which are processed by correct techniques and systematic procedures.

G/46 discusses the requirements for adequate sampling in the light of the flow systems encountered in the horizontal discharge piping of Wairakei. This paper is very adequately illustrated, which is another reason why it is so useful, besides being simply expressed. The gas contents are analysed in the steam samples, condensed in water-cooled flasks of several litres capacity. Analyses are also run for the dissolved components, ammonia, boric acid, fluorine and chlorine. The sampling necessary for specific estimation is given, such as that of the principal ions and the trace metals, the isotope ratios, and the determinations of pH and of dissolved gas.

G/30 mentions various methods suggested for measuring the quantities of steam and water discharged by the wells, and refers to the fact that the bulky equipment used to measure these quantities presents a practical problem. The author then recommends apparatus that is readily portable and will simply determine the mass flow at a certain pressure at the wellhead. He describes the methods used in New Zealand, including the beta ray method, the gas method, the magnesium sulfate injection method, and the critical pressure method.

From the work at the Kilauea-Iki volcano of Hawaii, G/5 estimates that the volcanic receiver contains $3 \times 10^{16}$ cal. To melt this amount of rock by a nuclear explosion, about 100 megatons would be required. If only the latent heat of fusion ($0.75 \times 10^{16}$ cal) were recovered and converted into electricity at a thermal efficiency of 25 per cent, this would yield $2 \times 10^9$ kWh.

An estimate given in G/48 suggests the idea that a cubic mile of rock, such as the Devil's Tower in Wyoming, in cooling from 1 800°F to 100°F, would liberate sufficient heat to operate a 4 000-kW power station for 7 000 years. Studies of igneous bodies of previous geological ages show that a cubic mile is a very small portion of the great masses exposed by erosion.

Dry steam cannot be expected normally in hydrothermal areas at depths above 3 000 m. Meteoric water must circulate to such depths to maintain a pressure higher than the critical pressure of pure water, embracing the zones of condensation and mixture. A column of pure water at boiling point reaches critical pressure at a depth of 3 500 m.

The apparent absence of chloride water in the areas of superheated steam suggests that meteoric water does not penetrate to such depths, or does not do so in appreciable quantities. The chlorine in these zones is probably retained in the magma.

According to the information from New Zealand, the existence of dry steam is improbable in an area where the superficial manifestations contain an appreciable amount of chlorine (over 20 ppm). An abundance of acid sulfate manifestations close to the boiling point, but of moderate flow, favours the possibility of the existence of dry steam at depth.

An area containing manifestations in the boiling state and sodium chloride in appreciable amounts, presenting relatively high K/Na and Li/Na ratios, may possibly have a considerable temperature rise with depth.

Diluted, neutral or alkaline spring waters will, in general, probably not have markedly higher temperatures in depth, even if their surface ambient is of moderately high temperature.

The maximum temperatures obtained from shallow wells may be used for an acceptable pre-development estimate of the continuous heat flux in a hydrothermal system. The total surface and subsurface discharges of water may likewise possibly be determined directly, or by a chlorine inventory. In this way it was possible to determine the heat fluxes for many New Zealand systems, amounting to millions of calories a second.

In Big Geysers, the zone of iron sulfides — pyrite and marcasite — indicates the possibility of subsurface correlation, but more data will still be necessary. A tendency to loss of circulation is noted, especially in areas where the cores show open seams. These data were useful in determining the steam-producing zones.

The experience in Italy, New Zealand and elsewhere permits us to observe that the preliminary evaluation, based on the superficial manifestations of the heat flux in a geothermal area, gives a figure lower than that subsequently obtained by drilling and steam production. It is thus of advantage to bear this experience in mind whenever, in dealing with investments, a higher recovery of steam can be ensured by means of production than could have been predicted from the preliminary analyses.

## The problem of deposition

It is important to mention the problem of silica and calcite deposition, since such incrustation reduces the rate of flow of the fluids.

Silica is precipitated from surface flows with water at temperatures under 100°C. Some waters are exceptionally high in $SiO_2$. The solubility of amorphous silica is about 350 ppm at 100°C, and probably 500 ppm at 150°C.

Deposition is considered to occur only when the silica content exceeds the solubility limit of amorphous silica as a result of the cooling and evaporation caused by the evolution of steam. In that case the polymeric forms of silica are suspended in the solution and deposit a film on the surface. The growth of quartz crystals appears to be too slow for this less soluble form of stable silica to form deposits in the casing, even though it does deposit in the rock of the hottest zones.

The waters of Wairakei reach the saturation point for amorphous silica at 140°C and saturated vapour pressures of about 40 psi. If the water is used at higher temperatures, very little difficulty can be anticipated.

As for calcite, it is known that the total concentrations of calcium and bicarbonate in thermal waters are usually high enough to cause calciting problems. A typical Wairakei well, discharging 200 tons of water per hour, has a loss of one ppm of calcium from solution, and can form 0.5 kg of $CaCO_3$ in an hour. If concentrated in a 1-metre length of 8-inch pipe (since these deposits are in general localized) the diameter would be halved in only 50 days.

Calcium carbonate is deposited in hydrothermal sources of pH 6 to 8, when the dissolved calcium exceeds a few ppm. The production of fluids at intermediate pressure can avoid the precipitation of carbonates in depth. Silica deposition gives serious trouble in waters with over 350 ppm of $SiO_2$.

## Brief considerations on costs and other economic aspects

Diamond drilling in 1950 cost $18 a metre in the west of the United States. In Mexico this cost today is about $25 a metre.

The drilling of the sixteen exploration and producing wells in Mexico, by the churn and rotary drilling systems, to the maximum depth of 700 m at present, including the first installation of a geothermal power plant at Pathé, has cost $640 000 in four years. This figure also includes the previous exploration and the pay of technical personel and labour. Of these sixteen wells, twelve are at Pathé, two at Ixtlân and two at Mexicali.

The annual cost of geothermal operations in New Zealand during the past ten years has ranged from $55 000 to $138 000. The cost of a portable laboratory for the chemical prospection of a field, including all the appropriate equipment, has been estimated in New Zealand at about $4 000.

G/48 states that the following factors very seriously deserve to be taken into consideration when contemplating an economic operation: the available market, the value of a kilowatt-hour of electric energy in that particular market, collective exploitation, and the production costs of natural energy. A field able to supply energy that can be used to generate between 2 000 and 3 000 kWh can be operated successfully. In the United States, the results obtained during the last two years give grounds for hoping that at least six areas in the west will be capable of competitive economic operation.

This disagrees with G/67, according to which an industrial geothermal field is one capable of producing about five million metric tons of steam a year. According to this paper, a commercial steam field produces a substantial amount of water—for instance, Larderello produces something like ten million metric tons of water a year.

In Japan, the partial information available indicates that investment has been about 119 million Japanese yen.

It has been demonstrated (G/5) that there exists a drilling rig capable of handling exploration work at over 1 000°C, and of resisting highly corrosive conditions.

From this, the authors infer that the design of craters engineered to trap a lava flow along known zones of passage in active volcanic areas is no longer beyond the realm of possibility. The lava basins could be sited around a central power station, and

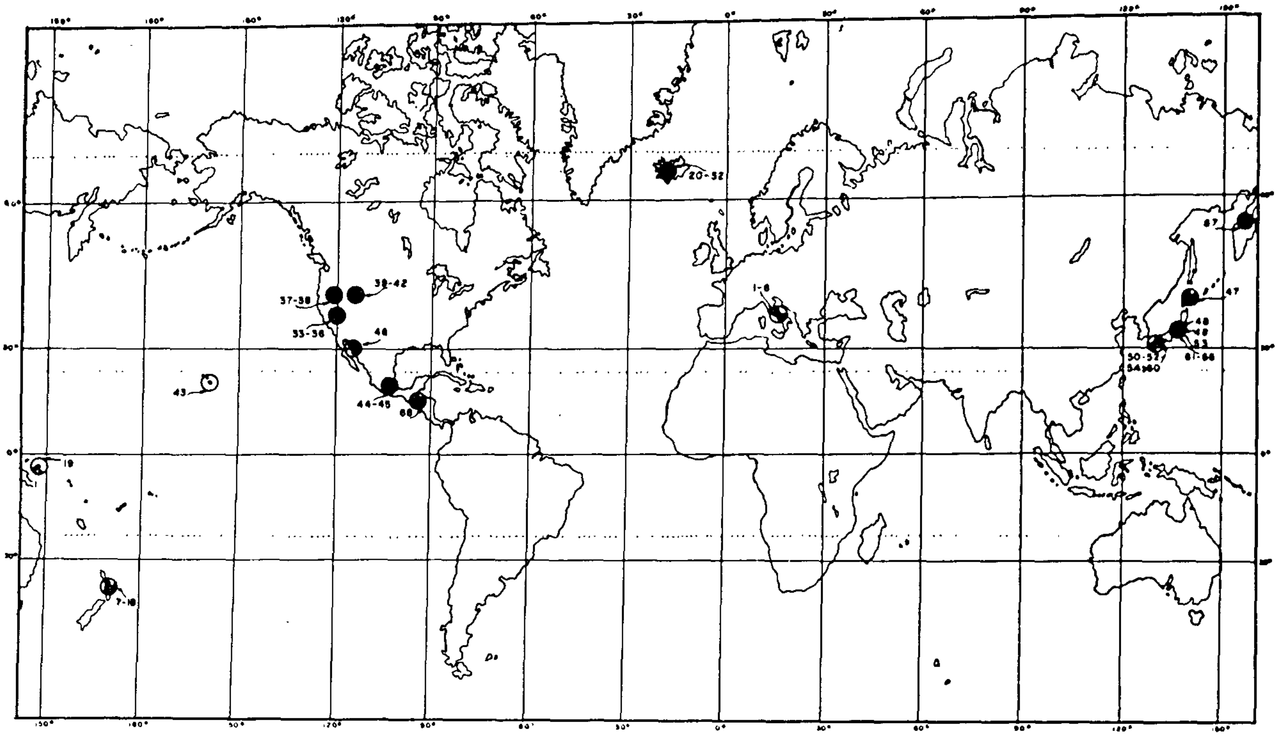
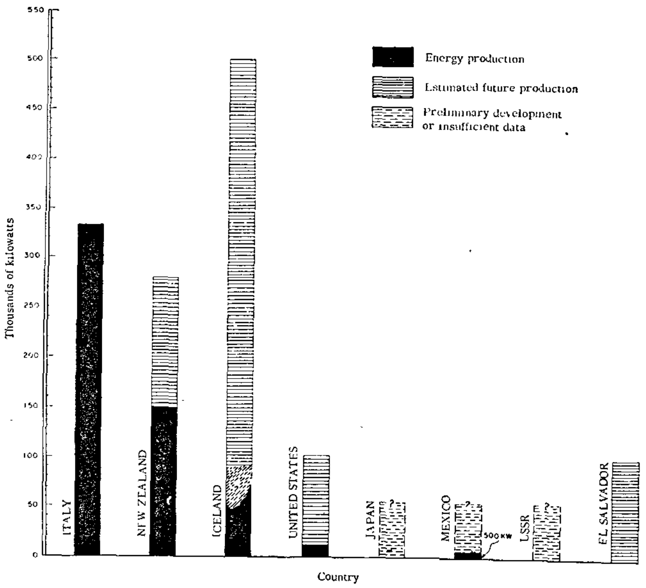


**Figure 1. Distribution of known geothermal zones in the world**

THEORETICAL GEOTHERMAL POWER AND ENERGY PRODUCED IN CERTAIN COUNTRIES




ITALY

1. Larderello
2. Monte Amiata
3. Roccastrada
4. Montecatini-Orciatico
5. La Tolfa
6. Monti Berici

NEW ZEALAND

7. Wairakei
8. Waiotapu
9. Kawerau
10. Orakeikorato
11. Tikitere
12. Tekopia
13. Waikiti
14. Taupo
15. Ngatamariki
16. Rautawiri
17. Rotokawa
18. Tauhara

NEW BRITAIN

19. Matupi
    Rabalanakaia-Vulcan

ICELAND

20. Reykjanes
21. Trolladyngja
22. Krysuvik
23. Hengill
24. Kerlingafjöll
25. Torfajökull
26. Vonarskard
27. Grimsvötn
28. Kverkfjöll
29. Askja
30. Namafjall
31. Krafla
32. Theistareykir

UNITED STATES

33. Big Geysers
34. Casa Diablo
35. Calistoga
36. Surprise Valley
37. Lakeview
38. Crump Lake
39. Wabuska
40. Steamboat Springs
41. Brady Hot Springs
42. Beowawe
43. Kilauea Volcano, Iki, Hawaii

MEXICO

44. Pathé
45. Ixtlan
46. Mexicali

JAPAN

47. Showa-Shinzan
48. Matzukawa
49. Onikobe
50. Beppu
51. Obama
52. Otake
53. Hakone
54. Noya
55. Takenoyu
56. Unzen
57. Ebino
58. Yunono
59. Tearai
60. Ibusuki
61. Kusatsu
62. Yamanouchi
63. Oshima
64. Atagawa
65. Narugo
66. Takinoue

SOVIET UNION

67. Pauzhetsk

EL SALVADOR

68. Aguachapan

in a region sufficiently active to supply continuous power. The natural period for the Kilauea basin to cool is estimated at over seventy-five years.

There is an opportunity to learn the industrial use of subsurface reservoirs of molten rock, such as could be formed by deep nuclear explosions, or from the magmatic subsurface deposits that could exist in active volcanic regions. At 5 mills/kWh, this energy would be worth $10 million. It is therefore very significant that the Kilauea lava deposits and similar bodies of molten rock constitute substantial natural resources.

The United States papers state that there has as yet been no prospection in the western United States outside of areas where thermal activity can be observed on the surface.

In that part of the world, the regions of late volcanism are suitable for steam prospection in an area of 60 000 square miles, including part of the States of Idaho, Oregon, California and Nevada. This type of prospection will also include the northern part of Oregon and the south-eastern part of Washington, in an area of 85 000 square miles, since there are favourable prospects for the existence of Miocene to Recent volcanism there.

### Proposed topics for discussion

1. In areas with volcanic Pliocene to Recent rock, lacking superficial hydrothermal manifestations, what will be the possibilities of finding commercial steam in the subsurface?

2. Should all pre-Pliocene volcanism and the igneous rocks associated with it (that is, more ancient than 500 000 years) be entirely eliminated from the natural-steam picture?

3. Discuss the economy of geothermal prospection—that is, what method of prospection has been found to be cheapest and most effective?

4. Is there an argument for the view that zones with credible evidence of hydrothermal activity are potentially vaporiferous?

5. How are thermal manifestations deriving their heat from tectonic, magmatic or volcanic effects to be distinguished? How is it possible to distinguish tectonic steam from magmatic steam?

6. How much can be said, on the basis of parameters, about the active life of a geothermal field? We mean parameters such as the gas-steam ratio; the steam-water ratio; the surface and subsurface temperatures and pressures; the mass-flow rate of fluid in kg/h; and the chemical composition of the fluids.

7. What parameter is in reality most important for the above question?

8. The variation and chemical composition of hydrothermal fluids collected at the surface indicates separate origin and paths for separate areas. Can this variation, assuming a primary influence, give us an idea whether the geothermal energy involves magmas (intrusive, in a state of cooling), acid, intermediate or basic?

9. How does the chemical composition of hydrothermal water vary from that of sea water?

10. How do the prospecting costs of steam wells (exclusive of drilling costs) compare with those required for other sources of energy, for instance petroleum?

11. What depth is considered economic in steam production? Certain authors apparently consider that a certain base temperature can be reached by going deeper than 3 000 m to obtain dry steam. Discuss this question as related to the varying nature of the formations.

12. Since it is of considerable importance in steam production, and in view of the trouble it causes, we propose discussion of the deposition of calcite and silica in the casing and pipelines, and in the zones adjacent to drilled wells. Specifically, from the experience up to now, what measures can be adopted to eliminate this incrustation?

13. How many kilowatts must a field produce to be considered pontentially economic?

14. We propose discussion of a general drilling programme to obtain steam at a certain depth in a fractured volcanic formation. What is the minimum diameter of the casing reaching the surface for the production to be commercial in the case where 150 kg/s of steam are produced, at given temperature and pressure?

# PROSPECTION DES CHAMPS GÉOTHERMIQUES ET RECHERCHES NÉCESSAIRES POUR ÉVALUER LA PUISSANCE UTILISABLE

*(Traduction du rapport précédent)*

*Jesús Ruiz Elizondo**

## Aspect général de l'énergie géothermique

De nombreux pays réalisent leurs programmes énergétiques grâce aux sources classiques d'énergie — pétrole, charbon et eau. Les perspectives offertes pour un avenir prochain par la disponibilité de l'énergie nucléaire dans des limites économiques, auront pour conséquence un prolongement de l'existence des hydrocarbures et du charbon dont l'importance pour l'obtention de produits divers est grande, plus grande, si on veut, que s'ils étaient utilisés simplement comme combustibles.

L'histoire rapporte que les sources, appelées aujourd'hui, sources nouvelles d'énergie, étaient en réalité connues des peuples de l'antiquité et il est probable que certaines d'entre elles ont été utilisées de façon rudimentaire. Ces nouvelles sources d'énergie sont les vents, le soleil, les marées, les réservoirs thermothalassiques, les champs géothermiques. La vie moderne et la nécessité d'assurer de plus grandes ressources d'énergie pour permettre à l'humanité de suivre son chemin de progrès et de bien-être exigent, chaque fois que cela est possible, de mettre à profit ces nouvelles sources d'énergie à l'aide de techniques modernes et à la lumière des progrès scientifiques.

Les pays qui se trouveront réellement dans des conditions plus favorables en ce qui concerne leur avenir économique, sont, on le sait, ceux qui disposeront de plus grandes ressources naturelles, techniques et économiques. Il est logique d'inclure les sources d'énergie parmi les ressources naturelles; les pays que la nature a pourvus de combustibles naturels en abondance, n'ont pas en réalité beaucoup de sujets de préoccupation. Cependant, ceux dont les ressources en combustibles naturels sont moins importantes, mais qui néanmoins progressent et désirent progresser, pour améliorer les niveaux de vie de leurs peuples, ce qui est naturel et à quoi il faut s'attendre, doivent invariablement chercher à découvrir d'autres sources d'énergie qui ont pu rester insoupçonnées pendant un certain temps et lorsqu'ils les trouvent, les faire produire pour éviter de la sorte les restrictions associées à l'obligation d'importer à cause d'une insuffisance de l'énergie disponible.

Au cours de nombreux siècles, l'existence de manifestations telles que les geysers et les fumerolles a joué un certain rôle dans diverses parties du monde. Dans certains cas, ces manifestations, qui constituent souvent un spectacle imposant, ont fait l'objet d'une exploitation primitive, sous la forme de lieux de récréation et de bain; il n'était pas rare, non plus, que les eaux thermales soient utilisées à des fins thérapeutiques ou, parfois, comme source de chauffage pour les habitations.

Il ressort d'un grand nombre d'études réalisées jusqu'à présent que la source géothermique d'énergie n'est pas renouvelable et que sa durée est de nature temporaire. Cette considération est valable toutefois à l'échelle de la vie moyenne de l'homme. Les régions du monde telles que l'Italie et la Nouvelle-Zélande, qui ont développé avec succès leurs programmes géothermiques, présentent des preuves qui permettent de dire que l'utilisation de l'énergie géothermique apporte des bénéfices incalculables aux pays et aux régions qui en disposent et que sa durée peut être en général suffisante pour permettre l'amortissement des investissements et cela avec une marge de bénéfices substantiels qui stimulent l'économie locale et générale.

L'énergie géothermique consomme la chaleur présente dans la croûte terrestre, près de la surface ou à une profondeur qui ne dépasse pas la limite de l'exploitation économique; elle est obtenue sous forme de vapeur. En outre, des sous-produits chimiques de grande valeur peuvent être obtenus, comme en Italie. La variation de la température en fonction de la profondeur s'appelle le gradient géothermique. Une anomalie géothermique est constituée par l'existence, en un lieu donné, de valeurs supérieures de l'accroissement de la température par mètre de profondeur, phénomène qui ne se produit pas dans les conditions normales. Par conséquent, l'étude de l'énergie géothermique proprement dite à des fins utilitaires, devra être effectuée en fonction des anomalies géothermiques.

A la prospection des champs vaporifères est associée la nécessité de perfectionner les techniques pour obtenir l'énergie disponible dans les régions thermales. La connaissance des recherches géothermiques est, en réalité, récente. Les méthodes de prospection ont fait l'objet de progrès sérieux, non seulement grâce à la recherche scientifique, mais également par suite de l'expérience pratique acquise. La méthode est la clé du succès pour le travail

* Comisíon Nacional de Energía Nuclear, Mexico (Mexique).

d'exploration et de recherche des champs vaporifères, circonstance commune à diverses branches du domaine de la géologie économique. Cet aspect réunit plusieurs paramètres bien connus : argent, temps, connaissances, objectifs et bénéfices. Il ne fait pas de doute que pour obtenir quelque chose de la nature, il est nécessaire de consentir à certains risques et à certains investissements. Les risques seront moindres et les investissements plus sûrement justifiés seulement lorsqu'une expérience solide aura été acquise; mais, en général, cette expérience coûte cher.

On connaît actuellement dans le monde un certain nombre de champs vaporifères qui sont la source de bien-être et de profit pour les habitants de divers pays. On pourrait dire que ces champs vaporifères ont tous un facteur commun : ils représentent la ténacité et la pensée authentique, pleine d'ingéniosité. L'homme, qui dédie son temps à la recherche du pétrole, du charbon, des matières fissiles et des sites pour les barrages, constate que l'énergie que peuvent fournir les champs vaporifères est plus facilement récupérable et permet d'omettre une série d'étapes qui sont inévitables dans l'exploitation de l'énergie provenant d'autres sources. C'est pourquoi la source géothermique d'énergie est l'une des moins chères. Certes, on l'a dit plus haut, cette source ne constitue pas une réserve renouvelable; il n'est pas facile de prévoir sa durée de vie à l'échelle d'une exploitation complète; à ce sujet, on ne peut qu'indiquer d'une façon générale sa nature temporaire.

## Objet de ce rapport

L'auteur participe aux travaux de cette conférence en qualité de rapporteur sur l'invitation du Secrétariat général de l'Organisation des Nations Unies. Lors de la rédaction de ce rapport, près de 40 communications étaient déjà parvenues révélant l'enthousiasme, l'intérêt suscité par cette matière et, peut-être au fond, un besoin latent d'augmenter le nombre de kilowatts par habitant, tendance qui est justifiée, naturelle et inévitable tant dans les pays à haut niveau de développement que dans les pays dits sous-développés. L'Italie, la Nouvelle-Zélande, l'Islande, les États-Unis d'Amérique, le Mexique, le Japon, l'Union des Républiques socialistes soviétiques, le Salvador, la France et la Belgique sont au nombre des pays qui présentent des travaux sur les divers aspects de la prospection géothermique. Le présent rapport a pour but de rendre compte d'une façon très générale du problème constitué par la prospection des zones géothermiques ainsi que des considérations et des critères qui permettent d'évaluer l'importance de ces dernières.

## Remerciements

L'auteur tient à exprimer sa profonde gratitude au Secrétariat de l'Organisation des Nations Unies qui lui a donné la possibilité de collaborer avec cette organisation à l'étude sur l'énergie géothermique et qui lui a offert une assistance constante sous la forme d'une orientation précise et sûre.

L'élaboration de ce rapport n'aurait pas été possible sans l'impulsion et sans l'aide de diverses organisations mexicaines, ou d'amis et de collègues. M. José Maria Ortiz Tirado, président de la Commission nationale de l'énergie nucléaire, a autorisé l'auteur à effectuer ce travail, tout en lui assurant les facilités correspondantes. La Banque du Mexique et la Commission de l'énergie géothermique ont également suivi avec un grand intérêt la rédaction de ce rapport.

L'auteur exprime ses remerciements les plus sincères à toutes les personnes citées ci-dessus et aux auteurs d'environ quarante ouvrages, dont les noms sont indiqués dans la table des matières, pour leur contribution substantielle.

## Description des champs vaporifères

Cette partie du rapport général contient une description sommaire des champs vaporifères connus. Les renseignements présentés sont fondés en grande partie sur les rapports revus par l'auteur et concordent avec certaines conclusions personnelles, obtenues antérieurement.

Les tableaux 1 à 9 ont été élaborés par souci de simplicité. Ils groupent par pays les champs vaporifères connus, en production au stade du développement préliminaire (fig. 1).

Ces tableaux comprennent trois colonnes : la première colonne à gauche contient l'indication du nom, de l'emplacement du champ vaporifère du pays considéré et de son état actuel : production, étude précédant la production ou, simplement, prospection et investigation initiales des étapes fondamentales qui aboutissent à la découverte d'un champ vaporifère; on a indiqué également dans cette colonne, les données historiques et l'altitude en mètres du champ géothermique en question, ainsi que la hauteur de l'horizon ou du gîte dont on extrait l'énergie géothermique sous forme de vapeur, dans la mesure où il est possible de connaître cette donnée. Le but de ces dernières indications est d'établir statistiquement la relation entre la production et l'altitude des champs vaporifères.

La deuxième colonne indique de façon concise la constitution et les formations rencontrées dans le piège géologique à vapeur du sous-sol. L'origine, le déplacement et l'emmagasinage de la vapeur souterraine qui fournit à la surface de l'énergie utilisable, feront l'objet d'un intérêt chaque jour croissant.

La dernière colonne de ces tableaux concerne les facteurs qu'il n'est pas toujours possible de connaître et qui, par conséquent, ne peuvent pas être tous indiqués. On a tenté de présenter les connaissances relatives au flux calorifique superficiel et au flux calorifique des fluides souterrains de champs vaporifères considérés, celles qui sont relatives à la quantité d'énergie produite par le champ, s'il se trouve à l'étape de la production, et celles qui concernent les recherches ayant trait à l'évaluation de cette production dans le cas où elle n'a pas encore été établie. Enfin, cette colonne contient également les renseignements complémentaires qui sont jugés nécessaires pour une description concise et rapide des champs, zones ou régions géothermiques de pays considérés. Il a semblé opportun de compléter cette description, séparément et en dehors du tableau, par des indications supplémentaires.

**Tableau 1. Caractéristiques générales des champs vaporifères connus**

ITALIE

| *Nom, lieu, état actuel, antécédents, altitude en mètres* | *Aspect géologique et structural des zones du sous-sol connues ou supposées, avec accumulation de vapeur* | *Remarques complémentaires* |
|---|---|---|
| *Larderello*, à 17 km au sud de Volterra. Le dégagement naturel de vapeur était connu avant 1777, année où fut découverte la présence d'acide borique.<br>Le fondateur de l'industrie boracique est le comte Francesco de Larderel. Le champ porte le nom de Larderello en son honneur. Autres points dans la proximité de Larderello: Serrazzano, Lagoni Rossi, Lago, Monterotondo, Sasso et Castelnuovo, tous en Toscane.<br>Larderello est un champ en production. La région de Larderello couvre une surface de 400 km² et empiète sur les provinces de Pise, de Grosseto, de Sienne et de Livourne. Son altitude maximum est de 1 000 m. | Couche imperméable de terrain de l'oligocène-miocène, appelée localement « argille scagliose » (argile schisteuse), surjacente en discordance à une série perméable anhydritique du rhétien qui contient la vapeur. Les fractures émergent d'une base cristalline et il est probable qu'elle est liée à une masse intrusive en refroidissement, située à quelques kilomètres de profondeur au-dessous de la série anhydritique. | La première usine géothermo-électrique de 40 CV a été installée en 1905.<br>La profondeur moyenne de forage est de 700 m, la profondeur maximum est de 1 600 m.<br>Un ensemble de 160 puits produit 2 850 000 kg de vapeur par heure à une température et à une pression absolue moyennes de 200 °C et 5 atm.<br>La production annuelle d'énergie du champ de Larderello est de $2 \times 10^9$ kWh. |
| *Monte Amiata,* à 70 km au sud-est de la zone de Larderello, dans les provinces de Sienne et de Grossetto, en Toscane. Ce champ se trouve au stade de l'exploration et de la production. Son altitude est de 1 738 m. | Comme à Larderello, l' « argille scagliose » est en contact direct avec la série sous-jacente anhydritique (qui contient de la vapeur), mais les sédiments contiennent des effusions d'ignimbrites volcaniques et plutoniques. | Les températures de surface des sources thermales ont varié entre 20 et 50 °C. La profondeur des sondages est de 400 à 1 000 m. Des 12 puits actuels, 5 produisent 1 000 kg/h d'un fluide qui contient 30 p. 100 de gaz à une pression absolue de 5,5 atm et à une température de 150 °C. |
| *Roccastrada*, à 30 km au sud-est de Larderello, dans les provinces de Sienne et de Grosseto, en Toscane. Se trouve au stade de l'exploration et de l'investigation. | Probablement semblables à ceux de Monte Amiata. | Les températures de surface des sources thermales oscillent autour de 55 °C. |
| *Région de Montecatini-Orciatico*, à 25 km au nord de Larderello, dans la province de Pise, en Toscane. Se trouve au stade de l'exploration et de l'investigation. | Semblables au précédent. | Les premiers sondages ont été commencés. En surface, les températures des sources thermales oscillent autour de 55 °C. |
| *Région de la Tolfa*, à quelques kilomètres du littoral tyrrhénien, dans la province de Rome. Se trouve au stade de l'exploration et de l'investigation. | Semblables au précédent. | Les sondages préliminaires ont été commencés. |
| *Région des Monts Berici*, dans la province de Vicence, en Vénétie. Se trouve au stade de l'exploration et de l'investigation. | Le réservoir géologique où s'accumule la vapeur est probablement formé de roches d'origine volcanique récente. | |

A la lumière de cette description générale des champs géothermiques italiens, dont les caractéristiques sont uniques, il n'est pas possible de procéder à un examen suffisamment concis de la question de savoir si la vapeur est d'origine endogène ou exogène (c'est-à-dire si elle provient de fluides magmatiques ou, principalement, d'eau météorique). L'acquisition de bases suffisantes pour pouvoir considérer un réservoir géologiquement favorable présente une importance primordiale dans une région où se produisent les manifestations thermales. Cette considération d'ordre pratique apparaît à tous ceux qui s'occupent d'exploration dans le domaine des champs de vapeur. Elle pourrait avoir pour conséquence l'exécution de sondages dans des régions de l'Italie où il n'existe pas de manifestations en surface. Après tout, si la chaleur est associée, ne serait-ce qu'en partie, à des masses intrusives situées à une certaine profondeur, il importe de connaître l'existence des formations perméables et imperméables successives capables de former des réservoirs géologiquement favorables de chaleur ; les fluides peuvent être le résultat d'une influence profonde magmatique et superficielle météorique. La considération pratique du piège peut être plus avantageuse en donnant l'idée correcte de la géométrie de structure des formations en profondeur. C'est pourquoi il convient de recommander l'exécution de recherches géologiques détaillées ainsi que d'études gravimétriques, électriques et sismiques avant celle de tout sondage. Les études hydrogéologiques constituent un outil complémentaire, tandis que la géologie isotopique et la géochimie ont le rôle important d'étudier l'origine et l'évolution des éléments constituant les fluides.

Malgré ce qui précède et compte tenu du fait que l'Italie est le premier pays en ce qui concerne le développement de l'énergie géothermique, le domaine d'investigation et de production y est encore très étendu.

**Tableau 2. Caractéristiques générales des champs vaporifères connus**

NOUVELLE-ZÉLANDE

| *Nom, lieu, état actuel, antécédents, altitude en mètres* | *Aspect géologique et structural des zones du sous-sol connues ou supposées, avec accumulation de vapeur* | *Remarques complémentaires* |
|---|---|---|
| *Wairakei*, à 16,5 km au nord-est du lac de Taupo, dans la partie centrale volcanique, district de North Island. L'altitude est de 396 m. Se trouve au stade de la production. | Prédominance des roches volcaniques. La formation de Waiora, avec des couches intrusives localisées de rhyolite, est composée de brèches de pierre ponce post-mésozoïque et forme un réservoir qui constitue le gîte de chaleur, avec des températures atteignant 260 °C. Elle est recouverte par des lits de lacs imperméables de la formation Huka. La succession des couches est traversée par des fractures de forte inclinaison du pléistocène moyen qui coupent les ignimbrites sous-jacentes.<br>Au sommet des ignimbrites, les fissures sont larges et ouvertes. On suppose qu'il peut exister d'autres pièges structuraux sous l'ignimbrite de Wairakei.<br>L'âge probable du champ hydrothermal est de 500 000 ans (pléistocène moyen, selon G/34). | La région thermale de Wairakei comprend des parties thermiques soit actives, soit éteintes. La vapeur sous pression de Wairakei provient de puits forés dans les failles principales actives.<br>La région située à l'ouest de ce champ comprend 20 puits qui produisent au total 480 000 kg/h de vapeur sous haute pression.<br>La partie orientale possède plusieurs puits produisant près de 135 000 kg/h de vapeur sous haute pression; 22 puits produisent de la vapeur sous une pression intermédiaire. Environ 10 puits ont été jugés improductifs. |
| *Waiotapu*, situé à 48 km au nord-est de Wairakei, North Island. Ce champ se trouve au stade de l'exploration. Tous les puits, à l'exception du nº 1 (6) débutent à une altitude inférieure à 457 m. | Brèches douces, tant au-dessus qu'au-dessous d'ignimbrites dures. L'ensemble porte le nom de formation Waiotapu. | Les sept puits forés jusqu'à présent atteignent une profondeur de 1 080 m. Le plan du puits 8 est achevé. La durée totale de l'investigation a été de trois ans.<br>Les forages les plus profonds fournissent des températures élevées, atteignant 295 °C selon G/17.<br>La puissance estimée est de 10 000 kW en utilisant la vapeur primaire et secondaire des eaux thermales. |
| *Kawerau*, à 98 km au nort-est de Wairakei et à 8 km du village de Teteko. Les manifestations de Onepu se trouvent à 2,5 km au nord de Kawerau qui est traversé par la rivière Tarawera. Ce champ se trouve actuellement au stade de l'investigation. Son altitude est supérieure à 20 m. | Le champ se trouve dans la bande volcanique principale du Quaternaire de North Island.<br>La brèche de pierre ponce forme un aquifère recouvert de laves rhyolitiques épaisses. De l'andésite fortement fracturée se trouve au-dessous de cette brèche, de même que de l'ignimbrite.<br>Ce champ est traversé par de nombreuses failles actives. | Douze puits ont été foncés en vue de l'exploration. L'andésite fissurée produit de la vapeur sous haute pression et à 270 °C. La pénétration d'eau froide agit de façon négative sur l'aquifère de la brèche en refroidissant les puits de vapeur qui ont fonctionné pendant trois ans.<br>Le niveau des eaux phréatiques a baissé. La différence entre ce champ et ceux de Wairakei et de Waiotapu est constituée par la présence de coulées rhyolitiques à la place des ignimbrites. La température la plus haute mesurée jusqu'à présent est de 253 °C à une profondeur de 500 m. L'observation publiée dans *N.Z.J. Geol. Geoph. 1* (1958) et selon laquelle, depuis le début |

| *Nom, lieu, état actuel, antécédents, altitude en mètres* | *Aspect géologique et structural des zones du sous-sol connues ou supposées, avec accumulation de vapeur* | *Remarques complémentaires* |
|---|---|---|
| | | de ce siècle et jusqu'à présent, les manifestations, qui avaient un caractère alcalin, sont devenues acides, est très intéressante. Toutefois, cette acidité n'est que superficielle puisque l'alcalinité augmente avec la profondeur. La teneur en chlore est de 300 à 600 ppm. Le flux calorifique estimé pour Onepu est de 25 000 kcal/s, ce qui correspondrait à 100 MW théoriques. |
| *Orakeikorato* se trouve au stade de l'investigation (?) [a]. | | Le flux naturel de chaleur, estimé relativement à 0 °C, est de $860 \times 10^6$ BTU/h. |
| *Tikitere* se trouve actuellement au stade de l'investigation (?) [a]. | | Le flux naturel de chaleur, estimé relativement à 0 °C, est de $570 \times 10^6$ BTU/h. |
| *Tekopia* se trouve actuellement au stade de l'investigation (?) [a]. | | Le flux naturel de chaleur, estimé relativement à 0 °C, est de $430 \times 10^6$ BTU/h. |
| *Waikiti* se trouve actuellement au stade de l'investigation (?) [a]. | | Le flux naturel de chaleur, estimé relativement à 0 °C, est de $290 \times 10^6$ BTU/h. |
| *Taupo,* régions thermales voisines du village de Taupo. Se trouve actuellement au stade de l'investigation [b]. | | Le flux de chaleur estimé est de 35 900 kcal/s. |
| *Ngatamariki,* dans les bancs de Orakonui, près de la rivière Waikato, se trouve actuellement au stade de l'exploration (?) [b]. | | Le flux calorifique n'a pas été évalué. |
| *Rautawiri,* à l'inclusion des régions thermales de Ohaki et de Broadland. Se trouve actuellement au stade de l'exploration (?) [b]. | | Le flux de chaleur estimé est de 23 100 kcal/s. |
| *Région de Rotokawa,* traversée par la rivière Parariki. Se trouve actuellement au stade de l'investigation [b]. | | Le flux de chaleur estimé est de 52 100 kcal/s. |
| *Tauhara,* près de la route Taupo-Napier, se trouve actuellement au stade de l'investigation (?). | | Le flux de chaleur est insignifiant. |

[a] J. A. H. Smith, "Production and utilization of geothermal steam", *N.Z. Engineering,* vol. 13, nº 10 (1958).
[b] D. R. Gregg, *N.Z.J. Geol. Geoph.,* vol. 1 (février 1958).

L'étude gravimétrique de la région de Wairakei a révélé l'existence d'une anomalie attribuée antérieurement à un soulèvement de la base; on a pu cependant vérifier qu'elle était due en réalité à une série de plus de 500 m d'épaisseur de roches rhyolitiques. Il en découle que l'application de la gravimétrie dans la prospection des champs vaporifères est sujette à des limitations.

Les puits ont été forés dans les failles à des distances de 150 à 300 m; dans certains cas, ils sont voisins et la production n'est pas affectée de manière sensible par la présence d'autres puits dans les failles, dans la partie ouest de Wairakei.

La connaissance de la stratigraphie et de la structure est indispensable pour économiser le temps et l'argent, puisque les fractures qui produisent de la vapeur sous haute pression sont grandes et ouvertes au sommet de l'ignimbrite de Wairakei. Si les forages n'atteignent que les parties supérieures, on ne peut être assuré de l'obtention de vapeur à haute pression; il en découle la nécessité de cimenter les fissures, ce qui demande du temps et de l'argent. Le sondage dans l'ignimbrite et dans les zones de failles n'a pas abouti à une augmentation importante de la production.

Dans les puits à haute pression (de plus de 200 livres par pouce carré) en production, le rôle des variations de la température et de la perméabilité est notable. La température diminue à partir de la fracture jusqu'à l'aquifère. La perméabilité de l'aquifère est affectée par les modifications hydrothermiques des roches. La brèche de Wairoa devient imperméable à cause du dépôt de substances minérales d'origine hydrothermale.

Les puits qui ont été forés près de fractures d'alimentation, sans les traverser, sont généralement improductifs; c'est pourquoi on a adopté la pratique de forer dans les fractures.

Le dégagement des puits subit l'influence du dépôt de calcite et de silice dans la roche encaissante (à 300-500 m); ce dépôt réduit le diamètre uniforme et la pression à la tête du puits ainsi que la production, mais ces phénomènes sont fréquemment accompagnés d'une légère augmentation de l'enthalpie. Il ne se produit pas de dépôt minéral dans les fissures produisant de la vapeur.

Le flux de chaleur de l'aquifère du champ de Wairakei est commandé par le même tableau d'intersection des failles.

Les rapports Na/K se présentent d'une manière qui peut permettre de supposer que même la vapeur d'une seule région ne provient pas d'une source unique.

En ce qui concerne l'estimation de la production de chaleur, il existe en Nouvelle-Zélande une méthode qui tient compte, dans le but d'obtenir une indication assez approchée, du contenu en chlore des forages et du contenu de la vapeur naturelle en chlore.

Le rapport gaz-eau est de 30 p. 100.

Il est très difficile d'évaluer la capacité totale de production du champ de Wairakei, la meilleure évaluation étant celle qui provient d'une étude minutieuse des orientations du flux de chaleur naturelle et du comportement des différents puits.

Le champ de vapeur de Waiotapu a été étudié, comme au Mexique et en d'autres endroits, à l'aide de photographies aériennes. Le dépôt de calcite dans les conduites de revêtement est plus rapide qu'à Wairakei.

Il en résulte que les forages peu profonds s'obstruent et sont inutilisables pour la production d'énergie. Les puits profonds où les pressions et les températures sont élevées, ne présentent pas de dépôts de calcite.

Comparé à Wairakei, ce champ possède un rapport élevé des bicarbonates et un rapport faible des chlorures. On considère généralement qu'une faible concentration de chlorures indique que l'eau a été chauffée par la vapeur.

**Tableau 3. Caractéristiques générales des champs vaporifères connus : Nouvelle-Bretagne (Territoire sous tutelle de la Nouvelle-Guinée)**

| *Nom, lieu, état actuel, antécédents, altitude en mètres* | *Aspect géologique et structural des zones du sous-sol connues ou supposées, avec accumulation de vapeur* | *Remarques complémentaires* |
|---|---|---|
| *Région de Rabalanakaia-Matupi-Vulcan*, Rabaul, au nord des baies Simpson et Blanche. En fait, la caldera est occupée par le village de Rabaul. Dans cette région, l'énergie électrique est produite à l'aide de générateurs Diesel. D'après G/12, la présence de phénomènes géothermiques a fait considérer la possibilité d'obtenir 5 MW dans un délai de 8 ans et d'arriver à 20 MW par échelons de 5 MW.<br>Les régions possédant un flux de chaleur notable se trouvent entre 15 et 30 m au-dessus du niveau de la mer. Les manifestations thermales naturelles se trouvent au-dessous du niveau supérieur de la marée haute et leur température varie entre 40 et 98 °C. Une éruption du volcan Matupi, actif en 1942, a eu lieu en 1937. Des éruptions du volcan Vulcan se produisirent en 1878 et 1937. | On n'a pas identifié de couche de recouvrement imperméable, mais il est possible que des coulées de lave provenant du Rabalanakaia aient formé des lits confinés.<br>Couches perméables entre les coulées de lave d'époque récente. Il se peut que les coulées de lave forment des recouvrements imperméables sur les sédiments à argile ou à pierre ponce. | Le flux de chaleur est associé étroitement à la présence des volcans Matupi et Vulcan, du cratère de Rabalanakaia et de la paroi orientale de la caldera.<br>La quantité de chaleur qui se dégage ne donne pas nécessairement une mesure de la quantité de chaleur qui pourrait être obtenue par forage profond. Selon G/12, si les résultats des premières investigations révèlent l'existence d'un flux de chaleur de l'ordre de $10^9$ BTU/h, il conviendra d'étudier le système en vue de la génération de 20 MW.<br>Il est recommandé de forer à plus de 500 m de profondeur; le prix de l'investigation proposée peut atteindre 200 000 livres sterling. Ces puits, s'ils s'avèrent productifs, pourront alimenter une usine, les conduites devant être recouvertes et cimentées convenablement. |

A Rabaul, en Nouvelle-Bretagne, si les résultats de l'exploration préliminaire se révèlent satisfaisants, on procédera au fonçage définitif qui décidera de la possibilité d'une production de 20 mégawatts dans ce champ.

Les derniers forages devraient débiter pendant au moins un an, aux valeurs de la pression et des dépenses prévues pour l'état final de production de puissance.

Au cours de cette période, on effectuerait des vérifications continues de la pression et de la température au fond du puits ainsi que de la variation du débit. Ce dernier point comprendrait également les mesures de la quantité de vapeur et de la quantité d'eau ainsi que celles de leur composition chimique.

La mesure du débit de chaleur naturelle et celle des autres propriétés physiques impliquerait une dépense d'environ 10 000 livres sterling.

**Tableau 4*a*. Caractéristiques générales des champs vaporifères connus : Islande**

*Zones thermales à haute température*

| *Nom, lieu, état actuel, antécédents, altitude en mètres* | *Aspect géologique et structural des zones du sous-sol connues ou supposées, avec accumulation de vapeur* | *Remarques complémentaires* |
|---|---|---|
| *Région de Reykjanes*, dans la zone néovolcanique du quaternaire, sud-ouest de l'Islande. Son altitude est de 15 m et son étendue de 1 km². | Zones perméables comprises entre des couches de lave, affectées par des filons perméables et des failles. | Le dégagement de chaleur a été estimé entre 5 et 25 × $10^6$ cal/s. Le seul puits qui ait été foncé atteint une profondeur de 162 m. |
| *Région de Trölladyngja*, dans la zone néovolcanique du quaternaire, sud-ouest de l'Islande. Son altitude est de 120 m et son étendue de 5 km². | Zones perméables comprises entre des couches de lave basaltique, affectées par des filons perméables et des failles. | La production de chaleur estimée se trouve entre 5 et 25 × $10^6$ cal/s. |
| *Région de Krysuvik*, dans la zone néovolcanique du quaternaire, sud-ouest de l'Islande. Son altitude est de 150 m et son étendue de 10 km². | Semblables aux précédents. | La production de chaleur varie entre 5 et 25 × $10^6$ cal/s. Quinze puits ont été foncés avec une profondeur maximum de 1 200 m. La température de base est d'environ 230 °C. |
| *Région de Hengill* dans la zone néovolcanique du quaternaire, sud-ouest de l'Islande. Son altitude est de 30 à 600 m et son étendue de 50 km². | Semblables aux précédents. | La production de chaleur estimée se trouve entre 25 et 125 × $10^6$ cal/s. La température de base est de 230 °C. De nombreux puits ont été foncés à une faible profondeur; 8 puits atteignent des profondeurs dont le maximum est de 1 200 m. |
| *Région de Kerlingafjöll*, dans la zone néovolcanique quaternaire de la partie centrale orientale, moitié ouest de l'Islande. Son altitude est de 900 m et son étendue de 5 km². | Zones perméables comprises entre des formations basaltiques, affectées de murs et de failles. | La production de chaleur estimée se situe entre 25 et 125 × $10^6$ cal/s. |
| *Région de Torfajökull*, dans la partie sud de la moitié orientale de l'Islande. Son altitude est de 900 m et son étendue de 100 km². | Semblables aux précédents. | La production de chaleur est de 125 à 750 × $10^6$ cal/s, avec une valeur moyenne de 5 × $10^8$ cal/s. |
| *Région de Vonarskard*, dans la zone néovolcanique quaternaire, presque dans la moitié orientale de l'Islande. Son altitude est de 1 000 m. | Semblables aux précédents. | La production de chaleur estimée se situe entre 5 et 25 × $10^6$ cal/s. |
| *Région de Grimsvötn*, dans la zone néovolcanique quaternaire de la moitié orientale de l'Islande. Son altitude est de 1 000 m et son étendue de 12 km². | Semblables aux précédents. | La production de chaleur est estimée entre 125 et 750 × $10^6$ cal/s. Cette région se trouve sous la couche de glace de Vatnajökull. |
| *Région de Kverkfjöll*, dans la zone néovolcanique quaternaire de la moitié orientale de l'Islande. Son altitude est de 1 500 m et son étendue de 10 km². | Zones perméables comprises entre des formations basaltiques affectées par des murs et des failles. | La production de chaleur est estimée entre 25 et 125 × $10^6$ cal/s. |
| *Région de Askja*, dans la zone néovolcanique de la moitié orientale de l'Islande, à 1 050 m d'altitude. | Semblables aux précédents. | La production de chaleur est estimée entre 5 et 25 × $10^6$ cal/s. |
| *Région de Namafjall*, dans la zone néovolcanique de la moitié orientale de l'Islande, à 350 m d'altitude. Superficie : 2,5 km². | Semblables aux précédents. | La production de chaleur est estimée entre 25 et 125 × $10^6$ cal/s. Il existe quelques puits peu profonds. |
| *Région de Krafla*, dans la zone néovolcanique de la moitié orientale de l'Islande; 450 m d'altitude. Superficie : 0,5 km². | Semblables aux précédents. | La production de chaleur est estimée entre 5 et 25 × $10^6$ cal/s. |
| *Région de Theistareykir*, dans la zone néovolcanique de la moitié orientale de l'Islande, à 330 m d'altitude. Superficie : 2,5 km². | Semblables aux précédents. | La production de chaleur est estimée entre 5 et 25 × $10^6$ cal/s. |

**Tableau 4b. Caractéristiques générales des champs vaporifères connus : Islande**

*Zones thermales (agglomération linéaire) à basse température*

| *Nom, lieu, état actuel, antécédents, altitude en mètres* | *Aspect géologique et structural des zones du sous-sol connues ou supposées, avec accumulation de vapeur* | *Remarques complémentaires* |
|---|---|---|
| 50 km (?) au nord-ouest de Torfajökull. | Terrains volcaniques dans des districts tertiaires. | Débit naturel total : 52 l/s; température maximum en surface : 100 °C; flux de chaleur : 25 à 125 × $10^6$ cal/s. |
| 50 km (+) au nord-ouest de Torfajökull. | Identiques aux précédents. | Débit naturel total : 140 l/s. Température maximum en surface : 100 °C. Flux de chaleur : 5 à 25 × $10^6$ cal/s. |
| 60 km (+) au nord-ouest de Torfajökull; comprend le Great Geyser. | Identiques aux précédents. | Débit naturel total : 6 l/s. Température maximum en surface : 100 °C. Flux de chaleur : 5 à 25 × $10^6$ cal/s. |
| 40 km à l'ouest de Krysuvik. | Identiques aux précédents. | Débit naturel total : 70 l/s. Température maximum en surface : 100 °C. Flux de chaleur : 5 à 25 × $10^6$ cal/s. |
| Près de Trolladyngia. La température à la base est de 98 °C à Reykir; il existe 70 puits avec une profondeur maximum de 1 380 m. Production des puits : 370 l/s à 87 °C. | Identiques aux précédents. | Débit naturel total : 120 l/s. Température maximum de surface : 83 °C. Flux de chaleur : 5 à 25 × $10^6$ cal/s. |
| Au nord-ouest de Reykjanes, près de Reykjavik. La température à la base est de 146 °C à Reykjavik. Il existe 40 puits avec une profondeur maximum de 2 200 m et une production de 134 l/s à une température de 138 °C. | Identiques aux précédents. | Débit naturel total : 10 l/s. Température maximum de surface : 88 °C. Flux de chaleur : 5 à 25 × $10^6$ cal/s. |
| Dans la partie sud-ouest de l'Islande : en fait, c'est un système de lignes qui comprend la plus grande manifestation d'eau chaude à Deildartunga. | Identiques aux précédents. | Débit total naturel : 400 l/s. Température maximum en surface : 100 °C. Flux de chaleur : 25 à 125 × $10^6$ cal/s. |
| A l'ouest de Akureyri. | Identiques aux précédents. | Débit naturel total : 70 l/s. Température maximum en surface : 89 °C. Flux de chaleur : 5 à 25 × $10^6$ cal/s. |

Le potentiel total des ressources thermiques naturelles de l'Islande est de l'ordre de 500 mégawatts d'énergie électrique.

Les régions thermales de l'Islande dépendent de contacts perméables entre des couches de lave, des filons perméables et des failles.

La « circulation » peut avoir lieu au fond des basaltes, c'est-à-dire à 2 ou 3 km de profondeur. Dans les régions de haute température, la chaleur semble être fournie par des structures volcaniques chaudes récentes. L'eau qui circule est en contact direct avec les roches chaudes. Par contre, les régions à basse température fournissent de la chaleur naturelle qu'elles semblent prendre des réserves existant dans les parties basses ou profondes des basaltes. Dans la région de circulation, la température peut être de 100 à 130 °C. Dans les régions de haute température, il existe des réserves de chaleur en excès qui peuvent être exploitées au moyen de forages.

Les régions de basse température sont caractérisées par des manifestations d'eau chaude et par des températures souterraines inférieures à 150 °C et se trouvent dans la zone du tertiaire. Les régions de haute température se trouvent dans la zone du quaternaire. Le débit total de chaleur naturelle est évalué à $10^8$ cal/s dans les régions à basse température et probablement à $10^9$ cal/s dans les régions à haute température.

On connaît environ 250 champs géothermiques de basse température répartis sur les terres basses de la moitié orientale du pays. Le nombre des manifestations est élevé — environ 600 — et le débit total estimé atteint 1 500 l/s. La production de chaleur des sources hydrothermales atteint $10^8$ cal/s, avec une température moyenne de 75 °C.

Selon Bodvarsson, la limite supérieure des températures souterraines est de 150 °C dans la zone de basse température (G/6). A partir de ce critère, cet auteur conclut que les conditions tant chimiques que physiques du sous-sol changent considérablement à mesure que la température s'élève au-dessus de 150 °C.

Près de 70 000 m de puits ont été forés en Islande dans le but d'exploiter les réserves naturelles de chaleur. Le puits le plus profond, qui se trouve dans la ville même de Reykjavik, atteint 2 200 m. On se propose de foncer plusieurs dizaines de milliers de mètres de puits dans les années à venir.

Les études des régions thermales de l'Islande, effectuées au moyen de forages, ont mis en évidence un fait important, savoir : la production de chaleur des puits est supérieure à celle que donnait la région thermale lorsque les puits n'existaient pas encore. Dans un cas, l'augmentation a atteint un facteur 20.

Le potentiel total de production continue et uniforme d'énergie des régions thermales de l'Islande a été évalué à 300 mégawatts, et le réservoir de chaleur récupérable serait de 15 000 mégawatts par an.

Actuellement en Islande, la chaleur naturelle est utilisée principalement pour le chauffage des maisons d'habitation et des serres. La quantité totale de chaleur utilisée correspond à une économie annuelle d'hydrocarbures d'environ 60 000 tonnes, soit 350 kg par an et par habitant (selon les renseignements tirés de G/24).

La température maximum mesurée jusqu'à présent dans les champs thermiques d'Islande est de 230 °C. Le gradient de température des régions non thermales varie entre 0,033 et 0,0165 °C/m.

Dans certains cas, les données géochimiques peuvent fournir des indications sur les températures de réaction.

Le fluide du forage provoque des conditions non stationnaires, refroidissant ou réchauffant les formations dans lesquelles sont pratiqués les trous.

Les méthodes géochimiques révèlent qu'il existe une corrélation positive entre la température de la source hydrothermale et la quantité totale de solides dissous. Ainsi, dans le cas des sources hydrothermales, l'eau qui sort à 30 °C peut contenir 150 ppm de solides alors que celle qui sort à 100 °C peut en contenir 300 ppm.

Des mesures combinées thermiques, gravimétriques et magnétométriques, effectuées dans la région thermale de Reykjavik, ont montré l'existence d'un flux ascendant d'eau chaude à l'ouest de l'intrusion. Au total, 25 puits ont été foncés dans cette région au cours des six dernières années, en se fondant sur les études antérieures. La température maximum de production est de 138 °C, la profondeur maximum est 2 200 m et le débit total d'eau chaude est de 135 l/s; cette eau est utilisée pour le chauffage des habitations de Reykjavik.

La température de base de la région est de 146 °C; elle se maintient à partir de 1 000 m de profondeur.

La région de Reykir est la première en date des grandes régions thermales exploitées en Islande. Les forages ont été entrepris en 1933; en 1954, il y avait déjà 70 puits dont la profondeur maximum était de 621 m. Ces puits produisent 360 litres par seconde d'eau à 87 °C de température moyenne. Cette région comporte des dislocations en blocs et une faille principale SO-NE de l'époque tertiaire. En 1959, un nouveau puits a été foncé jusqu'à une profondeur de 1 380 m. A la profondeur de 670 m, la production était insignifiante. Les mesures de température montrent qu'au passage d'une petite fissure située à 670 m, la température tombe de 98 à 90 °C. La région thermale de Reykir semble dépendre d'une couche horizontale poreuse et de plusieurs failles.

La région thermale de Hengill constitue l'un des champs vaporifères les plus étendus d'Islande. Il existe un projet de construction d'une usine d'énergie utilisant la vapeur naturelle.

Les forages à grande échelle ont été entrepris en 1958. Actuellement, huit puits sont achevés. Leur profondeur varie entre 300 et 1 200 m et leur production totale atteint 500 l/s avec une température de 180 à 230 °C.

Du point de vue géologique, cette région présente une structure complexe. Il existe, semble-t-il, une stratification horizontale du flux thermique. Audessous des horizons perméables, la température tombe.

La baisse de température dans le sens de la profondeur est un phénomène intéressant qui n'a pas encore reçu une explication satisfaisante. Cependant on peut en conclure pour la pratique que cette région n'est pas caractérisée par un courant ascendant important.

L'Islande présente un volcanisme tertiaire qui est encore actif dans certaines régions du pays.

**Tableau 5. Caractéristiques générales des champs vaporifères connus : États-Unis d'Amérique**

| *Nom, lieu, état actuel, antécédents, altitude en mètres* | *Aspect géologique et structural des zones du sous-sol connues ou supposées, avec accumulation de vapeur* | *Remarques complémentaires* |
|---|---|---|
| *Big-Geysers* (Californie). Les premières observations géologiques ont été faites par Brewer en 1861. Des études géologiques ont été effectuées à titre privé en vue de l'utilisation de la vapeur pour la production d'énergie électrique, tout d'abord par Decius en 1924; elles furent reprises en 1955 dans le même but.<br><br>Les manifestations hyperthermiques se produisent sur une distance de 8,5 km, dans le Sonoma County, en Californie. Les Big Geysers sont à une altitude de 519 m. | Les résultats obtenus grâce aux forages montrent que la zone productrice est constituée de grès à structure très tourmentée, avec fissures et failles, et soumise à une activité hydrothermique intense qui l'a modifiée. La roche elle-même est du grès dense, gris, avec des intrusions de lutite moins importantes; dans les conditions normales, sa porosité ne dépasserait pas 10 p. 100 et sa perméabilité serait inférieure à un millidarcy. Par conséquent, la production relativement élevée des puits provient de fractures. La formation gréseuse mentionnée est probablement jurassique. | Dans cette région, 6 puits ont été foncés à 87 et 121 m, puis approfondis à 226 et 290 m. Pendant le forage, les températures ont dépassé 400 °F à 280 m. Treize puits, foncés antérieurement dans cette région, vérifient les conditions géologiques susmentionnées. |

| *Nom, lieu, état actuel, antécédents, altitude en mètres* | *Aspect géologique et structural des zones du sous-sol connues ou supposées, avec accumulation de vapeur* | *Remarques complémentaires* |
|---|---|---|
| *Région de Casa Diablo*, dans la partie sud du Mono County, en Californie. Cinq puits ont été fondés en 1959 et 1960. | Masses volcaniques considérables en surface. L'horizon producteur est probablement semblable au précédent. La production de vapeur est prévue à une profondeur maximum de 325 m. | En 1960, trois puits ont été foncés sur un plan de faille active depuis plus de 100 ans; les profondeurs de ces puits sont de 192, 247 et 174 m. Les trois puits sont en production et fournissent ensemble 335 000 kg de vapeur par heure, avec une pression de 2,37 kg/cm². L'exploration du champ est considérée comme étant seulement partielle. |
| *Région de Calistoga*, (Napa County) [Californie]. Cette région se trouve au sud-est de la région des Big Geysers, à 29 km de ceux-ci. | Trois puits ont été foncés dans la formation sableuse jurassique appelée Franciscan, à une profondeur de plus de 100 m. La région étant recouverte d'une épaisse couche d'alluvions, il est difficile d'en déterminer la structure géologique. | |
| *Surprise Valley* (Californie). Une éruption volcanique explosive de boue a eu lieu dans le voisinage immédiat de cette région en 1951. | La région est couverte de sédiments quaternaires et de roches volcaniques. | Des 2 puits foncés dans cette région, l'un, qui traverse une roche volcanique jusqu'à une profondeur de 652 m, a été abandonné comme improductif; l'autre, situé à 1 029 m à l'est du premier, semble encore traverser à 357 m des alluvions de la vallée. |
| *Région de Lakeview* (Oregon). Des manifestations thermales, avec des températures atteignant 180 °C, ont incité à foncer un puits dans cette région. | La région est composée de coulées de laves du Tertiaire et du Quaternaire avec des dislocations en blocs. | Le puits a été foncé jusqu'à 199 m de profondeur, puis abandonné comme improductif. |
| *Région de Crump Lake*, (Oregon). | | Un puits, foncé jusqu'à 512 m, a permis de mesurer des températures atteignant 170 °F. |
| *Région de Wabuska* (Nevada). | Roches volcaniques du Tertiaire. On constate la présence d'une couche d'alluvions d'au moins 455 m d'épaisseur. | Trois puits, atteignant une profondeur supérieure à 610 m, ont fourni de l'eau chaude à plus de 140 °F très chargée en sulfate de sodium. On considère que ce projet n'a pas abouti à un succès. |
| *Région de Steamboat Springs*, à 16 km au sud de Reno (Nevada). | Les puits montrent l'existence de roches volcaniques entre 50 et 300 m; au-delà de cette profondeur, la granodiorite vient s'ajouter aux roches volcaniques. | La profondeur maximum des 4 puits qui ont été foncés est de 540 m; le premier puits a été abandonné comme improductif; le deuxième atteint la granodiorite à 295 m. Les premiers essais ont donné 57 000 kg de vapeur par heure à une pression de production de 2,61 kg/cm² pour une ouverture de 1/8 de pouce. Les deux autres puits ont rencontré de la vapeur qui provient probablement de la granodiorite; la source probable de la chaleur serait une rhyolite du quaternaire. |
| *Région de Brady Hot Springs* (Nevada). | La région est constituée par une vallée d'alluvions contenant des coulées volcaniques du quaternaire. | Sur trois puits, un est improductif. |
| *Région de Beowawe*, centre-nord du Nevada. | Les forages montrent l'existence d'andésite, de basalte et de roches volcaniques fragmentées à 50 m. Les traces de glissement rencontrées à 500 m indiquent la présence de failles. | Trois puits ont été foncés, dont le premier atteint 585 m et les deux autres sont bons producteurs à une profondeur de 152 et 213 m. On suppose qu'ils pénètrent dans une zone de faille. |
| *Volcan de Kilauea-Iki*, dans l'état d'Hawaii. L'éruption de ce volcan, en 1959, a produit dans le cratère un lac de lave de plus de 100 m d'épaisseur, contenant près de cent millions de tonnes de lave fondue. | Le réservoir de chaleur est la lave elle-même, accumulée dans le cratère. | Les travaux de forage et l'étude thermique révèlent la présence d'une source d'énergie dont on peut récupérer près de $2 \times 10^9$ kWh. |

Selon G/48, il existe dans l'ouest des États-Unis d'Amérique, à part les manifestations spectaculaires du parc national de Yellowstone, près de 700 sources d'eau thermale, dont 80 ou 90 p. 100 peuvent être classées comme hyperthermiques. Ces dernières se trouvent dans l'Oregon, l'Idaho, la Californie et le Nevada; elles sont réparties sur environ 10 p. 100 de la surface totale des États-Unis. A l'exception de cinq d'entre elles, toutes ces sources hyperthermiques sont situées suffisamment près d'une région volcanique du pliocène ou du quaternaire pour qu'il soit logique de conclure qu'elles sont directement liées à ces phénomènes. On estime que les magmas injectés qui conservent encore une grande partie de leur chaleur initiale constituent la seule origine des manifestations hyperthermiques.

Les failles et les fractures de roches qui se trouvent au-dessus du magma injecté constituent des voies de dégagement pour les gaz et les liquides. Les zones de roches très poreuses et très perméables, voisines des zones chaudes, peuvent également jouer un rôle important dans ce processus.

La prospection des régions hyperthermales peut fort bien être restreinte aux observations superficielles dans les zones volcaniques de géologie récente; la prospection des régions caractérisées par une activité hyperthermique, en vue de la production, doit être effectuée par fonçage de puits.

Compte tenu des deux puits qui sont actuellement en cours de forage, la partie ouest des États-Unis compte 43 puits forés dans le but de découvrir et d'exploiter la puissance géothermique. Dans l'une des régions mentionnées, l'énergie géothermique sert à produire de l'énergie électrique.

**Tableau 6. Caractéristiques générales des champs vaporifères connus : Mexique**

| *Nom, lieu, état actuel, antécédents, altitude en mètres* | *Aspect géologique et structural des zones du sous-sol connues ou supposées, avec accumulation de vapeur* | *Remarques complémentaires* |
|---|---|---|
| *Champ de Pathé* (État de Hidalgo), à 7 km à l'ouest de Tecozautla. Il se trouve actuellement au stade de l'exploration et des essais. Son altitude est de 550 m. Le fonçage des puits a commencé en 1955-1956. | La vapeur a été obtenue à des profondeurs variées du fait que la structure qui commande le champ est constituée de failles que les puits (12 en tout) ont rencontrées en des zones différentes. La zone probable de production est constituée de couches plus ou moins perméables de caractère volcanique qui sont du tertiaire supérieur (?) et dont l'alimentation en vapeur et en eau se fait par des fractures. | Un turbo-générateur produit de l'énergie électrique en utilisant la vapeur sèche du puits 2-A. La profondeur maximum atteinte dans les autres puits est de 700 m. |
| *Vallée de l'Ixtlán* (État de Michoacan) à 22 km au nord-ouest de Zamora. Actuellement au stade de l'exploration; quelques puits ont été foncés de manière rudimentaire. | Structure de graben; zone volcanique du tertiaire-quaternaire affectée de failles. Alluvions et basaltes altérés; leur présence a été révélée par deux puits foncés de manière incomplète dans cette région. | Après 150 m la température a baissé. Le petit lac de Chapala (à 35 km de Ixtlan) affecte et affectera la production de vapeur de ce champ. |
| *Région de Mexicali* (Basse-Californie), à une altitude de 42 m. Cette région se trouve entièrement au stade de l'exploration. | La structure du sous-sol dont dépend la production de vapeur est associée à la zone de fractures de San Andrès. L'activité de cette zone s'est manifestée par endroits jusqu'au Récent. Les roches affectées sont des alluvions du Quaternaire et des roches ignées du cenozoïque. | Le forage de puits d'exploration a pénétré dans une couche épaisse de recouvrement formée d'alluvions et de roches ignées altérées intrusives. On espère réduire la quantité d'énergie électrique importée si la prospection dans cette région aboutit à un succès. |

**Tableau 7. Caractéristiques générales des champs vaporifères connus : Japon**

| *Nom, lieu, état actuel, antécédents, altitude en mètres* | *Aspect géologique et structural des zones du sous-sol connues ou supposées, avec accumulation de vapeur* | *Remarques complémentaires* |
|---|---|---|
| *Région de Showa-Shinzan,* dans l'ouest de l'île d'Hokkaïdo. L'existence dans le sous-sol d'une masse magmatique à 800 °C a été déterminée par des méthodes géophysiques. | La région est constituée par des roches volcaniques du tertiaire. Showa-Shinzan est un dôme volcanique qui a fait son apparition il y a 16 ans sous la forme d'un dôme parasitique du volcan Usu. Il est constitué de roches dacitiques dont la température initiale était de 1 000 °C et qui sont actuellement à plus de 800 °C.<br>Dans cette région, les roches ignées forment des intrusions dans les dépôts du pliocène, du pléistocène et de | |

| *Nom, lieu, état actuel, antécédents, altitude en mètres* | *Aspect géologique et structural des zones du sous-sol connues ou supposées, avec accumulation de vapeur* | *Remarques complémentaires* |
|---|---|---|
| | l'holocène formés de lave, de cendres volcaniques, de sable, de lapilli, de sédiments clastiques et de pierre ponce. Le niveau économique et industriel des fluides dans les roches perméables situées au-dessus de l'intrusion n'a pas encore été vérifié. | |
| *Région de Matsukawa*, dans la partie nord de Honshu. Cette région comprend une vallée dans un district volcanique possédant trois volcans en activité et d'autres assoupis, ainsi qu'une multitude de manifestations thermiques, fumerolles et dépôts de soufre. | Les travaux géologiques réalisés en 1957 montrent que cette région est constituée par un volcan composé fragmenté, avec un cône central, et une structure de caldera d'effondrement. Les laves sont très denses; les parties inférieures de la carotte, à plus de 150 m sont formées de dacite qui est une accumulation de lave et de tuf poreux avec fragments de pierre ponce. Depuis 1953, on considère que la vallée possède des caractères particulièrement géothermiques, avec probablement une couverture imperméable (G/1). | En 1953, sept puits ont été forés en vue de la création d'une installation de bains; quatre d'entre eux ont fourni de la vapeur à 160 et 300 m de profondeur.<br>En tout, 10 puits ont été forés, avec une profondeur maximum de 450 m et des températures atteignant 189 °C. Les essais de production donnent un résultat de 1 tonne de vapeur par heure et 0,3 tonne d'eau par heure pour une ouverture de 45 mm de diamètre. |
| *Région de Onikobe*, dans la partie nord de Honshu. Cette région, de forme elliptique, est constituée par un bassin de 10 km sur 8. Ce bassin est le résultat d'une subsidence crustale du miocène supérieur. | Une partie considérable du bassin est formée de sédiments lacustres de plus de 300 m d'épaisseur, traversés par des dômes dacitiques contemporains. Cette région est volcanique quaternaire mais ne possède pas de volcans récents.<br>Le champ d'Onikobe est semblable à celui de Wairakei en Nouvelle-Zélande, étant donné que les failles de la base de roches très denses forment comme des conduits d'alimentation pour les fluides chauds, partant du fond et atteignant les couches lacustres de recouvrement, où l'élévaation de la température de l'eau météoritique accumulée dans les roches poreuses ainsi que dans les fractures provoque la formation d'un système géothermique convectif. | Trois puits ont été foncés dans la couche lacustre et atteignent des profondeurs de 255, 250 et 192 m, à l'écart des manifestations thermales. Les puits 2 et 3 ont permis de mesurer des températures de 90 à 130 °C à des profondeurs de 110 à 125 m; ces profondeurs correspondent à une couche intercalaire d'andésite compacte dans une couche de recouvrement de brèche de tuf. A 255 m de profondeur, la température était de 185 °C.<br>Les essais de production ont donné 2 tonnes d'un fluide comprenant de la vapeur et du gaz en parties égales. |
| *Région de Beppu*, au nord-est de Kyushu Phénomènes de surface intenses, comparables à quelques-uns de ceux qui se trouvent en Nouvelle-Zélande. | Région très volcanique. | Trois puits d'essai ont été foncés jusqu'à une profondeur de 110 m; la température est de 145 °C. L'ouverture étant de 75 mm, la production est de 2,4 tonnes par heure d'un mélange de deux parties d'eau pour une partie de vapeur. Production de 30 kW d'énergie géothermoélectrique. |
| *Région de Obama*, à l'ouest de Kyushu. | Région très volcanique. | Près de 80 puits ont été foncés dans cette région; ils produisent de la vapeur et de l'eau à 130 °C. La production totale atteint 4 700 tonnes par heure, ce qui correspondrait à 70 000 kW si elle était utilisée pour produire de l'énergie. |
| *Région de Otake*, centre ouest de Kyushu. | Région très volcanique. | Quatre puits d'exploration ont été foncés jusqu'à une profondeur maximum de 900 m; la température maximum est de 185 °C. L'ouverture est de 150 mm; les essais ont donné 9 tonnes par heure, dont 6 de vapeur. |
| *Région de Hakone*, centre ouest de Honshu. | Région très volcanique. | La production est de 2 tonnes par heure, dont une tonne de vapeur. |
| *Région de Noya*, nord de Kyushu. | Région très volcanique. | Un puits expérimental a atteint une profondeur de 200 m avec une température de 100 °C. La production d'eau chaude est de une tonne par heure. |

| *Nom, lieu, état actuel, antécédents, altitude en mètres* | *Aspect géologique et structural des zones du sous-sol connues ou supposées, avec accumulation de vapeur* | *Remarques complémentaires* |
|---|---|---|
| *Région de Takenoyu,* partie ouest de l'île de Kyushu. | Région très volcanique. | |
| *Région de Unzen,* à l'est de Takenoyu. Constitue actuellement un centre touristique. | La région est localisée sur un volcan. | Les trois puits de 30 m de profondeur atteignent 120 °C. La production est de une tonne par heure de vapeur. |
| *Région de Ebino,* dans le sud-ouest de l'île de Kyushu. | La région est localisée sur un volcan. | Trois puits ont été foncés jusqu'à une profondeur de 75 m. La température est de 108 °C et la production d'eau chaude atteint 12 tonnes par heure pour une ouverture de 125 mm. |
| *Région de Yunono,* dans la partie sud-est de Kyushu. | Zone située sur un volcan. | Un puits de 84 m de profondeur a atteint une température de 156 °C. Les essais montrent qu'il est possible d'obtenir 2 tonnes par heure d'un mélange de vapeur et d'eau en parties égales. |
| *Région de Tearai,* dans la partie sud-ouest de Kyushu. | Zone située sur un volcan. | |
| *Région de Ibusuki,* au sud de Tearaï. | La région est située dans une zone volcanique. | Les essais montrent qu'il est possible d'obtenir 2 tonnes par heure d'un mélange en parties égales d'eau et de vapeur. |
| *Région de Kusatsu,* dans la partie centrale de la Honshu. | La région est située dans une zone volcanique. | Deux puits de 200 m de profondeur atteignent une température de 100 °C. La production est d'une tonne par heure d'eau. |
| *Région de Yamanouchi,* à l'ouest de Kusatsu. | La région est située dans une zone volcanique. | On a mesuré une température de 100 °C. Les essais montrent qu'il est possible d'obtenir 2 tonnes par heure d'un mélange d'eau et de vapeur en parties égales. |
| *Région de Oshima,* à l'ouest de Atagawa. | Zone située sur un volcan. | Les trois puits foncés dans cette région atteignent une température de 70 °C. La production d'eau est d'une tonne par heure. |
| *Région de Atagawa,* au sud de la partie centrale de Honshu. | La région est située dans une zone volcanique. | Les essais montrent qu'il est possible d'obtenir 2 tonnes par heure d'un mélange de vapeur et d'eau en parties égales. |
| *Région de Narugo,* dans la partie nord de Honshu. | La région est située dans une zone volcanique du tertiaire. | On a foncé 22 puits à une profondeur de 213 m. La température atteinte est de 175 °C. Les essais montrent qu'il est possible d'obtenir de 2 à 7 tonnes par heure d'un mélange d'eau et de vapeur, pour une ouverture de 45 mm. La quantité d'eau varie entre 1 et 6 tonnes par heure. |
| *Région de Takinoue,* dans la partie nord de Honshu. | Terrains tertiaires. | |

Selon G/1, diverses institutions gouvernementales japonaises, telles que le Service géologique et les compagnies d'électricité, ont réalisé des prospections dans diverses régions importantes. Les températures souterraines mesurées jusqu'à présent ne dépassent pas 200 °C. Les quantités de vapeur obtenues ne sont pas suffisantes et la vapeur elle-même est mélangée à de l'eau chaude. La prospection géothermique au Japon se trouve dans sa phase initiale et préliminaire.

Les masses intrusives détectées en profondeur par des méthodes géophysiques ont été étudiées, de même que les régions où les failles du tertiaire, pénétrant dans une base de granit, conduisent les fluides chauds vers des sédiments plus jeunes situés plus haut et contenant des roches poreuses. Les structures volcaniques du type caldera ont été également explorées, ainsi que leurs fractures associées, dans le but de déterminer le potentiel géothermique correspondant au cas où les fluides émigrent des profondeurs et sont captés dans les couches supérieures de lave plus jeunes.

Le premier sondage d'exploration de la puissance géothermique a été effectué il y a 40 ans.

Jusqu'à présent, le nombre des puits dans la plupart des champs est faible et, à l'exception de quelques-uns, leur profondeur est inférieure à 200 m.

Il ressort des études réalisées actuellement qu'il est possible de récupérer des sources thermales connues une énergie minimum équivalente à 100 000 kW.

**Tableau 8. Caractéristiques générales des champs vaporifères connus : Union soviétique**

| *Nom, lieu, état actuel, antécédents, altitude en mètres* | *Aspect géologique et structural des zones du sous-sol connues ou supposées, avec accumulation de vapeur* | *Remarques complémentaires* |
|---|---|---|
| *Région de Pauzhetsk*, dans la presqu'île du Kamtchatka. Ce champ hydrogéothermique se trouve dans la partie méridionale du Kamtchatka et couvre une étendue de 400 km². Son altitude est de 100 m (?). Les sondages d'exploration par rotation, jusqu'à 800 m de profondeur, ont commencé en 1958. | La zone est constituée de roches volcaniques du quaternaire dans une dépression tectonique entourée de roches volcaniques de quaternaire inférieur. Ces roches se trouvent au-dessus d'une série de dépôts tertiaires qui sont constitués de turfs arénacés au-dessous de 650 m.<br>Une augmentation de la production de vapeur et d'eau a été constatée à la suite de l'intersection de fractures dans les roches agglomératives tufacées du tertiaire.<br>L'accumulation de chaleur dans les formations poreuses du tertiaire, d'où l'eau et la vapeur sont extraites à l'aide de puits, est due au volcanisme actif dans cette région. | Production d'eau thermale superficielle estimée à 100 l/s.<br>Jusqu'en 1960, 15 puits ont été foncés à des profondeurs de 200 à 800 m. La température maximum de 195 °C a été atteinte dans un puits dont la valeur calorifique est de 188 kcal/kg du mélange de vapeur et d'eau ; la pression maximum à la sortie du puits est de 6,7 atm. La décharge totale du champ est de 150 kg/s — quantité qui est estimée suffisante pour mettre en exploitation une usine géothermoélectrique pilote.<br>Le constituant gazeux principal de la phase vapeur est $CO_2$ dont la concentration dépasse plus de dix fois celle de $SH_2 + NH_3$. |

**Tableau 9. Caractéristiques générales des champs vaporifères connus : Salvador**

| *Nom, lieu, état actuel, antécédents, altitude en mètres* | *Aspect géologique et structural des zones du sous-sol connues ou supposées, avec accumulation de vapeur* | *Remarques complémentaires* |
|---|---|---|
| *Aguachapan*, dans la partie occidentale du Salvador. Le champ est caractérisé par deux types de fluides géothermiques : eau et vapeur acides et eaux thermiques neutres, riches en chlore.<br>Ce champ fait partie du graben central caractérisé par un volcanisme quaternaire dont l'activité s'étend jusqu'à la période historique. Cette zone présente une activité géothermique considérable; on connaît environ 40 champs distincts.<br>Les sondages de prospection ont été effectués de 1956 à 1958. Le puits le plus profond atteint 400 m. | Selon les renseignements fournis par les sondages, la vapeur est confinée dans les zones de fissures. Les manifestations géothermiques du pays se produisent dans la région volcanique du quaternaire composée de deux bandes distantes de 20 km. La plupart des recherches calorimétriques ont été effectuées dans la bande volcanique méridionale. La structure de Aguachapan a été soumise à des déplacements dans le graben atteignant 1 000 m dans le sens vertical; ces failles se sont produites à la fin du pliocène. Le graben est recouvert d'une couche pyroclastique de 300 à 500 m d'épaisseur. L'activité hydrothermale est située tant sur les limites du graben qu'à l'intérieur même de ce dernier. On suppose que la vapeur provient d'eaux filtrantes alimentées par les fluides chauds qui arrivent par des fissures de la base, surtout dans la région des volcans du pléistocène. Les sondages ont montré que la vapeur provient de fissures dans la couverture du pléistocène. | Les pertes superficielles de chaleur sont de $8 \times 10^4$ kcal/s, le flux moyen de chaleur est de $100 \times 10^{-6}$ cal/cm²/s, valeur que l'on peut comparer au flux normal de chaleur au Salvador, $2{,}5 \times 10^{-6}$ cal/cm²/s.<br>On espère trouver une quantité suffisante de chaleur pour installer une usine de 50 000 à 100 000 kW. La vapeur obtenue est humide et de faible pression.<br>Le potentiel hydroélectrique du Salvador atteint 10: kW; actuellement, on n'en utilise que 10 p. 100.<br>Tableau 10, f. 141. |

L'analyse, l'étude et la comparaison qui font l'objet de la section précédente sur les régions géothermiques connues dans le monde conduisent à constater de nouveau que la source nouvelle d'énergie, appelée source géothermique, a permis d'obtenir de bons résultats dans les régions où elle est exploitée, en Italie, en Nouvelle-Zélande et en Islande, et permet d'entrevoir des résultats fructueux aux États-Unis d'Amérique, en Union soviétique, au Mexique, au Japon et au Salvador. Il ne fait pas de doute que le perfectionnement rapide des techniques permettra d'obtenir l'énergie géothermique du sous-sol dans des limites économiques par comparaison avec les autres sources, classiques ou non, d'énergie. Il est donc indispensable d'utiliser des connaissances techniques, pratiques et scientifiques qui permettront de découvrir de nouveaux champs géothermiques. La section suivante traite des méthodes de prospection.

## Méthodes et techniques utilisées dans la prospection géothermique

Il est nécessaire de considérer cette source d'énergie comme quelque chose de réellement spécial, car les méthodes utilisées pour découvrir, localiser ou atteindre les zones thermales seront fondées d'une façon ou d'une autre sur la nature particulière à chaque zone ou, en d'autres termes, parce que l'on a affaire à des systèmes physiques, chimiques ou physico-chimiques. Dans le sous-sol, l'eau et la chaleur se comportent d'une manière différente de celle qui est observée en surface, par exemple, dans le cas des sources hydrothermales.

De même qu'à ses débuts l'exploration pétrolière avait pour point de départ l'existence de suintements de pétrole et qu'on forait des puits tout près de ces manifestations afin de situer exactement le gîte souterrain, et de même que dans de nombreux cas d'exploration minière, on considérait l'existence de chapeaux de fer, de carapaces ferrugineuses, etc., comme une base pour le sondage et la recherche de gîtes économiques dans le sous-sol, de même la prospection géothermique s'est fondée au début de la recherche des gîtes souterrains de vapeur sur l'existence des sources hydrothermales et des manifestations superficielles de vapeur. Mais on est arrivé rapidement à la conclusion que les manifestations superficielles d'une région, tout en indiquant l'existence d'une réserve souterraine d'énergie géothermique, ne constituent pas les points les plus propices pour le fonçage des puits.

Parmi les manifestations thermales figurent les geysers, les fumerolles, les sources d'eau chaude, les sources bouillonnantes, les bassins qui dégagent de la vapeur, les marmites de boue, de même que l'altération chimique des roches, les dépôts des sources d'eau chaude (geysérite, soufre, alun, etc.) et, en général, les produits qui peuvent être des indices d'une activité hydrothermale, tels que le kaolin, la pyrite, l'alunite, les chlorites, etc.

De façon générale, on peut donc dire qu'il faut commencer par délimiter géographiquement la zone thermale, conformément aux observations. Comme on dispose déjà d'une certaine expérience et, assurément, de bases de comparaison pour ce qui est des phénomènes souterrains auxquels on peut s'attendre lorsqu'on sait qu'il existe en surface un certain jeu de conditions, il convient de procéder à des travaux directs superficiels, détaillés et systématiques.

**Tableau 10. Évaluation du flux calorifique dans les champs géothermiques de la Nouvelle-Zélande**

| *Manifestations* | *Flux de chaleur* | *Remarques* |
|---|---|---|
| Gradient de température anormalement élevé dans les couches superficielles, mais non associé à des quantités importantes de vapeur. | Entre 1 et 20 cal/m²/s. | |
| Association d'un flux conductif et de la convection. | Entre 4 et 200 cal/m²/s. | |
| Flux de convection; la région est caractérisée par de la vapeur visible, surtout lorsque l'humidité atmosphérique est grande, | Entre 200 et 2 000 cal/m²/s. | Le flux le plus important provient de terrains légers et thermiquement altérés, ainsi que de petites fumerolles et parfois de marmites de boue. |
| Grandes fumerolles d'un diamètre de sortie allant de 15 cm à 1 m, débitant souvent de la vapeur légèrement surchauffée. | Entre $10^6$ et $2 \times 10^7$ cal/m²/s. | |
| Dégagement de vapeur des bassins d'eau chaude et des marmites de boue. | De $10^3$ à $1{,}5 \times 10^4$ cal/m²/s pour de l'eau tranquille et jusqu'à $1{,}5 \times 10^6$ cal/m²/s dans le cas d'eau en ébullition violente. | Le débit est généralement sous forme de vapeur d'eau. |
| Dégagement de vapeur et d'eau à partir de sources chaudes et de geysers; ces manifestations peuvent être assoupies ou actives. | Du même ordre de grandeur que le précédent. | |

En ce qui concerne ces travaux, les indications données dans le mémoire G/54 sont nombreuses, et il convient de les consulter. Dans de telles conditions, il est nécessaire de tracer des isothermes à la surface, à 1 m et 2 m de profondeur et, en général, pour toute profondeur qui n'exige pas un travail de trop grande envergure ou relativement trop difficile. Les thermomètres et les thermocouples permettent de détecter des températures dépassant d'au moins 1 °C la moyenne du terrain exploré, ainsi que celles qui sont en deçà d'une limite supérieure, par exemple 50 °C au-dessus de la température moyenne du terrain, ce qui rend possible la localisation des premières anomalies thermiques.

Le flux calorifique peut ensuite être évalué. Le tableau ci-après permet de se faire une idée de ce paramètre, selon l'expérience acquise dans les champs de la Nouvelle-Zélande.

Les méthodes utilisées pour les mesures directes font appel, selon la nature de la manifestation étudiée, à des instruments tels que le disque de Lee, le calorimètre à chaleur totale, le collecteur et le dispositif de Venturi, le thermocouple et le dispositif de Pitot statique. Il est indispensable de reconnaître les conditions superficielles de travail, et, en particulier, le genre de terrain dans la région où l'on mesure le flux de chaleur. Dans tous les cas, et pour des régions différentes, il faudra utiliser les graphiques représentant les variations de la température avec le flux de chaleur pour des types donnés de matériaux, que ce soit à quelques centimètres ou plus de profondeur.

On établit ensuite une répartition géologique de reconnaissance, générale et détaillée, en régions thermiques et en zones de voisinage immédiat suivant des échelles qu'il est difficile de généraliser puisque l'étendue des zones étudiées varie d'une région à l'autre. Dans la mesure du possible, il convient de rapporter à une échelle de travail uniforme tous les renseignements anciens tels que les données géologiques, les plans de communications, les plans des agglomérations, des centres industriels et démographiques (ces derniers renseignements ayant leur importance pour l'utilisation convenable de la vapeur dans le cas où elle est trouvée en quantité suffisante). Il n'est pas superflu d'indiquer l'opportunité des travaux d'étude aériens tels que les levés photographiques à une échelle de 1/10 000 par exemple, précédant le commencement des travaux géologiques de surface (G/69). Le travail géologique sur place servira de vérification aux données des photographies aériennes; on pourra ensuite interpréter les observations en vue de l'obtention d'un tableau de la structure stratigraphique et pétrologique, répondant le mieux à la réalité.

Il ne faut pas négliger, au cours de la reconnaissance superficielle, le fait que la végétation peut constituer un indice des régions thermales, certaines plantes se modifiant de façon caractéristique dans les conditions de température données. Cette indication obtenue sur le terrain, complétée par les prises de vues aériennes, peut expliquer la délimitation des régions thermales.

A cette étape de la vérification de l'inventaire des manifestations thermiques superficielles fait suite celle de l'analyse chimique qui peut donner des indications sur les conditions chimiques des manifestations.

Dans un programme rationnel de travail, la prospection chimique se situe convenablement à ce point. On trouvera des renseignements détaillés à ce sujet dans le mémoire G/35, qui accorde une importance particulière à la méthode chimique de prospection.

Les analyses chimiques effectuées par des procédés convenables comprennent le prélèvement d'échantillons et l'analyse des gaz contenus dans la vapeur des émanations ainsi que dans la vapeur condensée de l'eau chaude. Il est très utile de connaître le comportement des rapports entre les éléments que contiennent les eaux provenant de sources superficielles ou prélevées dans le fond d'un puits en production. Des indications sur le prix d'un laboratoire chimique de terrain sont données pour le cas de la Nouvelle-Zélande dans le mémoire G/29 qui décrit également, en détail, les méthodes d'analyse chimique utilisées dans ce pays.

L'observation du comportement chimique des fluides d'un champ géothermique pendant la période de prospection et, plus tard, pendant les essais de production donne des indications sur la durée possible et sur l'importance de la production de vapeur. Les mémoires G/42 et G/46 présentent des explications détaillées de la méthode de prélèvement d'échantillons chimiques convenant à l'étude des zones géothermiques.

Selon le mémoire G/35, il ressort de l'étude des régions actives que les régions thermales présentent souvent des rapports caractéristiques, constants dans une même région mais très différents d'une région à l'autre. Une faible concentration de gaz dans la vapeur des fumerolles et des variations appréciables des rapports $CO_2/SH_2$ et $CO_2/NH_3$ indiquent que la vapeur a pour origine de l'eau en ébullition dans le sous-sol, de l'eau chlorurée dans le cas de la Nouvelle-Zélande.

La détermination des valeurs des rapports Cl/As, Na/Li et Na/Ca, pour tous les champs d'une même région, permet de juger de l'uniformité du magma et de détecter les champs qui appartiennent à une période antérieure d'activité, ainsi que de comparer la région avec d'autres.

Les rapports Cl/B, Cl/F et $Cl/SO_4$ sont utiles pour déterminer l'opportunité de sondages, dans le cas où la zone étudiée présente une similitude avec celle de Wairakei.

En ce qui concerne le prélèvement d'échantillons des sources hydrothermales, les méthodes de prélèvement de gaz et de vapeur des fumerolles diffèrent selon le contenu en gaz de la vapeur, selon qu'il est élevé ou faible.

Dans les régions où l'on envisage de foncer des puits, il est indispensable de prélever tout d'abord des échantillons d'eau des manifestations à eau limpide et à débit suffisant. En outre, les principales manifestations de toute la région active devront être analysées, même si pour des raisons pratiques elles ne conviennent pas au forage.

Les rapports qu'il est recommandé de déterminer sont les suivants : $Cl/HBO_2$, Cl/F, Cl/As, $Cl/SO_4$, $Cl/NH_4$, Na/K, Na/Li, Na/Ca et Ca/Mg; il convient également de déterminer la concentration de la silice et celle des bicarbonates (ions) et, dans la mesure du possible, les rapports Cl/Br, Br/I, As/Sb, Na/Rb et Na/Ca.

A partir de ces rapports, on recherchera pour chaque champ une caractéristique commune.

Il convient de déterminer parallèlement la concentration des gaz dans la vapeur de toute fumerolle présente dans la région, ainsi que les rapports $CO_2/SH_2$ et $CO_2/NH_3$ (G/35).

Les conditions qui impliquent l'existence d'un piège souterrain favorable à l'accumulation d'une quantité de vapeur convenable du point de vue de l'exploitation commerciale, sous-entendent l'utilisation de divers paramètres physiques des roches.

Par certains de ses aspects, la prospection géophysique ressemble à celle qui a pour but la recherche des hydrocarbures. C'est pourquoi il convient d'utiliser des paramètres tels que la température, la susceptibilité magnétique, la densité, la conductivité électrique, la vitesse de propagation des ondes élastiques et la radioactivité.

Le gradient de température est déterminé par des mesures thermométriques. La portée et la méthode des mesures thermométriques sont décrites de façon détaillée dans les mémoires G/61, G/54 et G/25. Le mémoire G/25 présente les mesures de la température au fond de sondages ne dépassant pas 10 m de profondeur, ce qui permet de se libérer des fluctuations superficielles de la température. Il convient de tenir présent à l'esprit qu'au cours de la première phase de la prospection thermique, on indique non seulement l'extension géographique de l'anomalie thermique, mais aussi la fréquence des sources thermales.

Par propriétés magnétiques on entend l'intensité d'aimantation d'un petit volume de roche placé dans un champ unitaire. Les variations de la composante verticale du champ terrestre sont mesurées à l'aide de la balance de Schmidt. Le magnétomètre n'est utilisé que dans la prospection aéroportée. L'horizon magasin et sa couverture sont constitués de couches sédimentaires dont la susceptibilité magnétique est très faible. De plus, l'effet magnétique peut même être totalement masqué par des terrains volcaniques ou métamorphiques, de sorte que l'existence possible de la couverture peut passer plus ou moins inaperçue (G/25).

Il convient de noter que dans certaines régions la prospection magnétique a servi à situer avec précision les sources de chaleur, car l'altération hydrothermique de la magnétite, provoquée par $SH_2$, aboutit à la formation de pyrite non magnétique. Par conséquent, en observant les variations de l'intensité magnétométrique, il est intéressant de connaître les valeurs magnétiques décroissantes des terrains hydrothermiques, puisqu'elles indiquent l'origine de l'activité hydrothermique.

Un paramètre important est la densité, utilisée dans la méthode gravimétrique de prospection. On mesure les variations de l'intensité de la pesanteur entre une station de référence et les stations de mesure. Cette méthode est mieux adaptée que la méthode magnétique, qui a l'inconvénient d'inclure dans la mesure tous les effets des terrains superficiels et profonds. Cette méthode fournit des renseignements importants sur la tectonique.

On recommande de façon formelle l'utilisation de la méthode de la conductivité électrique pour la recherche des champs géothermiques étant donné qu'elle permet d'obtenir des résultats plus complets (G/25).

Lors d'une reconnaissance générale, il est recommandé d'exécuter des sondages électriques avec une maille de 500 × 500 m, soit quatre stations par kilomètre carré. Pour les études de semi-détail, on établira une maille de 250 × 250 m. Il convient d'établir également une carte de résistivité pour implanter au mieux les premiers forages de reconnaissance.

Il est à noter que la méthode électrique de prospection peut s'adapter aux divers problèmes techniques rencontrés et permet de réaliser une exploration et une reconnaissance plus complètes, plus rapides et plus claires. La résistivité d'une formation dépend étroitement de sa température : c'est ainsi qu'un terrain porté de 17 à 150 °C voit sa résistivité divisée par 5; elle est divisée par 9 si la température passe de 17 à 280 °C (G/25). La prospection électrique permet d'établir une carte de résistivité à la profondeur qui permet de déterminer s'il existe des zones chaudes à la base de la formation imperméable et aussi si une fracture, cause de la structure géologique, est alimentée ou non par des fluides.

Les méthodes sismiques sont basées sur la mesure de la vitesse de propagation des ondes élastiques, qui dépend de certains paramètres et constantes tels que le module d'élasticité, la densité, le coefficient d'incompressibilité. Il existe deux méthodes sismiques celle de la réflexion et celle de la réfraction, qui correspondent à l'utilisation de l'énergie réfléchie par des surfaces de séparation et à celle de l'énergie qui a traversé des formations de nature diverse avant de sortir à la surface après avoir décrit une certaine trajectoire. Les méthodes sismiques rendent compte de la structure géologique du sous-sol à partir de la vitesse des ondes sismiques.

La méthode radioactive, qui consiste à mesurer les substances radioactives véhiculées éventuellement par les failles et par les fractures, a été également considérée.

De toute façon, les résultats obtenus par n'importe quelle méthode unique sont aléatoires, et il convient d'utiliser des méthodes complémentaires. En fin de compte, c'est le foret qui aura le dernier mot à dire.

Le forage de puits est considéré comme l'une des phases de la prospection. Pour les travaux préliminaires d'un champ géothermique, on conseille de foncer des puits pilotes de diamètre AX (2 1/4 pouces) avec un foret de diamant et un tambour échantillonneur, afin de connaître la structure géologique en coupe de la formation où se trouve accumulée la vapeur, ou la profondeur où cette dernière est interceptée, dans le cas où on atteindrait une fracture.

L'utilisation de diamètres réduits au stade préliminaire a, en sa faveur, non seulement des considérations d'ordre économique, mais encore le facteur temps si on veut obtenir rapidement les conditions géothermiques générales. La mesure de la température, l'altération hydrothermique des roches traversées, l'analyse préliminaire des fluides recueillis et, même, l'observation des pressions dans les conditions produites, permettent de se faire une idée suffisamment concise pour établir un programme raisonnable de forage de puits de plus grand diamètre, forage qui exige de plus grandes dépenses (de l'ordre de grandeur de celles qui sont nécessaires pour le forage d'un puits à pétrole).

Le forage d'un puits d'un diamètre initial de 20 pouces, par exemple, n'a pas pour but unique la vérification des résultats de l'exploration géologique : on espère toujours qu'il pourra devenir un puits de production. La distance entre les puits sera fonction de la capacité de production du champ et du besoin d'assurer un débit de vapeur donné pour alimenter les turbines géothermo-électriques, si cette énergie est destinée à être transformée en électricité. Dans le cas où l'on se propose de l'utiliser pour le chauffage, les installations seront différentes.

L'Italie est un pays où les méthodes géophysiques de prospection, en particulier la méthode électrique, ont été utilisées avec succès. La méthode chimique a donné de bons résultats en Nouvelle-Zélande; au Japon, diverses méthodes géophysiques ont été utilisées de façon limitée. Tous les pays estiment qu'il convient d'effectuer des études préliminaires minutieuses et continues sur la thermométrie et les débits de chaleur.

Dans tous les pays, que leur programme géothermique soit mis en route ou que sa réalisation ne soit que prévue, il est indispensable de partir des connaissances géologiques les plus amples possibles de la région intéressante.

## Quelques considérations sur l'origine de la chaleur et de la vapeur des champs géothermiques

Il est difficile de trouver une explication unique de l'origine de la vapeur et de la chaleur pour toutes les régions où se produisent des manifestations géothermiques. Dans certains cas, les constatations mettront en évidence certaines causes; dans d'autres, il y aura des explications différentes, mais chaque fois, on recherchera l'accord avec les caractéristiques réelles des régions étudiées.

Les études isotopiques montrent que dans toutes les régions étudiées jusqu'à présent, la quantité de vapeur magmatique ne dépasse pas 5 à 10 p. 100 de la quantité totale des fluides hydrothermiques. Par conséquent, la composante d'origine météorique prédomine. En profondeur, la plus grande partie de la chaleur passe par conduction du magma aux roches, et ce n'est en réalité qu'en faible proportion qu'elle est transmise à la vapeur magmatique (G/2).

Les champs géothermiques de haute température doivent leur existence à la chaleur volcanique, et la plus grande partie de l'eau y est d'origine météorique. Lorsque la quantité de chaleur disponible est grande et lorsque la perméabilité de la roche est faible, on obtient de la vapeur sèche.

Dans le cas d'un système de fractures très profondes, l'eau météorique parvient à un système gigantesque de convection et se réchauffe d'abord par conduction dans les roches, puis grâce à la condensation de la vapeur volcanique. Divers auteurs supposent que, dans le cas de la Nouvelle-Zélande, les chlorures alcalins sont transportés continuellement à partir du magma. Un apport continu de chlorures impliquerait une profondeur de l'ordre de 3 000 m pour la zone où se condense la vapeur.

Selon le mémoire G/3, l'eau qui circule à une grande profondeur se réchauffe par conduction dans les roches chaudes. La principale composante serait l'eau primitive, qui provient de la profondeur et arrive à la surface mélangée dans une mesure plus ou moins grande à de l'eau météorique. L'eau primitive peut être soit métamorphique, soit fossile, soit magmatique.

Dans le cas des fluides hydrothermiques de la Nouvelle-Zélande, les résultats des études isotopiques mentionnées dans le mémoire G/31, montrent que la contribution magmatique est de l'ordre de 10 p. 100.

L'équilibre thermique normal d'une région peut être affecté par la présence d'un magma intrusif qui monte suffisamment près de la surface pour céder de la chaleur aux roches environnantes et, par conséquent, à l'eau interstitielle; par le déplacement de roches ignées extrusives qui conservent encore une grande quantité de chaleur du fait que leur activité appartient à une époque récente; par la présence de volcans; par la désintégration d'éléments radioactifs; et peut-être par la chaleur qui pourrait être dégagée par le frottement associé au déplacement de formations adjacentes aux failles.

L'effet calorifique d'une masse intrusive se manifestera à partir de la profondeur où cette dernière peut se trouver en contact avec l'eau interstitielle ou avoir une certaine influence sur elle, de telle sorte que la chaleur, transmise par conduction, apparaîtra en surface sous la forme de vapeur, suivant des voies d'échappement telles que les fractures, les discordances, etc. (G/48).

L'auteur du mémoire G/35 présente une étude intéressante d'une intrusion de 7 × 7 × 1 km, située à une profondeur de 3 km, qui se serait solidifiée en 40 000 ans, période pendant laquelle l'eau en circulation a absorbé la vapeur par conduction, ainsi que les produits chimiques du fluide magmatique séparé. Il s'est formé un réservoir de 20 × 10 × 1 km en strates d'une porosité de 5 p. 100, sous une couche d'ignimbrite à une profondeur de 3 km. La chaleur de l'eau et de la roche pourrait alimenter pendant 4 000 ans l'activité naturelle de Wairakei.

Les études fondées sur la prospection géochimique permettent de conclure que la chaleur de l'eau chlorurée ne peut pas être attribuée en totalité à la vapeur magmatique car, dans ce cas, le contenu en eau jeune serait d'environ 35 p. 100. A partir de la concentration du chlore, l'auteur déduit qu'elle est présente dans une proportion de 8 p. 100; d'après les données des isotopes de l'oxygène, cette proportion dans les eaux thermales pourrait être, en général, de 5 p. 100 (G/35).

La concentration élevée de lithium et du césium dans les eaux de Wairakei ou dans l'eau des champs thermiques ne peut être assurée par la lixiviation ou par l'entraînement avec la vapeur magmatique : elle doit provenir d'une phase aqueuse résiduelle d'un magma en cristallisation (G/35).

### Considérations relatives à l'évaluation de la capacité des champs géothermiques

Pour les zones qui se trouvent à un stage préliminaire de développement et qui ne produisent pas encore de vapeur, on procède habituellement par comparaisons. Que peut-on espérer d'une région nouvelle, possédant des caractéristiques données, lorsqu'on connaît les caractéristiques d'autres régions? Il n'est pas possible de tirer des conclusions sur la capacité de production sans avoir effectué des sondages. Les premiers renseignements relatifs à cette question seront obtenus au moyen des essais préliminaires pratiqués lors des sondages initiaux des puits de vapeur.

Dans toute région dont l'exploitation est prévue et pour laquelle on ne possède que très peu ou pas du tout de renseignements à partir de sondages antérieurs, les données pour le choix de l'emplacement des puits d'exploration doivent être tirées de reconnaissances superficielles, géophysiques, géologiques, géochimiques, etc. (G/53). Le but préliminaire du fonçage des puits d'exploration est donc de vérifier les renseignements donnés par les reconnaissances mentionnées et recueillir une information détaillée sur les formations présentes, leurs propriétés physiques les plus importantes (porosité, perméabilité, densité) et les conditions physiques telles que la température, la pression et la nature des fluides infiltrés, etc. A mesure que s'accumulent les renseignements fournis par les premiers sondages, on procède à l'établissement de coupes préliminaires et de courbes de température d'une façon qui permette de les utiliser comme guides dans le choix d'emplacements postérieurs.

Pour les champs ou régions produisant déjà de la vapeur, ou en ayant produit dans le passé, l'évaluation de la capacité dispose d'outils et de détails plus nombreux pour résoudre cette question. Les renseignements contenus dans les rapports gaz/vapeur, vapeur/eau, températures au fond du puits et à la surface; analyses chimiques des diverses phases fluides; pressions dans diverses conditions et quantités de fluides par heure; corrosion; dépôt de calcite et de silice; caractéristiques météorologiques et hydrologiques, constituent tous des facteurs connectés ou reliés entre eux d'une manière ou d'une autre qui sont des éléments importants des tentatives d'évaluation de la capacité d'un puits en production.

A Wairakei, les renseignements recueillis ont permis de tracer un jeu complet d'isothermes jusqu'à des profondeurs de 850 m.

Pour évaluer la capacité d'un champ géothermique, il convient de relever, outre les caractéristiques déjà mentionnées, celles de la pression hydrostatique, de la production de chaleur et de la chaleur dans la roche.

Les reconnaissances thermiques de surface permettent de connaître et d'évaluer la surface totale du champ thermique, le flux calorifique et le débit d'eau. A partir de ces données, on peut rechercher de façon préliminaire le potentiel de puissance au moyen des graphiques (G/53) qui relient :

1. La puissance disponible dans les débits d'eau pour des températures comprises entre 50 et 170 °C et le nombre de kilowatts par kilogramme de vapeur par seconde, en faisant intervenir également la profondeur en mètres.

2. L'enthalpie, en calories par gramme, reliée à la température, qui varie de 50 à 400 °C, en fonction du nombre de kilowatts par kilogramme par seconde (entre 0 et 700), compte tenu de la profondeur. Ce graphique montre la variation de puissance disponible dans les débits d'eau portée à des températures inférieures à la température critique.

3. On peut connaître la réserve d'énergie dans la roche saturée d'eau à une profondeur inférieure à celle qui correspond à la température d'ébullition. Ce graphique relie l'enthalpie, en calories par gramme, et l'énergie par unité de volume, en joules par centimètre cube, compte tenu de l'énergie totale exprimée en $10^6$ joules par centimètre cube, et représentée sur le même graphique ainsi qu'en fonction de la profondeur.

4. On peut évaluer les mégawatts par an en faisant intervenir l'enthalpie exprimée en calories par gramme, la profondeur en kilomètres et la surface en kilomètres carrés; on obtient des courbes de profondeur et de surface pour une réserve d'énergie donnée dans une roche saturée d'eau en admettant un rendement de 25 p. 100.

Le lecteur trouvera dans le mémoire G/53 des détails extrêmement précieux sur ces aspects de l'évaluation préliminaire, particulièrement pour la région de Wairakei.

Des considérations sur l'évaluation des caractéristiques fondamentales d'un nouveau puits producteur de vapeur sont présentées dans le mémoire G/75; il est nécessaire de réaliser un programme logique et rationnel pour déterminer la valeur du débit de vapeur, à partir de la mesure du rapport entre les pressions de décharge et de sortie à la bouche du puits, pour un orifice calibré.

Le rapport gaz/vapeur ou le volume de gaz correspondant à un certain poids de vapeur condensée, se mesurent à l'aide d'appareils spéciaux (G/75). On établit des valeurs déterminées de la pression à vanne fermée en relevant les valeurs de la pression à des intervalles de temps réguliers. Pour obtenir une mesure plus précise du mélange eau/vapeur d'un puits en production, il est nécessaire de séparer la vapeur et l'eau et de mesurer chaque phase indépendamment. On utilise pour cela des séparateurs du type cyclone ou du type axial.

Pour disposer des bases techniques et scientifiques nécessaires à la résolution du problème de l'évaluation des champs géothermiques, il est indispensable de disposer de renseignements satisfaisants. A ce sujet, l'auteur du mémoire G/76 résume les méthodes pour le prélèvement d'échantillons et d'analyse utilisées dans les laboratoires de recherche de Larderello. En général, les échantillons tant de gaz que de vapeur sont prélevés après refroidissement des fluides naturels au moyen de dispositifs réfrigérateurs à eau. Ces études ont permis d'aboutir à des conclusions intéressantes; ainsi, les fluides appelés endogènes présentent un enrichissement en $Ar^{40}$ par rapport à la concentration atmosphérique; la composition isotopique du $CH_4$ témoigne d'une origine organique; la composition isotopique de $CO_2$ indique une contribution de la part de la décomposition thermique des roches carboniques profondes. Les phases purement gazeuses sont recueillies globalement ou séparément de même que les gaz résiduels qui permettent de déterminer quantitativement les gaz nobles, l'argon et l'hélium; ces derniers, ainsi que les gaz résiduels ($CH_4$, $N_2$, $H_2$) sont récupérés par absorption des constituants gazeux principaux tels que $CO_2$ et $SH_2$.

Lorsque le gradient thermique est normal, la conductibilité thermique est de 12 000 cal/s/km². Les régions thermiques de grande intensité ont un flux calorifique au moins 50 fois supérieur au flux normal. C'est pourquoi il est nécessaire et souhaitable de mesurer et d'évaluer le flux calorifique des régions nouvelles, mais aussi celui des régions connues, dans le but de déterminer s'il existe des réserves géothermiques.

L'évaluation du flux calorifique, du rapport vapeur/eau, de la composition chimique et, par suite, de la production possible, exige une certaine expérience pour juger et recommander la réalisation de tel ou tel projet en vue de la production d'énergie ou de la récupération de sels précieux. Pour que l'évaluation soit valable, il est indispensable de prélever des échantillons de la décharge des puits selon des procédés corrects et des méthodes systématiques.

Les conditions d'un prélèvement convenable d'échantillons sont examinées dans le mémoire G/46 pour le cas des systèmes d'écoulement qui ont été trouvés dans les voies d'échappement horizontal de Wairakei. Indépendamment de sa simplicité de présentation, l'utilité de ce mémoire est accrue du fait des figures dont il est étayé. Les concentrations des gaz sont déterminées dans les échantillons de vapeur condensée dans des ballons d'une capacité de plusieurs litres, refroidis à l'eau; il en est de même pour celles des constituants dissous : ammoniaque, acide borique, fluor et chlore. On mentionne également le prélèvement d'échantillons en vue de certaines déterminations spécifiques telles que le dosage des principaux constituants ioniques, des traces de métaux, l'évaluation du rapport isotopique et celle du pH et des gaz dissous.

Diverses méthodes suggérées pour la mesure des quantités de vapeur et d'eau débitées par les puits sont mentionnées dans le mémoire G/30 où l'on constate, en outre, que ces méthodes présentaient l'inconvénient pratique d'exiger un matériel lourd et encombrant et où l'on recommande de disposer d'appareils de transport facile qui permettent de déterminer simplement le débit-masse à une pression donnée de bouche de puits. L'auteur décrit les méthodes utilisées en Nouvelle-Zélande et, en particulier, la méthode des rayons bêta, la méthode du gaz, la méthode par injection de sulfate de magnésium et la méthode de la pression critique.

Au sujet des travaux réalisés au volcan Kilauea-Iki, dans l'État d'Hawaii, le mémoire G/5 indique que ce réservoir volcanique contient $3 \times 10^{16}$ calories. Pour faire fondre une telle quantité de roche, il faudrait une explosion nucléaire équivalente à 100 mégatonnes. Dans le cas où seule la chaleur latente de fusion serait récupérée ($0{,}75 \times 10^{16}$ calories) et transformée en énergie électrique avec un rendement de 25 p. 100, on obtiendrait $2 \times 10^9$ kWh.

Selon une supposition présentée dans le mémoire G/48, un mille cube d'une roche comme celle de Devils Tower dans l'état de Wyoming dégagerait, en se refroidissant de 1 800 à 100 °F, une quantité de chaleur suffisante pour faire fonctionner une usine génératrice de 4 000 kW pendant sept mille ans. Les études des masses ignées de périodes géologiques plus anciennes montrent qu'un mille cube constitue une fraction fort faible des grandes masses qui ont été dénudées par l'érosion.

On ne peut espérer trouver normalement de la vapeur sèche dans les régions hydrothermales à une profondeur inférieure à 3 000 m. L'eau météorique doit circuler à des profondeurs semblables pour que sa pression soit maintenue à une valeur supérieure à la pression critique de l'eau pure, englobant les zones de condensation et de mélange. La pression critique d'une colonne d'eau pure, au voisinage de son point d'ébullition, est atteinte à une profondeur de 3 500 m.

L'absence apparente d'eau contenant du chlore dans les champs de vapeur surchauffée suggère que l'eau météorique ne pénètre pas aussi profondément ou qu'elle ne parvient pas à de telles profondeurs en quantités appréciables. Il est probable que, dans ces régions, le chlore reste dans le magma.

Selon les renseignements recueillis en Nouvelle-Zélande, il est improbable que la vapeur sèche soit présente dans les régions où les manifestations superficielles contiennent des quantités appréciables de chlore (plus de 20 ppm). L'abondance de manifestations acides sulfatées dans un état voisin de l'ébullition mais avec un flux modéré témoigne en faveur de l'existence possible de vapeur sèche en profondeur.

Une région qui possède des manifestations en ébullition avec des quantités appréciables de chlorure de sodium et des rapports K/Na et Li/Na relativement élevés peut présenter une augmentation considérable de température avec la profondeur.

Il n'est pas probable, en général, que les eaux de source, diluées, neutres ou alcalines, même si elles se trouvent dans des conditions de température modérément élevées en surface, présentent une température notablement plus grande à des niveaux profonds.

Les valeurs maximums de la température, mesurées au moyen de sondages peu profonds, peuvent être utilisées pour une évaluation acceptable du flux continu de chaleur dans un système hydrothermique avant sa mise en œuvre; il est possible que les valeurs de la décharge totale superficielle et de la décharge subsuperficielle puissent être aussi déterminées directement ou par l'intermédiaire d'un bilan du chlore. On a pu ainsi déterminer les flux de chaleur, en millions de calories par seconde, pour de nombreux systèmes de la Nouvelle-Zélande.

Aux Big Geysers, la zone des sulfures de fer (pyrite et marcassite) indique la possibilité d'une corrélation dans le sous-sol, mais les données sont encore insuffisantes. Une tendance aux pertes de circulation a été constatée, en particulier dans les régions où les noyaux présentent des fractures ouvertes. Les données obtenues antérieurement se sont révélées utiles pour la détermination des zones productrices de vapeur.

L'expérience acquise au cours des travaux réalisés en Italie, en Nouvelle-Zélande et dans d'autres régions permet de constater que l'évaluation préliminaire du flux calorifique, lorsqu'elle est fondée sur les manifestations superficielles d'un champ géothermique, aboutit à des valeurs inférieures à celles qui sont obtenues par la suite à partir des données fournies par les puits et la production de vapeur. Il convient donc de tenir compte de cette expérience lorsqu'il s'agit d'investir dans des conditions présentant une possibilité d'assurer, par la production, une récupération de la vapeur plus importante que celle qui a pu être déduite des études préliminaires.

## Le problème des dépôts

Il convient de mentionner le problème du dépôt de silice et de calcite dont l'importance réside dans l'influence négative de ce dépôt sur le rendement de décharge des fluides.

La silice est précipitée par les courants superficiels qui transportent de l'eau à une température inférieure à 100 °C. Certaines manifestations contiennent des quantités exceptionnellement élevées de silice. La solubilité de la silice amorphe est de 350 ppm à 100 °C et probablement de 500 ppm à 150 °C.

On admet qu'il ne peut y avoir précipitation que lorsque la solubilité de la silice amorphe devient trop faible à cause du refroidissement et de l'évaporation dus au dégagement de vapeur. Les formes polymères de la silice se trouvent alors en suspension dans la solution et forment une pellicule superficielle. La croissance des cristaux de quartz semble être trop lente dans le cas de cette forme moins soluble de silice stable pour que des dépôts se forment dans les conduites; cependant, il s'en forme dans les roches appartenant à des zones plus chaudes de la région.

Le point de saturation des eaux de Wairakei, pour la silice amorphe, est à 140 °C, et la pression de vapeur saturée atteint 40 livres par pouce carré. On ne peut prévoir que très peu de difficultés lorsque l'eau est utilisée à une température supérieure.

Quant à la calcite, on sait que les concentrations totales de calcium et de bicarbonate dans les eaux thermales sont généralement assez élevées pour poser des problèmes de dépôts. Dans un puits type de Wairakei, débitant 200 tonnes d'eau par heure, la solution perd 1 ppm de calcium et pendant le même temps, il peut se former 0,5 kg de $CaCO_3$. Si ce dépôt devait se produire sur 1 m de longueur d'une conduite de 8 pouces (en général les dépôts sont localisés), ce diamètre subirait une réduction de la moitié en 50 jours seulement.

Les dépôts de carbonate de calcium se forment dans les eaux thermales ayant un pH compris entre 6 et 8 lorsque la quantité de calcium dissoute dépasse quelques ppm. La production de fluides à une pression modérée peut empêcher la précipitation des carbonates dans les zones profondes. Les dépôts de silice constituent un ennui sérieux dans le cas des eaux contenant plus de 350 ppm de $SiO_2$.

## Brèves considérations sur les frais et les aspects économiques

En 1950, dans l'ouest des États-Unis, le forage avec un foret de diamant coûtait 18 dollars le mètre. Au Mexique, la même opération coûte actuellement 25 dollars.

Le forage de 16 puits d'exploration et de production au Mexique, par percussion et par rotation, jusqu'à des profondeurs qui atteignent actuellement un maximum de 700 m, a coûté 640 000 dollars pour quatre années, compte tenu de la première installation d'une usine géothermo-électrique à Pathé.

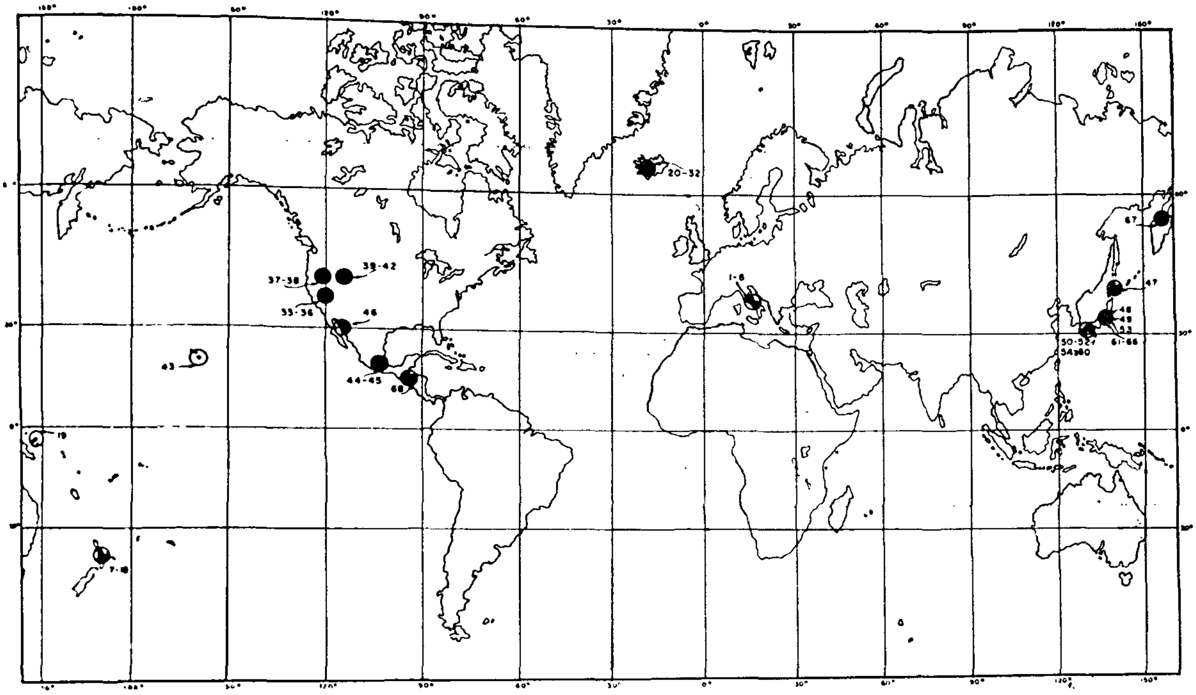
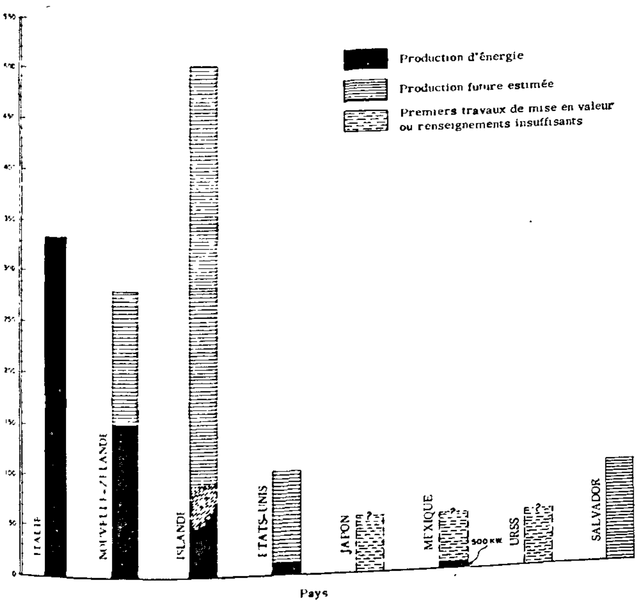


**Figure 1. Répartition des zones géothermiques dans le monde**

Énergie géothermique théorique et production d'énergie dans certains pays




ITALIE

1. Larderello
2. Monte Amiata
3. Roccastrada
4. Montecatini-Orciatico
5. La Tolfa
6. Monti Berici

NOUVELLE-ZÉLANDE

7. Wairakei
8. Waiotapu
9. Kawerau
10. Orakeikorato
11. Tikitere
12. Tekopia
13. Waikiti
14. Taupo
15. Ngatamariki
16. Rautawiri
17. Rotokawa
18. Tauhara

NOUVELLE-BRETAGNE

19. Matupi-Rabalanakaïa-Vulcan

ISLANDE

20. Reykjanes
21. Trolladyngja
22. Krysuvik
23. Hengill
24. Kerlingafjöll
25. Torfajökull
26. Vonarskard
27. Grimsvötn
28. Kverkfjöll
29. Askja
30. Namafjall
31. Krafla
32. Theistareykir

ÉTATS-UNIS

33. Big Geysers
34. Casa Diablo
35. Calistoga
36. Surprise Valley
37. Lakeview
38. Lac Crump
39. Wabuska
40. Steamboat Springs
41. Brady Hot Springs
42. Becwawe
43. Volcan Kilauea, Iki, Hawaii

MEXIQUE

44. Pathé
45. Ixtlan
46. Mexicali

JAPON

47. Showa-Shinzan
48. Matzukawa
49. Onikobe
50. Beppu
51. Obama
52. Otake
53. Hakone
54. Noya
55. Takenoyu
56. Unzen
57. Ebino
58. Yunono
59. Tearai
60. Ibusuki
61. Kusatsu
62. Yamanouchi
63. Oshima
64. Atagawa
65. Narugo
66. Takinoue

UNION SOVIÉTIQUE

67. Pauzhetsk, Kamtchatka

SALVADOR

68. Aguachapan

Ce chiffre comprend également le prix des explorations antérieures et les salaires du personnel technique et les dépenses en main-d'œuvre. Les 16 puits sont répartis comme suit : 12 à Pathé, 2 à Ixtlan et 2 à Mexicali.

En Nouvelle-Zélande, le prix annuel des travaux géothermiques a varié entre 55 000 et 138 000 dollars au cours de ces 10 dernières années. Le prix d'un laboratoire portatif, destiné à la prospection chimique des champs et comprenant tout l'équipement indispensable, est estimé en Nouvelle-Zélande à 4 000 dollars.

Selon le mémoire G/48, il est intéressant, lorsqu'on considère les possibilités d'une opération économique, de tenir compte du marché disponible, du prix du kilowattheure électrique sur le marché considéré, de l'exploitation collective et du coût de la production de l'énergie naturelle. Un champ capable de fournir une énergie dont on peut produire de 2 000 à 3 000 kWh peut assurer le succès de l'opération. D'après les résultats des forages d'exploration effectués au cours de ces deux dernières années, on peut espérer qu'au moins six des régions explorées dans l'ouest des États-Unis constitueront des opérations à succès du point de vue économique.

Ces considérations diffèrent de celles qui sont présentées dans le mémoire G/67, selon lesquelles un champ géothermique industriel doit pouvoir produire environ $5 \times 10^6$ tonnes de vapeur par année. Selon ce mémoire, un champ vaporifère commercial produit des quantités notables d'eau; ainsi le champ de Larderello produit annuellement près de $10 \times 10^6$ tonnes d'eau.

Les renseignements fragmentaires dont on dispose sur le Japon montrent que dans ce pays les investissements ont atteint près de 119 millions de yens.

On a démontré (G/5) qu'il existe un équipement de forage pouvant être utilisé à plus de 1 000 °C et résistant à l'action d'une forte corrosion.

Les auteurs en déduisent qu'il n'est pas impossible de concevoir des cratères réalisés techniquement et construits dans le but de capter la coulée de lave le long de zones qui présentent des voies d'échappement dans les régions de volcanisme actif. Les bassins de laves pourraient être localisés autour d'une centrale électrique, dans une région suffisamment active pour fournir une énergie continue. On estime que le temps naturel de refroidissement du réservoir de Kilauea est supérieur à 75 ans.

Il existe une possibilité de connaître comment pourraient être utilisés industriellement les « magasins » souterrains de roches fondues tels que ceux qui pourraient être formés par des explosions nucléaires profondes ou à partir des gîtes magmatiques souterrains qui peuvent exister dans les régions de volcanisme actif. En évaluant le kilowattheure à 5 mils, cette énergie correspondrait à 10 millions de dollars; le fait que le réservoir de lave de Kilauea et les masses semblables de roche en fusion représentent des réserves naturelles importantes est donc significatif.

Les auteurs américains constatent qu'à l'heure actuelle, la prospection dans l'ouest des États-Unis n'est pas sortie des limites des régions présentant une activité thermique de surface.

Dans le cas de l'ouest des États-Unis, les régions caractérisées par un volcanisme tardif du point de vue géologique, sont propices à la recherche de la vapeur sur une étendue de 60 000 milles carrés comprenant une partie des États suivants : Idaho, Oregon, Californie et Nevada. Ce genre de prospection pourrait s'étendre également à des roches du nord de l'Oregon et du sud-est de l'État de Washington, sur une superficie de 85 000 milles carrés, étant donné qu'il existe des indications favorables quant à l'existence d'un volcanisme du miocène jusqu'au récent.

### Sujets proposés pour la discussion

1. Quelles peuvent être les possibilités de trouver de la vapeur à l'échelle commerciale dans le sous-sol des régions comprenant des roches volcaniques du pliocène récent mais ne présentant pas de manifestations hydrothermales superficielles?

2. Doit-on éliminer totalement du panorama vaporifère le volcanisme prépliocénique et les roches ignées qui lui sont associées (c'est-à-dire remontant à plus de 500 000 ans)?

3. Examen de l'aspect économique de la prospection géothermique : quel est le procédé de prospection le moins cher et le plus efficace?

4. Peut-on soutenir que les zones qui présentent actuellement des preuves convaincantes d'activité hydrothermale ont été potentiellement vaporifères?

5. Comment distingue-t-on les manifestations thermales qui reçoivent la chaleur de phénomènes tectoniques, magmatiques ou volcaniques? Comment peut-on distinguer la vapeur tectonique de la vapeur magmatique?

6. Que peut-on dire au sujet de la durée de vie active d'un champ géothermique à partir des paramètres suivants : rapports gaz/vapeur, vapeur/eau, températures et pressions en surface et en profondeur, débit de fluides en kilogrammes par heure, composition chimique des fluides?

7. Quel est en fait le paramètre le plus important pour la question précédente?

8. Les variations et les compositions chimiques des fluides hydrothermiques recueillis en surface indiquent des origines et des trajectoires différentes dans les différentes régions. En admettant une influence primitive, ces variations pourraient-elles indiquer si les magmas du sous-sol (masses intrusives en refroidissement) sont acides, intermédiaires ou basiques?

9. Comment varie la composition chimique des sources hydrothermales par rapport à la composition de l'eau de mer?

10. Comment le coût de prospection des puits de vapeur (à l'exclusion du sondage) se compare-t-il

à celui des autres sources d'énergie, telles que le pétrole?

11. Quelle est la profondeur économique pour la production de vapeur? Selon divers auteurs, une certaine température de base pourrait être atteinte en dépassant la profondeur de 3 000 m pour obtenir de la vapeur sèche. Examiner cette question sous l'angle de la nature des différentes formations.

12. Étant donné l'importance considérable des dépôts de calcite et de silice pour la production de vapeur et les difficultés qu'ils causent, il est recommandé d'examiner le problème posé par l'accumulation de ces dépôts dans les conduites et dans les roches voisines des puits. De façon concrète, quelles sont les mesures qui peuvent être adoptées, à la lumière des connaissances acquises jusqu'à présent, pour éliminer la formation de ces incrustations?

13. Quelle quantité d'énergie, en kilowatts, doit produire un champ pour pouvoir être considéré comme potentiellement économique?

14. Nous proposons la discussion d'un programme général de forage en vue de l'obtention de vapeur à une certaine profondeur dans un terrain volcanique fracturé. Quel est le diamètre minimum de la conduite qui parvient à la surface pour que la production soit commercialement satisfaisante, dans le cas où l'on obtient 150 kg/s de vapeur à une pression et une température données?

# PROSPECTION OF GEOTHERMAL FIELDS AND INVESTIGATIONS NECESSARY TO EVALUATE THEIR CAPACITY

## *Rapporteur's summation*

The papers presented in connexion with agenda item II.A.1 are ample evidence of widespread interest in this field. A total of thirty-nine papers dealing with the technical and scientific problems of this aspect of geothermal energy gave extremely valuable information, and the discussion during the session devoted to the subject brought forth new ideas and exchanges of experience. Of equal importance were the interventions that indicated interest in the exploitation of geothermal energy in three areas about which no papers had been submitted, namely, Kenya, Fiji and Chile.

Those who look to geothermal energy as a means of earning a living or as a professional challenge have the important task of discovering new steam fields with economic potentials. The first problem the geothermal prospector must solve is to determine in which areas the search is likely to be profitable. The special conditions that make an area suitable for prospecting are easily recognized. A characteristic feature without analogy in other branches of economic geology is the presence of a source of heat which transfers thermal energy to fluids. The heat source is connected, through a formation of fractures, with a reservoir where fluids can be trapped under pressure.

Surface manifestations are a useful indication of what to expect, but in order to ensure economically successful exploitation of geothermal steam, sites should be tested which seem most promising against the background of the general geological characteristics of the area. A systematic inventory of thermal resources could be made of sites that look promising in countries where there are surface indications of geothermal activity. Thus it would be possible to select a number of areas for further investigation. Testing geothermal fields would become a continuing process, with first priority given to the most favourable fields, from an economic and social point of view, and difficult ones left to subsequent projects.

It is evident that geothermal energy is restricted to certain places and particular areas of the earth's crust. These limited areas, however, perhaps do not always coincide with surface thermal manifestations, which are not necessarily present in areas where geothermal steam may be found underneath.

On the basis of experience, particularly from the electrical geophysical method of prospecting, as described during the discussion, a method could perhaps be developed to determine where geothermal steam may be economically recovered in areas without surface manifestations.

A summary of the statements presented at the session follows.

So far as the economy of geothermal prospecting is concerned, there is no one-and-only method. Economy in prospecting is achieved by finding the most effective method for each geological problem and in planning the exploration so that a clear picture of the underground material may emerge. Moreover, the possibilities of successful results may depend on the use of very expensive tools. The refraction seismic method is effective in detecting deep faulting and in determining the shape and depth of a deep basement. According to the experience gained in some cases, it may be cheaper than the electrical method in dealing with the same type of problem. In central Italy and northern Sardinia, seismic refraction prospecting has proved advantageous.

In Kenya, the region of the Rift Valley, which runs north to south, is of considerable geothermal interest, although attempts at harnessing its energy have so far been disappointing. Volcanic and fissure eruptions are abundant in the valley, major faulting being generally of mid-Pleistocene age. The only active volcano in the country is Ol Doinyo Lengai. It is situated about 120 miles from Nairobi, which is built on volcanic rocks and lacks an adequate power supply for its growing urban and industrial development. Boring for water sometimes results in striking steam, and some farmers condense geothermal steam to augment their water supply.

A geological report has now been completed, and a company is proceeding to investigate further the geothermal potential of the Rift Valley from a commercial standpoint. Two deep boreholes were drilled one mile apart, with negative but interesting results. Bottom-hole temperature ranged from 93.3° to 101.6°C at approximately 500 metres in one hole, and it reached 204.4°C at about 950 metres in the other. In spite of the promising high temperature no steam escaped. It is thought that the steam at the lower levels may be due to reheating of water from near-by Lake Naivasha by vapour and gas escaping through fissures. Indications are that the source may be magmatic, or that the steam may be formed by ground water. There is no doubt that a reservoir of magma of an enormous energy content exists in the Rift Valley area; the problem is to intersect fissures leading primary steam and gases from the magma, but that has proved to be very difficult.

There has of late been an interesting development in shallow holes, between 100 and 180 metres, producing $CO_2$ (95-98 per cent content) at pressures varying between 1.5 and 3 atmospheres. One site, 120 miles from Nairobi, has one producing hole and one in reserve; the other, 45 miles from Nairobi, has one almost producing, and two in reserve.

In Chile, there is a promising zone amidst abundant geysers and fumaroles, located in the volcanic region of Tatio, near the most important copper and natural nitrate mining centres in the northern part of the country, close to the border with Argentina and Bolivia. Its elevation is over 4 200 metres, and it is surrounded by high mountains. This high plateau, tipped slightly towards the south-west, is full of thermal waters; some of them are stagnant, but others form currents for the headwaters of the river Tatio. Its temperature is between 84° and 87°C.

Earlier investigations are now being continued by the University of Chile on 40 geysers, 72 fumaroles, 62 thermal water springs and 5 mud-pools. The temperature of the geysers and fumaroles ranges from 81° to 90°C, and that of the springs and mud-pools from 41 to 62°C. The chemical characteristics follow:

| | |
|---|---|
| pH | 5.96-8 |
| $H_3BO_3$ | 0.06-1.05 g/l |
| $SiO_2$ | 0.011-0.036 g/l |
| $Al_2O_3$ | 0.005-0.036 g/l |
| $Fe_2O_3$ | 0.005-0.038 g/l |
| Ca | 0.07-0.028 g/l |
| $CO_2$ | traces. |

No borings have been made, and there have been only occasional pressure measurements at the site.

It is worth noting that the north of Chile is totally devoid of any hydro-power possibilities (the region is extremely arid) and of mineral fuels. The important mining industry of that region relies on the importation of fuel oil for its more than 300 000 kW power plants.

According to one participant in the discussion, it is almost impossible to lay down general rules as to the applicability of various geophysical methods to the exploration of geothermal fields. They depend largely on local conditions; the use of electrical geoprospecting is based mostly on experience at Larderello. It is thought to be valid for regions in which measurements of resistivity are in formations overlaid with strata of clay. The picture becomes much more confused, however, if, as is often the case, these overlays are mixed with sand, calcareous rocks or lava.

Gravimetric methods have been standard procedures and do not appear to be very expensive. One author, however, claims that the Larderello method of vertical electrical prospecting has borne very good results in another region, that of Mount Amiata. There, the large difference in resistivity between the impervious cover and the steam-bearing rocks has made it possible to draw a clear picture of the formation and to determine the most favourable locations of productive borings. The geological complications diminish the usefulness of the electrical method.

Supplementary information was given about the borings at Larderello, which amount to 360 holes over almost 200 000 m, 160 of which are now active, producing 3 000 000 kg steam per hour. At Mount Amiata there are 5 active holes with an output of 200 000 kg steam per hour. The region of Mount Amiata proves that in volcanic formations without steam manifestations, economically viable geothermal deposits may be found. Larderello is now boring a 3 000 m hole, to study the temperature behaviour at great depths. It has reached the 1 500 m mark. Reference was also made to the fact that careful and methodical measurements of flow, pressure and temperature are being conducted for each hole.

In Japan, electrical methods in drilling holes have proved satisfactory with the use of specially protected cables that resist high temperatures. In Japan prospecting for steam for power generation is done in areas where manifestations at the surface are weak, because at the present time any geothermal prospecting in places which are hot-spring resorts would be impractical.

A statement regarding a problem previously dealt with expressed the views that the possibilities of producing natural steam depended upon the existence of a source of heat, on the presence of a permeable horizon and an impermeable cap-rock, and on the absence of infiltrations of either fresh or salt water if superheated steam was expected.

The economic question of geophysical prospecting was again raised. It was maintained that through electrical prospecting, important discoveries had led to an increase of 4 500 tons per hour of steam at Larderello after 1949. The electrical method offers the advantage of being dynamic. It is adaptable to different stratigraphic and tectonic conditions and shows the evidence of thermal anomalies on account of differences in resistivity caused by different temperatures.

Prospecting activities have a few aspects in common, whether the intention is to look for steam or for oil; although there is the important difference that the oilfield has a finite reserve, varying from field to field. In a geothermal field, the amount of energy obtainable is indefinite, as is its exploitation lifetime. On the other hand, a single well in a geothermal field has a limited duration; its production time depends on the well's diameter, the chemical composition of the "productive strata", the temperature, the corrosive conditions and other factors. A most important factor which determines the producing period of a well is that of incrustations. Some incrustation problems have been solved by drilling a well close to the one affected. In contrast to steam, the oil industry has achieved a high degree of technical perfection, whereas the geothermal industry is still at an early stage.

Workers in isotope chemistry constantly strive for the answer to the important questions of the origin, nature and composition of fluids in geothermal steam. An interesting view was presented to the effect that the isotope composition of magmatic water is unknown because of sampling problems. Isotopic evidence does not point to the existence of volcanic water in many of the known hydrothermal springs, but chemical and heat flow evidence points to the possibility of some volcanic water.

A no less interesting aspect of isotopic chemistry was outlined in connexion with the oxygen isotopic composition of limestone. This line of research has been followed in verifying the existence of deeply located intrusive bodies and in prospecting for geothermal fields.

The experience gained in oil reservoir mechanics over the past thirty years could usefully be drawn upon for making a better survey of current work on geothermal steam production. In this connexion, experience in special well tests, based on the downhole measurement of the rate of pressure buildup, may lead to an evaluation of the maximum efficient rates at which wells can be operated.

It appears, however, that reservoir mechanics is not quite the same for oilfields as for geothermal steam fields; in the Wairakei area of New Zealand a decrease of pressure in the field was obtained as a result of abundant water production. This brought about an increase in temperature, improving the general situation in the field.

# PROSPECTION DES CHAMPS GÉOTHERMIQUES ET RECHERCHES NÉCESSAIRES POUR ÉVALUER LA PUISSANCE UTILISABLE

*Résumé du Rapporteur*

Les mémoires présentés au sujet du point II.A.1 de l'ordre du jour témoignent amplement du très grand intérêt que suscite cette question. Trente-neuf mémoires traitant des problèmes techniques et scientifiques posés par cet aspect de l'énergie géothermique ont fourni des renseignements précieux, et les débats qui ont eu lieu aux séances consacrées à ce sujet ont donné aux participants l'occasion d'exprimer des idées nouvelles et d'échanger des données d'expérience. Également importantes ont été les interventions qui ont montré l'intérêt que l'on porte à l'exploitation de l'énergie géothermique dans trois régions pour lesquelles aucun mémoire n'avait été présenté : le Kenya, les îles Fidji et le Chili.

C'est à ceux pour qui l'énergie géothermique est un moyen de subsistance ou un objectif professionnel qu'incombe la tâche importante de découvrir de nouveaux gîtes de vapeur offrant des possibilités économiques. Le premier problème que le prospecteur géothermique doit résoudre est de déterminer dans quelles régions la prospection a des chances d'être fructueuse. On reconnaît facilement les particularités d'une région propice à la prospection. Un trait caractéristique sans analogie dans les autres branches de la géologie économique est la présence d'une source de chaleur qui cède de l'énergie thermique aux fluides. La source de chaleur est reliée, par une formation de fractures, à un réservoir où les fluides peuvent être retenus sous pression.

Les phénomènes de surface constituent une indication utile de ce que l'on peut attendre, mais, pour s'assurer d'une exploitation rentable de la vapeur géothermique, il faut éprouver les emplacements qui semblent les plus favorables, eu égard aux caractéristiques géologiques générales de la région. On pourrait dresser un inventaire méthodique des ressources thermiques des emplacements qui semblent prometteurs, dans les pays où des phénomènes de surface indiquent une activité géothermique. Il serait ainsi possible de choisir un certain nombre de régions pour y faire des enquêtes plus poussées. L'examen de champs géothermiques deviendrait un processus continu permettant d'accorder la priorité aux champs les plus favorables du point de vue économique et social et de réserver les champs d'exploitation difficile pour des projets ultérieurs.

Il est évident que l'énergie géothermique ne se trouve qu'à certains endroits et dans des régions particulières de l'écorce terrestre. Or, la situation géographique de ces régions peu nombreuses ne coïncide peut-être pas toujours avec celle des phénomènes thermiques de surface, qui ne se produisent pas nécessairement dans des régions où l'on peut trouver de la vapeur géothermique dans le sous-sol. Se fondant sur l'expérience acquise notamment par l'application des méthodes électriques de prospection géophysique qui ont été décrites pendant les débats, on pourrait peut-être mettre au point un procédé pour déterminer les endroits où de la vapeur géothermique peut être recueillie de façon rentable dans des régions sans manifestation en surface.

Voici un résumé des exposés présentés à la Conférence.

En ce qui concerne l'économie de la prospection géothermique, il n'existe pas de méthode seule et unique. Une prospection économique exige l'emploi de la méthode la plus efficace pour chaque problème géologique et une exploration organisée de manière à donner une idée très nette des éléments du sous-sol. De plus, la possibilité d'obtenir d'heureux résultats peut dépendre de l'emploi d'instruments très coûteux. La méthode de la réfraction des ondes séismiques est efficace pour déceler les failles profondes et déterminer la forme et la profondeur d'un soubassement profond. D'après l'expérience acquise dans quelques cas, elle peut être moins coûteuse que la méthode électrique pour résoudre le même genre de problème. Dans le centre de l'Italie et dans le nord de la Sardaigne, la prospection par réfraction des ondes séismiques s'est révélée avantageuse.

Au Kenya, la région de la Grande fosse, qui est orientée du nord au sud, présente un très grand intérêt du point de vue géothermique, bien que les efforts accomplis jusqu'à présent pour exploiter son énergie aient donné des résultats décevants. Les éruptions provenant de volcans ou de fissures abondent dans la vallée; les principales failles datent généralement du milieu du pléistocène. Le seul volcan actif dans le pays est le Ol Doinyo Lengai. Il est situé à environ 190 kilomètres de Nairobi, qui est bâtie sur des roches volcaniques et ne dispose pas de ressources énergétiques suffisantes pour son développement urbain et industriel croissant. En effectuant des sondages pour trouver de l'eau on rencontre parfois de la vapeur, et certains agriculteurs condensent de la vapeur géothermique pour augmenter leur approvisionnement en eau.

Un rapport géologique vient d'être rédigé et une société privée poursuit l'étude du potentiel géothermique de la Grande fosse du point de vue commercial. On a effectué deux sondages profonds à 1,6 kilomètre l'un de l'autre; les résultats en ont été négatifs mais intéressants. La température de fond variait entre 93,3 °C et 101,6 °C à environ 500 mètres dans un trou et atteignait 204,4 °C à environ 950 mètres dans l'autre. En dépit des promesses de cette température élevée, aucune vapeur ne s'est échappée. On pense que la vapeur qui se trouve aux niveaux plus profonds résulte peut-être du réchauffement de l'eau du lac Naivasha tout proche par la vapeur et le gaz qui s'échappent des fissures. Il se peut que la source soit magmatique, ou que la vapeur soit formée par de l'eau souterraine. Il n'est pas douteux qu'un réservoir de magma d'une très grande richesse énergétique existe dans la région de la Grande fosse; il faudrait entrecouper les fissures qui amènent de la vapeur et des gaz primaires en provenance du magma, mais cela s'est révélé très difficile.

Un fait nouveau intéressant s'est produit récemment. Dans des puits peu profonds (de 100 à 180 mètres), il y a eu production de $CO_2$ (teneur de 95 à 98 p. 100) à des pressions variant entre 1,5 et 3 atmosphères. A un endroit situé à 190 kilomètres de Nairobi, il y a un puits productif et un puits en réserve; à un autre endroit, à 70 kilomètres de Nairobi, il y a un puits sur le point de produire et deux en réserve.

Au Chili, il existe une zone riche de promesses au milieu de geysers et de fumerolles abondants, situés dans la région volcanique de Tatio, près des centres miniers de cuivre et de nitrate naturel les plus importants de la partie nord du pays, à proximité de la frontière de l'Argentine et de la Bolivie. La zone se trouve à plus de 4 200 mètres d'altitude et est entourée de hautes montagnes. Ce haut plateau, légèrement incliné vers le sud-ouest, abonde en eaux thermales dont certaines sont stagnantes et d'autres forment des courants qui se dirigent vers le cours supérieur du Tatio. La température varie entre 84 et 87 °C.

Des études entreprises antérieurement sont actuellement poursuivies par l'Université du Chili au sujet de 40 geysers, 72 fumerolles, 62 sources d'eau thermale et 5 bourbiers. La température des geysers et des fumerolles varie entre 81 et 90 °C et celle des sources et des bourbiers entre 41 et 62 °C. Les caractéristiques chimiques sont les suivantes :

| | |
|---|---|
| pH : | 5.96 — 8; |
| $H_3BO_3$ : | 0.06 — 1.05 g/l; |
| $SiO_2$ : | 0.011 — 0.036 g/l; |
| $Al_2O_3$ : | 0.005 — 0.036 g/l; |
| $Fe_2O_3$ : | 0.005 — 0.038 g/l; |
| Ca : | 0.07 — 0.028 g/l; |
| $CO_2$ : | traces. |

On n'a effectué aucun forage, et les mesures de pression sur les lieux ont été peu fréquentes.

Il convient de remarquer qu'il n'y a, dans le nord du Chili, pas le moindre potentiel d'énergie hydroélectrique (la région est extrêmement aride) ni aucun combustible minéral. L'importante industrie extractive de cette région est tributaire de l'importation de fuel-oil pour faire fonctionner ses centrales, dont la puissance dépasse 300 000 kW.

D'après un participant à la Conférence, il est presque impossible d'énoncer des règles générales concernant l'applicabilité des diverses méthodes géophysiques à l'exploration des champs géothermiques. Ces règles dépendent dans une large mesure des conditions locales; l'emploi de la méthode de prospection électrique est principalement fondé sur l'expérience acquise à Larderello. On estime que cette méthode est valable pour les régions où les mesures de la résistivité ont lieu dans des formations recouvertes de couches d'argile. La situation devient beaucoup plus confuse si, comme c'est souvent le cas, ces recouvrements sont mélangés de sable, de roches calcaires ou de lave.

Les méthodes gravimétriques sont d'un emploi courant et ne semblent pas très coûteuses. Un auteur prétend toutefois que la méthode de prospection électrique verticale employée à Larderello a produit de très bons résultats dans une autre région, celle du mont Amiata. La grande différence de résistivité entre le mort-terrain imperméable et les roches vaporifères a permis de se faire une idée nette de la formation et de déterminer les emplacements les plus favorables pour des forages productifs. Les complications géologiques réduisent l'utilité de la méthode électrique.

Des renseignements supplémentaires ont été fournis sur les forages de Larderello. Il y a 360 puits sur près de 200 000 mètres; 160 d'entre eux sont en exploitation et produisent 3 millions de kilogrammes de vapeur par heure. Au mont Amiata, il y a cinq puits en exploitation qui produisent 200 000 kg/h de vapeur. La région du mont Amiata prouve que l'on peut trouver des gisements géothermiques économiquement viables dans des formations volcaniques où ne se produit aucun dégagement naturel de vapeur. A Larderello, on creuse actuellement un puits de 3 000 mètres pour étudier le comportement de la température à de grandes profondeurs. Le forage a maintenant atteint 1 500 mètres. On a également signalé que des mesures minutieuses et méthodiques du débit, de la pression et de la température sont en cours dans chaque puits.

Au Japon, les méthodes électriques de forage se sont révélées satisfaisantes, avec l'emploi de câbles spécialement protégés, qui résistent à des températures élevées. Dans ce pays, on procède à la recherche de vapeur pour la production d'énergie dans des régions où les manifestations de surface sont faibles, car toute prospection géothermique dans des endroits qui sont des stations thermales serait actuellement impossible.

Dans un exposé relatif à un problème précédemment traité, on a exprimé l'avis que la possibilité de produire de la vapeur naturelle dépend de l'existence d'une source de chaleur, de la présence d'un horizon perméable et d'un chapeau imperméable, ainsi que de l'absence d'infiltrations d'eau douce ou salée, si l'on désire obtenir de la vapeur surchauffée.

L'aspect économique de la prospection géophysique a de nouveau été évoqué. On a affirmé que, grâce à la prospection électrique, d'importantes découvertes avaient permis d'augmenter de 4 500 tonnes par heure la production de vapeur à Larderello, après 1949. La méthode électrique offre l'avantage d'être dynamique. Elle peut être adaptée à différentes conditions stratigraphiques et tectoniques et met en évidence les anomalies thermiques en raison de différences de résistivité causées par des températures différentes.

Qu'il s'agisse de chercher de la vapeur ou du pétrole, les activités de prospection ont quelques aspects en commun. Cependant, il y a cette grande différence que les champs pétrolifères ont une réserve limitée, qui varie de l'un à l'autre. Dans un champ géothermique, la quantité d'énergie disponible est indéfinie, de même que la durée de son exploitation. En revanche, la vie utile de chaque puits dans un champ géothermique est limitée; la durée de sa production dépend du diamètre du puits, de la composition chimique des « strates productives », de la température, de la corrosion et d'autres circonstances. Un facteur très important qui détermine la durée de production d'un puits est celui des incrustations. On a résolu certains problèmes d'incrustation en forant un puits près de celui qui est affecté. A la différence de l'industrie du pétrole qui a atteint un degré élevé de perfection technique, l'industrie géothermique en est encore à ses débuts.

Les travailleurs de la chimie isotopique s'efforcent constamment de trouver la réponse aux questions importantes que posent l'origine, la nature et la composition des fluides dans la vapeur géothermique. On a exprimé l'avis intéressant que la composition isotopique de l'eau magmatique est inconnue à cause des difficultés de l'échantillonnage. La preuve isotopique n'indique pas l'existence d'eau volcanique dans un grand nombre de sources hydrothermiques connues, mais les éléments d'information fournis par l'analyse chimique et le débit de chaleur indiquent l'existence possible de quelque eau volcanique.

Un aspect non moins intéressant de la chimie isotopique a été exposé au sujet de la composition de la pierre à chaux en isotopes d'oxygène. On a employé cette méthode de recherche pour vérifier l'existence de corps intrusifs situés à de grandes profondeurs et pour chercher des champs géothermiques.

On pourrait utilement mettre à contribution l'expérience acquise au cours des 30 dernières années sur la mécanique des bassins pétrolifères pour améliorer l'examen des travaux actuels relatifs à la production de vapeur géothermique. A ce sujet, les données d'expérience fournies par des recherches spéciales sur les puits, fondées sur la mesure, au fond du puits, du taux d'accroissement de la pression, peut faciliter l'évaluation des taux maximaux d'efficacité auxquels les puits peuvent être exploités.

Il semble cependant que la mécanique des bassins n'est pas tout à fait la même pour les champs pétrolifères et pour les champs de vapeur géothermique; dans la région de Wairakei (Nouvelle-Zélande), on a obtenu une diminution de pression dans le champ à la suite de la production d'une grande quantité d'eau. On a ainsi déterminé un accroissement de la température, ce qui a amélioré la situation générale du champ.

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# THE TECHNIQUE OF TESTING GEOTHERMAL WELLS

*V. V. Averiev**

The testing of geothermal wells is a methodologically new department in the practice of hydrogeological surveying, a department that has originated only during the last few years. Its development is connected with the establishment of geothermal power stations utilizing the energy of geothermal steam and hot water which occur in volcanic regions. The number of locations with operating geothermal wells is small today, but it may increase during the next few years as geothermal exploration progresses.

The testing of geothermal wells requires the use of various devices and instruments, and demands a very high level of general technical equipment. In this paper, however, the author deems it necessary to discuss primarily the fundamental methodological aspects of the question, to bring out the necessary initial data that will make it possible to obtain a complete and meaningful characterization of a well.

The technique of testing geothermal wells that has been developed by the Pauzhetsk Observation Station of the USSR Academy of Sciences in Kamchatka is based on hydrogeological principles, since this ensures the most rational approach to the study of a deposit of thermal water as a whole. This method, however, is distinguished by a number of specific features from the technique of hydrogeological testing in common use. The specific nature of this method is due, in the last analysis, to the high temperature, which introduces various complications into the hydrodynamics of these wells.

The peculiar features in the dynamics of geothermal wells are due to the fact that they reach deep pressure water at a temperature considerably above 100°C. Thus, in the Pauzhetsk geothermal field, the temperature of the water at a depth of 250-350 m is 185-195°C. As a result of the ebullition of the water, the output at wellmouth consists of a two-phase medium (water plus saturated steam), and, as the water-steam mixture rises in the well, the quantity of steam increases progressively. The velocity of the steam-water mixture increases accordingly, and in many cases reaches a value of hundreds of metres a second at wellmouth.

There is a complex functional relationship between the depth at which the vapour phase is formed and the temperature of the water reached by the well, its flow rate, and the conditions of motion through the well and of its discharge to the surface. According to the results of experimental work at the Pauzhetsk hydrothermal field, the level of steam generation in the operating wells runs down to depths of tens and hundreds of metres.

The depth of steam generation found always corresponds to a strictly determinate pressure — namely, to the pressure of saturated steam at the given temperature. This circumstance enables one to evaluate the hydrodynamic condition of a well. Indeed, if at a certain depth there exists a pressure considerably lower than the seam pressure at the same level, then water will be drained from the seam, owing to the deep descent of the steam generation level, thus giving a vapour-lift effect. In this case, to each position of the level of steam generation corresponds a definite pressure drop and a definite flow rate. The high flow-rate of geothermal wells, which usually amounts to tens of kilogrammes a second, is a consequence of the vapour lift.

Thus the dynamics of geothermal wells obeys the fundamental hydrogeological laws. This makes it possible to apply the formulas of underground hydraulics, more particularly the Dupuy formula for artesian wells, for calculating the coefficient of filtration and the specific flow of the well:

$$Q = \frac{2\,\pi\,MKS}{\ln\frac{R}{r}}$$

According to this formula, the discharge of a well (Q) is directly proportional to the coefficient of filtration (K) and to the depth of the level below the surface (S), whence one may also calculate the increase of discharge per metre of increased depth—i.e., the specific flow of the well (q) equal to $\frac{Q}{S}$.

It must be borne in mind that the quantity S in this formula represents the difference between the static and dynamic levels of the water in the well, with both levels under the same atmospheric pressure. In a geothermal well, however, as already stated, the level of steam generation is not under atmospheric pressure, but is instead under the pressure of saturated steam at the temperature existing in the well. In order to pass from the depth of steam formation to the lowering of the steam formation level during drainage from the seams, in the sense in which this is used in the Dupuy formula, the level of steam generation must be raised by the height of a column exerting the same pressure as the excess pressure of saturated steam under the given conditions (figure 1).

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On the basis of the foregoing we have:

$$S = H_{st} - H_s - h_{w(at)}, \text{ where}$$

S is the dynamic lowering of level;
$H_{st}$ is the static level of the underground water;
$H_s$ is the level of steam generation; and
$h_{w(at)}$ is the height of a column of water exerting a pressure equal to the excess pressure of saturated steam.

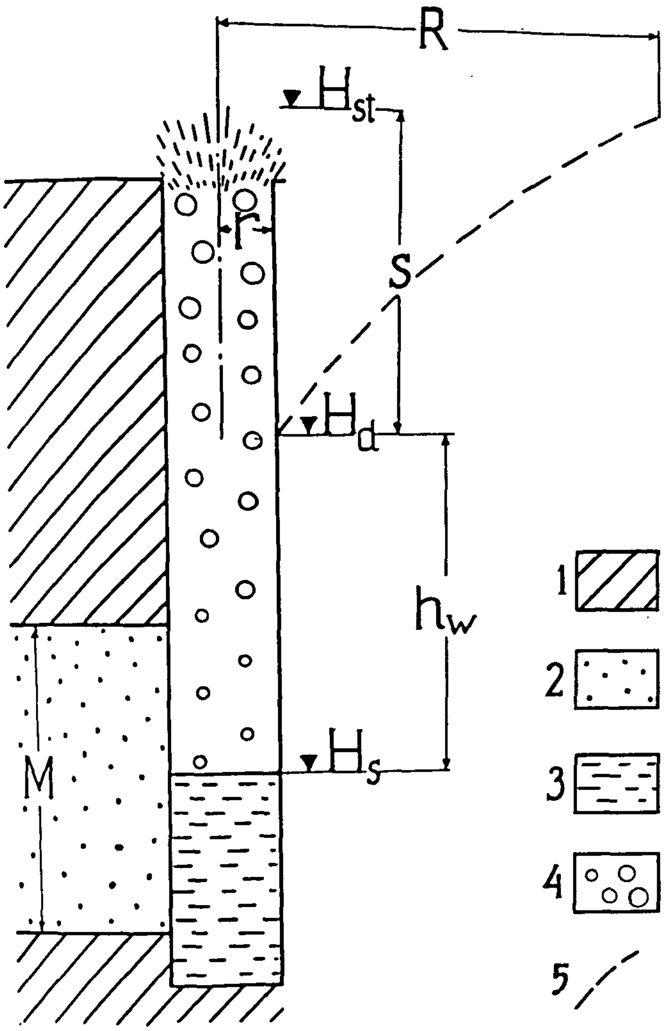


**Figure 1. Hydrodynamic scheme of an operating geothermal well**

1 Water-permeable rocks at temperature over 100°C.
2 Aquiferous horizon
3 Water
4 Steam-water mixture
5 Curve of depression

M Thickness of aquiferous horizon
$H_{st}$ Static level of thermal waters
$H_d$ Dynamic level
$H_s$ Level of steam generation
S Depression of dynamic level
$h_w$ Height of water column exerting pressure equivalent to excess pressure of saturated steam at the given temperature
R Radius of depression funnel
r Radius of well

Such data as the depth of steam generation and the pressure of saturated steam at that level cannot be obtained by means of the conventional hydrogeological procedures. To determine them it is necessary to take account of a number of phenomena that occur during the boiling of water.

By the technique developed at the Pauzhetsk Station of the USSR Academy of Sciences, the depth of steam generation is determined by measuring the temperatures in the bore of an operating well. This method is based on the fact that steam generation in a well is accompanied by a decrease in the temperature of the effervescing water. In this connexion, the temperatures over the entire distance between the level of steam generation and the wellmouth are lower than would be expected from the enthalpy of the steam-water mixture ($\mathcal{T}$) measured at the surface. Two regions will be seen on the temperature graph of figure 2, one of which is curvilinear and characterizes the temperature rise in the zone of the steam-water mixture, while the second is steeper and rectilinear, and characterizes the temperature of the deep water. At the point where these two parts of the curve meet, we have a temperature corresponding to the mean enthalpy of the steam-water mixture and to the depth of steam generation corresponding to that mean enthalpy.

The pressure of saturated steam at this level at a given temperature may be easily determined from the heat engineering tables.

As for the static level of high-temperature waters, this is usually determined by a manometer installed at the wellmouth. This method is applicable to the case when the static level is above the earth's surface, and under the condition that no steam bubbles are formed in the upper part of the bore. Such bubbles may badly distort the pressure readings, and they must not be attributed to the hydrostatic head of the aquifer tapped.

Based on the above considerations, we may conclude that, to obtain the required data, it is possible, at least in principle, to reduce the technique of testing geothermal wells to the conventional technique of hydrogeological testing, and to consider the discharge of the steam-water mixture as a function of the decrease in level on pumping out. However, technical difficulties would interfere with this in many cases. More specifically, it is not always possible to determine precisely the level of steam generation, especially if it is near the well-bottom. In practice, therefore, it has proved more rational to represent the discharge of the steam-water mixture as a function of the wellmouth pressure of the steam: $Q = f(p)$. Here the relation between the flow and pressure is of inverse character. The maximum flow of the steam-water mixture is observed on free gushing of the well—i.e., at a wellmouth steam pressure of 1 atm.

Just as in testing artesian wells one plots the relation between flow and lowering of level (for at least three different values of the lowering), in geothermal wells we determine the relation between flow and wellmouth steam pressure (for at least three values of the pressure). This graph is the basic characteristic of geothermal wells with respect to their productivity. A similar system of testing is extensively used in New Zealand at the Wairakei geothermal field, as well as the Pauzhetsk geothermal field in the USSR.

The steam pressure is one of the main parameters recorded in testing geothermal wells. Its maximum value is limited by a quantity corresponding to the temperature of the thermal water tapped by the well. The working pressure is always considerably lower than this maximum value, since the level of steam generation is at a great depth, and during the ascent of the steam-water mixture to the surface, part of the thermal energy is expended on the expansion of the steam and on overcoming the hydraulic resistance. It is only when a well is opened, after a long shut-down, that, in connexion with the violent ebullition of the water close to the wellmouth, a pressure approaching the maximum is observed on the manometer. This pressure must be noted, since the lower boundary of the enthalpy of the steam-water mixture is disclosed by the temperature corresponding to this pressure.

The minimum pressure at wellmouth is reached during free gushing, without installation of auxiliary equipment. When the piping for the measurements is installed, the lower limit of pressure is increased, and is inversely proportional to the diameter of the branch.

The steam pressure is an index of temperature at a given point, since, in a system containing saturated steam, there is a strictly determinate temperature corresponding to each pressure. Moreover, the steam pressure at wellmouth may also serve as an index of the flow rate of the steam-water mixture. Indeed, this pressure reflects the value of the hydraulic resistance of that part of the path from wellmouth to the discharge of the steam into the atmosphere. These resistances are determined by the design features of the given section, and by the velocity of the steam-water mixture, which in turn depends on the flow rate and enthalpy. It follows that under constant conditions of efflux of the steam-water mixture, and when its enthalpy is constant, variations in the steam pressure at wellmouth will reflect changes in the flow rate. All of this, taken together, makes the steam pressure one of the principal elements of the observations of operating conditions, permitting one to dispense with simultaneous measurements of the temperature and flow rate of the steam-water mixture. This pressure is usually most efficiently recorded by means of a recording manometer, giving a continuous 24-hour record (figure 3).

The above hydrodynamic propositions are applicable to wells which, in the character of their flow, are constantly operating. But the flow of some geothermal wells is of the pulsating type, and sometimes even intermittent, of the geyser type. The causes of geyser conditions reside in the low filtering power of the rocks, resulting in a failure of the flow of water into the bore of the well to compensate the ejection of the steam-water mixture. With a bore of relatively large diameter, the steam formed from the water is able to move faster than the water; this leads to exhaustion of the vapour lift and to interruptions in the discharge.

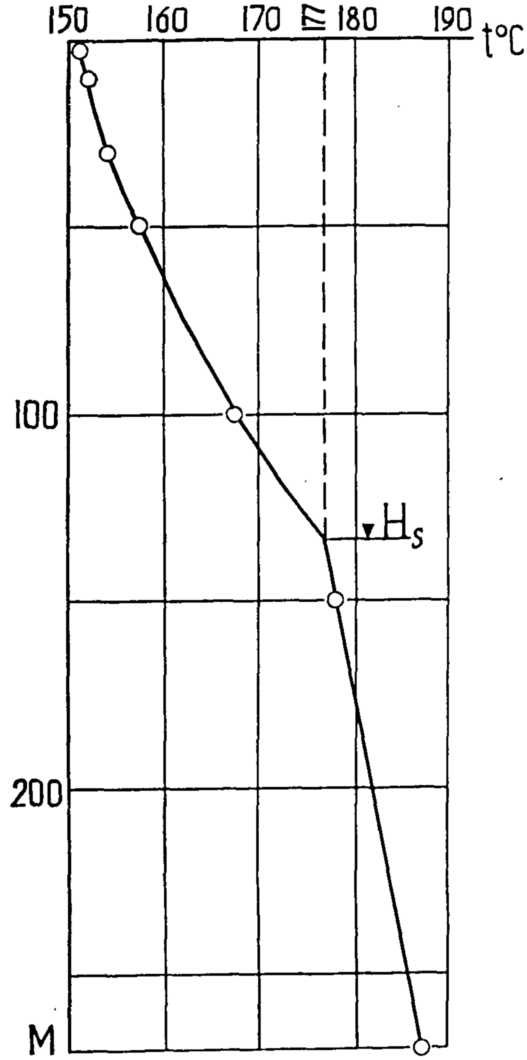


**Figure 2. Temperature in an operating geothermal well**

*(Pauzhetsk field, well No. 2-K)*

Steam pressure at wellmouth 4.4 atm; mean enthalpy of steam-water mixture 177 kcal/kg; $H_s$ = level of steam generation.

Geyser and pulsating conditions cause, in all respects, an extraordinary increase in the difficulty of testing, since the various stages of the ejection cycle are characterized by different values of the flow rate and enthalpy, and also differ from each other in chemical indices. In this connexion, it is extremely desirable to convert the geyser conditions into continuous operating conditions. Experience shows that in most cases this can be accomplished by using gate valves to close the well, since the additional resistance limits the outflow of steam and thereby establishes more favourable conditions for the motion of the steam-water system as a whole.

Since the diameters of geothermal wells have a substantial effect on their operating conditions, which is an important factor in operation, the question of the choice of the rational design of future production wells arises. During exploration drilling, when the water content of the rock and the parameters of the steam-water mixture are still unknown, the design of a well will naturally fail to be optimum. The diameter of the casing string may either be too great, which will lead to intermittent flow, or too small, which will involve a certain artificial decrease in well productivity. However, after hydrogeological testing, when data on the specific flow of the well and the enthalpy of the steam-water mixture become available, the calculation of the production well becomes realistic. Knowing the specific flow rate of a well, and knowing its depth, one can determine the level to which the water should be lowered in order to provide a given well productivity, and one can accordingly select a casing of the required diameter.

The processes of differentiation of the chemical composition of the high-temperature water tapped by a well are closely related to the specific features of the dynamics of geothermal wells. As the vapour phase is formed, highly volatile substances dissolved in the water pass over into it. This results in almost total degassing of the water, accompanied by impoverishment in certain salts. But with respect to most of its salts, the water becomes more concentrated.

To get a correct idea of the chemical composition of the steam-water mixture and of the water that is encountered at depth by the well, one must first know the composition of the vapour phase and the composition of the water at wellmouth, and secondly the steam-water ratio when samples are taken for analysis.

The composition of the vapour phase is of very great practical importance in itself, since the choice of the scheme of steam utilization at the projected geothermal power station depends on it.

In chemical testing, geyser conditions cause particular trouble. During the boiling stage, the water in the well is strongly degassed, while the concentration of salts, as shown by observations, is almost doubled. During the ejection, therefore, the first portions of the steam-water mixture are exceedingly

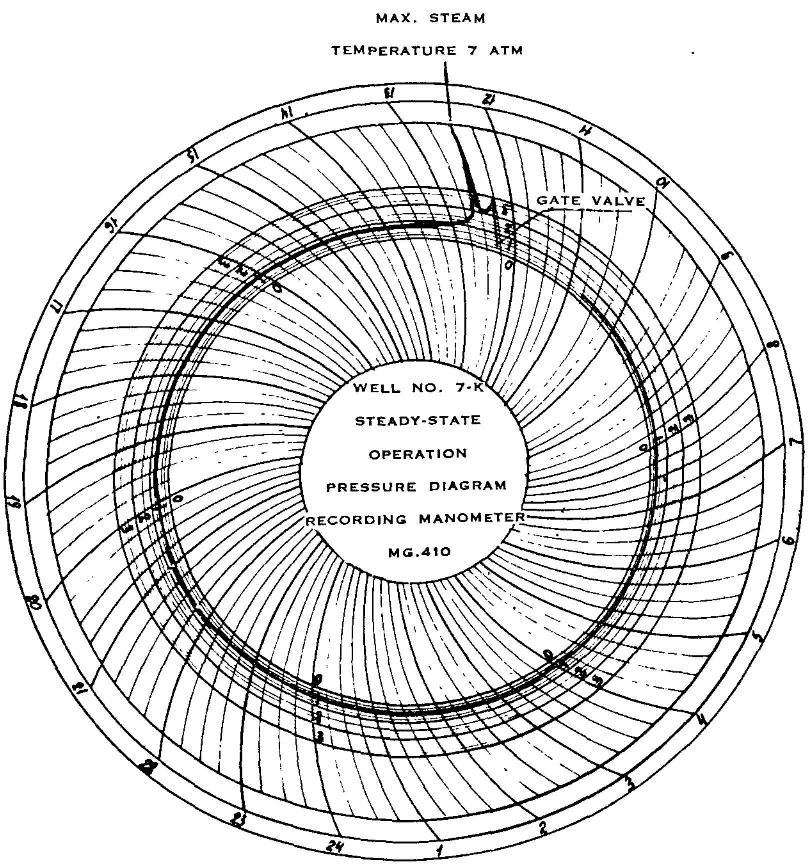


**Figure 3. Daily variation of steam pressure at wellmouth**

*(Pauzhetsk field, well No. 7-K)*

1215 h gate valve fully opened after long shut-down of well; 1230 h maximum steam pressure (7 atm), which explains the violent ebullition of the water near the wellmouth; 1230-2400-0400 h establishment of steady-state operation; 0400-1045 h steady-state operation.

low in gas content and have an increased mineral content. The analytical data can of course not be applied to the entire volume of water. In exactly the same way, the data obtained by the analysis of steam samples taken during the boiling stage and at the end of ejection, when the quantity of steam becomes very great by comparison with the water, can likewise not be considered characteristic. It is only during the approximate middle of the ejection, when portions of water that have not first been degassed come to the surface, that their analysis can reflect the actual composition of the deep water. Since sampling takes a considerable time (about one hour, on the average), a well with geyser conditions can be satisfactorily tested only if the stage of ejection lasts several hours. But if the stage of ejection is brief, then when taking a single sample there will unavoidably be a portion of steam with a different gas concentration, and, what is also important, in a different ratio to the water. In interpreting the data of chemical analysis from wells with geyser conditions, one must therefore adopt a very cautious attitude toward the figures, especially those on the gas composition, in view of the fact that they may characterize random and temporary concentrations.

Thus, as follows from the above methodological propositions, the following basic data are required for the formulation of an energetic and hydrogeological characteristic of a geothermal well :

1. *Thermophysical data :*

(*a*) Temperature of the water and rocks in the resting well;

(*b*) Enthalpy of the steam-water mixture at discharge;

(*c*) Steam pressure at wellmouth.

2. *Hydrodynamic data :*

(*a*) Position of the static level of the thermal water;

(*b*) Flow rate of the steam-water mixture at various steam pressures at wellmouth;

(*c*) Position of the levels of steam formation at various flow rates.

3. *Chemical data :*

(*a*) Chemical composition of the water;

(*b*) Chemical composition of the steam;

(*c*) Weight-ratio of water to steam in drawing samples for analysis.

To be able to rely with confidence on the data obtained, the design and equipment of the well must meet certain requirements, which are as follows : high-grade cementing, and flawless well-mouth equipment, free from all leakage. Otherwise, operating geothermal wells under various conditions may be subject either to absorption in the upper unpressurized aquiferous horizon, or on the other hand, suction from it; if there are leaks in the well head, the static level cannot be measured, nor can the well be prepared for temperature measurements.

If these requirements are met, the analysis of the original data will permit assessment of the energy capacity of the well, selection of rational operating conditions, and elucidation of the hydrogeological conditions at its site.

## *Summary*

Methods for testing geothermal wells developed by the Pauzhetsk Observation Station of the U.S.S.R. Academy of Sciences in Kamchatka are based on hydrogeological studies, since this provides the most reliable approach to the study of hydrothermal fields. Since the thermal water tapped by the well at depth is in the liquid phase, its dynamics is governed by the fundamental hydrogeological laws. This permits use of the formulas of underground hydraulics in the calculations.

The high temperature creates considerable difficulty in the dynamics of geothermal wells. In operating wells, steam generation is at great depth, which results in the formation of a vapour-lift, assuring a high yield for the well. Consequently, in evaluating the hydrodynamic conditions of the well, the analysis of the thermophysical data is of particular importance.

The processes of differentiation in the chemical composition of the geothermal water tapped by a well are closely associated with the specific features of the dynamics. During ebullition, the volatile substances are readily transferred from the water phase to the steam phase, while the concentration of most salts in the water increases. To obtain a correct idea of the composition of the steam-water mixture, one must know the composition of the steam phase and the water at the point of discharge, as well as the water-steam ratio.

To formulate a complete hydrogeological and energetic characteristic of a geothermal well, the following are the principal original data required:

1. *Thermophysical data*

(*a*) Water and rock temperatures in a steady-state well;

(*b*) Enthalpy of the steam-water mixture at discharge;

(*c*) Steam pressure at wellmouth.

2. *Hydrodynamic data*

(*a*) Position of the static level of the thermal water;

(*b*) Rate of flow of the steam-water mixture at varying steam pressures in the wellmouth;

(*c*) Position of steam-generation levels at varying flow rates.

3. *Chemical data*

(*a*) Chemical composition of water;

(*b*) Chemical composition of steam;

(*c*) Weight ratio of water to steam in drawing samples for analysis.

Analysis of the above basic data permits evaluation of the energy capacity of the well, selection of the most practical regime of operation for it, and establishment of the hydrogeological conditions prevailing at the site of the well.

## MÉTHODES D'ESSAI CONCERNANT LES PUITS DE VAPEUR ET D'EAU


### *Résumé*

Les méthodes d'essai concernant les puits de vapeur et d'eau mises au point par la station de contrôle et d'observation de l'Académie des sciences de l'URSS installée à Paoujetsk au Kamtchatka sont fondées sur l'hydrogéologie, qui permet l'étude la plus rationnelle possible des nappes aquifères hautement thermales. Dans la mesure où l'on rencontre au fond d'un puits des eaux très chaudes en phase liquide, leur dynamique obéit aux lois fondamentales de l'hydrogéologie. Ainsi, on peut leur appliquer, dans les calculs, les formules de l'hydraulique souterraine.

Dans le même temps, les hautes températures compliquent singulièrement la dynamique des puits de vapeur et d'eau. Dans les puits en activité, la formation de vapeur gagne les grandes profondeurs, ce qui provoque une « poussée de vapeur », phénomène qui assure au puits un débit élevé. C'est pourquoi l'analyse des données thermophysiques est d'une extrême importance lorsqu'on veut connaître les conditions hydrodynamiques du puits.

Les processus de différenciation de la composition chimique des eaux hautement thermales provenant d'un puits sont étroitement liés aux caractéristiques de la dynamique. Lorsque l'eau entre en ébullition, les substances les plus volatiles passent à la phase vapeur et la concentration de l'eau en sels minéraux devient plus élevée. Pour se faire une idée exacte de la composition du mélange vapeur-eau, il faut connaître celle de la phase vapeur et celle de l'eau à la sortie, ainsi que la proportion d'eau et de vapeur.

Pour déterminer exactement les caractéristiques hydrogéologiques et énergétiques d'un puits de vapeur et d'eau, il faut disposer des données de base suivantes :

1. *Données thermophysiques*

*a*) Température de l'eau et des roches dans un puits au repos;

*b*) Enthalpie du mélange vapeur-eau à la sortie;

*c*) Pression de la vapeur à la bouche du puits.

2. *Données hydrodynamiques*

*a*) État du niveau statique de l'eau thermale;

*b*) Importance de la consommation du mélange vapeur-eau lorsque la pression de la vapeur varie à la bouche du puits;

*c*) État des niveaux de formation de vapeur lorsque la consommation varie.

3. *Données chimiques*

*a*) Composition chimique de l'eau;

*b*) Composition chimique de la vapeur;

*c*) Rapport des masses de l'eau et de la vapeur lors du prélèvement d'échantillons pour analyse.

L'analyse des données énumérées ci-dessus permet de calculer la puissance énergétique du puits, de choisir le régime d'exploitation le plus rationnel et de connaître les conditions hydrogéologiques sur les lieux mêmes.

# GEOTHERMAL DRILLHOLES: PHYSICAL INVESTIGATIONS

*C. J. Banwell**

The final test of the usefulness of a hydrothermal system for power production is the quantity and quality of the heat which can be withdrawn from it, and for how long. In most cases, this involves the drilling of holes to obtain data about the essential physical properties of the producing zones, and their extent. Since the drilling of holes is relatively costly, it is important to make the fullest possible use of the data from each stage of the exploration of the field, beginning with surface surveys of different kinds, so as to site both exploratory and production holes to the best advantage.

## Data required from drillholes

The following are the more important physical data required from drillholes in a hydrothermal system. The ways in which this information is used for assessing the power potential of the area and for planning exploration and production programmes will be discussed below.

### Properties of rocks

#### *Porosity*

Porosities are determined by laboratory measurements of wet and dry densities of core samples from drillholes. Assuming that cores are taken at frequent enough intervals to identify all the more important geological formations met with, porosity measurements should be made on enough samples from each formation to allow characteristic values and variability to be determined.

#### *Permeability*

The mean permeability of a large volume of rock may sometimes be much greater than that of small samples owing to the presence of joints or fissures, and both permeabilities should be known as accurately as possible. Knowledge of the large-scale permeability is generally built up progressively from observation of fissures encountered while drilling, by drillhole output measurements, and from the aquifer pressure changes which develop as bore drawoff is increased. Small-scale permeability is measured in the laboratory, using core samples. Permeability to air and water is sometimes found to differ widely, and it is generally desirable to determine water permeability on fresh specimens which have not been allowed to dry out before measurement. Number and selection of samples will generally be the same as for porosity.

### Physical conditions

#### *Temperature*

In the Wairakei area, temperatures are normally measured in drillholes at depth intervals of 100 feet (approx. 30 metres) by means of the geothermograph, which is capable of recording temperatures in the range from 20 to 300°C. Measurements are made in new holes at frequent intervals after drilling until temperatures have stabilised, which commonly takes from one to several months. The form of the temperature pattern observed during the early stages of the approach to equilibrium will often show the location of fissures and permeable zones intersected by the hole. Temperature measurements are also made in the majority of holes in the area as often as circumstances permit, so that changes in temperature with time can be followed.

#### *Hydrostatic pressure*

Pressures in closed drillholes at any depth may be determined by calculation from a knowledge of wellhead pressure, water level, and temperature distribution. Determination of pressures by this method has become difficult in holes in certain parts of the Wairakei area owing to the presence of steam and lack of a recognisable water level, and direct pressure measurements with a recording gauge lowered into the hole are now proving more satisfactory.

#### *Mass and heat output*

These physical conditions are also important and should be suitably determined.

The foregoing list of measurements covers only those required for this paper. It is not exhaustive, and further observations of different kinds may be necessary for geophysical, geological, chemical or other purposes. Under favourable conditions, surface geological and geophysical surveys may provide valuable indications of the kind of formations which may be met by drillholes, and of their depths and extent. Hence, some information concerning certain of the physical conditions at depth may be available from these sources before drilling commences, and, by similar means, it will sometimes be possible to

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make useful estimates of probable conditions in parts of the system remote from areas already drilled.

## Data from surface thermal surveys

### Estimates of power potential

By thermal surface surveys, which are described in another paper of this series, it is possible to estimate the total area of hot ground at the surface associated with the system, and the total water and heat flow. From this information, preliminary estimates of the power potential may be made by means of the graphs of figures I to IV.

*Continuous power*

Figures 1 and 2 give the power produced by an ideal heat engine from a flow of hot water at the temperature $T_0$. The engine is assumed to discharge heat into a sink (condenser) at a temperature of 30°C, and to use the heat available from the water down to a temperature of 50°C. Figure 1 covers the lower part of the temperature range on a larger scale, and figure 2 the full range up to the critical temperature. Comparison with actual or projected power plants designed to operate with heat sources of this kind shows that the power generated can be expected to range from about 28 per cent of theoretical for a small single-stage station operating from water near 100°C, to 63 per cent for a large multi-stage station with an effective initial water temperature of 253°C. Water temperatures below boiling point can be measured directly, while in hotter systems $T_0$ is estimated from the enthalpy (ratio of heat to mass flow) of the natural discharge. A supplementary enthalpy scale has been added to figure 2 for this purpose. The depth scales at the top of figures 1 and 2 give the depth at which the estimated initial temperature will be reached on the assumption that the hot water in the system is at boiling point at each depth under the hydrostatic head. From these scales, the minimum depth to which the hot water system extends is thus

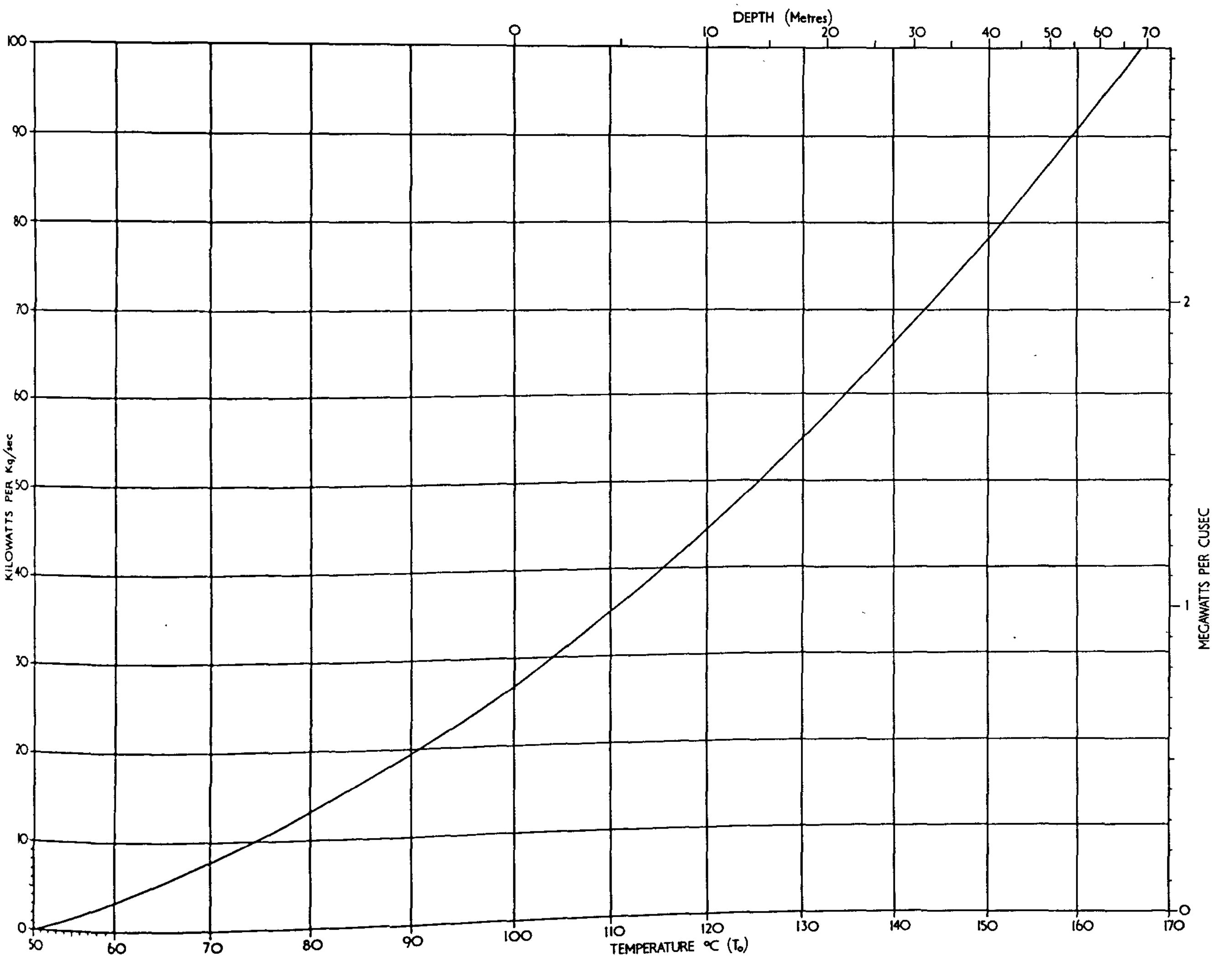


Figure 1. Power available from hot water flows up to 170°C

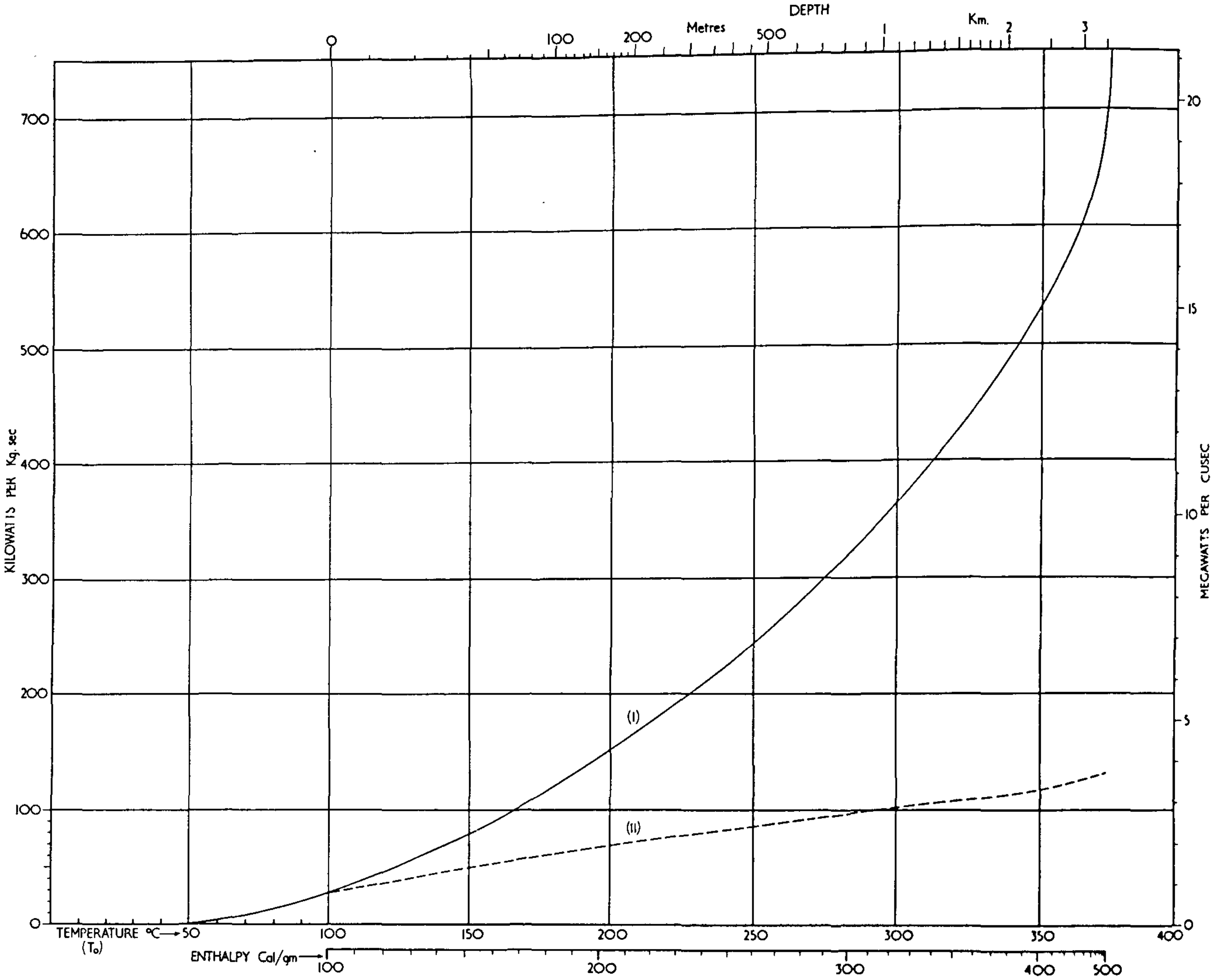


**Figure 2. Power available from hot water flows up to critical temperature**

estimated, and a preliminary indication is obtained of the depths required for prospecting drillholes.

If the hot water becomes mixed with cold ground water on its way to the surface, the enthalpy at the discharge point will not give a true indication of the initial temperature, and the power potential will be underestimated. The dashed curve (II) of figure 2 shows the relation between initial temperature ($T_0$) and power potential represented by a hot spring discharging water at 100°C, on the assumption that the spring water has been diluted with just enough ground water at 15°C at each depth to reduce the temperature to boiling point under the hydrostatic pressure. While this is doubtless an extreme case, the curve shows that the true power potential of a hot spring heavily contaminated with surface water may be much higher than the estimate from surface measurements.

The total power available from the natural heat flow is calculated by multiplying the observed natural mass flow (water plus steam) by the theoretical output given by the graph and by an efficiency factor corresponding to the type of generating station to be used. Provided all the natural flow is in fact diverted to power generation, this output can be expected to be maintained for an indefinite period.

### *Stored energy*

If the total of bore drawoff and residual surface activity exceeds the original natural discharge, the extra heat must be drawn from storage in some part of the system, and figure 3 has been prepared to show the quantities of energy stored in rock saturated with hot water. The same ideal heat engine and working conditions as before have been assumed. The heat capacity of the rock has been calculated for a particle density of 2.5 gm/cc and a specific heat of 0.2 cal/gm°C, which are assumed constant over the temperature range; changes in density and specific heat with temperature of the water filling the pores are taken into account in the calculations. Curves (I) and (II) give the total mechanical energy available per unit volume for porosities of 40 per cent and 20 per cent respectively. Curve (IV) is obtained by integrating curve (I) with respect to depth from the surface to a given depth, and thus gives the total amount of energy available in a column of unit area to this depth. The temperature scale superimposed on curves (I), (II) and (III) is based as before on the assumed boiling point-depth relationship of figures 1 and 2.

### *Storage estimates from surface data*

The family of curves in figure 4 gives the relationship between the cross-sectional area and depth of a hydrothermal system required to provide the amounts of energy shown beside the curves. The system is assumed to consist of a column of constant area within which conditions correspond to those assumed for the calculation of curve (I) of figure 3. However, in calculating the curves for figure 4, it has been assumed that only 25 per cent of the theoretical energy will be delivered by the power station, in order to take account both of the finite efficiency of the power station and of the probability that only a limited fraction of the stored heat will be recoverable from an actual hydrothermal system.

By means of figure 4, it is possible to make an immediate estimate of the storage potential from a knowledge of the area of hot ground and of the enthalpy of the natural activity given by the surface surveys. The enthalpy scale included in figure 4 is based, as before, on the assumption of boiling point-depth conditions down to the level of maximum temperature.

### *Production from intermediate depth*

Under suitable conditions, it may be possible to induce an upward movement of hot fluid to drillholes which do not penetrate to the full depth, and curves (III) and (V) have been included for the special case of drillholes producing from a depth of 550 metres, where the temperature under boiling point-depth conditions will be 260°C. The theoretical loss of available energy is not serious for the example chosen, and development from this limited depth would have evident economies. However, in practice, if the drillholes terminate in a permeable formation

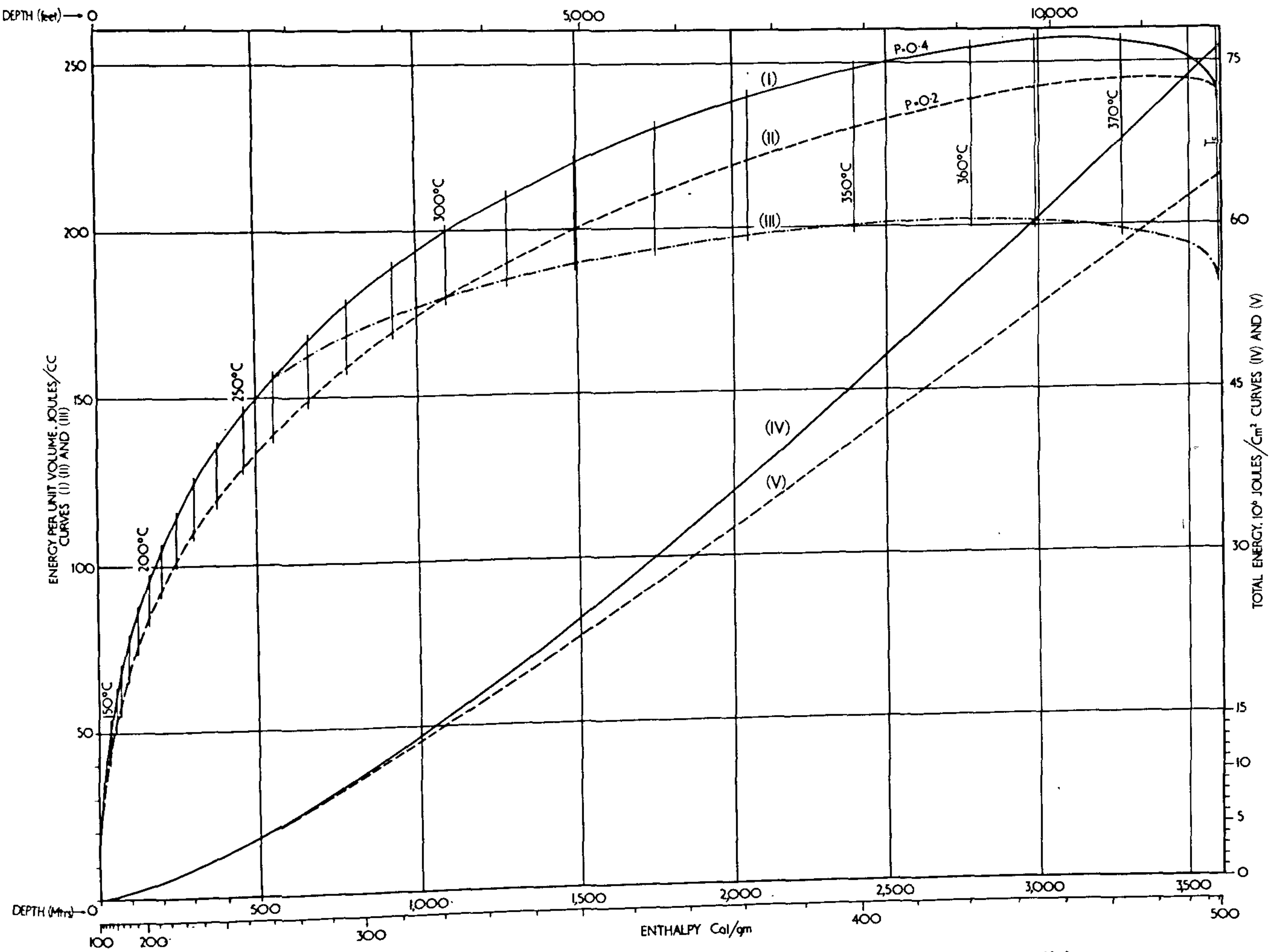


**Figure 3. Energy storage in water-saturated rock under boiling point-depth conditions**

it may be difficult to prevent the steam which will have separated from the water from escaping into the upper parts of the permeable region and eventually to the surface. These difficulties are likely to be much reduced if the rising hot fluid can be tapped by the drillholes in restricted passages in generally impermeable formations, or in permeable trap structures immediately beneath such formations.

## Siting of drillholes

It will be evident that preliminary estimates of the power potential of a hydrothermal system based on surface data alone must be subject to various uncertainties. One of the first objects of a drilling programme must be to reduce these uncertainties by checking the initial assumptions regarding the shape and volume of the hot region, and the temperature distribution within it. Quantitative drillhole data will also allow the observed values for the various variables to be used in the energy calculations in place of the idealized quantities used for figures 1 to 4, so that estimates will improve progressively as drilling data accumulate.

In the early stages of a drilling programme, holes must be sited largely on surface evidence of various kinds, and account will need to be taken, not only of the actual surface temperature patterns, but also of such factors as geological structure, where this is known in sufficient detail, topography, hydrology, chemistry, etc., many of which will be peculiar to each area. Some of these questions will be found discussed in other papers of this series, and only a very limited account of some of the others is possible here, but the following points may be noted briefly.

The form of the surface temperature pattern may be modified by a migration of surface water associated with the general water drainage of the area. Often the direction of the near-surface hydraulic gradient can be inferred from the topography, and the possible nature of the distortion judged; on the down-gradient side the hot areas are liable to spread excessively, so the drillholes on this side may quickly penetrate colder formations, while on

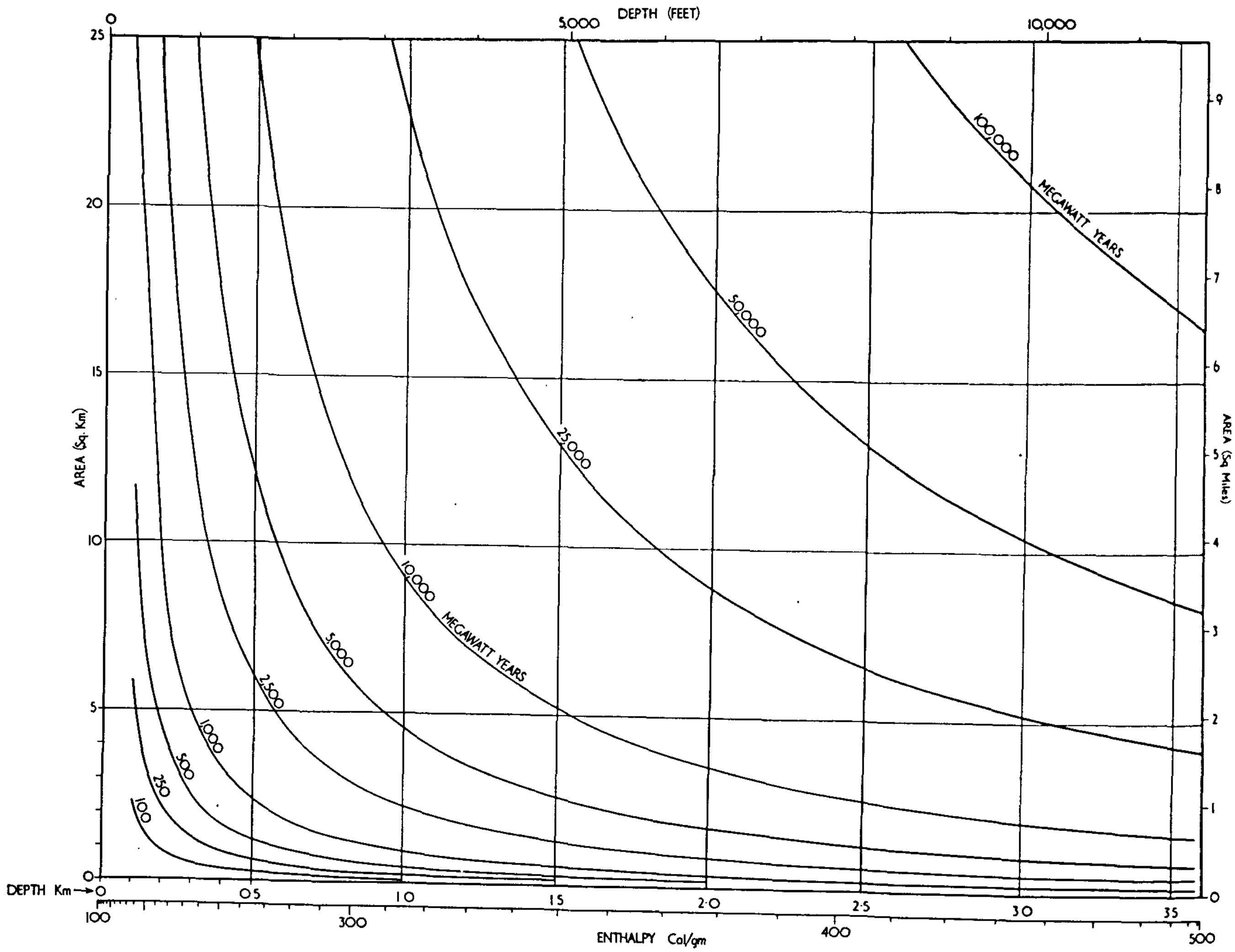


**Figure 4. Depth-area curves for given energy storage in water saturated rock. Net yield of 25 per cent assumed**

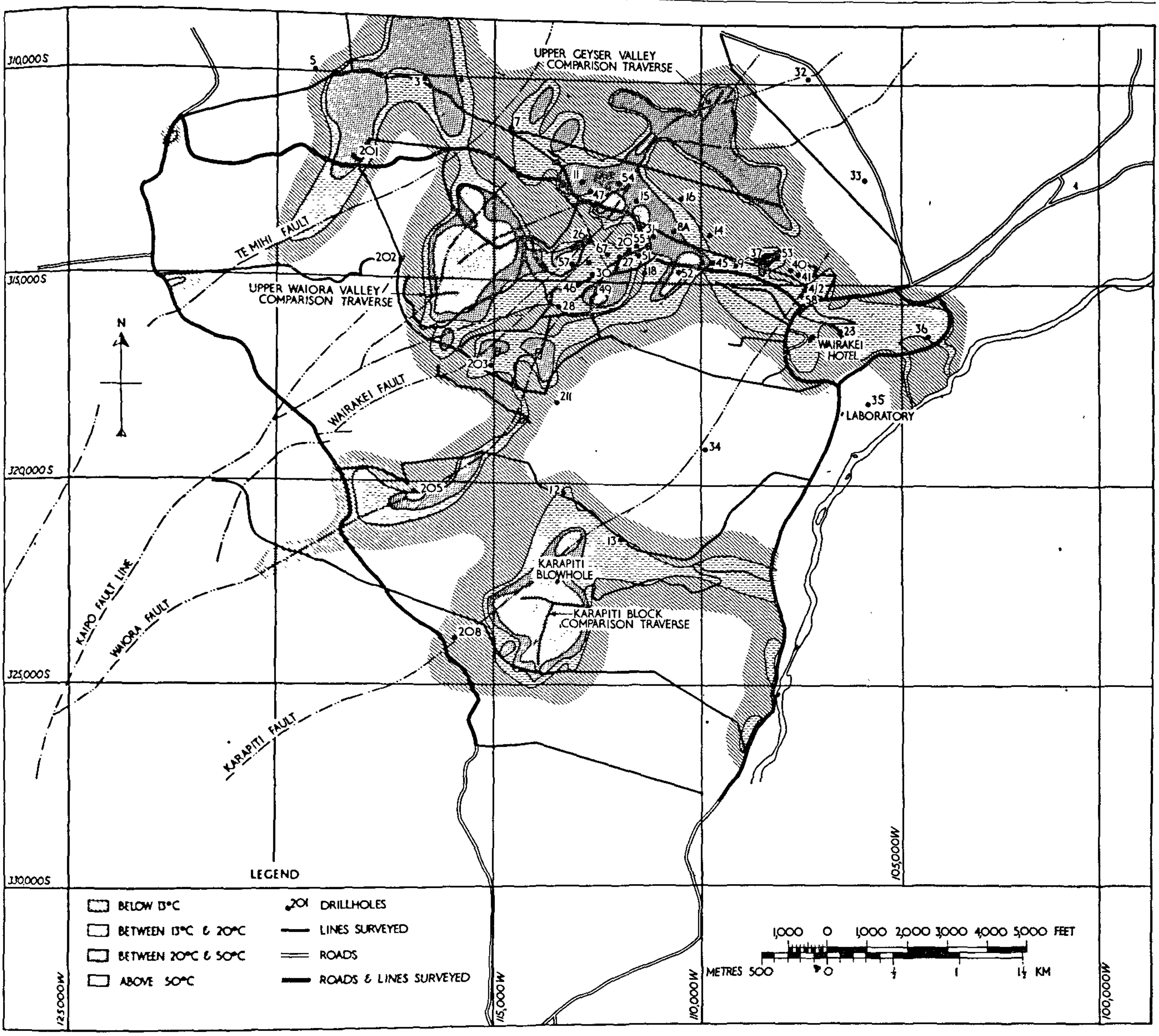


**Figure 5. Isotherms at one metre depth, Wairakei, 1958**

the up-gradient side there may be potential producing areas beneath country which is cold at the surface.

The succession of permeable and impermeable formations beneath the surface, their dips and directions, are all liable to cause a displacement of the surface activity relative to the sources at depth, and may lead to some degree of separation of areas of steam and water discharge. If surface geology can provide indications of the displacements to be expected, it will be of much value in early siting programmes.

Faults, by breaching impermeable members near the surface, may impose characteristic forms on the patterns of surface activity which are not necessarily correlated with feed sources or hot regions at greater depth. However, certain of the larger or more active faults may also maintain permeable routes in deeper cap formations through which hot fluid migrates, and one of the later objects of production drilling will be to establish whether any such associations with identifiable faults exist, and to locate the flow routes with precision. Location is often assisted by a study of the temperature pattern from groups of holes in the neighbourhood, and from certain chemical data which will be discussed elsewhere in this series.

If the expected power demand is small compared with the estimated potential of the hydrothermal system under consideration, it may be possible in some cases to limit the size of the area to be proved by drillholes. Thus, if the probable energy requirement in megawatt years can be decided, figure 4 may be used to determine the area required either for a chosen drilling depth, or for the depth to maximum temperature given by the enthalpy of the natural discharge. However, there are evident dangers in partial development of an area, especially if this takes the form of drilling in a limited sector towards the boundary, since the hot fluid tapped may not be typical of the area as a whole, and drawoff by bores is much more likely to lead to rapid falls in output and quality through invasion of the bore area by cooler water from outside. These difficulties are liable to be further aggravated by the reduced chances of tapping some part of the main flows of hot fluid maintaining the activity, so that production will be dependent almost entirely on local heat storage, the efficient recovery of which may be uncertain.

## The Wairakei area

The following maps and other data provide illustrations of the information obtained by drilling in this area up to January 1961, and of the uses of the foregoing diagrams for estimating power potential.

The procedures for making the one metre probe map and measuring the heat and mass flows are described in another paper of this series.[1] All the data used here are for the period 1958-59. Because of difficulties of measurement, relatively wide limits of error must be allowed for the mass and heat flows, but this is not important for these preliminary estimates of potential, which are necessarily provisional, and subject to larger uncertainties of their own.

### Surface thermal surveys

*One-metre probe survey*

Figure 5 shows the form of the 13°C, 20°C and 50°C isotherms at one metre depth determined from a survey of the area in 1958. Virtually all the hot areas can be enclosed within a circle of radius 2.7 km and area 23 km². The total hot area within the 13°C isotherm is 6.28 km², and within the 50°C isotherm 1.15 km². Drainage of surface water in the area is predominantly to the Waikato River, on the eastern side, so that some of the hot areas shown by the map on this side may be superficial. Similarly, the western boundaries of the surface map may have been displaced eastwards by the same process, so that hot areas may underlie superficially cold ground.

The surface locations of major faults crossing the area, as mapped by Grindley, are shown, and some measure of correlation between the distribution and shape of hot areas and some of these faults is observable. In particular, the elongated hot area near the centre of the map coincides well with a sector of the Waiora fault, and one branch of the hot area on the NW boundary with part of the Te Mihi fault. There is also a general correspondence between the NE-SW elongation of many of the smaller hot areas and a similar trend on the main fault pattern.

*Natural heat and mass flow and enthalpy*

To illustrate the use of figures 2 and 4, mass and heat flows of 429 kg/sec and 162 400 kg/cal/sec respectively will be used. The mean enthalpy is then 379 cal/gm relative to 15°C, or 394 cal/gm relative to 0°C.

*Continuous power potential*

Assuming there has been no important dilution of the hydrothermal fluid by local ground water on the way to the surface, and that the hot fluid comes ultimately from a single source, use of the enthalpy scale of figure 2 shows that the theoretical maximum temperature will be 346°C, at a depth of approximately 2.3 km, and the power potential will be 516 kW per kg/sec. Multiplying this by the mass flow of 429 kg/sec gives a gross potential of 221 megawatts, and, assuming an over-all conversion efficiency of 63 per cent, a final generated potential of 139 megawatts. Realisation of this potential would require that all the natural heat flow be diverted to drillholes at the theoretical maximum temperature and depth, but reference to the special case illustrated by curve (III) of figure 3 shows that the theoretical loss of potential resulting from tapping the hot fluid at a much shallower depth is not serious. Problems associated with this mode of exploitation are likely to be peculiar to each area, and the final efficiency achieved will depend strongly on many accidental local factors which must be evaluated principally by means of drillhole data.

*Stored energy potential*

Insertion of the enthalpy value of 394 cal/gm in figure 4 gives a generated energy potential (on the assumptions stated above) of about 22 000 megawatt years if an average area equal to that of all hot ground (6.28 km²) is used, and about 4 000 megawatt years if only the areas of high activity (1.15 km²) are included. In one respect, these may be considered minimum values, since the possibility cannot be excluded that the hot water system extends to depths below the level of maximum temperature, to limits set only by diminishing rock porosity and permeability.

*Total power potential*

To express stored energy in terms of power potential, it is necessary to decide upon a value for the rate of withdrawal or life required. Considering first a requirement in the form of a base-load station with a continuous generated power of 250 megawatts, the above estimates show that full exploitation would yield 139 megawatts from the natural heat flow, leaving 111 megawatts to be supplied from storage. Taking the smaller area, the estimated storage of 4 000 megawatt years would give a life of 36 years at this rate. Since a life of the order

[1] G. E. K. Thompson, C. J. Banwell, G. B. Dawson, and D. J. Dickinson, *Prospecting of Hydrothermal Areas by Surface Thermal Surveys* (G/54).

of 20 years is generally considered economic for a power station, these results show that, with reasonably efficient exploitation, the potential of the area should be adequate to meet the requirement of 250 megawatts for a sufficient period. Alternatively, if full use of both flow and storage could be assured, the latter would yield 200 megawatts for a period of 20 years, and the total capacity over this period would be 339 megawatts. Estimates based on the larger storage area (6.28 km$^2$) would give much greater power potential, but temperature data from drillholes, which now provide fairly complete cover for the whole system down to approximately one kilometre depth, do not yet fully justify such estimates.

## Data from Wairakei drillholes

### *Temperature*

Figure 6 is an isothermal map of the Wairakei system at a level of 150 metres above datum (between 300 and 400 metres below ground surface) based on temperature data from the selection of drillholes shown. The data permit a satisfactorily complete pattern to be drawn at this level, and the system appears to constitute a distinct unit with a major hot centre (W) to the north-west, and a smaller one (P) to the east.

Comparison with the surface map of figure 5 shows a general similarity, but as expected from hydrological considerations, the surface hot areas which extend as far as the Waikato River on the eastern side overlie regions of rapidly falling temperature, while on the west hot regions reach well out beneath cold ground. The large central cold area surrounding bore 34 in figure 5 correlates satisfactorily with a similar feature at the Level of figure 6, the form of the pattern here suggesting a zone of inward migration of cooler water. Towards the southern limit of the area, the strongly active Karapiti area (K), which forms a large feature in the surface map, has little apparent expression in

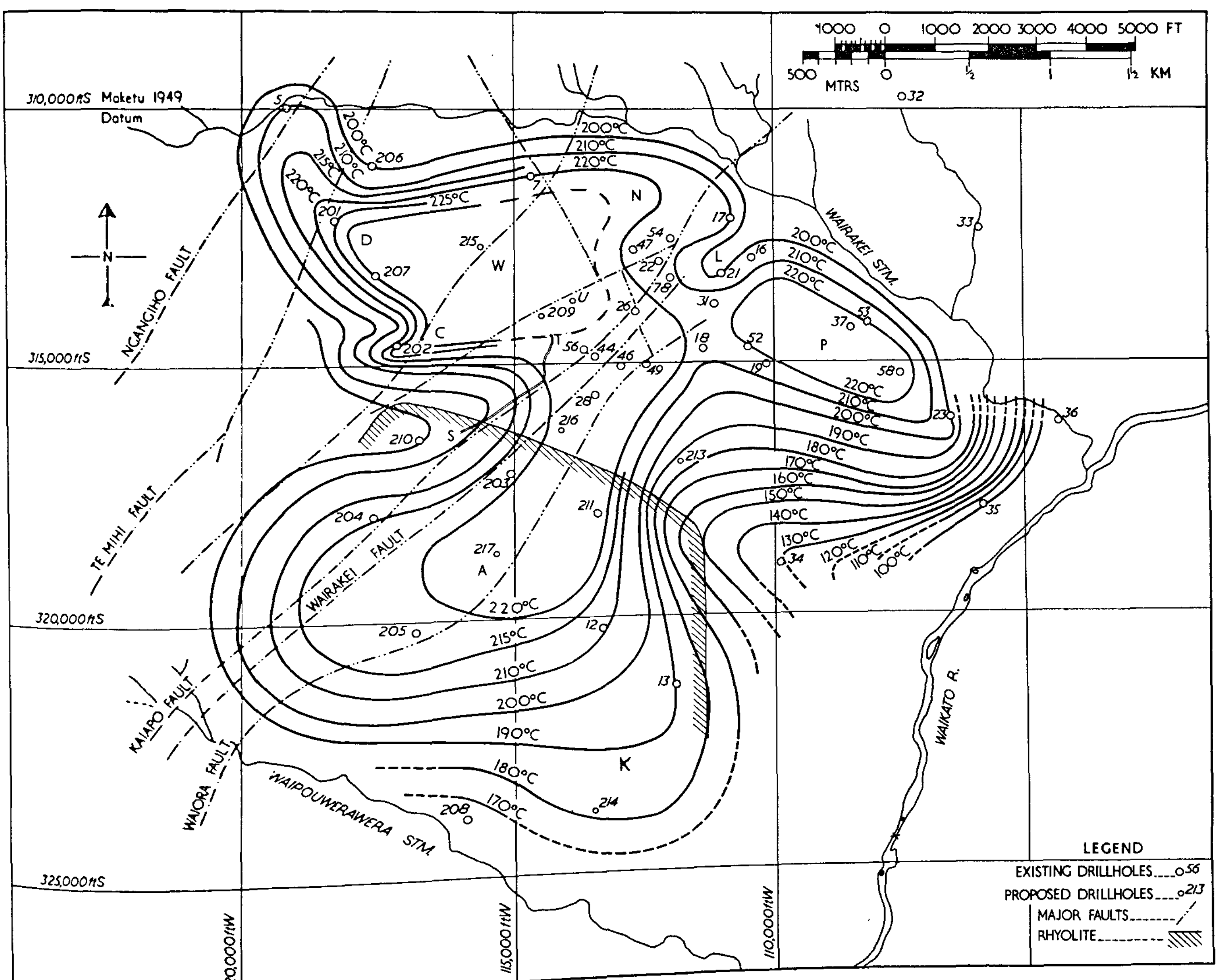


**Figure 6. Isotherms 150m (492ft) above datum (sea level), Wairakei, March 1960**

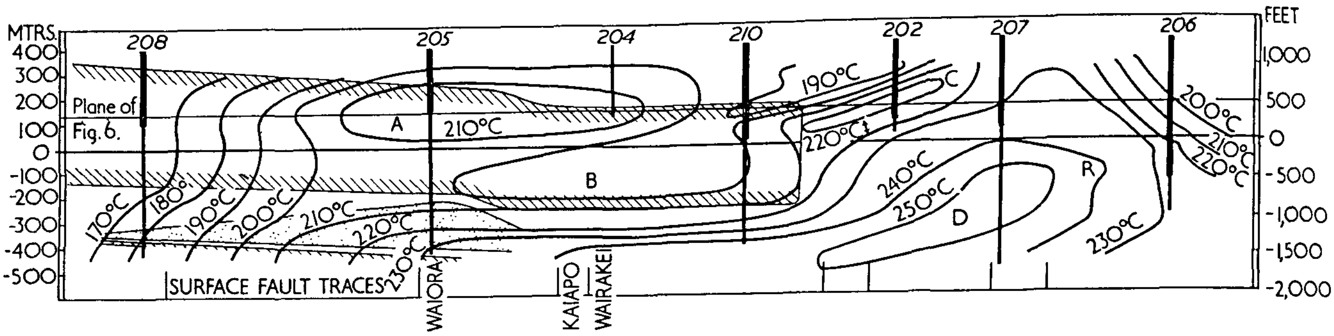


**Figure 7. Isothermal profile through bores 208, 205, 204, 210, 202, 207, 206, Wairakei, March 1960**

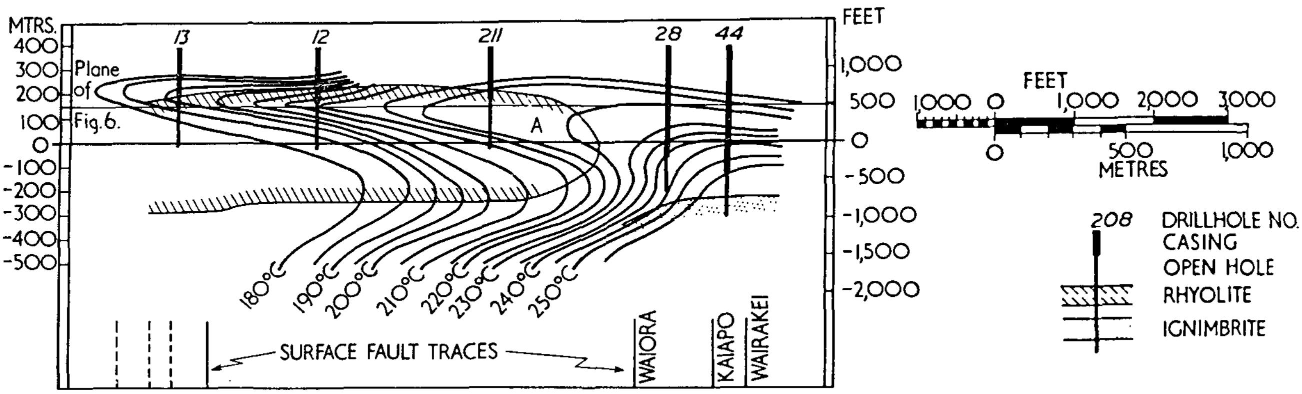


**Figure 8. Isothermal profile through bores 13, 12, 211, 28, 44, Wairakei, March 1960**

figure 6, though the isotherms extend well out in this direction. Thus, the Karapiti area is apparently superficial, and is merely a somewhat remote area of escape of steam from the feed areas to the north.

Figures 7 and 8 are vertical profiles running approximately N-S through the western and central parts of the area, respectively. Their actual courses are shown by the locations of the drillholes through which they pass. Both profiles show clearly that the hot region A extending south from the centre W in figure 6 consists of a relatively thin sheet which overlies lower temperatures. Several drillholes tapping region A (e.g., bores 203, 204 and 211) are now producing steam almost completely free from water, thus confirming the suggestion that there is a route of steam flow here; the increasing proportion of steam from these drillholes, together with increases in the heat flow and number of fumaroles in the Karapiti area over the last few years, indicates an increased flow of steam from the source areas.

Temperature maxima like D and A in figures 6 and 7, and N in figure 6, can be correlated satisfactorily with areas of steam or water discharge at the surface. By analogy, it might be expected that temperature minima like B in figure 7 and the re-entrant form of the isotherms beneath drillholes 12 and 13 in figure 8 would represent regions of inflow of colder water forming parts of a circulatory system. However, this is not supported by present temperature trends, which are rising in nearly all parts of the area, including most of the minima (several more minima are shown by drillholes in other parts of the area). The form of the patterns certainly suggests circulation, but this now appears to have been stopped or even reversed.

A feature of the profiles of figures 7 and 8 is the tendency of temperatures to increase again with depth towards the bottom (i.e., about one kilometre from the surface). Only a few drillholes are deep enough to establish this tendency very clearly, but it does provide some evidence for an enlargement of the hot areas at greater depths, and consequently for increased heat storage deeper in the system. A few drillholes to depths of the order of 1.5 to 2 kilometres are required to check this point effectively, and to show the deeper geological structure.

*Energy storage from drillhole data*

In figure 6, the 230°C isotherm represents approximately boiling point at this depth. From the temperature data available, it is not possible to complete this isotherm satisfactorily throughout its whole length, but the dashed outline is believed to represent its shape within fairly close limits. The area within this outline is about 1 km², which agrees closely with the value quoted above for the total area within the 50°C isotherm at one metre depth, so

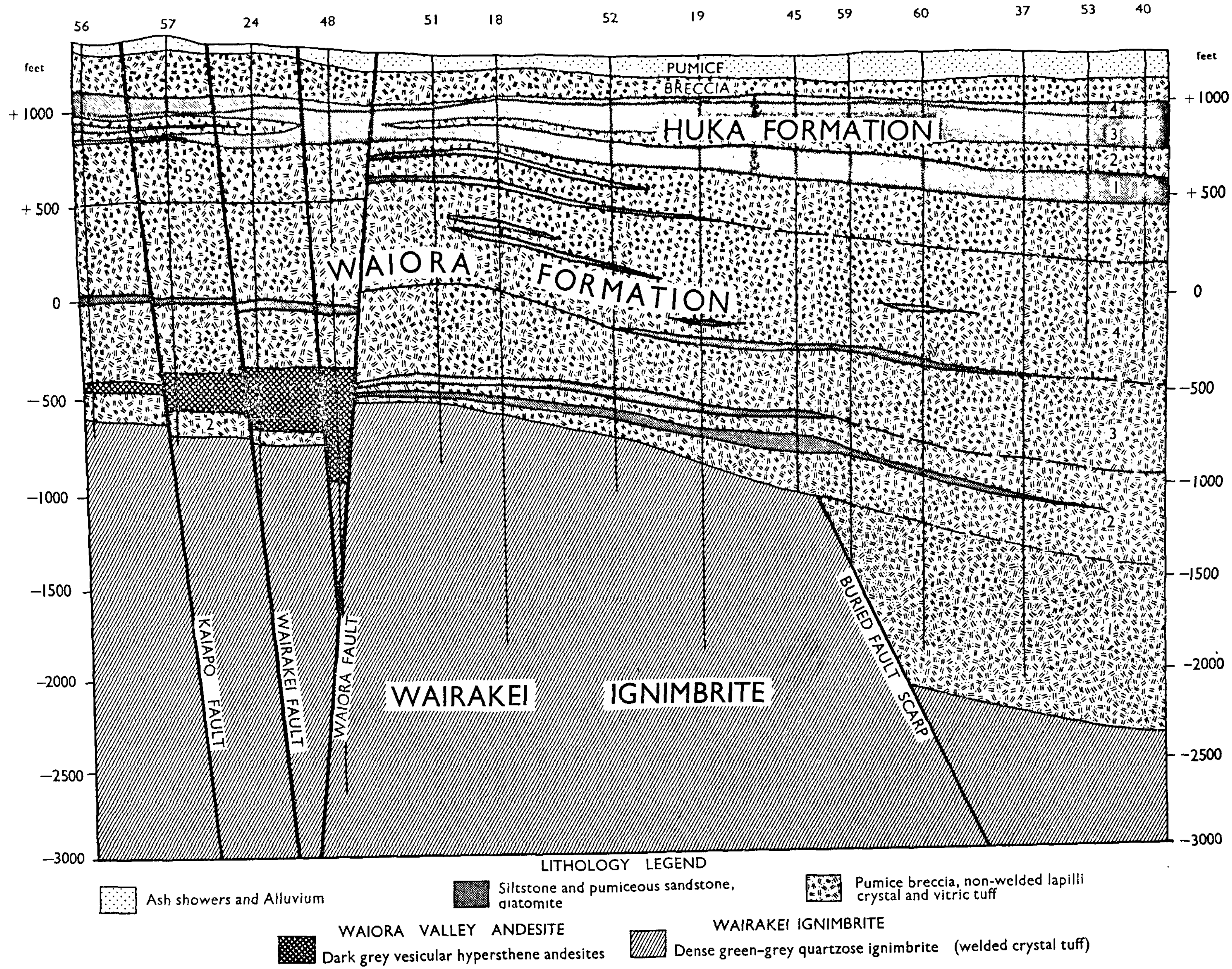


**Figure 9. Cross section from hole 56 to hole 40**

that the estimate of energy storage based on this area and used in the calculations above is effectively unaltered. There is some additional storage in the outer areas, but most of this is at relatively low temperatures, and the hotter regions (such as A) appear to be now filled with a large quantity of steam. Total energy in the regions explored by drilling remains small, and production from storage must depend very much on development, direct or indirect, from greater depths.

*Structure*

Figure 9 is a geological profile, prepared by Grindley, through the area in which the majority of the drillholes feeding the present power station are located. The Huka formation, in the upper part of the profile, covers much of the area of figure 6, and consists of impermeable material; it is probable that leakages of hot water and steam through breaches in this formation by faults are responsible for much of the characteristic form of the surface temperature pattern. The next formation, the Waiora, is much thicker, and consists mostly of permeable material. In addition to a general permeability, which is recognisable from core samples, information from drilling logs shows this formation to be traversed by many fissures or highly permeable zones through which steam and water move with greater freedom. Many of the drillholes with high outputs appear to be producing from large feeding fissures near the bottom of the formation. Beneath the Waiora formation are the ignimbrites, of unknown thickness. These rocks are generally impermeable in core specimens, but permeable in the mass because of the presence of open joints, fault fractures and the like. Geological profiles for the remainder of the area drilled are not yet available, but the locations of certain other formations, identified as ignimbrites and rhyolites, are shown superimposed on the isothermal profiles of figures 6, 7 and 8. Like ignimbrite, rhyolite is generally permeable by large-scale jointing rather than inherent permeability of the rock itself. Correlation between temperature and structure in these profiles is not very evident, except that the hot zone A lies mostly in the upper section of a thick rhyolite formation which reaches into the area from the south.

*Energy storage in the light of structure*

From the viewpoint of power production, the withdrawal of stored heat from jointed but otherwise impermeable rocks such as ignimbrites and rhyolites is likely to be inefficient because water movement through them will be confined mostly to the joints, and large temperature differences will tend to develop between the interior of the rock and the incoming cooler water to which the heat must be transferred. Hence, much of the useful heat storage in the parts of the Wairakei area so far explored by drillholes will be confined to the permeable members above the ignimbrites—that is, roughly from the surface to a depth of some 600 metres.

*Location of heat source feeding drillholes*

For a rough estimate of the energy storage in permeable formations down to 600 metres, let it be assumed that the effective cross section of the storage region is twice that of the source area W in figure 6, or 2 km$^2$, to allow for heat stored in the outer areas. From figure 4, the net available energy for this combination of area and depth is about 1 000 megawatt years. In comparison, the total mass of hot water and steam withdrawn from the Wairakei area by drillholes between April 1953 (when production first became significant) and the end of January 1961 was $1.68 \times 10^8$ metric tons, with an equivalent temperature (based on the mean enthalpy) of about 253°C. This represents 830 megawatt years of energy at an assumed over-all station efficiency of 63 per cent. Over the same period the surface heat flow has remained roughly constant (it has in fact increased somewhat), so that the drillhole energy must have been derived from storage. Clearly, it cannot have come from the storage in the upper 600 metres, since this would have become almost completely exhausted, and temperatures would have fallen drastically, whereas they have in fact remained nearly constant, or even risen in some regions over the past year. Hence, it must be concluded that the production drillholes are at present drawing their heat supply mainly from some deeper source, presumably beneath the ignimbrites, through existing permeable paths, and storage in the upper system has remained virtually intact.

*Aquifer pressure changes*

In the course of tests to determine possible drawoff rates by drillholes from the production area, the mass discharge from drillholes was progressively raised until it reached a maximum value 2 070 kg/sec in February 1960, which is about 25 per cent more than the estimated requirement for the 250 megawatt power station. The rate of drawoff has since been reduced, and in January 1961 it was about 960 kg/sec. Assuming the original natural mass discharge to have been equal to that measured in the 1958-59 survey (425 kg/sec), the sum of surface flow and bore drawoff has therefore ranged from over five times the natural flow at the peak period to about three times in January 1961. Changes in drawoff rate as large as this would be expected to give measurable pressure falls in the producing aquifer, and large falls in water level have in fact been observed in a number of drillholes. As an example, the water level in bore 34 has fallen from approximately ground surface in 1956 to 75 metres below ground surface at the end of 1960. Comparable falls have taken place in several other drillholes on the eastern and southern boundaries of the area. These drillholes are all far from the area where most of the drawoff is taking place, and it is to be expected that pressure falls would be still larger in this area; in fact, pressure falls in drillholes in the production area, although they are often difficult to measure accurately, appear to be much smaller. The system is apparently not behaving like a simple cold-water aquifer with drawdown, and the reasons for this behaviour are still not clear, though certain theories can be suggested. However, the absence of large pressure falls in most of the production area, and lack of evidence of any important inward movement of cold water in the regions above the ignimbrites suggest strongly that hot water from deeper sources is available in large quantities to the producing drillholes through channels of high permeability.


### *Summary*

This paper deals primarily with the siting of bores in a thermal area for the purpose of obtaining scientific data, and with the interpretation of the physical data so obtained for the assessment of the potentialities of the area for power production, for the siting of production bores, and for the subsequent monitoring of the behaviour of the hydrothermal system during exploitation. The siting procedures and interpretations discussed here are based on experience gained in approximately ten years' exploration in the thermal area in the North Island of New Zealand, with particular reference to the Wairakei area, where large-scale development is now well advanced.

In a new development area, where information from previous drilling is scanty or absent, the basic data for siting investigation bores must be derived from the results of various surface surveys — geophysical, geological, chemical, etc.; further details of some of these surveys are dealt with more fully in companion papers, to which reference should be made. The object of the first prospecting bores is then to check the inferences of the surface surveys, and to provide detailed information concerning the rock formations present, their more important physical properties (e.g., porosity, permeability and density), and physical conditions (e.g., temperature, fluid pressure, nature of permeating fluid, etc.). As information from the first bores becomes available, preliminary sections and temperature profiles can be prepared and used as a guide for further siting.

In later stages of the development of an area, when bore drawoff has become considerable, temperature and pressure measurements in both prospecting and production bores provide important data concerning the response of the hydrothermal system, and the rate at which the known heat storage is being used.

At Wairakei, temperature data from recent prospecting bores distributed over the outer areas, taken in conjunction with data from the numerous development bores and some earlier prospecting bores, have enabled a reasonably complete set of isotherms to be drawn down to depths of the order of 3 000 feet. Down to this depth a hydrothermal system which constitutes a distinct entity appears to exist, most of the heat supply being derived from a relatively small group of sources which feed hot water or a mixture of steam and hot water from below into a region near the western end of the production area.


## PUITS GÉOTHERMIQUES : RECHERCHES PHYSIQUES


### *Résumé*

Cette communication s'intéresse au premier chef au choix de l'emplacement des puits à forer dans une région thermique pour recueillir des renseignements scientifiques et interpréter les données physiques ainsi obtenues, ainsi que pour évaluer les possibilités de la région en ce qui concerne la production d'énergie, pour choisir l'emplacement des puits de production et la surveillance ultérieure du comportement des systèmes hydrothermiques pendant leur exploitation. Les techniques de choix des emplacements et d'interprétation passées en revue dans le mémoire reposent sur l'expérience acquise en dix années environ d'exploration dans le champ géothermique de l'île du Nord de la Nouvelle-Zélande, en s'intéressant particulièrement à la région de Wairakei, où les réalisations à grande échelle sont maintenant en plein développement.

Dans toute région en cours de mise en œuvre, pour laquelle les renseignements dus à des fonçages antérieurs sont peu abondants ou manquent même totalement, les données de base pour le choix des puits d'exploration doivent être établies à partir des résultats de diverses études de surface géophysiques, géologiques, chimiques, etc. On trouvera des descriptions plus détaillées de certains de ces travaux dans les mémoires qui accompagnent cette communication, qu'il conviendra de consulter. L'objet des premiers puits de prospection est donc de vérifier les indications que donnent les travaux de surface et de se procurer des renseignements détaillés sur les formations rocheuses présentes, leurs propriétés physiques les plus importantes (porosité, perméabilité, densité) et la situation physique générale (température, pression, nature des fluides qui s'infiltrent, etc.) Dès que l'on disposera de renseignements sur les premiers puits, on pourra préparer des coupes préliminaires et des courbes de température, pour s'en servir comme de guides en vue du choix d'emplacements ultérieurs.

Dans les stades plus avancés de la mise en œuvre d'une région, lorsque les puits ont déjà beaucoup donné, les mesures de la température et de la pres-

sion, tant dans les puits de prospection que dans les puits de production, fournissent des renseignements importants en ce qui concerne les réactions du système hydrothermique et le régime d'utilisation de l'énergie thermique que l'on sait être accumulée dans ces puits.

A Wairakei, les données sur la température fournies par des puits de prospection récents, répartis sur les régions extérieures, prises en liaison avec les données des nombreux puits en exploitation et quelques puits de prospection préliminaires, ont permis de tracer un jeu raisonnablement complet d'isothermes jusqu'à des profondeurs de l'ordre de 3 000 pieds. Jusqu'à cette profondeur, il semble exister un système hydrothermique constituant une entité clairement définie, la majeure partie de la chaleur étant fournie par un groupe relativement petit de sources qui fournissent de l'eau chaude ou un mélange de vapeur et d'eau chaude en provenance des couches inférieures à une région proche de l'extrémité occidentale de la surface en production.

# ÉTUDE STRUCTURALE DE LA ZONE DE ROCCASTRADA EN VUE DE LA RECHERCHE DE VAPEUR PAR LES MÉTHODES GÉOPHYSIQUES, GRAVIMÉTRIQUES ET ÉLECTRIQUES

*Ferdinando Battini* et Paul Menut†*

Depuis près de 13 ans, la Compagnie générale de géophysique et sa filiale la Compagnia Generale di Geofisica ont effectué des prospections géophysiques appliquées à la recherche de vapeurs endogènes pour le compte de la société Larderello, S.p.A. Nous remercions ces sociétés d'avoir bien voulu autoriser cette communication.

Du point de vue géophysique, les recherches de vapeur sont souvent assez analogues aux recherches d'hydrocarbures, du fait, en particulier, de la nécessité d'une couverture imperméable et de roches réservoirs poreuses et fissurées.

Leur aspect plus particulier réside dans le facteur température et dans la recherche des fractures éventuelles par lesquelles les fluides peuvent alimenter leur réservoir.

C'est dire que l'on peut *a priori* songer à appliquer aux recherches de vapeurs endogènes tous les procédés géophysiques classiques dans la recherche du pétrole, tels que :

Pour la reconnaissance : magnétisme aéroporté, gravimétrie, méthodes électriques (principalement sondages électriques) et telluriques, réfraction sismique;

Au stade du détail : méthodes électriques de détail, réflexion sismique.

Le facteur température peut être étudié par les méthodes thermométriques (malgré de très grandes difficultés d'interprétation) ou par les méthodes électriques.

Le choix entre ces diverses méthodes doit être fait suivant les conditions locales, le problème posé et les conditions économiques de la recherche.

Ayant rappelé ces généralités, nous exposerons l'exemple de la prospection de la région de Roccastrada-Monticiano, située à une quarantaine de km au sud-sud-ouest de Sienne et à une trentaine de km du littoral de la mer Tyrrhénienne, en Italie centrale.

Cette prospection a été effectuée en deux stades : par gravimétrie puis par sondages électriques. Le choix de ces deux méthodes a été dicté par les conditions locales et par des raisons économiques.

La couverture gravimétrique a pu être exécutée rapidement et à peu de frais, permettant d'éliminer certaines zones reconnues peu intéressantes pour les recherches ultérieures. Il est à noter que l'interprétation de la gravimétrie a pu, comme nous le verrons par la suite, fournir certains éléments quantitatifs.

L'étude par sondages électriques, plus détaillée, a donné des indications de profondeur.

La comparaison des résultats basés sur deux paramètres physiques différents (densité et résistivité électrique) a permis une interprétation plus poussée que si une seule méthode avait été appliquée.

## Cadre géologique

La zone prospectée est située sur le flanc occidental de la ride permo-triasique de Roccastrada-Monticiano. Elle s'étend au nord-ouest jusqu'aux affleurements de même âge de Boccheggiano-Prata et au sud vers la plaine de Grosseto, recouverte de sédiments récents.

Sur la partie centre-orientale affleurent des laves trachytiques que nous appellerons par la suite « ignimbrites ». Leur présence et celle de rares manifestations thermales (eaux chaudes ou sulfurées) ont suggéré une étude géophysique aux fins de la recherche de fluides endogènes.

La série stratigraphique schématique est la suivante :

Néogène : alluvions récentes, sables, argiles et sables gypseux, conglomérats.

Allochtone : argiles « scagliose », argileuses à l'est et plus calcaires à l'ouest; roches vertes.

Autochtone : calcaires et anhydrites de la série d'anhydrites du rhétien, schistes et quartzites du permo-trias.

Les horizons éventuellement productifs se situeraient dans l'autochtone, tandis que l'allochtone et une partie du néogène ont les caractéristiques d'imperméabilité et d'épaisseur requises pour une bonne « couverture ».

## Étude gravimétrique

Le but assigné à cette étude était la reconnaissance générale des caractères structuraux de la zone (grandes fractures, toit de l'autochtone, remplissage d'argiles « scagliose » et de néogène, etc.) afin, en

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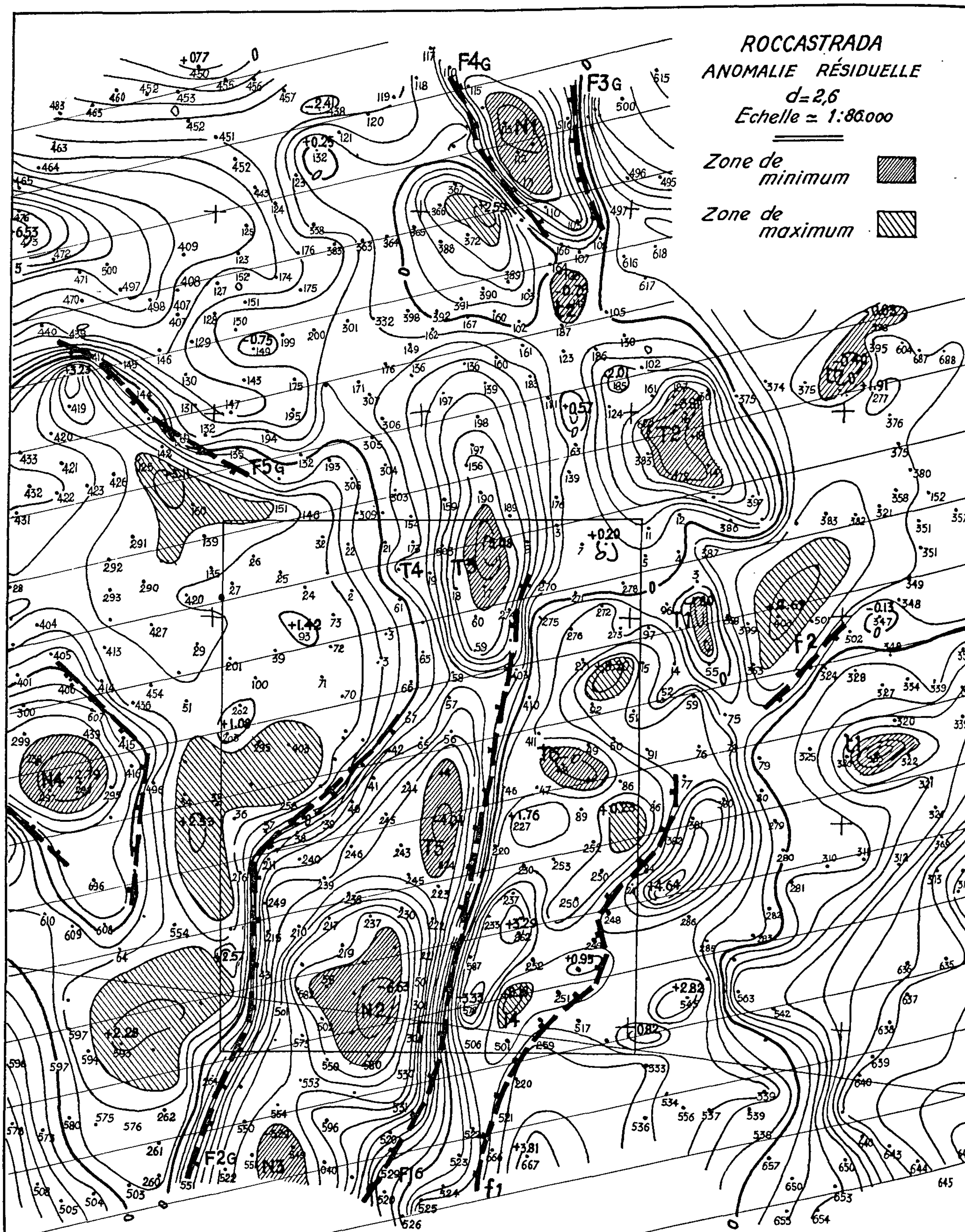


**Figure 1.** Anomalie résiduelle

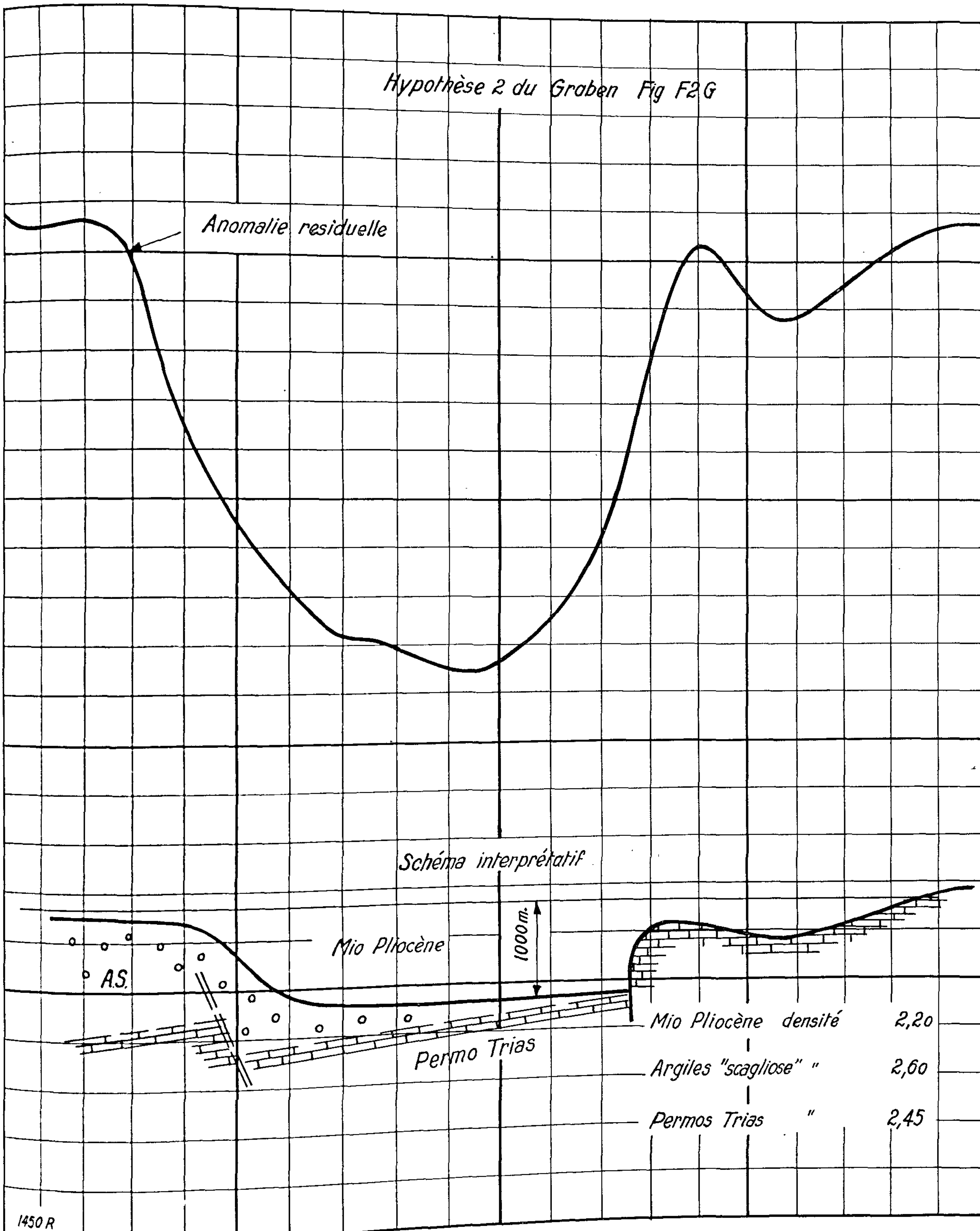


Figure 2. Section

particulier, de délimiter les zones à détailler par la suite.

Sept cents stations ont été exécutées sur une surface d'environ 625 km².

Nous avons dressé une carte de l'anomalie de Bouguer en densité 2,6 puis une carte résiduelle (fig. 1). Elles mettent bien en évidence les grands traits structuraux de la région.

On remarque principalement les deux « graben » limités par les failles *F 1 G*, *F 2 G* et *F 3 G*, *F 4 G*. Ces failles encadrent les zones d'anomalies négatives correspondant à des zones de plus grand remplissage néogène (lettre *N* sur la figure 1).

Sur la figure 2, nous avons tracé une section représentant l'allure présumée du toit de l'autochtone. Sa détermination est complexe, car sur le flanc oriental les failles *F 1 G*, *F 3 G* mettent probablement au contact le néogène et l'autochtone, tandis que sur le flanc occidental au voisinage des failles *F 2 G*, *F 4 G* la situation est plus complexe. Il y a en effet apparition des argiles « scagliose » allochtones. La densité de ces argiles est d'environ 2,6; ce sont donc les terrains les plus lourds rencontrés dans cette prospection.

On a calculé lors des essais d'interprétation quantitative que, pour un même gradient gravimétrique, le rejet des failles du type *F 1 G*, *F 3 G* doit être supérieur à celui des failles *F 2 G*, *F 4 G*, ceci à cause de la présence desdites argiles.

Pour la même raison, la cote du toit de l'autochtone à l'ouest de *F 2 G*, *F 4 G* sera probablement inférieure à sa cote à proximité des failles *F 1 G*, *F 3 G*.

Les plages négatives marquées *T* et *t* correspondent aux effusions d' « ignimbrites ». Les plus importantes sont *T2*, *T3*, *T5*.

La coulée visible en affleurement entre *T3* et *T5* ne doit pas avoir une grande épaisseur, tandis que la partie superficielle de *T5* a été érodée et recouverte par les alluvions.

Les anomalies *T2*, *T3* font supposer de grandes épaisseurs d'ignimbrite et doivent correspondre aux centres effusifs principaux.

Les fractures qui ont donné naissance aux épanchements sont très vraisemblablement liées aux systèmes *F 1 G* et probablement à *F 3 G*, *F 4 G*.

L'interprétation de la carte montre que l'autochtone s'approfondit d'une façon générale d'est en ouest; toutefois, on ne peut exclure qu'il y ait des rehaussements locaux au voisinage des failles *F 2 G* et *F 4 G*.

Le recouvrement passe de formations essentiellement néogènes à l'est à des formations d'argiles « scagliose » allochtones à l'ouest. L'épaisseur maxima de ces dernières serait atteinte dans le compartiment entre la faille *F 5 G* et l'anomalie *N4*.

En résumé, la gravimétrie a attiré l'attention sur certains graben qui présentent pour la recherche un double intérêt :

Ils ont une épaisseur satisfaisante de recouvrement imperméable;

Ils sont bordés par des lignes de fractures en rapport avec les effusions ignimbritiques et qui en conséquence sont probablement le siège de manifestations thermales.

Il a donc été décidé d'explorer en détail par prospection électrique la zone centre-sud de l'étude gravimétrique.

## Étude électrique

Deux cent trente sondages électriques ont été exécutés sur une superficie d'environ 85 km².

L'expérience des prospections électriques antérieures montre que dans la majorité des cas les terrains allochtones sont conducteurs dans leur ensemble, les séries résistantes correspondant à l'autochtone. Cependant, lorsque l'autochtone commence par des couches minces de « macigno » de l'oligocène ou de « scaglia » du crétacé, séries relativement conductrices, la prospection électrique les englobe dans le recouvrement.

Dans la région de Roccastrada, les affleurements autochtones les plus récents sont d'âge rhétien; on ne peut cependant exclure qu'il existe, sous recouvrement, une série autochtone plus complète.

La figure 3 montre un exemple caractéristique de sondages électriques.

Quant à la précision que l'on peut attendre de l'évaluation des profondeurs (outre l'indétermination due à la présence éventuelle de séries autochtones relativement conductrices), il faut noter qu'aucun forage n'existant dans cette région à l'époque de la prospection, nous n'avons pu étalonner nos mesures, ce qui évidemment n'est pas une condition très favorable pour une bonne précision des évaluations absolues. Toutefois, les profondeurs relatives se ressentent moins de cet état de choses et l'on peut espérer que l'allure de la carte du toit du substratum résistant reflète bien la réalité.

Les figures 4 et 5 résument l'interprétation. Les grandes lignes de la tectonique du substratum résistant sont les suivantes.

Le substratum s'enfonce d'une façon générale dans le sens NNE-SSO. Un système principal de fractures de direction NNE-SSO accentue localement le pendage général, ainsi d'ailleurs que des failles de direction sensiblement orthogonales de moindre importance. Un certain nombre de compartiments sont ainsi délimités, identifiés par les lettres *C* sur la figure 4.

Le compartiment *C1* est compris entre les affleurements situés au sud-est de Sticciano et la faille *F1*, dont le rejet passe du nord au sud de 100 à 450 m environ. Le recouvrement est peu épais, et sa résistivité correspond à celle d'un terrain alluvial de perméabilité moyenne. Sauf à l'extrémité sud-est, où le pendage s'accentue, le toit du substratum fait penser à une surface d'érosion.

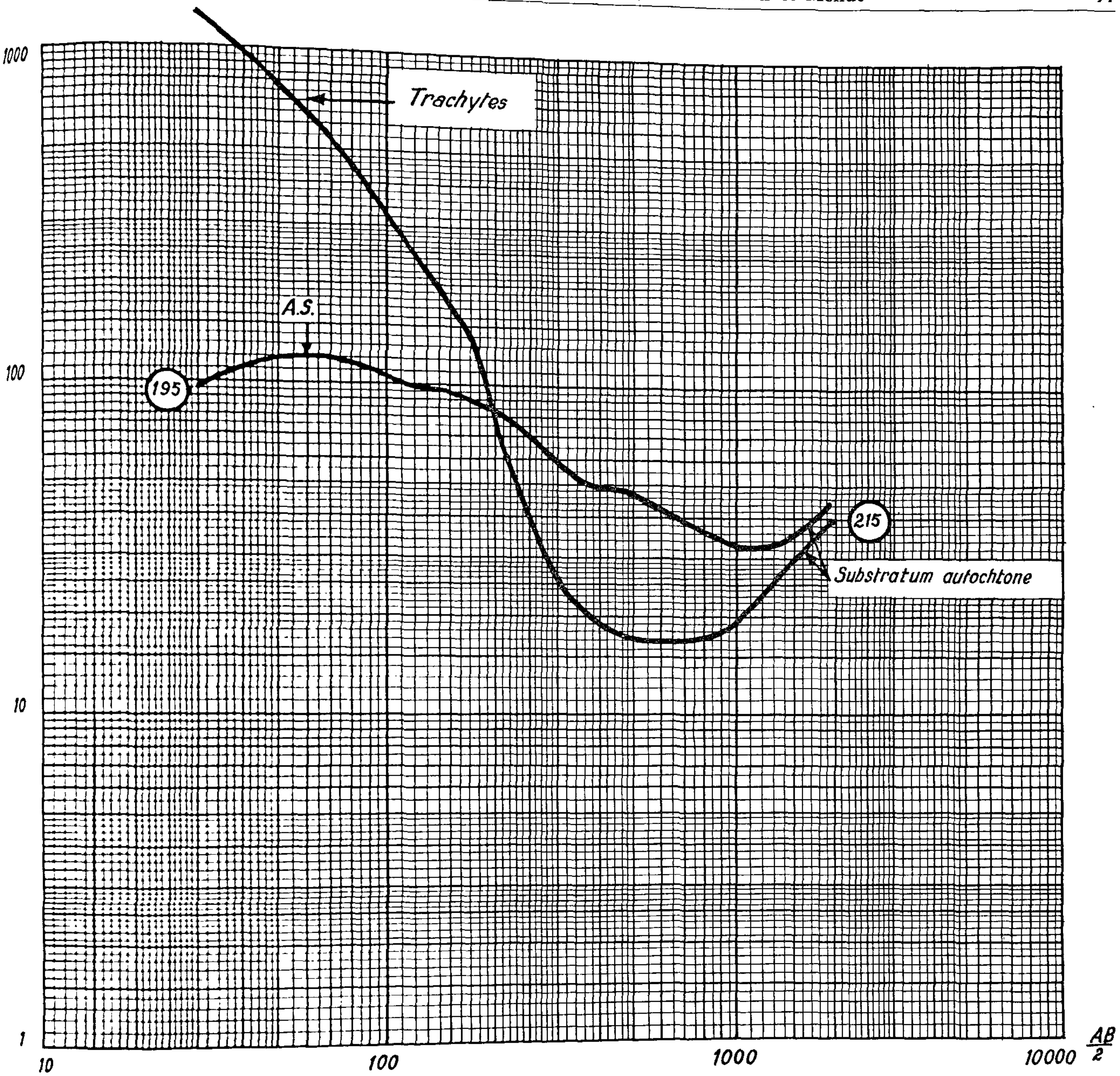


**Figure 3. Exemple de sondage électrique**

Le compartiment *C6* apparaît comme le prolongement nord de *C1*. Cependant il pourrait être séparé de ce dernier par le prolongement nord de la faille *F1*, qui n'apparaît pas nettement sur les résultats électriques à cause de son rejet qui diminue vers le nord, diminution due peut-être à l'érosion de la partie nord du compartiment *C1*. A noter une faible épaisseur de recouvrement ignimbritique et néogène. Au voisinage de la faille *F4*, certaines anomalies des sondages électriques nous laissent croire que ladite fracture pourrait être liée à un centre effusif.

Le compartiment *C5* au nord de la faille *F4*, qui a un rejet d'environ 200 m, est limité à l'est par les affleurements du torrent Bai et à l'ouest par la faille *F2*, dont le rejet passe de 200 m au nord à 400 m environ au sud. Le recouvrement n'est pas très épais et est assez perméable.

Le compartiment *C4* est limité par les failles *F2*, *F4* (dont le rejet est ici de 200 à 300 m) *F6*, de rejet moyen 450 m, probablement en relation avec les effusions de Sassoforte. Le recouvrement est sensiblement plus épais que dans les compartiments précédents (500 m à l'est de *F6*). Ce recouvrement comporte des ignimbrites, bien visibles sur les sondages électriques, reposant sur un ensemble conducteur représentant les argiles « scagliose ».

Le compartiment *C3*, qui recouvre toute la partie ouest de l'étude, dénote une allure assez régulière du toit du substratum résistant, avec pendage vers l'ouest-sud-ouest, et une épaisseur maximum de

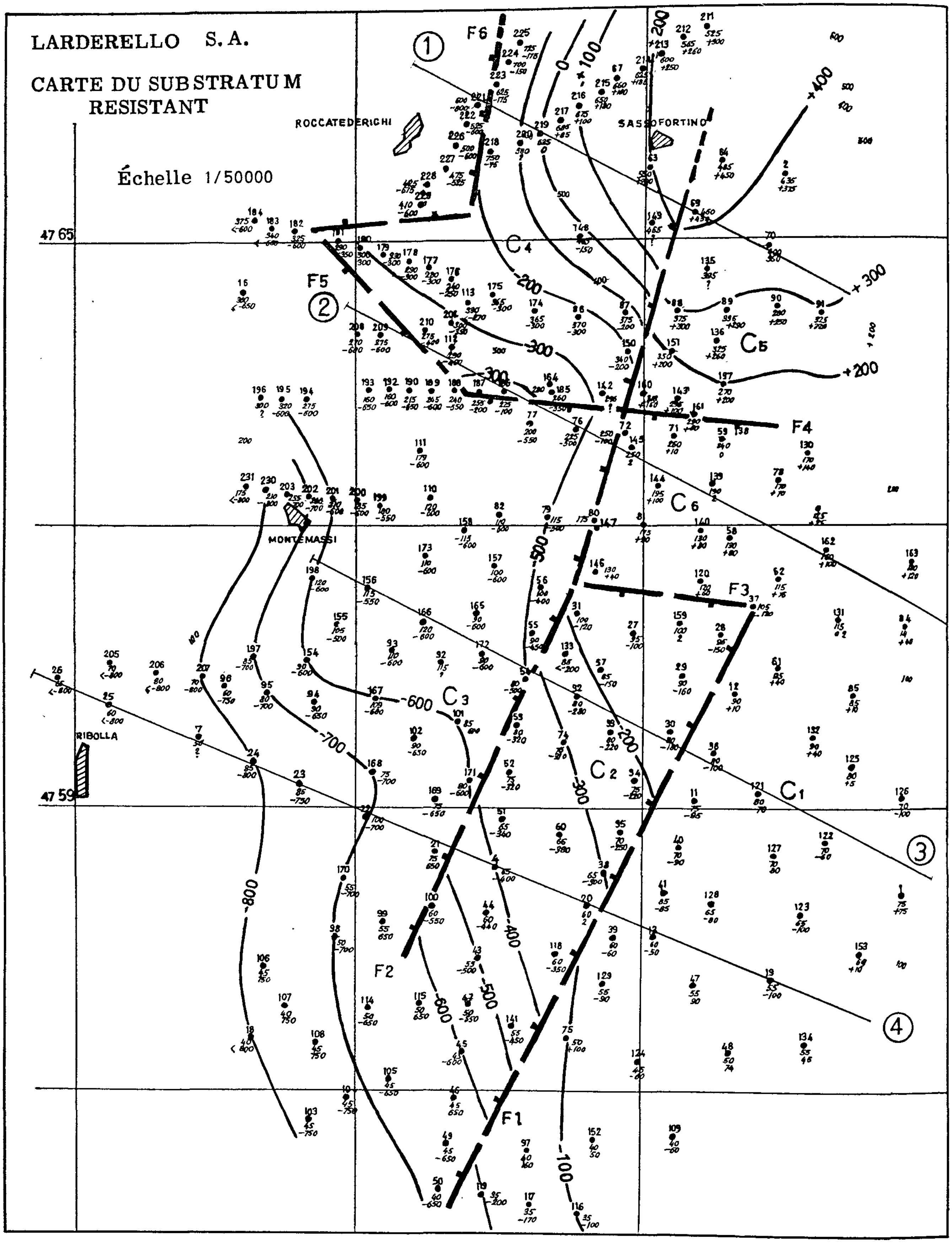


Figure 4. Carte du substratum résistant

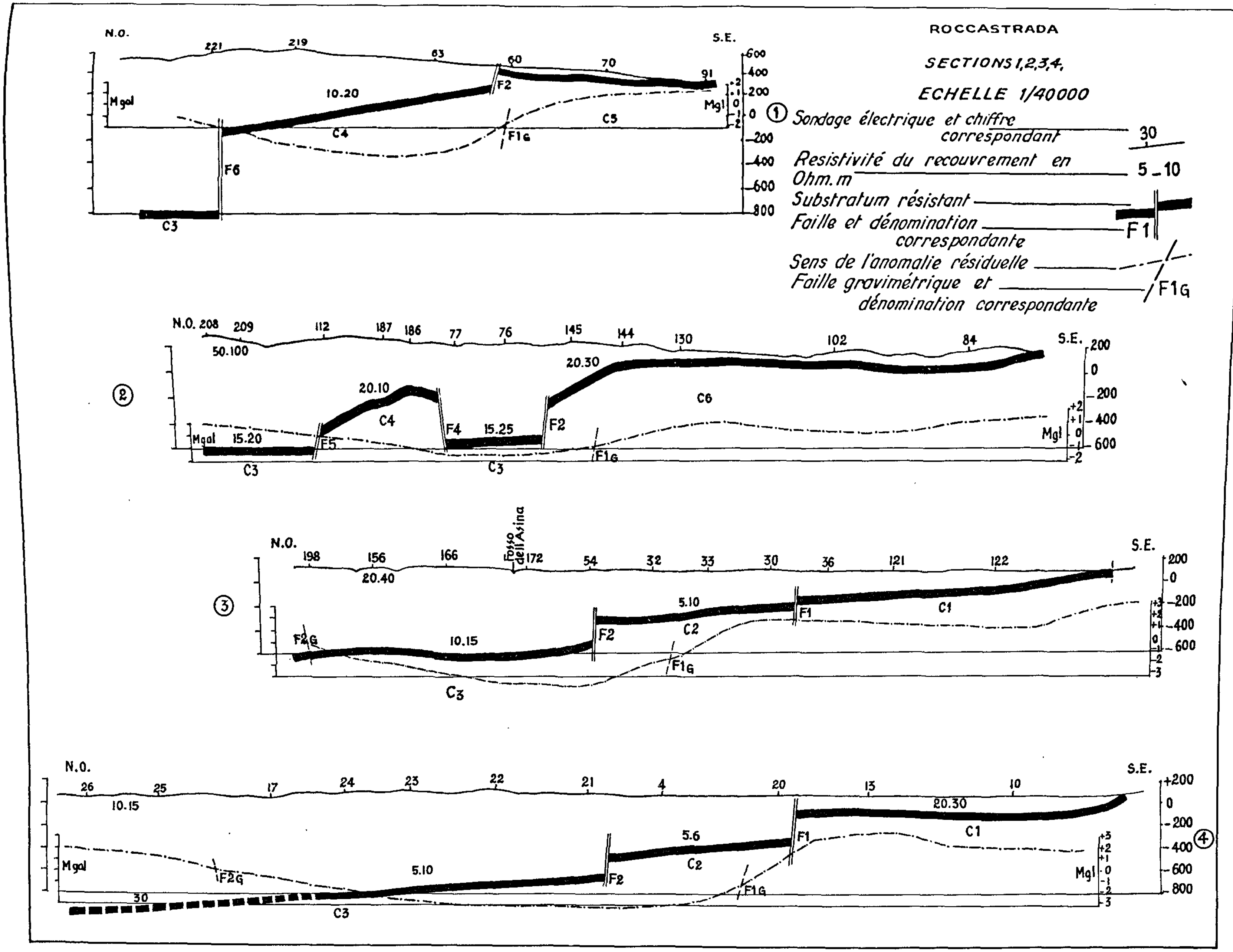


Figure 5. Sections

recouvrement. La résistivité de ce recouvrement, basse au sud de Montemassi, augmente notablement au nord, dénotant la présence dans les argiles « scagliose » d'éléments calcaires, marneux et ophiolitiques.

Le compartiment *C2*, qui ne se différencie pas de *C3* dans sa partie sud-ouest, est délimité par les failles *F1-F3-F2*, cette dernière disparaissant vers le sud-ouest. Le recouvrement est partout très conducteur (5 à 10 ohms/m) et doit donc présenter une bonne imperméabilité.

Le résultat le plus intéressant de cette étude électrique est la mise en évidence des fractures principales de direction NNE-SSO, en particulier dans la région du compartiment *C2*, qui présente toutes les probabilités d'une bonne couverture.

Malheureusement, l'épaisseur de recouvrement sur le flanc est de la faille *F1* est faible, et un défaut de couverture est à craindre. Cependant cet inconvénient s'atténue à l'extrémité sud-ouest de *F1* et disparaîtrait peut-être plus au sud, zone qui n'a pas été touchée par la présente étude électrique.

La faille la plus intéressante par son rejet, surtout dans sa partie centrale vers son croisement avec *F3*, est indubitablement la faille *F2*.

### Comparaison des résultats électriques et gravimétriques

Sur la figure 5 nous avons reporté sur les diverses sections les profils de l'anomalie gravimétrique résiduelle ($d = 2{,}6$) et l'allure du substratum résistant déduit de l'interprétation des sondages électriques.

Rappelons que l'étude électrique ne recouvre que le centre et le flanc oriental d'un graben mis en évidence par la gravimétrie.

D'une façon générale, on remarque que les zones hautes du substratum résistant (compartiments *C5-C6-C1* des sections 1-2-3-4) correspondent à des anomalies résiduelles gravimétriques positives.

En ce qui concerne les failles, comme on pouvait s'y attendre étant donné les caractères respectifs des deux prospections, la carte électrique présente un plus grand détail. Il faut toutefois remarquer la bonne correspondance entre les représentations de la faille *FG1*, qui sur la section 1 correspond bien à la faille *F2*, sur la section 2 se place au voisinage de cette dernière, et sur les sections 3 et 4 représente une position moyenne entre les failles *F1* et *F2*, tendant à se rapprocher localement de celle dont le rejet est le plus grand.

L'inflexion de la résiduelle gravimétrique qui a été interprétée vers le nord-ouest des sections 3 et 4 comme une faille *F2G* n'apparaît pas sur la carte électrique, mais nous ne saurions tirer aucune conclusion de ce fait, car d'une part le nombre de sondages électriques au nord-ouest de cet accident est vraiment trop faible et d'autre part une partie de l'effet gravimétrique observé peut être due à la présence d'argiles « scagliose » de densité élevée. Il y a là un problème qui resterait à résoudre.

Sur le profil 2 qui traverse des accidents localisés, la gravimétrie qui, rappelons-le, était utilisée comme méthode de reconnaissance, ne pouvait mettre en évidence les compartiments relativement étroits indiqués par les sondages électriques. Il n'y a toutefois pas de contradiction entre les résultats des deux méthodes. La même remarque vaut pour les failles transversales telles que *F3-F5*.

Avant de conclure il est bon de remarquer que les conditions topographiques étaient relativement défavorables :

Altimétrie difficile (altitude variant de 50 à 700 m);

Viabilité très restreinte (plus de 20 p. 100 du travail a dû être fait à pied, aussi bien en gravimétrie qu'en électrique);

La présence de broussailles a nécessité le tracé préalable de layons pour le déroulement des câbles électriques.

Malgré cela, la prospection n'a nécessité que cinq mois pour l'électrique, trois mois pour la gravimétrie.

### Conclusions

On voit par cet exemple qu'une étude critique poussée des résultats des deux prospections électrique et gravimétrique a permis de mettre en évidence, à moindres frais, une première zone présentant les caractéristiques requises pour l'implantation de forages d'exploration.

Si ceux-ci s'avéraient encourageants, il n'y a pas de doute que des méthodes de plus fin détail telles que la réflexion sismique à haute résolution permettraient de serrer encore le problème de plus près.

### *Résumé*

Entre la recherche du pétrole et celle de vapeur endogène, il existe certaines analogies liées à la coexistence de « roche magasin » et d'une couverture imperméable suffisamment épaisse. Il est donc possible d'appliquer à la recherche de la vapeur les méthodes géophysiques déjà utilisées avec succès dans la recherche pétrolière.

La Compagnia Generale de Geofisica, qui depuis plus de 13 ans collabore avec la Société Larderello dans la zone boracifère toscane, a effectué récemment une étude structurale près de Roccastrada, par méthodes gravimétrique et électrique. Étaient confiées à la gravimétrie la reconnaissance structurale générale de la zone, à l'électrique l'étude de détail dans les secteurs d'intérêt majeur.

La gravimétrie, exécutée sur une superficie de 625 km², a mis en lumière deux « graben » de caractéristiques favorables, en révélant simultanément les

principaux systèmes de fractures intéressant le substratum potentiellement productif et en indiquant en partie la nature des terrains de couverture.

A la suite de ces résultats, une étude de détail du graben sud fut effectuée par sondages électriques, sur une superficie d'environ 80 km². On a pu ainsi mieux définir les zones de fracture et les caractéristiques d'imperméabilité du recouvrement. Les résultats obtenus par les deux méthodes sont illustrés sur des figures. De leur confrontation, il résulte une concordance notable dans le cadre des hypothèses géologiques admises. On en conclut qu'il convient, pour l'étude de vastes superficies, d'utiliser plusieurs méthodes géophysiques afin de mettre rapidement en évidence les zones les plus intéressantes et de les étudier ensuite en détail.

# STRUCTURAL STUDY OF THE ROCCASTRADA ZONE IN PROSPECTING FOR STEAM BY GEOPHYSICAL, GRAVIMETRIC AND ELECTRICAL METHODS


## *Summary*

There are certain analogies between prospecting for oil and prospecting for steam, since in both cases one seeks structures having both reservoir rock and an impermeable cover of sufficient thickness. The geophysical methods already successfully employed in oil prospecting may therefore be applied to steam prospecting as well.

The Compagnia Generale di Geofisica (GGC), which has been collaborating with the Larderello Company for over thirteen years in the boraciferous zone of Tuscany, has recently conducted a structural study near Roccastrada by gravimetric and electrical methods. The gravimetric method was used for the general structural survey of the zone, while the detail survey in the areas of greatest interest was run by the electric method.

The gravimetric survey of an area of 625 sq. km. revealed two graben with favourable characteristics, simultaneously disclosing the principal fault systems associated with the potential producing layer and indicating in part the nature of the cover.

Following these results, a detail survey of the south graben was run by electric logging over a surface of about 80 sq. km. This gave better definition of the fault zones and the impermeability characteristics of the cover. The results of both methods are illustrated by figures. Their comparison shows good agreement under the geological hypotheses adopted. It is concluded that the use of several geophysical methods for prospecting large areas is advisable, so that the zones of greatest interest may be rapidly determined for subsequent detail study.

# PHYSICAL CHARACTERISTICS OF NATURAL HEAT RESOURCES IN ICELAND

*Gunnar Bodvarsson**

Thermal activity is a very common phenomenon in Iceland. Hot-water springs and natural steam outlets are scattered over large parts of the country and constitute a striking and unusual natural phenomenon. In the course of the past decades the thermal activity has become an important natural resource which is now being exploited on an increasing scale. Modern geological, geophysical and geochemical methods are now applied in order to explore the characteristics of the subsurface phenomena. Drilling for hot water and natural steam is being carried out on a relatively large scale.

The present paper is written for the purpose of giving a brief report on the main results of the geological and geophysical exploratory work. The paper is based mainly on results obtained in the period after 1945. For further information the reader is referred to other papers by the present author (Bodvarsson, 1949, 1950, 1951, 1956, and 1957).

Important contributions to the study of the thermal activity in Iceland have been made by Thoroddsen (1925) and Thorkelsson (1940, and earlier works). The book by Barth (1950) contains a wealth of descriptive material. Moreover, the work by Einarsson (1942) deserves special attention for the emphasis it places on the physical aspects of the geothermal phenomena.

## Geology

Iceland is a member of the Brito-Arctic basalt province. The total series of flood basalts in Iceland is believed to reach a thickness of several kilometres.

According to the results of the seismic refraction studies of the Swedish-Icelandic expeditions in 1959 (Båth, 1960) and 1960 (Båth and Tryggvason, 1961), the section through the upper crust, from Reykjavík in the south-west to Tjörnes in the north-east, appears to be as shown in the sketch in figure 1. Formations A and B are flood basalts. Formation C does not outcrop, but may be composed of basalts of a relatively early origin. The composition of D and E is unknown. The Moho-discontinuity appears to be at a depth of 28 km.

The flood basalts are relatively inhomogeneous, and the average nature of the figures is therefore to be emphasized. A striking feature is the practical absence of a continental structure.

The Tertiary basalt plateau is the predominant surface formation in the north-west, the north and the east of the country. Quaternary volcanics cover only small parts of these districts. The central, southern and south-western parts are, on the other hand, covered by Quaternary lava flows and tuffs. The Tertiary plateau appears to underlie these formations. Post-Glacial volcanism is confined to the Quarternary districts, as shown in figure 2. The shaded areas indicate roughly the extent of the Neo-Volcanic zone of Iceland.

## Types, magnitude and distribution of thermal areas

### Relation between type and subsurface temperatures

Two main types of thermal area can be distinguished in Iceland. Firstly, the areas with hot-water springs and a relatively low degree of thermal metamorphism. Secondly, the large areas with natural-steam holes and a high degree of metamorphism. Various investigations have indicated that the two types differ mainly in the subsurface temperature and that most other factors can probably be regarded as functions of this quantity.

The hot-water areas are characterized by a relatively low subsurface temperature, in the upper flood basalts at least. Most of the areas in the north-west and north appear to have a temperature below 100°C. Some of the large hot-water areas in the south-west and the west have temperatures between 100°C and 150°C.

The large natural-steam areas, on the other hand, are characterized by subsurface temperatures above 200°C. The maximum measured is about 230°C.

The thermal areas are preferably classified on the basis of the temperature conditions. The hot-water areas are classified as the low-temperature activity, and the natural-steam areas as the high-temperature activity.

As a matter of course, there are no well-defined limits between the two groups. There are a number of important borderline cases, as can be expected. The classification can be made somewhat more quantitative on the basis of the concept of the base temperature, which will be discussed below.

### Magnitude of the thermal areas

The heat flow to the surface—that is, the heat output of the thermal areas, varies within wide

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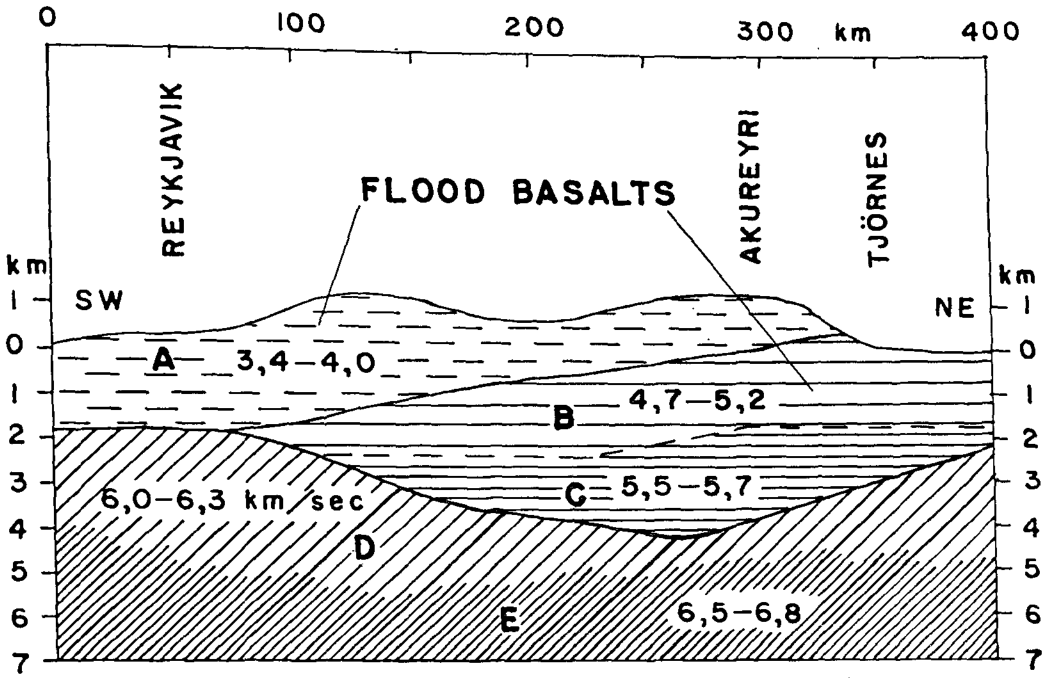


Figure 1. Crustal structure of Iceland in a SW-NE section

imits. The output of some of the smallest hot-water areas is only of the order of $10^5$ cal/sec, whereas the largest natural-steam areas have an output of the order of $10^9$ cal/sec. This great variation suggests the introduction of a scale of magnitude in order to classify the areas with regard to the heat output. On the other hand, the heat output is a figure which in most cases is known with little accuracy and is even somewhat uncertain by definition. This situation warrants only a scale with relatively wide steps.

A scale with three steps appears appropriate, as follows :

| *Magnitude* | *Total heat output* |
| --- | --- |
| I | 5-25 $\times 10^6$ cal/sec |
| II | 25-125 |
| III | 125-750 |

This scale will be applied mainly to systems of thermal areas, as will be discussed below, where the various components of the heat output will also be discussed in some detail.

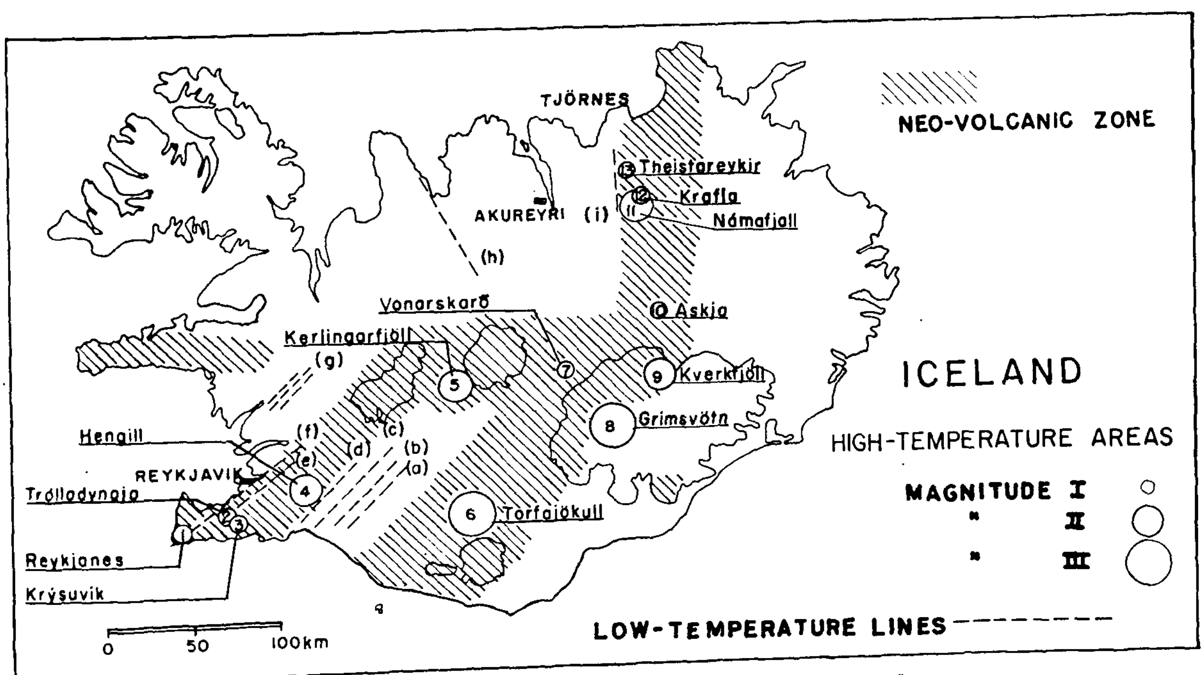


Figure 2. Distribution of thermal areas in Iceland

Table 1. Major low-temperature thermal lines in Iceland

| Total natural flow, litres/sec. | Max. surface temp. C | Heat output magnitude | Remarks on drilling, base temperature, etc. |
|---|---|---|---|
| (a) 52 | 100 | I | |
| (b) 140 | 100 | I | |
| (c) 60 | 100 | I | Includes the Great Geyser, borderline case. |
| (d) 70 | 100 | I | Borderline case. |
| (e) 120 | 83 | I | Base temp. at Reykir 98°C, 70 wells at Reykir, max. depth 1 380 metres. Output of wells 370 litres/sec. at 87°C. |
| (f) 10 | 88 | I | Base temp. in Reykjavik 146°C, 40 wells in Reykjavik, max. depth 2 200 metres. Output of wells 134 litres/sec at a max. temp. 138°C. |
| (g) 400 | 100 | II | System of lines. Includes largest hot water spring at Deildartunga. |
| (h) 70 | 89 | I | |
| (i) 145 | 100 | I | Borderline case. |

### The low-temperature activity

There are approximately 250 low-temperature thermal areas scattered over the lowlands of the western half of the country. The number of major springs is about 600 and the total integrated flow of all hot-water springs is roughly 1 500 litres per second. The total sensible (above 4°C) heat output of the springs amounts to some $10^8$ cal/sec, giving an average temperature of 75°C.

The low-temperature areas are in a great number of cases distributed in a linear pattern. This suggests a common structural control and interrelation between the individual thermal areas on the lines. In accordance with the discussion below, the individual lines will be regarded as hydrothermal systems, each related to certain relatively large geological structures.

The geographical distribution of the major low-temperature systems is given in figure 2 and some data are given in table 1. The magnitude applies in each case to the system as a whole. Moreover, the table contains information on temperature conditions and drilling performed on the individual systems. The subsurface temperature is characterized by data on the base temperature in the individual thermal areas. This concept will be discussed below.

### The high-temperature activity

There are thirteen high-temperature areas, all in the Neo-Volcanic zone, as shown in figure 2. These areas are quite extensive, and can probably be regarded as individual hydrothermal systems. They are characterized by a great number of steam holes, large areas of hot ground and a very high degree of thermal metamorphism.

The total heat output of all high-temperature areas has been very roughly estimated at the order of $10^9$ cal/sec. Data on the individual high-temperature areas are given in table 2.

## The main characteristics of the hydrothermal systems

### Basic concepts

The circulation and heating of water in geologic bodies depends on the structural control and the nature of the heat source. Further items of interest are the depth of the circulation base and the temperature of the water as it enters the upward movement. These two concepts will be called the base depth and the base temperature, respectively.

Moreover, the total amount of water and heat transported through individual systems is of interest; also, the total amount of surplus heat accumulated in the upstream and discharge zone. A brief discussion of these concepts and topics follows.

### Structural control

The seismic results given in figure 1 indicate a relatively sharp velocity contrast between the flood basalt A and the underlying formation D. In the south-west, the P-velocity jumps from 4 to 6 km/sec. The lower formation appears to be a dense and probably an impermeable formation. It is therefore probable that the circulation of the water is confined to flood basalts and that the base depth in the south-west in general does not exceed 2 km.

Conditions in the north appear to be complicated by the presence of the layer C, which is of an unknown composition and permeability. The maximum base depth may here exceed 3 km.

In general, flood basalts may be permeable owing to (1) tubes and openings at the contact of lava beds, (2) columnar structure in and fissures along the walls of intrusive bodies, and (3) recent faults.

In the literature a considerable emphasis has been placed on the importance of faults. In the case of the low-temperature activity in Iceland, the evidence appears to be somewhat on the contrary. Contacts between lava flows as well as dikes and sills appear to furnish the main permeability. The hot springs in the north are in a great number of cases controlled by dikes. In the south-west, the low-temperature activity appears to be largely controlled by outcropping contacts.

The high-temperature areas, on the other hand, appear to be controlled by faults and fissures of relatively recent age. Many of the structures may have been formed or reopened in very recent times.

It is possible that the isostatic upwarping of Iceland at the end of the Pleistocene may have influenced the general permeability conditions in the flood basalts. The stresses which were induced by differential movement of the individual blocks may have formed new faults, and also reopened old passages in faults and along dikes.

## The heat source

The extensive volcanic activity in Iceland immediately suggests a connection between the thermal activity and the volcanism. It is evident that recent volcanic processes can influence the subsurface temperature field and build up the heat sources of thermal activity.

This appears to be the case as far as the high-temperature activity is concerned. All areas of this type are located in regions of post-Glacial and in some cases very recent volcanism. The fissures controlling the areas are closely connected to the volcanic structures. Moreover, subsurface temperature of more than 200°C has been observed in shallow wells in these areas. It is difficult to account for the high temperatures without relying on the presence of volcanic structures of a very recent age.

On the other hand, it should be emphasized that the heat output of the large high-temperature areas is of considerable magnitude. The upflow of juvenile water from magmatic sources can hardly account for a comparable heat transport (Einarsson, 1942 and Bodvarsson, 1951). There are therefore reasons for assuming that the circulating water has a direct contact with the source rock. Moreover, recent isotopic studies of thermal waters are not indicative of major juvenile components (see Craig, Boato and White, 1956). For a broad discussion of relevant problems, the reader is referred to the paper by White and Brannock (1950).

Banwell (1958) is aware of a similar difficulty in the case of the large thermal areas of New Zealand. He suggests the presence of large convective magma chambers in order to explain the necessary flow of juvenile water.

The heat supply of the low-temperature areas appears in most cases to be closely related to the physical conditions in the Tertiary districts. These parts of the country have not been subjected to volcanism through the Quaternary period at least. Intrusives with elevated temperatures are therefore not to be expected in these districts.

On the other hand, the temperature in the lower parts of the flood basalts in the Tertiary districts appears to be relatively high. Temperature measurements in both shallow and deep holes (Bodvarsson and Palmason, 1961, G/24) indicate a temperature of 100° to 150°C at the bottom of the flood basalts. The lower figure applies to the conditions in the northern districts, where the temperature gradient is relatively low but the flood basalts relatively thick.

Some non-thermal boreholes in the western regions indicate higher temperature gradients. This may be due to local anomalies, partially a very rapid erosion during the Pleistocene (Bodvarsson, 1957).

The temperature conditions in the Tertiary districts imply that water circulating to the lower

**Table 2. High-temperature thermal areas in Iceland**

| | *Name* | *Elevation m* | *Area $km^2$* | *Heat output magnitude* | *Remarks on drilling, base temperature, etc.* |
|---|---|---|---|---|---|
| 1. | Reykjanes | 15 | 1 | I | One well 162 m deep. |
| 2. | Trölladyngja | 120 | 5 | I | |
| 3. | Krijsuvík | 150 | 10 | I | 15 wells, max. depth 1 200 m. Base temp. approx. 230°C. |
| 4. | Hengill | 30-600 | 50 | II | Base temp. about 230°C. Numerous shallow wells, 8 deep wells max. depth 1 200 m. |
| 5. | Kerlingafjöll | 900 | 5 | II | |
| 6. | Torfajökull | 900 | 100 | III | |
| 7. | Vonarskard | 1 000 | | I | |
| 8. | Grímsvötn | 1 000 | 12 | III | Under the Vatnajökull ice sheet. |
| 9. | Kverkfjöll | 1 500 | 10 | II | |
| 10. | Askja | 1 050 | | I | |
| 11. | Námafjall | 350 | 2.5 | II | A few shallow wells. |
| 12. | Krafla | 450 | 0.5 | I | |
| 13. | Theistareykir | 330 | 2.5 | I | |

parts of the flood basalts can be heated to a temperature of 100°C or more. Water percolating down through dikes and faults can be heated by a contact with the hot rock and ascend again, either by hydrostatic head or by convective movement.

This heat supply is probably of a transient nature. The rock adjacent to the channels of flow is gradually cooled and the heat supply decreases.

In fact, it appears difficult to account for the heat supply of the largest low-temperature springs on the basis of a stationary supply. For example, the large spring at Deildartunga in Borgarfjordur issues about 250 litres per second of water at 100°C corresponding to a heat output (above 4°C) of $2.4 \times 10^7$ cal/sec. By a stationary outflow of terrestial heat of the order of 2 to 3 microcal/cm²sec, the spring would theoretically have to drain the heat supply through an area of some 1 000 square kilometres. Actually, the heat take-up is incomplete and the area drained has to be considerably greater. This appears unreasonable, especially in view of the fact that there is a number of other springs in the vicinity of the Deildartunga spring.

### The base temperature

Theoretical investigations (Bodvarsson, 1951) and temperature measurements in boreholes (Bodvarsson and Palmason, 1961) indicate that a fairly uniform temperature generally prevails through a greater part of the upstream zones of the hydrothermal systems. This temperature should approximately be equal to the temperature which the water has acquired at the circulation base—that is, equal to the base temperature. A decrease in temperature is appreciable only in the uppermost 1 000 metres.

The base temperature is consequently a figure of fundamental importance. It affects both the physical and the chemical conditions in the thermal areas. The technique of measuring or inferring the base temperature is discussed elsewhere (Bodvarsson and Palmason, 1961).

The above classification of the thermal areas into two groups, that is, the low-temperature and high-temperature groups, respectively, is preferably carried out on the basis of the base temperature. The present author has adopted a base temperature of 150° as the upper limit for the low-temperature group.

This procedure is based on the fact that the subsurface chemical and physical conditions appear to change considerably as the base temperature increases beyond 150°C. Of course, this is no sharp limit.

Data on the measured base temperature in a number of thermal areas are given in tables 1 and 2. The maximum encountered is about 230°C.

### The total transport of heat and water

Natural heat escapes from thermal areas in the following ways: (1) as the sensible heat content of hot water and steam issued at the surface, (2) by conduction and radiation from hot ground, (3) by conduction from the channels of flow, and (4) by underground drainage of water.

The first two factors appear to predominate. In principle there are no major difficulties in measuring the heat escaping at the surface. However, the field work involved is quite substantial, and accurate determinations have not yet been carried out in any of the high-temperature areas in Iceland. The situation is better in the case of the low-temperature areas, as the sensible heat content of the water predominates there, and this factor can be measured with relative ease.

Data on the flow characteristics of the various major hydrothermal systems are given in tables 1 and 2. The data on the heat output are given in the previously defined magnitude scale. The largest high-temperature thermal area, the Torfajökull area, appears to have a total heat output of the order of $5 \times 10^8$ cal/sec. This averages to about 500 microcal/sec and cm² of the thermal area.

The global average of the normal conduction flow of terrestial heat is about one microcal/cm²sec. On this basis, the total flow through the surface of Iceland (100 000 km²) should be about $10^9$ cal/sec. This is of the same order as the heat output of the Torfajökull area.

### The accumulation of heat in the upflow zones

The rock formations in the upflow zones of the thermal areas are heated by the ascending hot water and steam. Mainly the high-temperature areas include large volumes of rock heated to temperatures approximately equal to the base temperature. The upflow zones of these areas therefore contain a substantial amount of surplus heat.

Rough estimates indicate that in the case of individual areas the surplus heat accumulated divided by the total heat output gives a time of accumulation of several thousand years. The surplus heat is therefore a substantial part of the total heat output during post-Glacial time.

### The chemical composition of water and steam

A considerable amount of geochemical data has been collected in Iceland. The hot-water and the natural-steam in most areas have been sampled and analysed. It has turned out that the majority of the results are of a relatively uniform nature. Table 3 furnishes data on the thermal water in three areas, one low-temperature area and two high-temperature areas. Table 4 furnishes data on the composition of the natural steam in the two latter areas.

It should be realized that the water sampled in the high-temperature areas is not identical with the thermal ground water. The samples were collected from wells and are a residue after flashing.

**Table 3. Chemical composition of water from steam wells in the Reykjavík, Hengill and Krijsuvík areas**
(Analyses : U.S. Geological Survey, Menlo Park, California)

| Chemical / Date of collection → | *Reykjavík Spring, 88°C* 2/10/58 | *Hengill Well at Hveragerdi* 31/8/58 | *Krijsuvík Well at Seltun* 10/9/58 |
|---|---|---|---|
| $SiO_2$ | 126 ppm | 283 ppm | 425 ppm |
| Al | 0.13 | 0.37 | 0.10 |
| Fe | 0.00 | 0.12 | 0.02 |
| Mn | 0.00 | 0.00 | 0.00 |
| Cu | 0.00 | 0.00 | 0.00 |
| Pb | 0.00 | 0.00 | 0.00 |
| Zn | 0.00 | 0.00 | 0.00 |
| As | 0.00 | 0.08 | 0.00 |
| Ca | 1.90 | 2.80 | 8.70 |
| Mg | 0.30 | 0.00 | 0.50 |
| Na | 159 | 174 | 500 |
| K | 1.40 | 10 | 68 |
| Li | 0.00 | 0.10 | 0.60 |
| $NH_4$ | 0.00 | 0.10 | 0.00 |
| $HCO_3$ | | 24 | 0.00 |
| $CO_3$ | 43 | 57 | 50 |
| $SO_4$ | 17 | 72 | 67 |
| Cl | 30 | 152 | 735 |
| F | 1.00 | 2.10 | 0.70 |
| Br | 0.90 | 0.50 | 4.80 |
| I | 0.10 | 0.00 | 0.10 |
| $NO_2$ | 0.00 | 0.00 | 0.03 |
| $NO_3$ | 0.00 | 0.00 | 0.40 |
| $PO_4$ | 0.10 | 0.08 | 0.15 |
| B | 0.06 | 0.85 | 1.70 |
| Sulfides as $H_2S$ | 0.2 | 5.20 | 7.00 |
| Dissolved solids residue at 180°C | 285 | 913 | 2,030 |
| Hardness as $CaCO_3$ | 5 | 6.2 | 24 |
| pH | 9.40 | 9.40 | 9.30 |
| Specific conductance micro-ohms/cm at 25°C | 281 | 941 | 2 760 |

## Exploitation and reservoir mechanics

To date, a total of approximately 70 000 metres have been drilled for the purpose of the exploitation of natural heat resources in Iceland. The deepest well, reaching a depth of 2 200 metres, is located within the city of Reykjavík. Several tens of thousands of metres are planned to be drilled within the coming few years.

The exploitation of the natural heat resources involves geological and physical considerations of a rather special nature. This subject can be referred to as the science of the reservoir mechanics of natural heat resources.

**Table 4. Chemical composition of natural steam in two places**
(Analyses : Department for Natural Heat, Reykjavík)

| | *Hengill high-temp.* | *Krijsuvík high-temp.* |
|---|---|---|
| Gas content, millilitres/gramme steam | 1.43 | 7.50 |
| Composition of gases, per cent: | | |
| $CO_2$ | 84.6 | 83.9 |
| $H_2S$ | 4.9 | 9.6 |
| $H_2$ | 2.1 | 5.4 |
| $CH_4$ | 0.0 | 0.1 |
| Residue ($N_2$, etc.) | 8.4 | 1.0 |

The present writer has elsewhere (Bodvarsson, 1949 and 1951) discussed this subject and given a number of case histories from Iceland, mainly from the Hengill area, listed as No. 4 in table 2. Although a considerable amount of new data has been collected during the past ten years, the basic conclusions still appear valid. The reader is therefore referred to these papers. For a very interesting discussion of similar topics in the case of the Wairakei thermal area in New Zealand, the reader is referred to the fine paper by Studt (1958).

For the sake of completeness, a point of major interest will be discussed briefly.

The drilling carried out in the thermal areas of Iceland has revealed the important fact that the heat output of the wells can surpass the natural output of the area before drilling. An increase by a factor as high as 20 has been obtained in one case. This poses the important problem as to the origin of the additional flow of heat and water.

It is possible that the wells may induce a considerable decrease of the natural impedance of the flow and thus lead to an increased circulation in the entire hydrothermal system.

On the other hand, a transitory increase of the flow may also be obtained on the basis of the large amount of heat accumulated in the upflow zones of the individual areas. The density of water decreases with increasing temperature, mainly above 100°C. The density of water at 100°C is 0.96 gr/ml, at 200°C 0.87 and at 250°C only 0.80. Therefore, cold water in the formations surrounding the thermal areas has a tendency of encroaching on the hot water within the discharge zone to drive it out. However, the cold water entering the hot rock is heated by the contact with the rock, and new hot water is formed. This transitory circulation can therefore be maintained by the surplus heat in the rock and will last as long as there is surplus heat present.

Moreover, the steam flow from wells in high-temperature areas may partially depend on the boiling of pore-water in the hot rock. Porous rock at temperatures above 100°C and saturated with water can act as a heat reservoir in a somewhat different way. Wells drilled into the rock may induce a decrease of pressure and a subsequent boiling of the water in the pores. At a not too great porosity, the boiling will largely depend on the heat content of the rock. Of course, the temperature of the rock has to be near to the boiling temperature of water at the depth of the rock formations. Both types of heat reservoirs may be encountered in the high-temperature areas.

The present author (Bodvarsson, 1956) has estimated the total potentialities of thermal areas in Iceland for power production at some 300 megawatts steady power and a recoverable heat reservoir of some 15 000 megawatt years.

At present, natural heat is utilized in Iceland mainly for domestic and green-house heating. The total amount of heat utilized corresponds to a yearly saving of fuel oil of approximately 60 000 metric tons, or about 350 kilogrammes per year per capita.

## Geophysical exploration of the natural heat resources

Geophysical exploration has been of considerable importance for the development of the natural heat resources of Iceland. In some cases, the exploration work has been of a decisive importance. A review of the methods involved and a number of case histories have been given elsewhere by the present writer (Bodvarsson, 1950). For detailed information, the reader is referred to this paper.

The geophysical exploration is carried out mainly for two purposes. Firstly, for the uncovering of structural features. Secondly, for the study of the subsurface temperature field. The latter methods are generally referred to as the direct methods, whereas the structural methods represent the indirect methods.

The indirect methods involve conventional techniques such as the magnetic, gravitational and the seismic methods. Their application to natural-heat prospecting does not generally differ much from the methods of prospecting for oil and minerals. The main purpose is the uncovering of intrusives, mainly dikes, and tectonic structures.

The introduction of the seismic methods for the study of the general structure of the flood basalts probably represents the main advance during the past ten years. For further information, the reader is referred to the papers by Båth (1960) and by Båth and Tryggvason (1961).

The direct methods involve a technique specially adapted to natural-heat prospecting. The main purpose is the study of the subsurface temperature field, mainly the base temperature and the extension of the rock heated to this temperature. The methods involve the thermal, the electric resistivity and the geochemical methods. The thermal methods are discussed in a special paper by Bodvarsson and Palmason (1961).

The application of the electric resistivity method is based on the fact that the electric resistivity of rock decreases with increasing temperature and increasing degree of thermal alteration. The mapping of the subsurface resistivity is therefore a quasi-quantitative method of studying the subsurface temperature field. A case history is given by Bodvarsson (1950). The main limitation of this method is the low depth penetration.

A large-scale investigation of the chemical composition of the thermal waters and gases in Iceland has revealed the fact that the chemical composition appears to depend on the base temperature. This is mainly the case for the $SiO_2$ content of the water and the $CO_2$ content of the gases intermixed with the steam. Chemical components are therefore indicative of the temperature conditions. For further information, the reader is referred to the paper by Bodvarsson and Palmason (1961).

Modern isotope methods are interesting recent newcomers to the field of natural-heat prospecting. A laboratory for the study of the D and $O^{18}$ content of natural waters in Iceland is being built.

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## *Summary*

The present paper discusses the physical characteristics of natural heat resources in Iceland on the basis of geophysical, geological and geochemical data.

Iceland is, according to recent seismic studies, built up of a layer of Tertiary basalts which reaches a thickness of 2 to 3 km. The Tertiary formations are in some regions, mainly in the central and southern parts, covered by Quaternary volcanics.

Two types of thermal areas can be distinguished. Firstly, the low-temperature areas which are characterized by hot-water springs and subsurface temperatures below 150°C. These areas are located mainly in the Tertiary districts. Secondly, the high-temperature areas which are located within the Quaternary districts and are characterized by natural-steam holes and large areas of hot ground. The subsurface temperature in these areas is above 200°C at a relatively very shallow depth. The total heat output of the low-temperature areas is estimated at $10^8$ cal/sec, whereas the high-temperature areas appear to have an output of $10^9$ cal/sec.

In general, the thermal areas are controlled by permeable contacts between lava-beds, permeable dikes and faults. The circulation base may be the bottom of the flood basalts, that is, at a depth of 2 to 3 km. Recent hot volcanic structures appear to supply the heat in the case of the high-temperature areas. The circulating water appears to have a direct contact with the source rock. The low-temperature areas, on the other hand, appear to draw on the natural heat content of the rock in the lower parts of the flood basalts. The temperature at the circulation base may be 100°C to 150°C.

A considerable amount of surplus heat is accumulated in the subsurface formations of the large high-temperature areas. The time of accumulation is of the order of several thousand years. The surplus heat is a vast heat reservoir which can be exploited by drilling. Some aspects of the reservoir mechanics are discussed. Also, exploration methods are reviewed briefly. The integrated potential of the natural heat resources in Iceland is estimated, in terms of electric power, to be of the order of 500 megawatts.

# CARACTÉRISTIQUES PHYSIQUES DES RESSOURCES THERMIQUES NATURELLES DE L'ISLANDE

## *Résumé*

Le présent mémoire passe en revue les caractéristiques physiques des ressources thermiques naturelles de l'Islande, sur la base de données géophysiques, géologiques et géochimiques.

D'après les études sismiques les plus récentes, l'Islande est constituée par une couche de basaltes appartenant au tertiaire, dont l'épaisseur est de 2 à 3 km. Dans quelques régions, particulièrement dans les zones du centre et du sud, ces formations tertiaires sont recouvertes par des roches volcaniques appartenant au quaternaire.

On peut distinguer deux genres de champs géothermiques. Ce sont tout d'abord les zones à basse température, qui se caractérisent par des sources d'eau chaude et des températures de sous-sol inférieures à 150 °C. Elles se trouvent principalement dans les districts constitués par le tertiaire. La deuxième catégorie est celle des zones à haute température, situées dans les districts quaternaires et caractérisées par des trous, d'où jaillit de la vapeur naturelle, et par d'importantes étendues où le sol est chaud. La température du sous-sol y

dépasse 200 °C à une profondeur relativement très faible. Le débit total des régions à basse température est évalué à $10^8$ calories/seconde, tandis que celui des zones à haute température semblerait s'établir à $10^9$ calories/seconde.

Les champs géothermiques, d'une manière générale, sont régis par la perméabilité des roches assurant le contact entre les gîtes de lave, par l'existence de filons également imperméables et par les failles. La base de la circulation peut être au fond des écoulements de basalte, c'est-à-dire à une profondeur de 2 à 3 km. Ce sont des structures volcaniques chaudes récentes qui semblent fournir la chaleur dans le cas des régions à température élevée. L'eau de circulation semble y trouver un contact direct avec les roches qui fournissent cette chaleur. Dans le cas des régions à basse température, au contraire, il semble que des emprunts soient faits aux réserves naturelles de chaleur des roches des niveaux inférieurs de l'écoulement de basalte. Cette température, à la base de la circulation, peut aller de 100 à 150 °C.

Un gros excédent de chaleur est accumulé dans les formations situées dans le sous-sol des grandes zones à haute température. Cette accumulation s'est faite en un temps qui est de l'ordre de plusieurs milliers d'années. L'excédent de chaleur constitue un vaste réservoir que l'on peut exploiter par des forages. Le mémoire passe en revue certains des aspects de la cinématique de ces réservoirs. L'auteur examine succinctement les méthodes d'exploration. Le potentiel intégré des ressources thermiques naturelles de l'Islande est évalué à quelque 500 mégawatts d'énergie électrique.

# EXPLORATION OF SUBSURFACE TEMPERATURE IN ICELAND

*G. Bodvarsson* and G. Palmason**

The subsurface temperature field constitutes the most important set of physical data to be assessed in any exploration of natural heat phenomena. The temperature studies are carried out for three purposes. First, as a method of prospecting. Second, for the purpose of obtaining important quantitative data on the physical conditions in thermal areas under exploitation. Third, in order to obtain observational data on regional temperature conditions and the thermal mechanism generating thermal areas.

Temperature data can be obtained directly by measurements in boreholes, or indirectly, on the basis of geochemical inference. The latter method is based on the fact that the equilibrium conditions of certain geochemical reactions depend substantially on the reaction temperature. Geochemical data can therefore in some cases be indicative of reaction temperatures.

The purpose of the present paper is to give a brief review of the thermal methods applied in Iceland and report results from a few thermal areas. The background of the paper is based on observational material from a great number of boreholes in Iceland with a total depth of 70 000 metres. The maximum depth drilled is 2 200 metres. Moreover, extensive analytical material on thermal waters and gases has been available for the purpose of thermochemical inference.

For general information on the physical condition in thermal areas in Iceland the reader is referred to papers by Einarsson (1942) and Bodvarsson (1961, G/6). The latter paper contains further references. A wealth of descriptive material is given by Barth (1950). Data on utilization and economical aspects are given by Bodvarsson and Zoëga (1961, G/37).

## Theoretical remarks

The temperature of the earth increases with depth. A part of the associated heat flow is generated by radioactive decay, and a part may be due to a general cooling of the earth. The temperature field is no simple function of the depth, as complications may arise because of the following factors:

(1) Non-uniform distribution of the radioactive sources.

(2) Possible local generation of heat by the dissipation of mechanical energy and by chemical processes.

(3) Non-uniform thermal properties of the material.

(4) Movement of fluids, gases and magmas.

(5) Tectonic movements.

(6) Irregular topography and surface changes due to erosion and sedimentation.

(7) Long-period variations of the surface temperature.

These factors have to be taken into account in any evaluation of observational temperatures. The equation for the temperature field, the heat transport equation, can be written as follows:

$$\nabla . \, (k\nabla T - S) + h = \rho c - \frac{\partial T}{\partial t}, \tag{1}$$

where $T$ = temperature,
$k$ = heat conductivity,
$S$ = vector of mass transport of heat per unit surface and time,
$h$ = generation of heat per unit volume and time,
$\rho$ = density of the material,
$c$ = heat capacity of the material.

The heat transport equation is quite complicated if all of the above factors have to be taken into account. However, in the study of natural heat resources most are of minor importance, with the exception of the mass transport of heat by fluids, gases and magmas, which is one of the main factors causing thermal activity. The implications of the mass transport can be illustrated on the basis of the following simple considerations.

Thermal areas are the outlets for extensive circulations of water in geological bodies. The water after being heated at depth moves upward and is issued in the thermal areas. The depth of the circulation base will here be called the base depth, and the temperature of the water as it enters the upward movement will be called the base temperature. The latter quantity is an important physical characteristic of the individual thermal areas.

The upflowing water loses heat because of the conduction of heat from the channels of flow, and sometimes because of intermixture with colder water. Moreover, the water may lose temperature because of flashing if the base temperature is above 100°C.

Suppose that the water flows vertically up through a rock of uniform permeability and heat conduc-

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tivity and that the flow is uniform over a large area. In case of stationary conditions and no heat sources or flashing in the upflow zone, the heat transport equation reduces to the following simple equation:

$$k d^2T/dx^2 + sq\, dT/dx = 0 \qquad (2)$$

where $s$ is the specific heat of the water and $q$ the upward mass flow per unit surface. The quantity $x$ represents the depth. With a base depth $D$ and a base temperature $T_b$, the following solution is obtained:

$$T = T_b \frac{(1 - e^{-sqx/k})}{(1 - e^{-sqD/k})} \qquad (3)$$

In general, the base depth is a relatively large quantity and the second term in the denominator negligible. The simplified solution is in this case:

$$T = T_b\,(1 - e^{-sqx/k}) \qquad (4)$$

This relation, although obtained by means of great simplifications, is of conceptual importance. It illustrates in a qualitative manner the temperature-depth relation in thermal areas.

Of course, the permeability and the specific flow are never uniform. This leads to deviations which have to be discussed in the individual cases.

## Temperature measurements in boreholes

Borehole temperatures are measured primarily for the purpose of inferring formation temperatures. At stationary conditions in a non-flowing borehole, the measured data are simply equal to the formation temperature. On the other hand, complications arise from any flow of fluids. Thus the drilling fluid induces instationary conditions by cooling or heating the formations around the hole. All measurements carried out during or shortly after drilling are therefore seriously affected. This effect will be discussed below.

### Experimental technique

Three types of temperature measuring devices have been applied: mercury maximum thermometers, electric resistance thermometers, and thermometers of the vapour pressure type.

The maximum thermometer is a simple and inexpensive device. It has several disadvantages, however. First, in practice only monotonously increasing temperature-depth relations can be recorded satisfactorily. The use of high-inertia thermometers for decreasing temperature is possible but is quite time consuming. Second, no telerecording is possible. Third, although the accuracy may be good, the mercury column may tend to drop under hoisting out of the hole. Moreover, the device is slightly sensitive to pressure. These disadvantages are quite serious, and the maximum thermometer is therefore not a satisfactory instrument.

The semiconductor resistance thermometers, the thermistors, are high-accuracy instruments which can be used for telerecording. In routine work, an accuracy of 0.1°C is easily attainable. The accuracy can be increased considerably by a careful repeated calibration. Moreover, the thermistor responds relatively rapidly to temperature changes.

The thermistor is an ideal instrument for low-temperature boreholes. Experience indicates that the telerecording system is reliable up to a temperature of about 150°C. On the other hand, the insulation of the cable and the thermistor-connection presents difficulties at higher temperatures. It is hoped, however, that the insulation difficulties may be resolved.

The temperature recorders based on the vapour pressure system are as yet the only reliable instruments available for temperatures above 150°C. Present instruments are applicable up to 260°C. They are quite rugged devices, but the accuracy is only about 1°C. Another drawback is a relatively slow response. Several minutes are required for equilibrium. In most high-temperature work, however, this accuracy and response time do not impose serious limitations.

### The influence of the drilling fluid

The transient temperature conditions induced by the drilling result mainly from the cooling effect of the drilling fluid. This effect is particularly great in modern rotary drilling, where circulations up to more than 100 metric tons per hour are applied. The fluid is kept at a relatively low temperature which in drilling for natural steam may be as much as 150°C below the formation temperature.

At the moment drilling is discontinued, and the circulation comes to rest, the borehole temperature will be equal to the temperature of the fluid during drilling. The recovery to the formation value is very slow due to the thermal properties of the rock. The relaxation time for a borehole of 1 000 metres, which may be completed in three to four weeks, is more than two months.

On the other hand, the formation temperature is of fundamental importance and estimates of this quantity may be required during drilling. In natural-heat work, the decision whether the drilling of a well should be continued or not will in general depend to a large degree on the temperature of the formations penetrated. The question arises whether the formation temperature can be estimated on the basis of an extrapolation of transient borehole data measured during breaks in the drilling operation.

The extrapolation of the borehole data involves two steps. Firstly, an estimation of the temperature field in the formation as the drilling is discontinued. This represents the initial condition for the second step. Secondly, a computation of master curves for the temperature rise at the various formation temperatures possible. A matching of the computed curves and a sufficient amount of observed data should theoretically yield the formation temperature, although equilibrium has not been attained. The assumption of a pure conduction flow of heat may at first appear to be a plausible basis for the computations involved in both steps. There are, however, several difficulties, some of which will be listed below.

There is considerable uncertainty as to the relevance of the pure conduction theory, mainly in the case of the first step. The formations penetrated may be permeable to the drilling fluid, at least at the conditions imposed during drilling. The walls of the borehole may be invaded, resulting in an unknown mass transport of heat into the formation. The initial conditions may thus deviate largely from those computed on the basis of a pure conduction flow of heat.

Further uncertainty results from the fact that the temperature conditions in the borehole during drilling are not known accurately. The counterflowing streams of drilling fluid exchange heat through the drillpipe, leading to a downhole increase of the temperature. The temperature of the fluid at the bottom can be tens of degrees higher than is measured at the outlet or the inlet at the surface. A quantitative estimate of this effect is difficult to obtain.

In addition, the thermal properties of the rock penetrated are generally not known accurately.

A further difficulty arises in the case of a pure conduction process. The initial slope of the temperature rise is not sensitive to the true formation temperature. A record of a considerable time-length would be required.

On the other hand, the computational work involved can be carried out on a high-speed computer. The first set of master curves has been computed by the State Electricity Authority, Reykjavík. They are based on the conduction theory and intended as a check of the applicability of that theory to the present case.

The experience gained in Iceland so far indicates that conduction theory is correct as far as the temperature recovery is concerned. The basaltic rock encountered in the thermal areas of Iceland is relatively impermeable. On the other hand, the other difficulties listed imply that further studies have to be carried out in order to attain a satisfactory solution.

At this juncture, it appears that a borehole-record of the order of one day or more is necessary in order to obtain a reasonable estimate of the formation temperature. In the meantime the drilling rig would have to be idle, but the rig operating cost is relatively high. It is therefore questionable, in some cases at least, whether the value of the information gained is not lost in rig time.

## Geochemical methods

Samples of water from almost all thermal areas in Iceland have been analysed for contents of dissolved solids. A comparison of results from the various thermal areas indicates a positive correlation between the spring temperature and the total amount of solids dissolved. For instance, water issued by springs at 30°C may contain only about 150 ppm (parts per million) of solids, whereas water from springs at 100°C contains more than 300 ppm.

An explanation of this phenomenon is illustrated in the relatively clear correlation between the amount of dissolved silica, $SiO_2$, and the spring temperature. On the average, the amount of silica increases by one ppm for each degree C of spring temperature. The data at hand indicate that the base temperature, $T_b$, is a main factor regulating the contents of silica and that the following relation,

$$25 + T_b = SiO_2 \text{ in ppm,} \tag{5}$$

where $T_b$ is in degrees C, gives a semi-quantitative illustration of the conditions.

A plausible interpretation of relation (5) is that it simply illustrates the solubility of silica from basaltic rock in water at different temperatures. Iceland is built up of flood basalts, and there are reasons for assuming that the hydrothermal circulation systems are entirely within the flood basalts (Bodvarsson, 1961, G/6).

This interpretation is supported by laboratory studies. Krauskopf (1956) and White, Brannock and Murata (1956) have studied the solubility of silica in water. The experimental data of Krauskopf indicate that the solubility of amorphous silica in distilled water amounts to approximately 70 ppm at 0°C and to 350 ppm at 90°C.

Crystalline forms of silica should have lower solubilities. Relation (5) indicates that the ultimate solubility of silica from basaltic rock is 25 to 35 per cent of that of amorphous silica. This appears a reasonable ratio.

Laboratory tests on the solubility of silica from samples of basalts have been carried out in Reykjavík. The results confirm the above interpretation.

An important property of dissolved silica is that it precipiates extremely slowly from weak oversaturated solutions. This is mainly the case for saturations below 200 ppm. Thus, water saturated at one temperature and cooled to a lower temperature will not precipitate the silica. A polymerization takes place, but the colloids are kept in a fine dispersion for a long time and are chemically reactive in much the same way as dissolved matter. The main implication is that thermal water which has been saturated at one temperature and is cooled by conduction losses or flashing will keep the initial silica content reactive in spite of the temperature loss.

This rather anomalous behaviour of the silica implies that relation (5) can be applied in order to obtain a semi-quantitative estimate of the base temperature. The method is of practical importance in cases where it is possible to obtain samples of water from hydrothermal systems. The amount of silica in the sample is indicative of the base temperature, although the sample has been cooled by conduction losses.

Some thermal springs with a temperature less than 50°C and a flow of one or two litres per second represent leaks from hydrothermal systems with high base temperatures. The small flow implies large conduction losses on the way to the surface, and the springs may be rather insignificant. But the amount of silica in the water reveals the high base temperature and furnishes a positive evidence as to the prospects of the area. The method has been of some practical importance in Iceland.

In conclusion, it may be mentioned that some of the gases issued by thermal springs in Iceland appear to furnish some evidence as to the base temperature. It has been observed that $CO_2$ and $H_2S$ are practically absent in springs having a base temperature below 90 or 100 degrees. The presence of these gases can therefore be regarded as evidence of a base temperature above 100°C. However, the experimental data are still too few to warrant definite conclusions.

## Results from thermal areas

This section illustrates a few results which have been obtained on the basis of thermal methods in Iceland. The observational data are from three major thermal areas which are now being exploited. One of the areas is located in the city of Reykjavík, and the two other areas, the Reykir area and the Hengill area, are located 16 km north-east and 45 km east of the city, respectively (figure 1). The emphasis is placed on temperature data which have been of practical importance for exploration and exploitation.

### Reykjavík thermal area

The presence of a thermal area in the city of Reykjavík is indicated by two natural thermal springs. The larger spring issued about 10 litres per second of water at 88°C. Drilling for hot water was initiated in 1928. Some moderate results were obtained in the following two years after the completion of thirteen relatively shallow boreholes. An additional borehole of 760 metres was completed in 1944.

The exploration of the area was resumed in 1954. In view of the difficulties involved in the application of electrical resistivity methods in a populated area, it was decided to carry out thermal prospecting by means of a few shallow boreholes. A total of twelve boreholes, 30 to 80 metres deep, was drilled in the area. Temperature measurements in these boreholes and data from the existing boreholes furnished a relatively good picture of the variation of the surface temperature gradient in the area.

Moreover, gravity and magnetic surveys were carried out in the area. The results revealed the presence of a large basaltic intrusive in the eastern parts of the city. The combined evidence furnished by the temperature, gravitational and magnetic data indicated an upflow of thermal water west of the intrusive.

Drilling was resumed on the basis of this set of data. During the past six years, a total of twenty-five

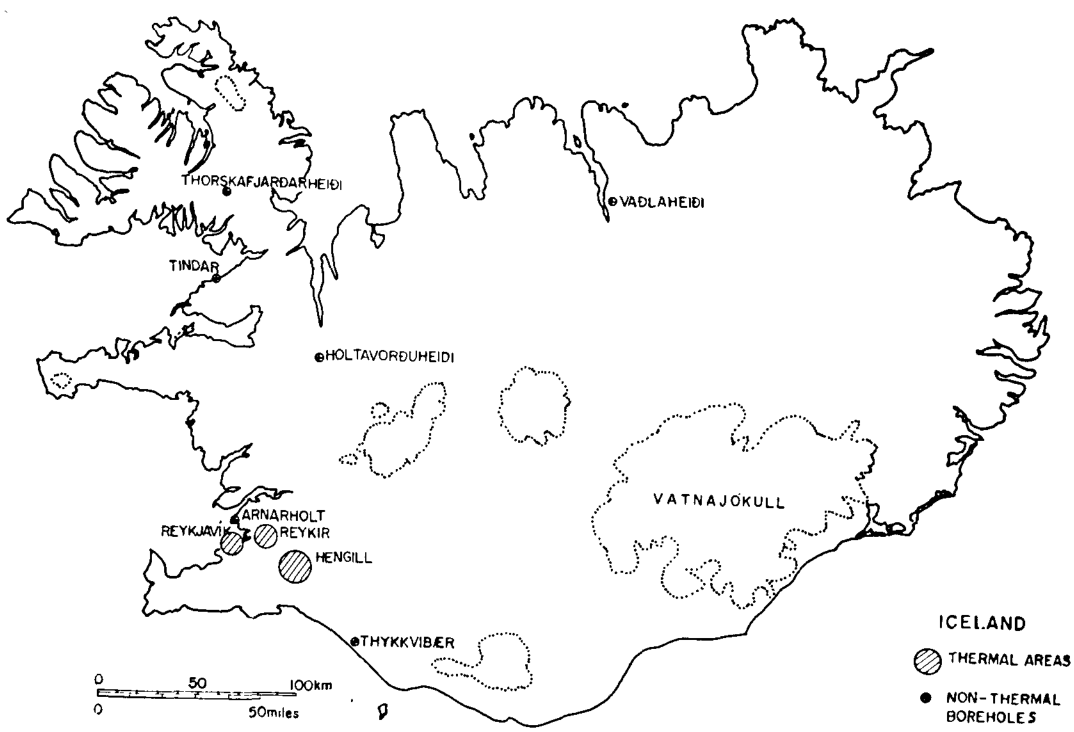


Figure 1. Locations of relevant thermal areas and non-thermal boreholes in Iceland

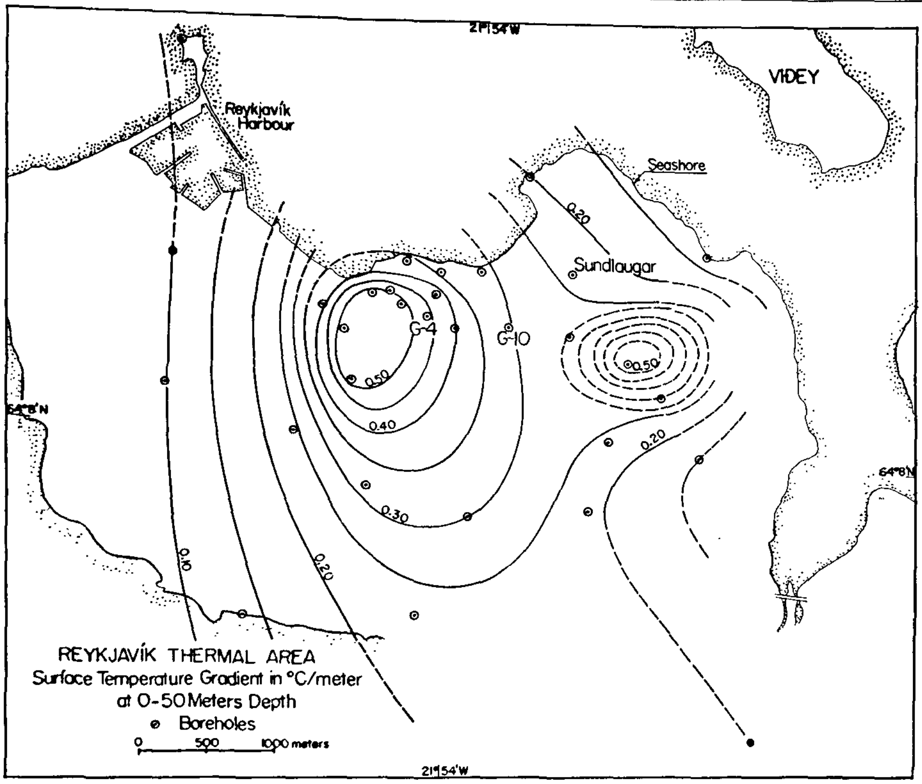


**Figure 2. Reykjavík surface temperature gradient**

boreholes have been drilled in the area. A borehole of 2 200 metres was completed in 1959. This drilling has been successful, and the total output of the boreholes amounts to about 135 litres per second of thermal water. The maximum production temperature is 138°C. The water is utilized for domestic heating in the city of Reykjavík.

Figure 2 shows the lines of equal surface temperature gradient in the city, compiled on the basis of all boreholes drilled so far. Figure 3 gives a temperature survey of the deepest borehole. The data represent equilibrium temperatures in the closed borehole. The same figure also gives temperature data from two shallower boreholes. The borehole G-4 is located close to the main zone of upflow of thermal water, whereas boreholes G-10 and Sundlaugar are located in the intrusive body mentioned above. The temperature measurements were carried out with thermistors, with the exception of the deep data in figure 3, which were obtained by a vapour-pressure thermometer.

The data in figure 2 show quite clearly the area of maximum surface temperature gradient. This maximum is due to the presence of a thin permeable sill with a slight northward slope. The depth to the southern edge is about 160 metres. The sill is permeated by water of 80 to 95 degrees and is covered by impermeable basalts. Some shallow wells produce from the sill.

Figure 3 reveals quite clearly the base temperature of the area, which is about 146 °C. This temperature prevails in the lowest 1 000 metres of the borehole.

## Reykir thermal area

The thermal area at Reykir was the first large thermal area to be exploited in Iceland. Until recently, all thermal water distributed by the Reykjavík Municipal District Heating Service was supplied by this area.

Drilling was initiated in 1933. In 1954, when drilling was discontinued, a total of seventy boreholes had been completed in the area. The maximum depth reached was 612 metres. The output of the boreholes is 370 litres per second of water at an average temperature of 87°C.

The drilling, although quite successful, had not furnished any evidence as to the general structural control of the area. The presence of permeable basaltic layers was indicated at 200 to 400 metres, but the structure controlling the water supply was unknown.

The area is located in a blockfaulted country, and there is topographical evidence that a major SW-NE fault line of Tertiary age runs through the area. The importance of this fault appeared obvious.

In 1959 it was decided to drill a new deep borehole in the area in order to cut this fault at a relatively great depth—that is, at about 1000 metres. It was hoped that the new borehole would reveal the structural importance of the fault and possibly produce water at a higher temperature than the previous boreholes.

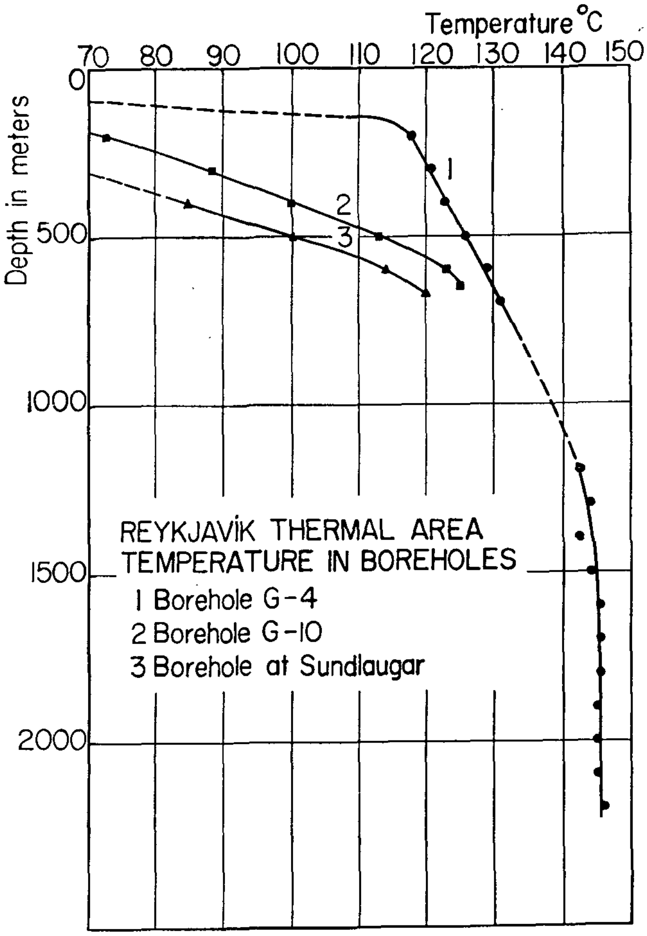


**Figure 3. Reykjavík: temperature in boreholes**

The borehole was completed at a depth of 1 380 metres. Only insignificant production was obtained from the depth of 670 metres.

An accurate temperature survey was carried out with a thermistor when the borehole had reached temperature equilibrium. The results are given in figure 4.

The results give a temperature of 98°C at the small fissure cut at 670 metres. Immediately below the fissure, the temperature drops to 90°, and is fairly constant in the lower part of the borehole.

The temperature data are indicative of a horizontal permeable layer at the depth of 670 metres. Moreover, no upflow of thermal water through the fault is indicated. Thus the results appear negative as to the importance of the Tertiary fault line. The Reykir thermal area appears to be controlled by a horizontal layer rather than the fault. None of the older boreholes had been drilled deep enough to cut the horizontal layer.

### The Hengill thermal area

This area is one of the great natural-steam areas of Iceland. The southern part of the thermal area, the region around the small community of Hveragerdi, is favourably located as to exploitation. A natural-steam power plant is now planned in this part of the area.

Large-scale drilling was initiated in 1958. A total of eight boreholes has been completed. The depth varies from 300 to 1 200 metres, and the total output now amounts to 500 litres per second at 180 to 230°C. Temperature surveys have been carried out in most of the boreholes by means of a vapour pressure thermometer. The data have been obtained at equilibrium conditions. Data from two boreholes are given in figure 5.

The area is geologically complex, and the structural control has been revealed neither by the drilling nor by other investigations. The most prominent feature of the temperature data is the apparent horizontal stratification of the flow. This is apparent from the temperature data. The temperature drops below the permeable horizons which are indicated by the temperature maxima.

This decrease of the temperature with depth is an interesting phenomenon which is at present not wholly understood. However, the main practical implication appears to be that the Hveragerdi area is not an area of major upflow and that the major structures of upflow have to be found elsewhere in the main thermal area.

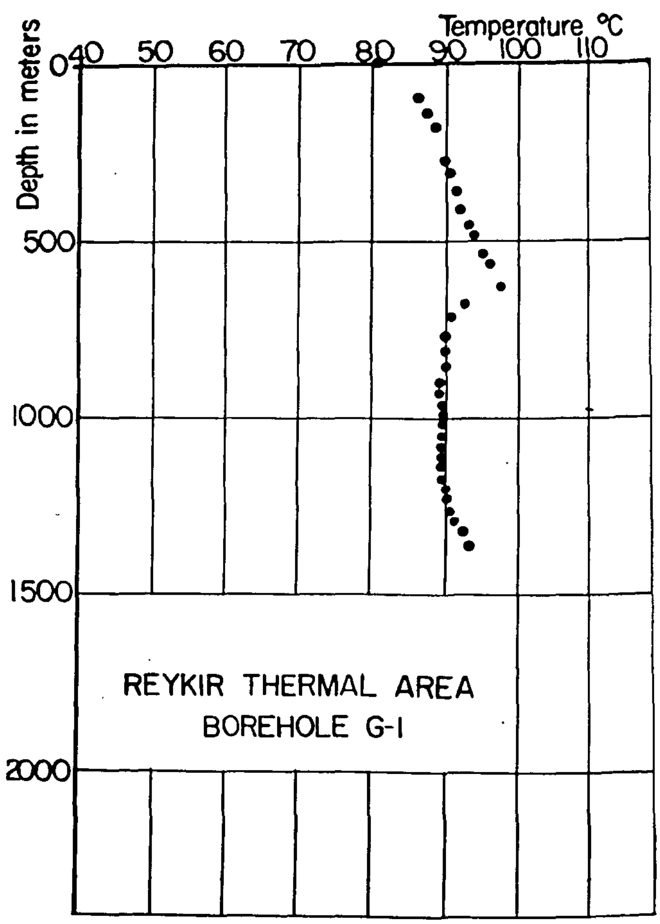


**Figure 4. Temperature in borehole G-1, Reykir area**

## Regional temperature conditions in Iceland

Iceland was subjected to volcanism throughout the Tertiary period. Several thousands of metres of flood basalts have been built up during this period. The volcanism is still active in some parts of the country.

A study of the thermal conditions within the flood basalts is of scientific as well as practical interest. The State Electricity Authority has initiated a general survey of the temperature and heat flow conditions. A number of relatively shallow boreholes have been drilled in non-thermal areas, and further holes are planned. The location of present holes is given in figure 1.

Most of the non-thermal boreholes have been successful and have revealed a fairly linear increase of temperature with depth. The surface temperature gradient is clearly revealed by the boreholes. The results are given in table 1. The data were obtained at equilibrium conditions with thermistors.

A thorough discussion of the data given in table 1 requires a study of the influence of the various factors given at the beginning of the paragraph devoted to theoretical remarks. The main factors of interest are percolation of subsurface water, erosion and topography. The present paper does not allow space for a discussion of this kind. Some pertinent questions have been reviewed in a paper by Bodvarsson (1957).

The main implication of the data is that it appears possible to estimate the temperature at the bottom of the flood basalts. The results of the seismic work of the Swedish-Icelandic expedition in 1960 (see Båth and Tryggvason, 1961) indicate that the flood basalts in the south-west of Iceland have a thickness of 2 km, whereas in the north a figure of more than 3 km is probable.

**Table 1. Surface temperature gradient in non-thermal boreholes**

| | Location | Elevation (metres) | Depth (metres) | Temperature gradient (degrees C/metre) |
|---|---|---|---|---|
| (1) | Thykkvibær | (5) | 90 | 0.093 |
| (2) | Arnarholt | (20) | 240 | 0.165 |
| (3) | Holtavörduheidi | 340 | 32 | 0.054 |
| (4) | Tindar | 15 | 105 | 0.11 |
| (5) | Thorskafjardarheidi | 460 | 48 | 0.034 |
| (6) | Vadlaheidi | 570 | 40 | 0.033 |

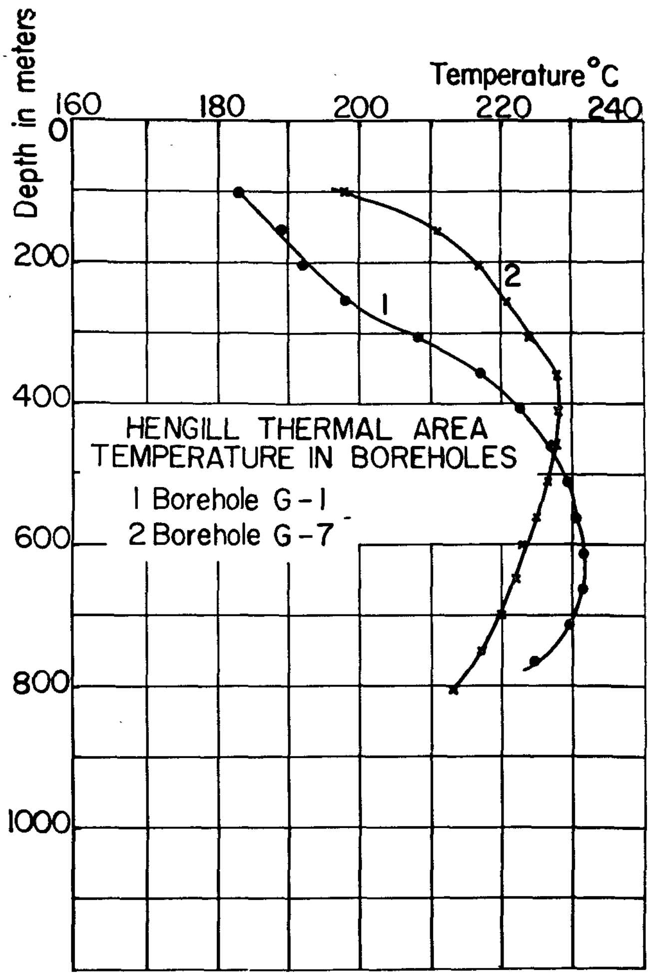


**Figure 5. Temperature in boreholes, Hengill area**

An extrapolation of the data in table 1, combined with a correction for possible influences of erosion, indicates a temperature of the order of not less than 150°C at the bottom of the flood basalts in the south-west. In the north, a figure of the order of 100°C is obtained. Of course, the average nature of these results is to be emphasized and further observational data are needed. But the present results appear to be of general interest for the study of the thermal activity in Iceland as shown by Bodvarsson (1961, G/6).

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*Summary*

A considerable amount of data on borehole temperatures has been collected in Iceland. This work has been carried out for three purposes. First, as a means of prospecting, second, in order to obtain data on the physical conditions in thermal areas, and third, in order to obtain a comparison between thermal and non-thermal regions. The results have furnished data on the temperature of the water circulating in the thermal regions and on the average outward conduction flow of heat in non-thermal regions.

The main part of the data has been collected on the basis of temperature measurements in boreholes. The boreholes are of various depths, the maximum depth being 2 200 metres. Temperature gauges consist of maximum mercury thermometers, electric resistance thermometers and vapour pressure thermometers. The applicability of the various types is discussed.

In general, boreholes are cooled by the drilling fluid. Instationary temperature conditions are therefore encountered, and the correct evaluation of this effect is of great importance. Theoretical studies have been carried out and the results are presented.

There appear to be possibilities of estimating the base temperature of hydrothermal systems on the basis of the chemical constituents in the thermal water. Mainly, the amount of silica dissolved in the water appears to depend on the temperature conditions. This phenomenon is discussed briefly.

Results from thermal areas in Iceland are given in the final section of the paper, where the main implications of the results are also discussed. The maximum temperature so far measured in thermal regions in Iceland is approximately 230°C. The temperature gradient in non-thermal regions has been found to vary between 0.033 to 0.165°C per metre.


## EXPLORATION DES TEMPÉRATURES DU SOUS-SOL EN ISLANDE


*Résumé*

Beaucoup de données ont été recueillies en Islande sur les températures qui règnent dans les puits forés dans des champs géothermiques. Ces travaux avaient trois objectifs. En premier lieu, ils avaient une indéniable utilité pour la prospection, en second lieu, ils visaient à obtenir des renseignements sur la situation physique qui règne au site de chaque champ géothermique et, finalement, ils permettaient d'établir une comparaison entre les régions où règne cette activité et les autres. Les résultats de ces travaux ont permis d'établir des données sur la température de l'eau qui circule dans les zones géothermiques et sur le régime moyen de conduction vers l'extérieur de la chaleur dans les autres régions.

La majeure partie de ces données ont été recueillies sur la base de mesures de la température dans les puits. Ces puits ont des profondeurs variables, le maximum étant de 2 200 mètres. Les indicateurs de température sont constitués par des thermomètre sà vapeur de mercure du type à maximum, des thermomètres à résistance électrique et des thermomètres à tension de vapeur. L'auteur passe en revue les domaines d'application des divers modèles.

D'une manière générale, les puits sont refroidis par le liquide de forage. C'est dire que la température en est instable, effet qu'il faut évaluer d'une manière correcte, car il est fort important. On a procédé à des études théoriques sur la question et les résultats en sont exposés dans le présent mémoire.

Il semble se présenter une possibilité d'évaluer la température de base des systèmes hydrothermiques en se basant sur la composition chimique des eaux thermales. La quantité de silice dissoute dans l'eau, en particulier, semble être déterminée par la température. L'auteur passe brièvement ce phénomène en revue.

Il donne les résultats obtenus dans divers champs géothermiques islandais dans le dernier paragraphe du présent mémoire, où il examine également les conclusions les plus importantes à tirer des résultats. La température maximum mesurée jusqu'à présent dans les champs géothermiques d'Islande est de l'ordre de 230 °C. La variation de température, dans les régions où il n'y a pas de sources thermales, s'est établie à une valeur comprise entre 0,033 et 0,165 °C par mètre.

# PROSPECTION DES CHAMPS GÉOTHERMIQUES ET RECHERCHES NÉCESSAIRES A LEUR VALORISATION, EXÉCUTÉES DANS LES DIVERSES RÉGIONS D'ITALIE

*Renato Burgassi* *

Quiconque se trouve amené, pour une raison ou une autre, à s'occuper d'une manière plus ou moins approfondie des problèmes touchant l'énergie géothermique, ne peut manquer de rencontrer, dès les premiers pas dans sa recherche, le nom de Larderello.

La raison en est vite expliquée; c'est uniquement en cette localité, dont je devrai inévitablement parler beaucoup plus longuement que de toutes les autres qui seront citées dans ce mémoire, que depuis plus d'un siècle ont été entrepris des travaux de recherche puis d'utilisation de l'énergie endogène à l'échelle industrielle.

Il paraît donc normal de donner à la région de Larderello la priorité absolue dans une communication qui traite justement de la recherche et de la valorisation de l'énergie géothermique.

## Région de Larderello

### Généralités

Cette région, souvent connue sous le nom de région boracifère, nom dû au bore contenu dans ses eaux thermales et vapeurs, est située au centre de la péninsule italienne, à courte distance du littoral tyrrhénien (en moyenne 30 km). Elle couvre environ 400 km², entièrement en Toscane sur les provinces de Pise, Sienne, Grosseto et Livourne (fig. 1 et 2).

Coordonnées géographiques : latitude de 10° 45′ à 11° 3′, longitude de 43° 9′ à 43° 18′.

La région est accidentée, avec des sommets dont l'altitude maximum atteint 1 000 mètres. Ces sommets appartiennent à une chaîne d'environ 50 km de long appelée « monts métallifères » à cause de l'abondance des minéraux qu'elle recèle (sulfures, oxydes et carbonates de fer, de cuivre, de plomb, de zinc, etc.). Ces minéralisations sont très probablement liées aux phénomènes magmatiques relativement récents (mio-pliocène et quaternaire) de la Toscane, et sont donc en rapport avec les fluides endogènes de la région boracifère.

Sans vouloir le moins du monde faire de ce mémoire un récit historique, il m'est indispensable de rapporter quelles furent les origines de la recherche des fluides endogènes dans cette région, afin d'évaluer pleinement les faits et les circonstances qui en ont déterminé l'évolution.

Les premiers chercheurs eurent comme seuls guides les nombreuses manifestations naturelles, constituées par des jets de vapeur d'eau et de gaz, qui très fréquemment bouillonnaient avec violence dans des bassins naturels localement appelés « lagoni » (fig. 3); ces manifestations parfois impressionnantes se groupaient en divers centres parfois éloignés les uns des autres (10 à 15 km), dispersés sur une grande étendue, et qui occupaient chacun une surface d'un demi-kilomètre carré au maximum.

Ceux qui, les premiers, entreprirent la mise en œuvre de sondeuses rudimentaires (fig. 4) implantèrent leurs puits, qu'ils poussèrent à peu de mètres au-dessous de la surface, au voisinage immédiat des manifestations naturelles; le résultat fut de réaliser le drainage des fluides chauds qui affleuraient grâce à une abondante circulation au travers des cavités et discontinuités d'un terrain superficiel devenu éminemment perméable du fait même de cette circulation.

Ces premiers puits eurent naturellement des débits très modestes, de l'ordre de quelques centaines de kilogrammes par heure, sous forme de vapeurs saturées, accompagnées d'eaux météoriques en circulation pratiquement superficielle, qui dégradaient et déclassaient notablement le fluide-vapeur.

Par la suite, grâce aux progrès des sciences géologiques, à la meilleure connaissance du cadre général et au perfectionnement des appareils de forage, on parvint à obtenir des renseignements de plus en plus complets sur les conditions locales du phénomène.

Cette évolution de la recherche qui a amené un perfectionnement continu des connaissances peut être symbolisé par l'exemple suivant : dès les premières phases de la recherche proprement dite, on avait noté que les centres de manifestations naturelles et très souvent les manifestations individuelles se trouvaient alignées sur des lignes directrices bien déterminées; aujourd'hui nous pouvons dire que ces lignes correspondent aux grandes directions structurales et tectoniques.

Comme il a déjà été dit, le perfectionnement des connaissances permet maintenant une vision beau-

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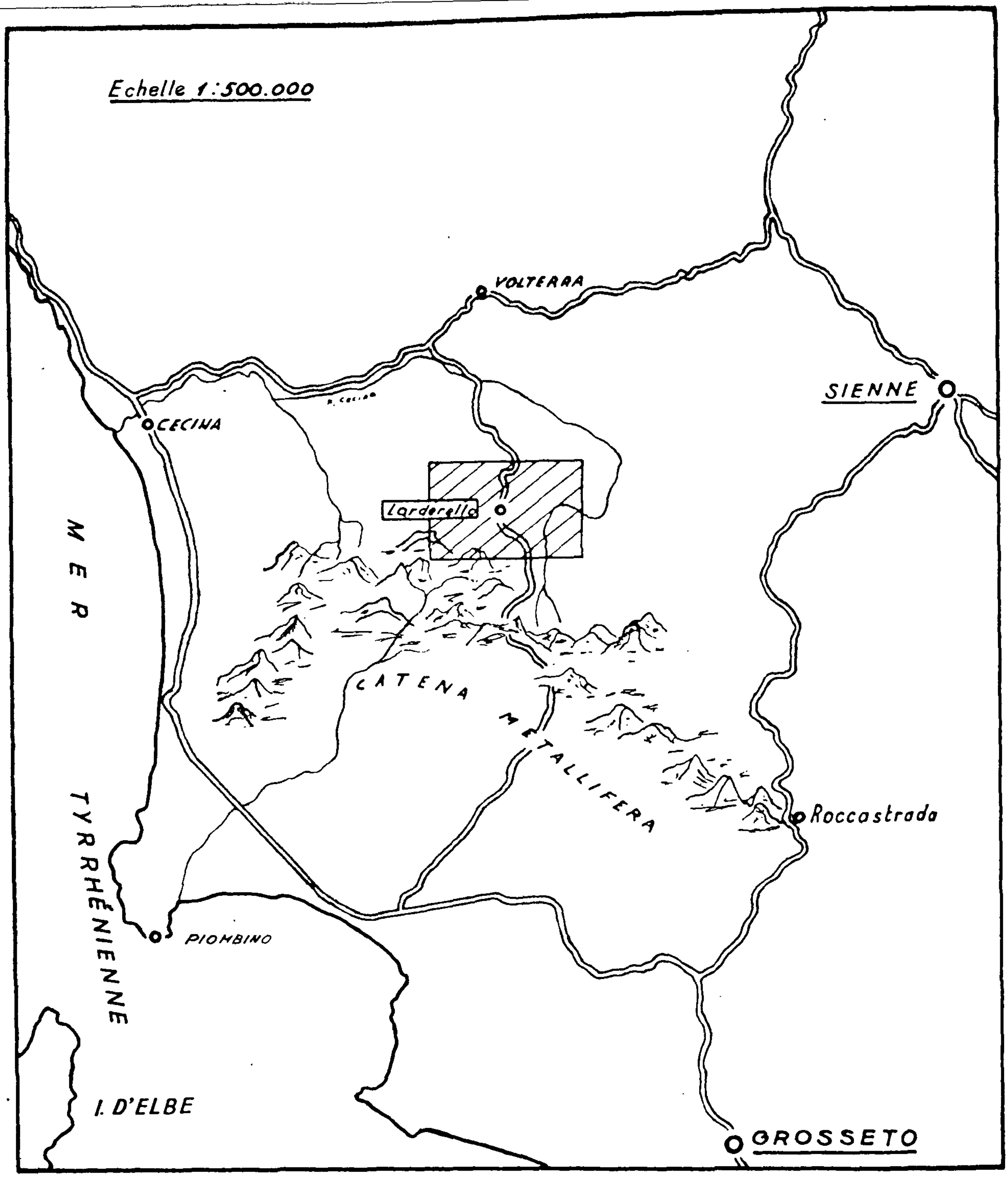


**Figure 1. Région boracifère : planimétrie**

coup plus claire, sinon parfaite, du cadre géologique général. Nous allons donc examiner brièvement les principales caractéristiques de ce cadre.

### Conditions géologiques

La région des « soffioni » est caractérisée, du point de vue géologique, par la présence de nombreux îlots de terrains anciens, tertiaires, secondaires et primaires, composés d'un socle cristallin paléozoïque (schistes, phyllades et quartzites) et d'une série sédimentaire à dominante calcaire (mésozoïque-cénozoïque). Ces terrains, autochtones assurément, affleurent au milieu d'une couverture allochtone formée par une coulée tectonique (« argille scagliose») déplacée au cours de l'orogenèse de l'Apennin.

Après les phases de glissements de terrains et de formation et émersion des rides tectoniques, il y eut un nouvel abaissement de la région et un retour de la mer provoquant une nouvelle sédimentation de terrains que l'on peut donc qualifier de « néo-autochtones ».

La série stratigraphique de tous ces terrains peut être ainsi décrite dans l'ordre chronologique, de haut en bas (tableau 1).

## Tectonique régionale

Pour bien comprendre les caractéristiques de la tectonique de la région des « soffioni », il est indispensable de rappeler le résultat structural de la formation des Apennins : par suite de la compression tangentielle de l'écorce terrestre, celle-ci s'est arquée vers le haut (et corrélativement s'est épaissie en profondeur) pour former un certain nombre de rides allongées

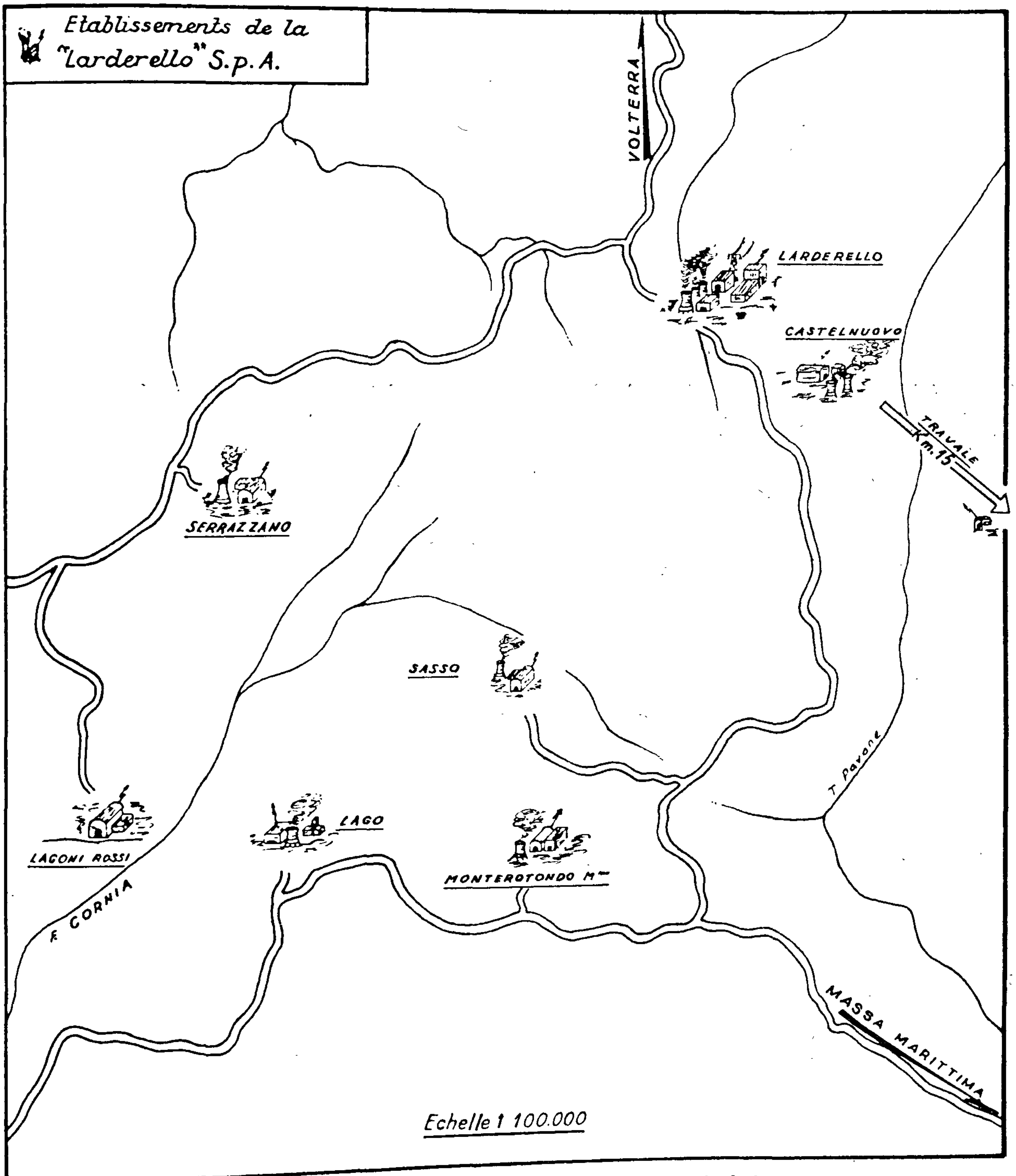


Figure 2. Région boracifère : détail de la planimétrie

dans le sens de la chaîne apennine (des « anticlinaux », pour employer un terme plus courant).

Ces rides n'ont pas toutes le même âge, car de solides raisons générales permettent de démontrer que les rides sont de plus en plus anciennes quand on se rapproche de la mer Tyrrhénienne, et que chacune est antérieure à celle qui la borde immédiatement à l'est et au nord-est.

Sans entrer dans les détails, nous nous limiterons à observer que, par suite de la rigidité relative des terrains qui constituent la partie supérieure de la lithosphère (jusqu'à 10 km environ), la déformation anticlinale est advenue au moyen de fractures avec rejet, c'est-à-dire de failles, convergentes en profondeur et de direction identique à celle de la ride; les parties surélevées le long de l'axe de la ride (culminations axiales) sont délimitées par des faisceaux de failles transversales à la structure (NE-SO) et probablement subverticales.

En même temps que le plissement anticlinal superficiel (au moyen de failles convergeant en profondeur) et par suite de la même cause générale, selon toute probabilité une compression tangentielle de la tranche de lithosphère intéressée par l'orogenèse, s'est formée une intumescence vers le bas.

La conséquence en a été la descente progressive, à des zones de températures de plus en plus élevées, de masses rocheuses considérables, dans les conditions requises pour leur transformation en granite.

La naissance de chaque ride est donc typiquement accompagnée par la formation de macules magmatiques dans sa racine profonde (en gros, à une profondeur de 20-25 km et plus).

Pendant le vieillissement de la ride et son affaissement graduel, lors d'une des phases de relâchement et de distension de la croûte, dont on doit admettre qu'elles suivent les phases de compression qui furent à l'origine de la ride, les macules magmatiques, potentiellement mobiles, trouveront les possibilités d'une remontée et même d'une effusion superficielle (phénomène d'intrusion). Dans cette nouvelle position plus superficielle, le magma se consolide par refroidissement à la température du milieu, en expulsant une bonne partie de ses constituants volatils.

En effet, à Gavorrano et près de Campiglia, le granite est inclus dans le calcaire massif du Lias inférieur, dans une série où il n'y a pas de métamorphisme régional et seulement un métamorphisme de contact. Il est donc vraisemblable que le magma est remonté jusqu'au-dessus de la limite du méta-

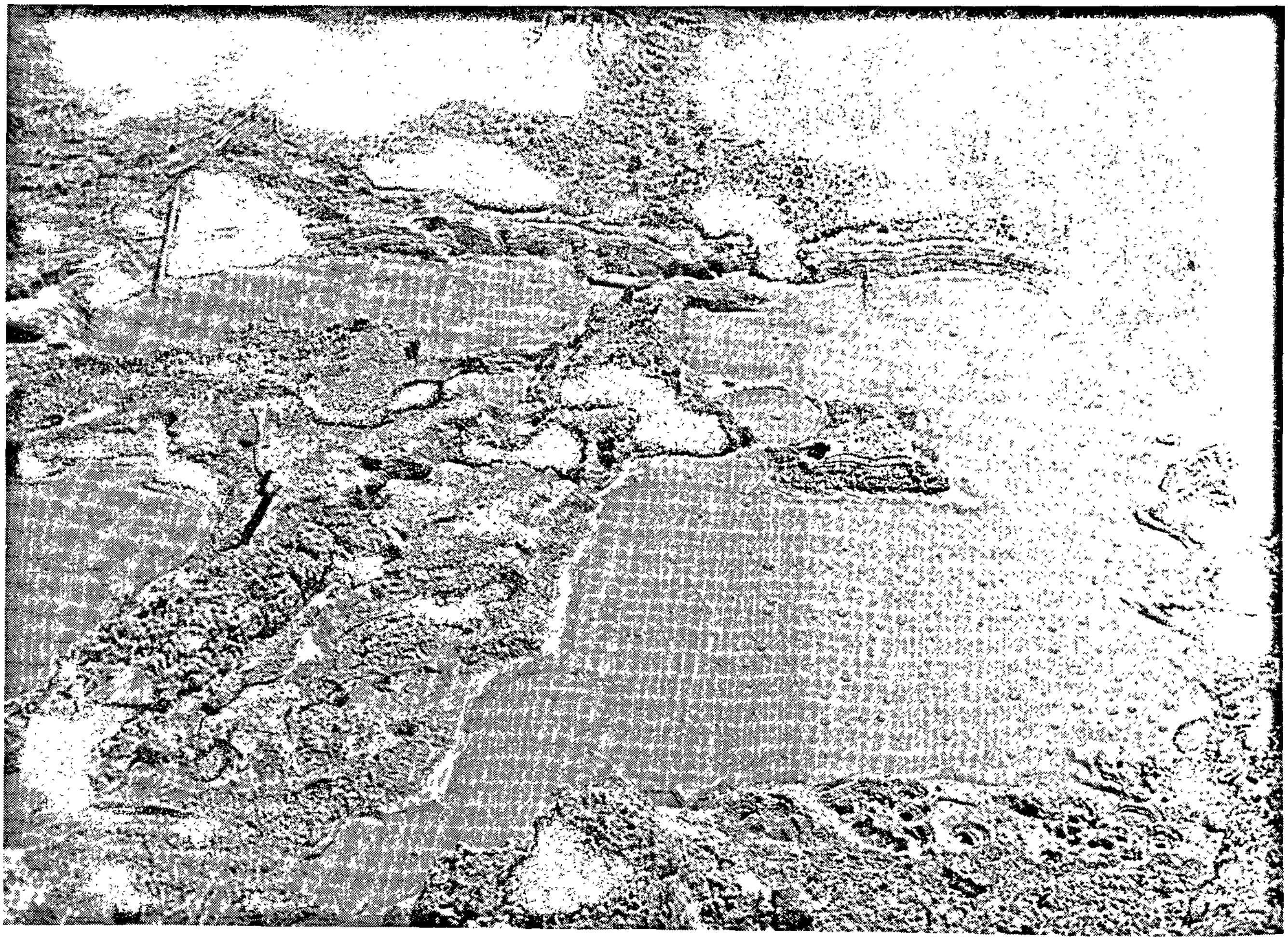

**Figure 3. Manifestation naturelle de la région boracifère (« lagone »)**

**Tableau 1. Série stratigraphique de la région boracifère**
*d'après G. Merla* (1952)

| *Ensembles tectoniques* | *Age* | *Formations* |
|---|---|---|
| NÉO-AUTOCHTONE . . . | Pliocène. | Conglomérates, sables et argiles. |
| | Miocène. | Conglomérates, sables, argiles, marnes. |
| | *Surface de transgression* | |
| ALLOCHTONE . . . . . | Age divers (du jurassique inférieur-crétacé inférieur à l'oligocène). | « Argille scagliose », roches vertes, calcaires « palombini », agglomérés cahotiquement. |
| | *Surface de glissement et dénudement tectonique* | |
| AUTOCHTONE : *Série sédimentaire mésozoïque-oligocène* | Oligocène. | « Macigno », bancs gréseux et argileux. |
| | Oligocène. | Schistes polychromes, plus rarement calcaires. |
| | Éocène-crétacé. | Nummulitiques intercalés vers le haut. |
| | Crétacé inférieur. | Jaspes. |
| | Jurassique supérieur. | |
| | Jurassique moyen. | Calcaires à silex, stratifiés. |
| | Lias. | |
| | Lias inférieur (sinémurien). | Calcaires rouges à ammonites. |
| | Lias inférieur (hettangien). | Calcaire « cireux » massif. |
| | Rhétien. | Calcaires foncés avec intercalations d'argiles grises et jaunâtres (schistes à *avicula contorta*). |
| | Trias supérieur (carnien-norien ?). | Série anhydritique (alternances d'anhydrite dolomie et calcaires dolomitiques), sur les affleurements on passe par élimination du gypse à une brèche résiduelle dite « calcaire caverneux ». |
| | *Surface de transgression* | |
| *Socle cristallin*. . . . | Permien. | Quartzites et anagénites intercalées de schistes. |
| | Carbonifère ? | Schistes phylladiques. |

Nota. — En de nombreuses zones de la région boracifère on note d'importantes lacunes de la série stratigraphique, lacunes dues à des causes tectoniques ou à l'érosion.

morphisme régional, située entre 4 000 et 7 000 mètres de la surface.

Le cadre régional dans lequel se situe la région boracifère, du littoral et des monts de Campiglia aux monts de Monticiano-Roccastrada, correspond au domaine de trois rides tectoniques : la première, la deuxième et la troisième (fig. 5).

Ici, comme en général dans l'Apennin septentrional, les rides ont été partiellement couvertes et ennoyées, surtout après la phase d'affaissement, par la nappe allochtone des « argille scagliose » qui s'est formée et s'est propagée par glissement sur les flancs des rides durant leur surrection. On voit que les rides occidentales sont actuellement, parce que plus anciennes, fortement disloquées par l'affaissement, et d'autant plus qu'elles sont plus anciennes. Entre une ride et la suivante, il n'y a aucun affleurement d'autochtone au milieu des « argille scagliose », et ceci précisément parce qu'il s'agit de zones affaissées où ont pu s'accumuler davantage les masses de glissement allochtones. La zone boracifère correspond dans son ensemble à une culmination tectonique et constitue la deuxième ride; celle-ci, comme les autres, présente tout un système de failles, vastes surfaces de cisaillement des masses rocheuses accompagnées d'un déplacement relatif des deux compartiments jointifs. Ces failles ont des directions soit longitudinales (NO-SE) soit plus ou moins transversales à la ride.

Les diverses fractures existantes ne sont pas nécessairement toutes contemporaines. Au contraire, il y a des raisons et des faits d'observation qui nous font supposer que certaines sont plus anciennes et d'autres plus récentes. La génération la plus ancienne est celle des fractures longitudinales et transversales qui ont accompagné la surrection de la ride; leur âge peut être attribué au miocène inférieur et moyen.

Au même moment se réalisaient en profondeur les conditions de naissance des magmas trachytiques (mais pas encore celles de leur migration dans une zone plus voisine de la surface et encore moins de leur consolidation avec expulsion des vapeurs). Par la suite se produisirent de nombreux autres mouvements tectoniques régionaux, liés à l'expansion de la racine de la ride et aux affaissements correspondants, à l'invasion de la mer au miocène supérieur et au pliocène, et à l'émersion définitive après le pliocène.

Il est plus que vraisemblable que ces mouvements se sont produits au moyen de nouvelles fractures et très souvent en faisant rejouer les anciennes, plus particulièrement les failles subverticales. Une bonne partie des mouvements qui ont suivi la surrection de la ride ont eu un caractère de distension; l'âge des derniers mouvements est nettement quaternaire, c'est-à-dire qu'ils datent seulement d'une centaine de milliers d'années environ. Ce sont précisément ces derniers mouvements et leur âge récent qui semblent avoir favorisé la remontée du magma et l'émission de vapeur. En effet, les vieilles failles qui n'auraient pas rejoué dans les mouvements successifs sont probablement rendues depuis longtemps étanches et imperméables par les dépôts de fluides minéralisateurs.

Il semble logique de préciser que ces générations de fractures les plus récentes sont justement les voies majeures de remontée du fluide endogène (fig. 6 et 7).

### Considérations relatives au gisement

Si nous examinons les caractéristiques géotectoniques de la région boracifère toscane, nous voyons aussitôt se dégager quelques traits fondamentaux pour la recherche des fluides endogènes dans cette région. Ces traits peuvent se décrire brièvement comme suit.

Les terrains les plus bas dans la série stratigraphique explorée par sondage sont constitués de roches (schistes, phyllades et quartzites) fortement siliceuses qui forment le socle cristallin ancien de la région. Ces terrains ont été le siège d'importants phénomènes tectoniques qui ont déterminé leur plissement, la formation de structures positives (dorsales), et en conséquence une abondante fracturation suivant des directrices bien déterminées.

Immédiatement au-dessus de ces terrains se trouve la formation d'anhydrites et de calcaires dite « série anhydritique ». L'épaisseur de cette formation à l'origine peut être évaluée d'après des données régionales à 300-400 m, mais elle se trouve très souvent réduite à cause de sa plasticité à 50-100 m. Dans ce dernier cas (exemple du voisinage de Larderello), sa perméabilité naturelle s'est considérablement accrue par suite des circulations de fluides chauds établies depuis des millénaires, au point qu'on peut la comparer à une éponge. La preuve en est que sur de telles zones (dont la superficie peut atteindre plusieurs kilomètres carrés) où se trouvent réalisées ces conditions particulières, plus de 90 p. 100 des forages qui ont atteint la « série anhydritique » ont été positifs.

La série stratigraphique décrite plus haut est souvent réduite au point qu'on ne trouve aucun des éléments qui devraient normalement recouvrir la « série anhydritique », et que celle-ci n'est alors recouverte que par les « argille scagliose » allochtones et parfois les terrains néogènes. De telles zones correspondent en général aux culminations des anticlinaux mineurs ( les « dorsales », dans la terminologie locale), et c'est là que la recherche s'est développée avec le plus d'intensité et de succès.

Les zones où existe la série stratigraphique plus ou moins complète, c'est-à-dire où l'on trouve, au-dessus de la série anhydritique triasique, les for-

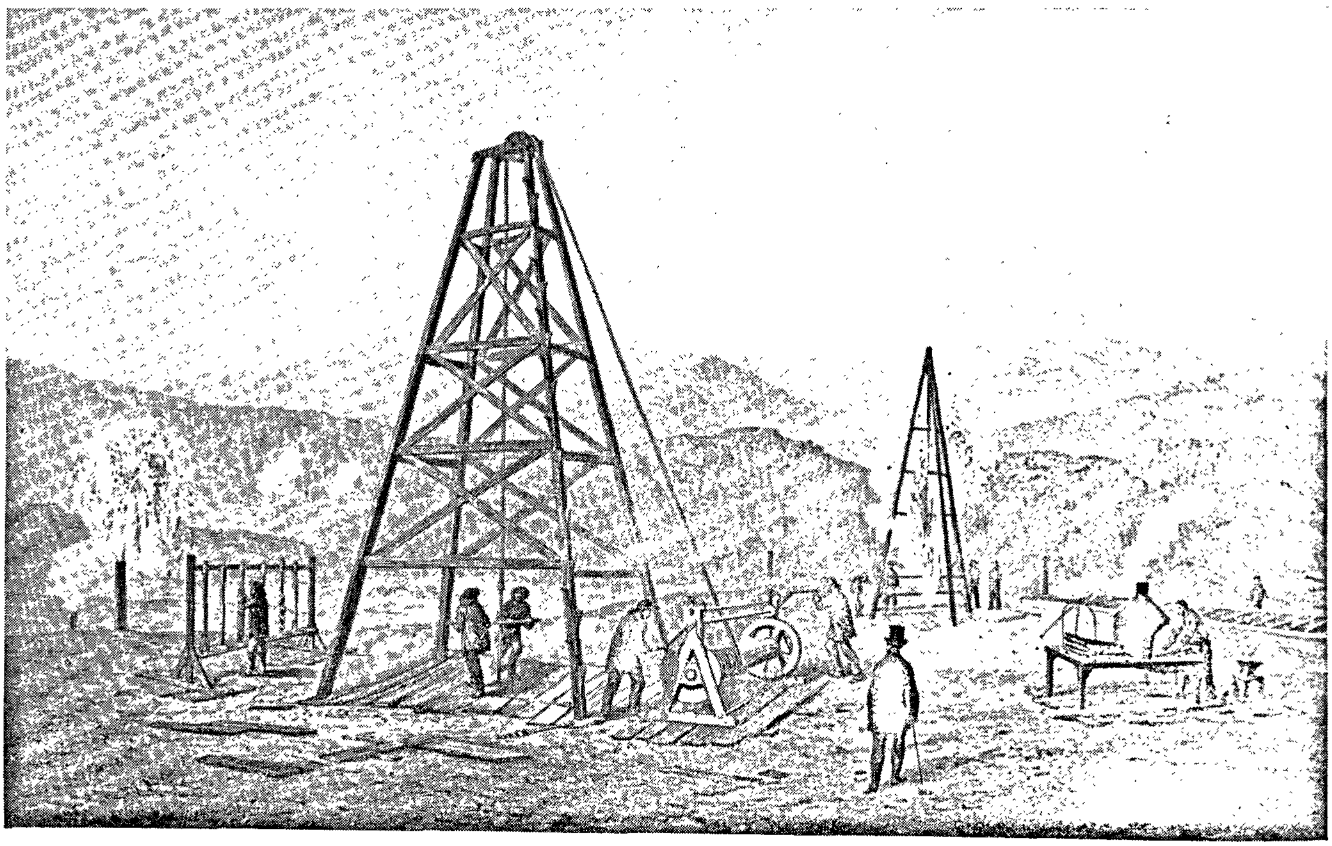

**Figure 4. Premières tentatives de sondage dans la région boracifère**

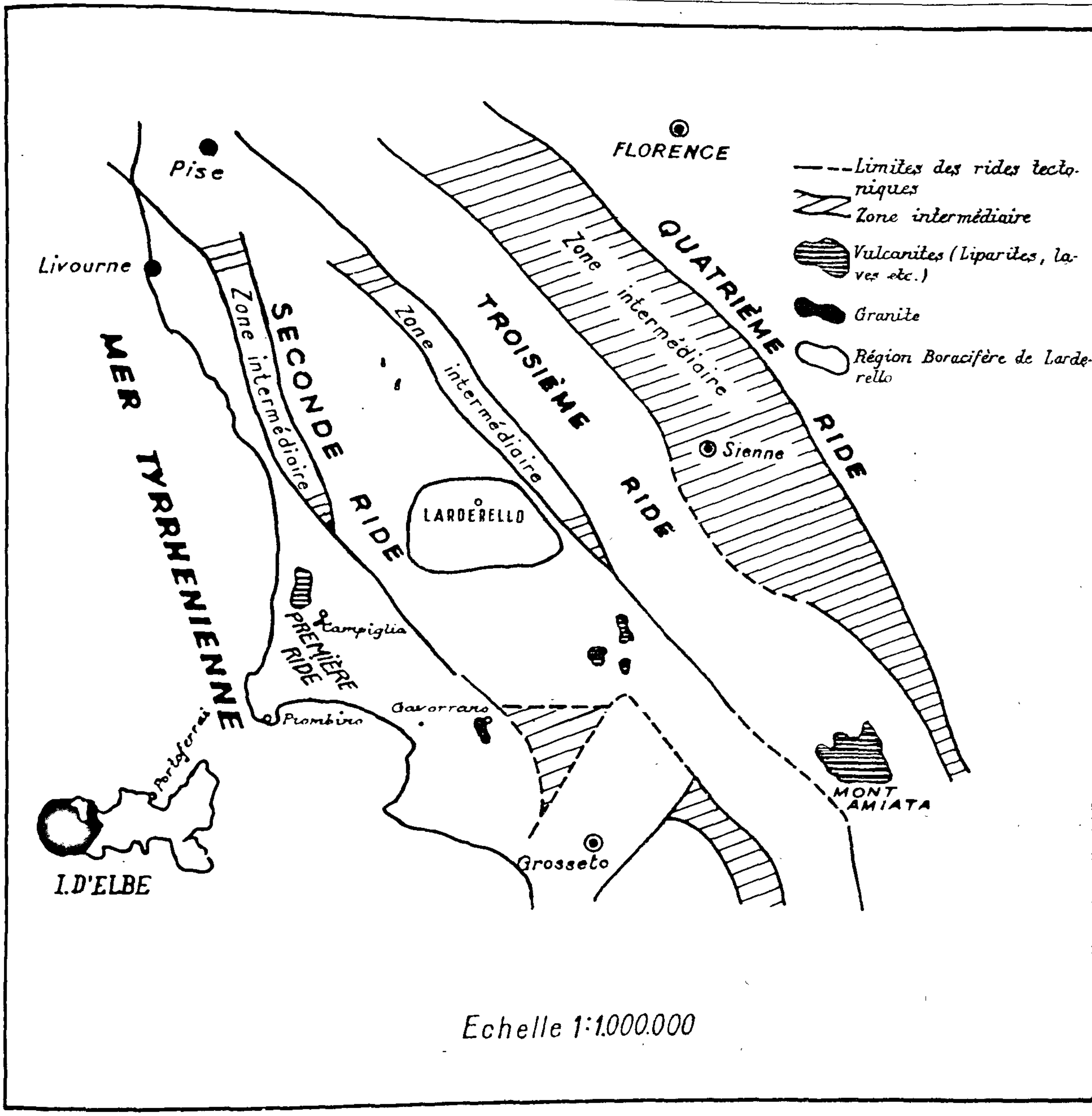


**Figure 5. Schéma tectonique de la Toscane**

mations à dominante calcaire du lias et du jurassique puis les horizons successifs jusqu'à l'oligocène sont généralement des zones synclinales où la série anhydritique elle-même est très souvent moins perméable qu'ailleurs et par suite moins productive parce que, à cause de sa grande épaisseur, les circulations se cantonnent au voisinage de son toit et de son mur. Dans de telles zones, la série stratigraphique comprend un autre terme assez perméable, qui est l'horizon supérieur du jurassique (« Malm ») constitué de jaspes (95-98 p. 100 de silice) très fracturés et perméables. De toute manière, les productions obtenues de cet horizon sont beaucoup plus modestes que celles obtenues de la « série anhydritique ».

Le dernier terme de la série stratigraphique locale est constitué par la couverture allochtone d' « argille scagliose » dont l'épaisseur peut varier de 200 à plus de 2 000 mètres, formée essentiellement de schistes argileux accompagnés de calcaires et autres roches. Cette formation, au-dessus de laquelle reposent parfois des terrains plus récents (néogène) eux aussi essentiellement argileux, est imperméable et joue le rôle de « couvercle » pour tout le système géo-hydrothermal.

## Manifestations naturelles

Il a semblé opportun de reprendre ici l'examen des manifestations naturelles citées au début de ce paragraphe. Il était indispensable de décrire d'abord, au moins sommairement, le cadre général dans lequel elles se trouvent (ou se trouvaient) afin de déduire les raisons de leur existence.

**Tableau 2. Vieilles analyses de gaz prélevés sur des manifestations naturelles de la région boracifère**

| *Localité* | *Hydrogène sulfuré* | *Gaz carbonique* | *Azote* | *Hydrogène* | *Gaz de marais* |
|---|---|---|---|---|---|
| Larderello | 4,20 | 90,47 | 1,90 | 1,43 | 2,0 |
| Castelnuovo | 3,76 | 92,63 | 1,08 | 0,90 | 1,63 |
| Sasso | 5,43 | 88,33 | 1,55 | 2,01 | 2,55 |
| Serrazzano | 6,10 | 87,90 | 2,93 | 2,10 | 0,97 |

La majeure partie de ces manifestations ont aujourd'hui disparu, à cause du drainage exercé par les forages sur les horizons les plus perméables; elles étaient ou sont encore constituées par de la vapeur d'eau et des gaz. Comme exemple nous donnons une vieille analyse effectuée vers 1870 (tableau 2).

Les données recueillies grâce au développement des recherches nous permettent maintenant de dire que les manifestations naturelles se produisaient dans des conditions locales particulières, plus précisément :

*a*) Là où la couverture argileuse (« argille scagliose ») est peu épaisse (200-300 m) et recouvre directement la « série anhydritique », coïncidant avec de notables plissements du socle cristallin (zones de Larderello, Castelnuovo, Serrazzano, Lagoni Rossi);

*b*) Là où affleurent, au milieu des « argille scagliose », des terrains particulièrement perméables de la série stratigraphique inférieure, par exemple la série anhydritique ou les jaspes du « Malm » (Castelnuovo, Sasso, Monterotondo, Lago);

*c*) Dans une moindre mesure, le long de certains contacts par failles entre terrains différents.

On peut admettre que les manifestations naturelles, surtout là où elles étaient les plus importantes, en développant une voie directe de dégagement des fluides chauds vers la surface, ont permis et déterminé l'évolution naturelle du phénomène, perfec-

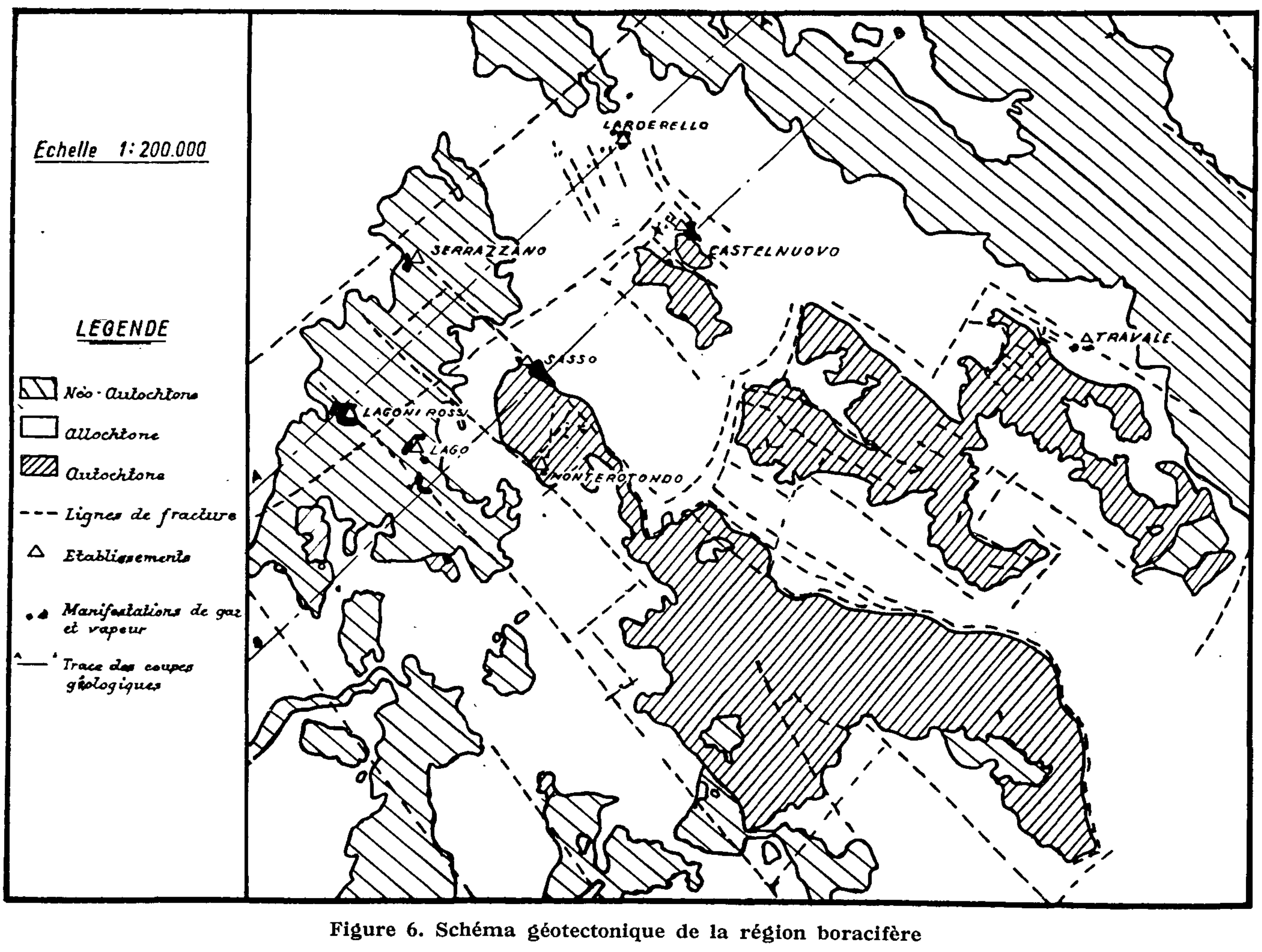


Figure 6. Schéma géotectonique de la région boracifère

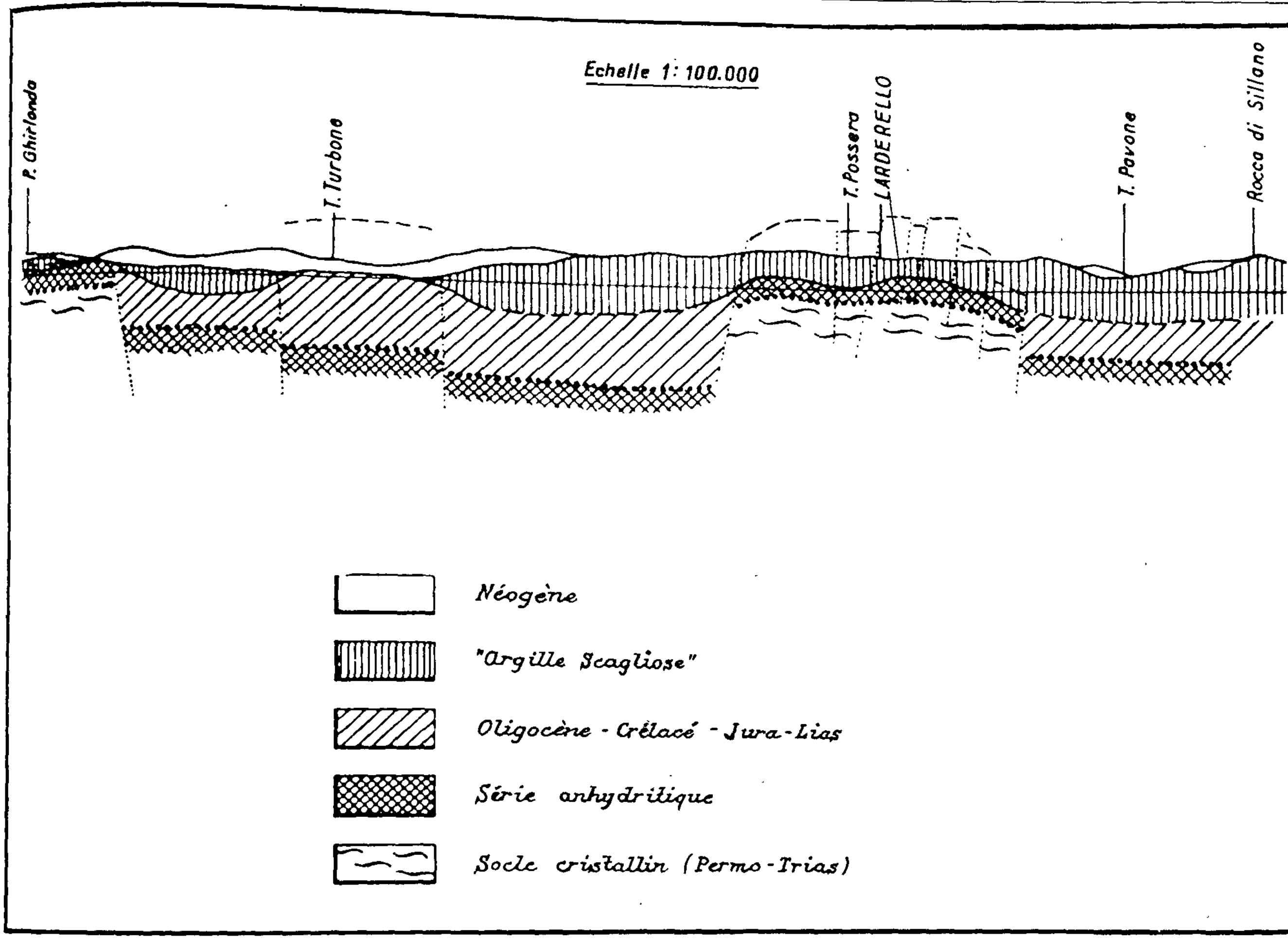


**Figure 7. Section du schéma géotectonique de la région boracifère**

tionnant le cycle géo-hydrothermal jusqu'à l'apparition de vapeur à la surface.

En outre, en maintenant un régime dynamique à la circulation, elles ont très probablement permis le développement de celle-ci dans les horizons perméables de la série stratigraphique, en particulier la série anhydritique, spécialement dans les zones où elle est la moins épaisse.

## Études et prospections géologiques et géophysiques

Les critères qui avaient guidé la recherche dans le passé furent plus que simplistes, comme il a déjà été dit, puisque les chercheurs se préoccupaient seulement d'exécuter les sondages le plus près possible des manifestations superficielles; celles-ci furent donc pendant longtemps l'unique guide de la recherche.

Par la suite, on remarqua de plus en plus la nécessité d'exécuter un ensemble d'études et de prospections afin de recueillir le plus grand nombre possible d'informations aptes à fournir de nouveaux critères pour orienter les forages.

C'est ainsi que l'on effectua des *levers géotectoniques de surface*, sur fonds topographiques très détaillés (échelle 1/10 000 et 1/25 000) établis parfois spécialement à cet effet. Ces levers et les études pétrographiques et paléontologiques annexes ont permis de tracer des cartes géologiques de détail et des coupes structurales. Ces documents indiquent :

*a*) Les terrains affleurants, et sur les coupes les terrains présents en profondeur;

*b*) Les principales lignes de fracture;

*c*) Les caractéristiques stratigraphiques et structurales.

Ces levers ont couvert sur la région boracifère une surface globale de 450 km².

Comme nous l'avons déjà signalé, la série allochtone des « argille scagliose » couvre la majeure partie de la région boracifère. Ce recouvrement allochtone, plus qu'hétérogène et disloqué, n'a aucune relation stratigraphique avec les terrains autochtones sous-jacents. Cela complique donc notablement l'interprétation de la géologie de surface, et c'est pourquoi l'on essaya également diverses méthodes de prospection *géophysique* dans le but de fournir des informations sur le substratum de la couverture argileuse. Les méthodes suivantes furent essayées à plusieurs reprises et en plusieurs endroits :

*a*) Électrique par potentiel spontané;

*b*) Électrique par résistivité (quadripôle);

*c*) Magnétique;
*d*) Gravimétrique;
*e*) Par observations de radio-activité;
*f*) Sismique par réfraction et par réflexion;
*g*) Thermométrique.

Certaines de ces méthodes durent être écartées pour diverses raisons, en premier lieu parce qu'elles ne se montraient pas aptes à résoudre les problèmes posés, tandis que d'autres (méthodes gravimétrique et thermométrique) se montrèrent adaptées à une prospection régionale ayant pour but de reconnaître les grandes masses magmatiques en intrusion profonde et les grandes structures du socle (gravimétrie) ou d'importantes anomalies géothermiques (thermométrie).

Enfin, la méthode électrique par résistivité a pu être employée intensivement; elle a réussi à donner une représentation assez fidèle de la forme du substratum des « argille scagliose », d'où la possibilité de reconstruire le schéma structural et de tracer avec une bonne approximation les lignes de fracture.

Sur la région boracifère, les prospections électriques ont couvert une surface globale de 495 km² environ avec 4 900 sondages électriques.

## Sondages

De très nombreux sondages ont été exécutés (fig. 8) sur diverses zones, parfois distantes l'une de l'autre (jusqu'à 15 km) et appelées conventionnellement « champs vaporifères ». D'autres sondages ont été forés dans les positions intermédiaires entre champs; dans l'ensemble, l'exploration par sondages s'est étendue jusqu'à ce jour à une surface de 70 km²; leur nombre atteint un total de 380 sans compter ceux exécutés avant l'adoption des sondeuses mécaniques en 1926. Les caractéristiques moyennes de ces sondages sont les suivantes :

| | |
|---|---|
| Profondeur moyenne | 700 m |
| Profondeur maximum | 1 600 m |
| Diamètre maximum | 584 mm |
| Diamètre minimum | 143 mm |

Les sondages sont tous tubés en acier cémenté, les diamètres et profondeurs des tubages variant suivant les circonstances.

La profondeur des sondages varie suivant l'épaisseur de la couverture imperméable (« argille scagliose ») et, par suite, la profondeur des terrains perméables vaporifères (série anhydritique, série des jaspes, quartzites du socle).

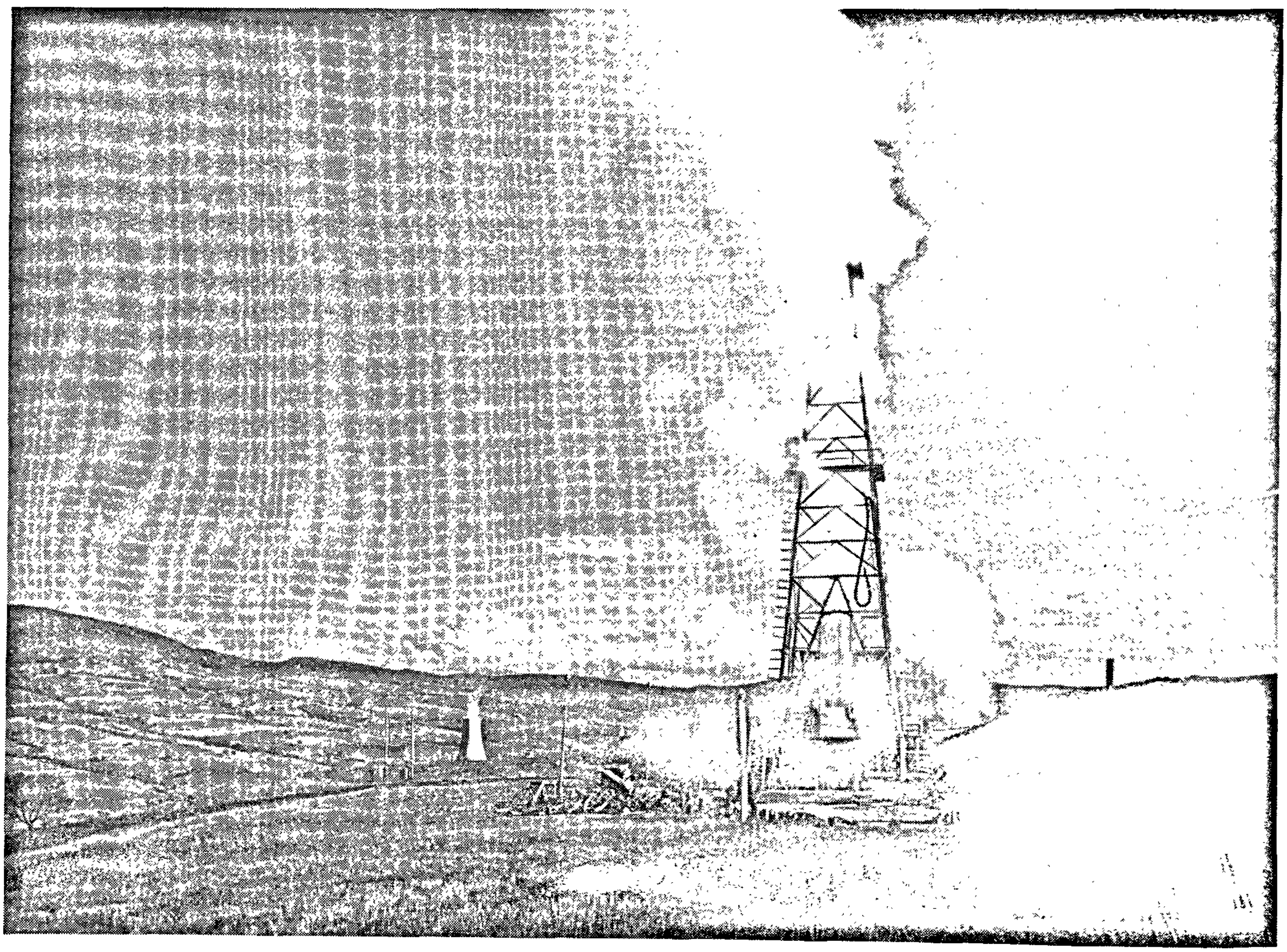

**Figure 8. Sondage en éruption dans la région boracifère**

PRODUCTION

Pour les 160 sondages actuellement en production sur la région boracifère et qui alimentent les industries électriques et chimiques de la Larderello, S. p. A., la production est la suivante :

| | |
|---|---|
| Débit de vapeur . . . . . . . . . | 2 850 000 kg/h |
| Pression moyenne en service . . . . | 5 atm absolus |
| Pression à puits fermé . . | de 10 à 32 atm absolus |
| Température moyenne . . . . . . . . . . . | 200 °C |
| Température maximum . . . . . . . . . . . | 245 °C |

La composition chimique moyenne du fluide produit est la suivante :

| | |
|---|---|
| Vapeur d'eau ($H_2O$) . . . . . . . . . . . | 955,0 g |
| Anhydride carbonique ($CO_2$) . . . . . . | 42,5 g |
| Gaz combustibles ($CH_4$, $H_2$) . . . . . . | 0,2 g |
| Hydrogène sulfuré ($H_2S$) . . . . . . . | 0,9 g |
| Azote ($N_2$) . . . . . . . . . . . . . . | 0,16 g |
| Acide borique ($H_3BO_3$) . . . . . . . | 0,25 g |
| Ammoniac ($NH_3$) . . . . . . . . . . . | 0,30 g |
| Gaz rares (He, Ar, Ne) . . . . . . . . | 1,0 cm³ |

A titre d'exemple, nous présentons un diagramme (fig. 9) sur lequel on a reporté en abscisses le temps en mois et années, et en ordonnées la variation du débit d'un sondage en kg/h. En examinant ce diagramme, qui est pratiquement semblable à ceux de tous les sondages de la région, on peut voir clairement que dans la première période de vie d'un sondage il se produit un rapide déclin de la production; ce déclin s'amortit ensuite progressivement et la courbe de production rejoint une valeur asymptotique. Il y a des sondages qui produisent depuis environ 40 ans, avec un débit réduit au dixième de la valeur initiale.

## Région du mont Amiata

### GÉNÉRALITÉS

La région du mont Amiata se situe elle aussi à brève distance du littoral tyrrhénien (50 km) et à 70 km environ au sud-est de la région de Larderello, entièrement en Toscane, dans les provinces de Grosseto et Sienne (fig. 10). C'est un massif montagneux qui s'élève brusquement au-dessus de la région environnante jusqu'à une altitude de 1 738 mètres. Coordonnées géographiques : longitude de 11° 31′ à 11° 41′ est, latitude de 42° 49′ à 42° 57′ nord.

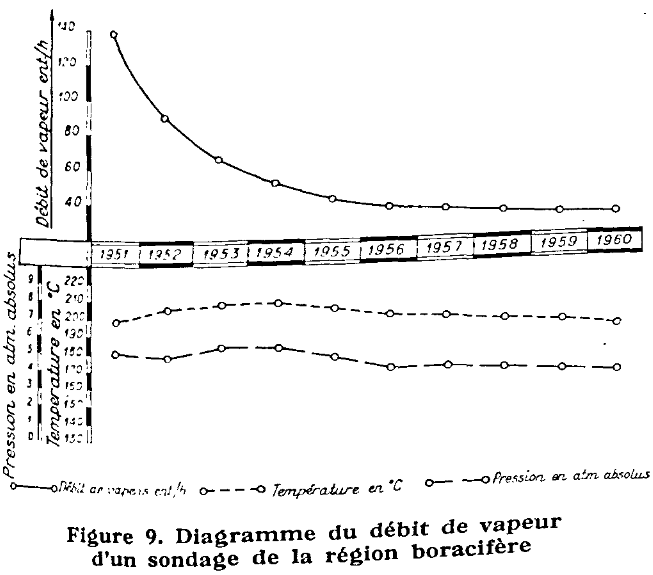


**Figure 9. Diagramme du débit de vapeur d'un sondage de la région boracifère**

### GÉOLOGIE

La série stratigraphique des terrains sédimentaires existant dans cette région ne diffère guère de celle de la région de Larderello précédemment commentée, et l'on peut donc se dispenser de la décrire.

Une différence substantielle correspond par contre à la présence de produits volcaniques, représentés par les « ignimbrites » (trachytes dans la vieille terminologie) qui constituent justement le relief du mont Amiata depuis la cote 800 mètres environ jusqu'au sommet.

Ces ignimbrites ont été produites par un volcanisme acide qui s'est manifesté en grande partie par des nuées ardentes.

Dans la masse d'ignimbrites on trouve aussi des laves proprement dites constituant des coupoles et croupes d'extrusion qui se sont formées le long des fractures à travers lesquelles s'est produite l'éruption du magma.

### TECTONIQUE

La tectonique de la zone du mont Amiata reproduit elle aussi en partie le motif dominant à Larderello. La série stratigraphique se trouve, en de nombreux points, réduite et laminée, mettant les « argille scagliose » directement en contact avec la série anhydritique. Une complication ultérieure a été introduite par l'intrusion magmatique et ensuite par l'effondrement vulcanotectonique causé par l'éruption et qui a engendré une nouvelle série de failles.

### MANIFESTATIONS

A l'intérieur du mont Amiata, au voisinage de la carapace volcanique, on relève une série de modestes manifestations consistant en des sources thermales de température variable entre 20 et 50 °C, et principalement en des émanations gazeuses froides, composées essentiellement de $CO_2$ et $H_2S$, qui s'alignent le long des principaux systèmes de fractures. Ces manifestations très modestes, à cause de l'imperméabilité élevée de la couverture argileuse, différencient nettement, à ce point de vue, la zone de l'Amiata de la zone classique de Larderello.

### ÉTUDES ET RELEVÉS GÉOLOGIQUES ET GÉOPHYSIQUES

Dans cette région aussi nous avons exécuté une série de relevés et d'études préliminaires comprenant un relevé géotectonique de détail comportant des analyses et études en rapport avec le problème,

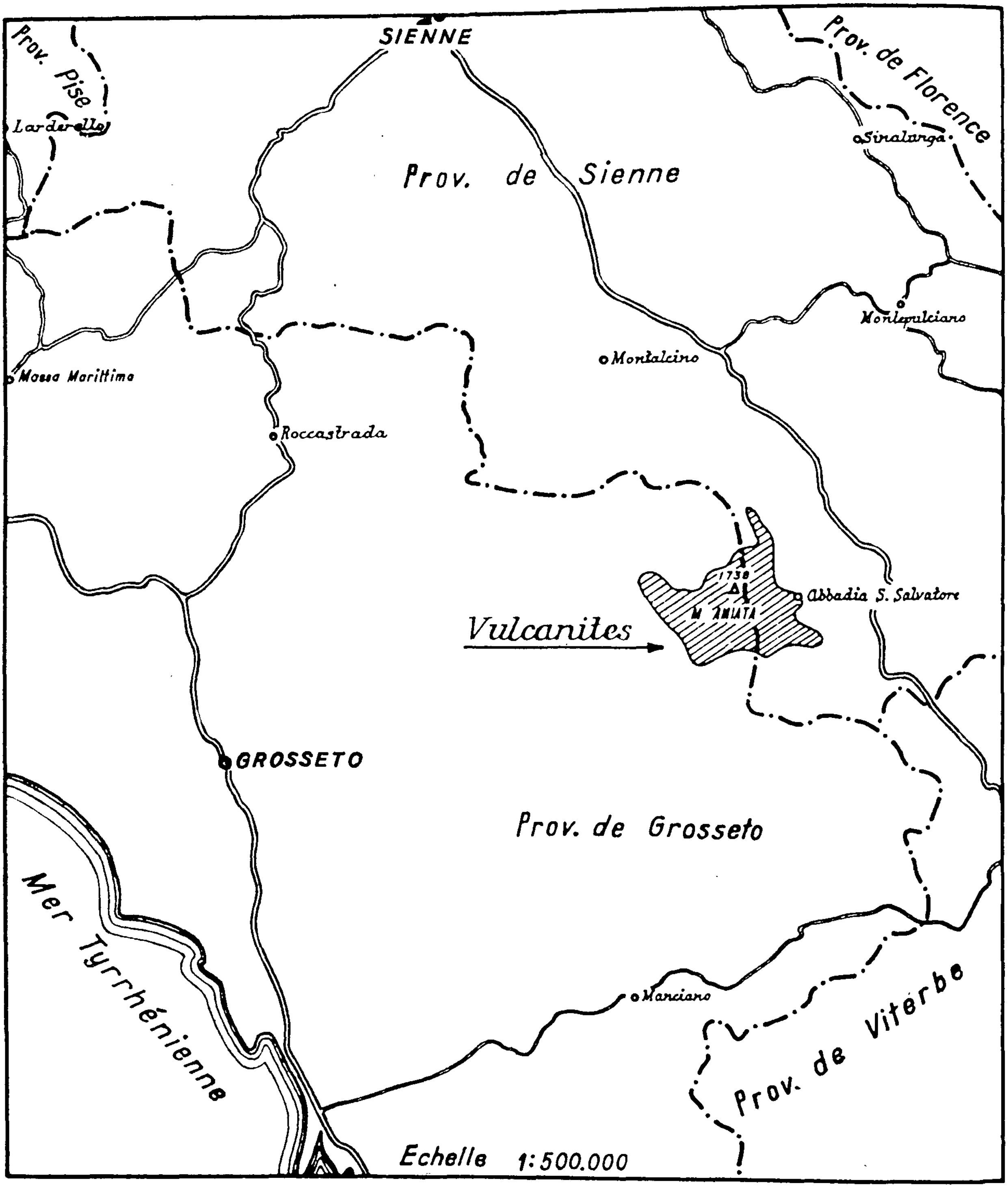


**Figure 10. Région du mont Amiata : planimétrie**

ainsi que des prospections géophysiques par la méthode électrique de résistivité et par la méthode gravimétrique.

SONDAGES

Dans cette région, 12 sondages ont été forés jusqu'à présent, près de Bagnore où les travaux de recherches préliminaires avaient fait entrevoir un notable soulèvement du substratum de la couverture constituée par les « argille scagliose », en correspondance duquel il était permis de supposer, par ressemblance avec d'autres zones fortement soulevées, que l'on pourrait rencontrer la série anhydritique très perméable directement en contact avec la couverture d' « argille scagliose ». Les premiers forages ont pleinement confirmé cette hypothèse.

Les sondages de cette région ont des caractéristiques identiques à ceux de Larderello, et leur profondeur va de 400 à 1 100 mètres.

### Production

Comme il a été dit précédemment, les manifestations naturelles de cette région sont plutôt modestes, et en conséquence il ne s'est pas produit comme à Larderello une évolution naturelle du cycle géohydrothermal, avec libération spontanée de la majeure partie des gaz et présence de vapeur à la surface.

Par suite, les premiers sondages ont débité d'énormes quantités de gaz ($CO_2$ et $H_2S$) qui se trouvaient en profondeur en véritables accumulations et peut-être en grande partie émulsionnés ou dissous dans l'eau; le volume de gaz a notablement diminué avec le temps.

Il suffira comme exemple de se reporter aux relevés du pourcentage gaz/vapeur dans le fluide débité par le sondage « Bagnore 1 », le premier foré sur cette zone (tableau 3).

Actuellement, la production globale des cinq sondages en production dans la région du mont Amiata est de 200 000 kg/heure d'un fluide ayant les caractéristiques moyennes suivantes :

| | |
|---|---|
| Rapport gaz/vapeur . . . . . . . . | 30 p. 100 de gaz |
| Pression à puits fermé . . . . . . | 8,5 atm absolus |
| Pression en régime de production . | 5,5 atm absolus |
| Température . . . . . . . . . . . | 150 °C |

## Régions diverses

En plus des régions précédemment décrites où la Larderello, S.p.A., exerce son activité industrielle (depuis plus d'un siècle dans la première et depuis trois ans dans la seconde), il y a aussi d'autres régions d'Italie (fig. 11) où cette même société a entrepris d'importants travaux de recherches préliminaires afin de déterminer les possibilités de découvrir des fluides endogènes utilisables industriellement.

Par suite justement de l'état préliminaire de ces recherches, il ne semble pas opportun de décrire en détail les caractéristiques de chaque région, caractéristiques d'ailleurs très semblables; de ce fait, ces régions seront seulement citées à titre indicatif, tandis que nous exposerons globalement les traits communs des conditions géologiques et hydrothermales, ainsi que les travaux entrepris.

### Région de Roccastrada

Cette région est située à 30 km environ au sud-est de Larderello, à la partie méridionale des « monts métallifères », dans les provinces de Grosseto et Sienne, en Toscane. Coordonnées géographiques : latitude de 42° 55′ à 43° 4′, longitude de 11° 2′ à 11° 16′.

### Région de Montecatini-Orciatico (près de Volterra)

Cette région est située à 25 km environ au nord de Larderello, dans la province de Pise, en Toscane. Coordonnées géographiques : latitude de 43° 24′ à 43° 27′, longitude de 10° 28′ à 10° 45′.

### Région de La Tolfa

Cette région se situe elle aussi à quelques kilomètres du littoral tyrrhénien près de Civitavecchia et Santa Marinella, en province de Rome, dans le Latium. Coordonnées géographiques : latitude de 42° 1′ à 42° 12′, longitude de 11° 47′ à 12° 4′.

### Caractéristiques générales

Toutes ces régions ont comme traits communs l'existence d'une série de terrains sédimentaires analogue à celle de Larderello, avec des horizons très imperméables recouvrant des termes profonds plus ou moins perméables, et surtout la présence en masse plus ou moins grande de produits volcaniques acides récents (ignimbrites), semblables à ceux du mont Amiata et peut-être contemporains de ceux-ci.

On y retrouve une tectonique comportant des structures fortement soulevées par rapport aux autres et des directrices de fractures d'orientation diverse.

Les manifestations naturelles sont représentées principalement par des eaux thermales dont la température peut atteindre 50-60 °C et des gaz sulfo-carboniques froids, en tout point semblables aux manifestations du mont Amiata.

### Région des monts Berici

La société Larderello effectue en outre des études tout à fait préliminaires sur la région des monts Berici située en Italie du nord, dans la province de Vicence, en Vénétie. Coordonnées géographiques : latitude de 45° 23′ à 45° 29′ longitude de 11° 27′ à 11° 36′.

Dans cette région, on trouve d'importantes traces d'un volcanisme assez récent et l'on relève des mani-

**Tableau 3. Pourcentages de gaz et de vapeur du sondage « Bagnore n° 1 » (région du mont Amiata)**

| *Avril 1959* | | *Octobre 1959* | | *Avril 1960* | | *Octobre 1960* | | *Mars 1961* | |
|---|---|---|---|---|---|---|---|---|---|
| *Gaz p. 100* | *$H_2O$* | *Gaz p. 100* | *$H_2O$* | *Gaz p. 100* | *$H_2O$* | *Gaz p. 100* | *$H_2O$* | *Gaz p. 100* | *$H_2O$* |
| 81,0 | 19,0 | 77,1 | 22,9 | 64,4 | 35,6 | 35,0 | 65,0 | 23,2 | 76,8 |

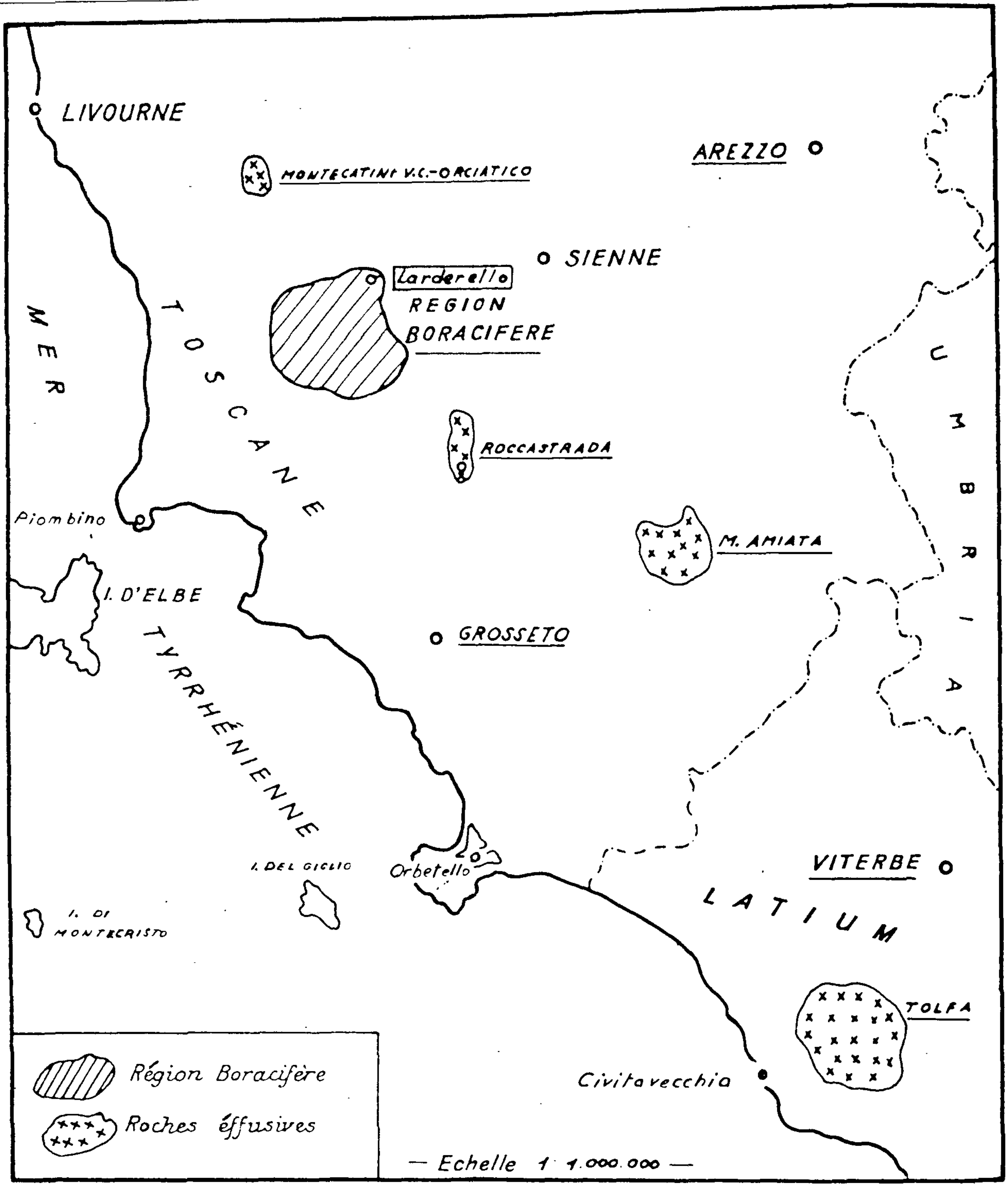


**Figure 11. Régions de Roccastrada, Montecatini-Orciatico, La Tolfa**

festations naturelles consistant en sources thermales et émanations de gaz ($CO_2$ et $H_2S$) [fig. 12].

### Études et levers géologiques et géophysiques

Des levers et études géologiques de détail intéressant une superficie globale de 1 050 km² ont été exécutés sur les régions ci-dessus. Les prospections géophysiques suivantes ont également été exécutées :

Gravimétriques sur 1 760 km² avec 2 300 stations;

Électriques (résistivités) sur 650 km² avec 1 150 sondages électriques.

### Sondages

Dans les régions de La Tolfa et de Montecatini, les premiers sondages ont déjà commencé, tandis que l'on prévoit d'en entreprendre à brève échéance dans les autres régions.

### Indices probables et caractères particuliers pouvant orienter la recherche de fluides endogènes dans de nouvelles zones

Nous avons déjà vu que ni dans la région boracifère de Larderello ni dans son voisinage immédiat on ne rencontre en affleurement aucune manifestation de roches magmatiques récentes, et d'autre part les sondages eux-mêmes, tout au moins jusqu'aux profondeurs de 1 500 et 1 600 mètres atteintes pour le moment, n'ont pas rencontré de roches de cette catégorie. De ce fait, on peut dire que la présence d'effusions magmatiques n'est pas une condition indispensable à un projet de recherche.

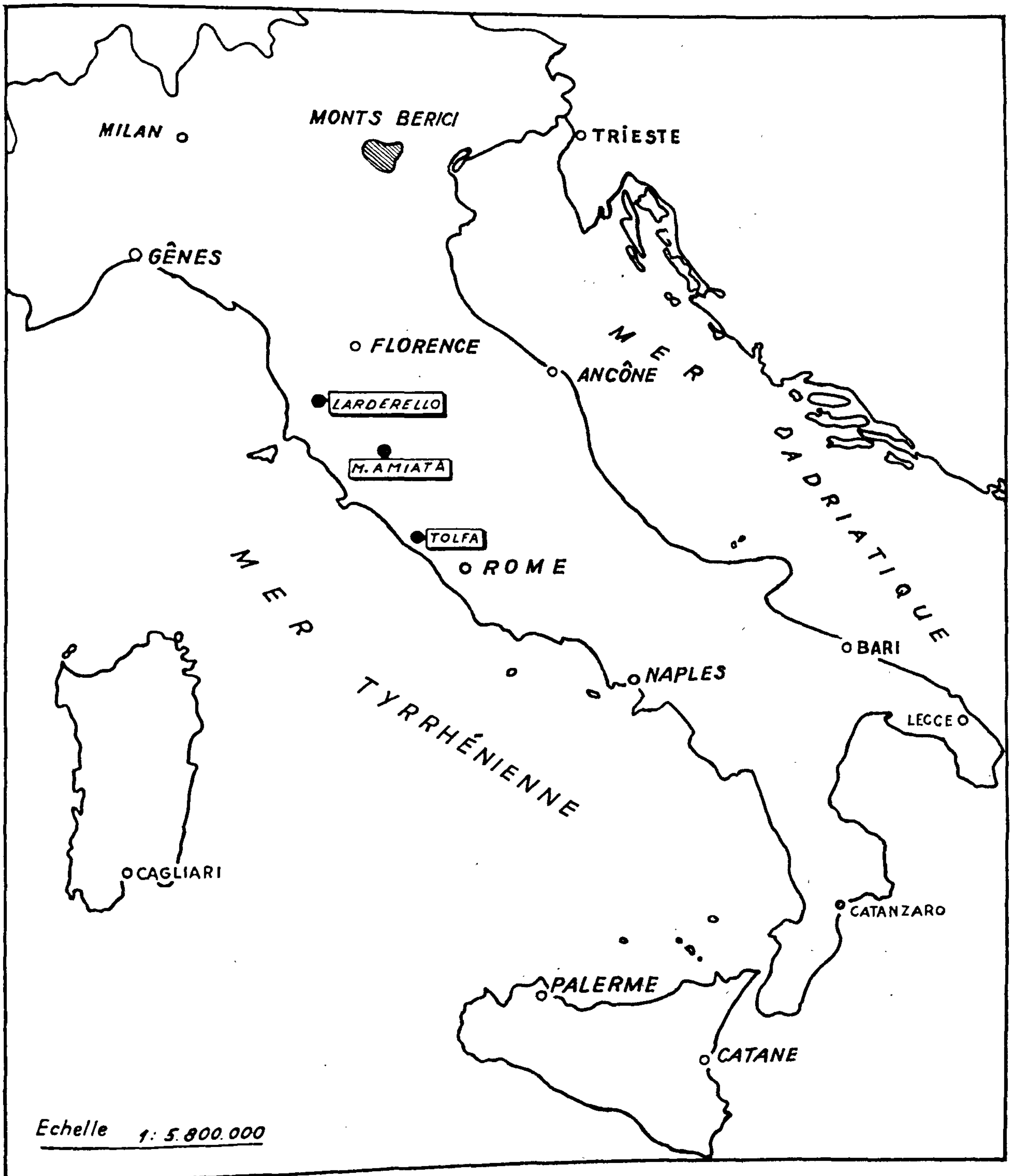


Figure 12. Carte d'Italie avec indication de la région des monts Berici

Par ailleurs, en ce qui concerne les zones comme le mont Amiata où existent des effusions magmatiques, il convient de considérer avant tout l'âge de ces phénomènes, qui, tant au mont Amiata que dans les autres régions citées au cours de cette communication (La Tolfa, Roccastrada, etc.) sont tous postérieurs au pliocène.

Une condition indispensable est l'existence dans les zones prises en considération d'une anomalie géothermique sensible qui pourra être révélée notamment par la présence de sources thermales et, dans les conditions les plus favorables, par des émanations de vapeur, mais encore mieux par des prospections thermométriques régionales effectuées au moyen de petits sondages (profondeur maximum 50 mètres) disposés suivant une maille de un à deux kilomètres de côté.

Il semble intéressant de signaler que dans la zone de Larderello les sondages ont noté des gradients géothermiques atteignant 9 °C en 10 mètres.

D'autres indices symptomatiques peuvent être, outre la présence de sources thermales, les manifestations de gaz $CO_2$ et $H_2S$ (même froids), qui sont généralement liées à des phénomènes magmatiques.

Une autre indice important est encore la présence du bore qui, en plus ou moins grande quantité, est toujours présent dans les fluides des manifestations naturelles rencontrées dans les zones où la recherche a eu un résultat favorable (Larderello, mont Amiata, La Tolfa, etc.).

En ce qui concerne le cadre géologique général, nous considérons comme indispensables les conditions suivantes :

*a*) Existence d'une couverture imperméable qui interdit dans un sens une diffusion ou une dispersion trop grandes des fluides à la superficie et en sens contraire une infiltration rapide des eaux météoriques froides en profondeur;

*b*) Présence d'horizons perméables dans la série stratigraphique locale, à des profondeurs économiquement accessibles par les sondages. Par conséquent, une autre condition favorable est le phénomène de plissement qui permettra l'existence dans les zones prises en considération de certaines structures hautes, évidemment plus intéressantes pour l'exploration, et en particulier dans la première phase des recherches;

*c*) Fracturation suffisante des terrains qui constituent le socle régional, de manière à faciliter la remontée des fluides chauds.

D'après ce que nous avons exposé dans ce paragraphe, il semble évident que pour établir un programme de recherche de fluides endogènes on devra prévoir les travaux préliminaires suivants :

*a*) Lever géotectonique de détail de toute la région prise en considération, sur cartes topographiques d'échelle non inférieure à 1/25 000;

*b*) Relevé de toutes les manifestations hydrothermales et gazeuses et analyses correspondantes;

*c*) Prospection thermométrique régionale au moyen de petits sondages disposés suivant une maille régulière;

*d*) Prospections géophysiques suivant la méthode la plus adéquate, pour obtenir le maximum d'informations sur les structures profondes (méthode gravimétrique, électrique, etc.);

*e*) Quelques forages d'exploration pour recueillir en profondeur des données sur la série stratigraphique et les gradients géothermiques.

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## *Résumé*

Une brève introduction met en évidence le fait que la région de Larderello a un caractère d'antériorité par rapport aux autres régions d'Italie et du monde où des recherches d'énergies géothermiques ont été entreprises. Depuis un siècle déjà on y exécute ces recherches et on y traite industriellement les fluides endogènes trouvés. Les caractéristiques de cette région sont décrites en mettant en évidence avant tout sa position géographique au centre de l'Italie (Toscane), à faible distance de la côte tyrrhénienne (30 km en moyenne).

Il s'agit d'une région vallonnée faisant partie d'une chaîne de hauteurs nommée « monts métallifères », à cause des minéraux métalliques qu'elle recèle, minéraux probablement liés aux « magmatisme » Toscan et donc à mettre en relation avec le phénomène de Larderello.

Les premières recherches, consistant en de modestes travaux de forage, ont été guidées exclusivement par les manifestations naturelles constituées de vapeur d'eau et de gaz ($CO_2$-$H_2S$) en différentes localités de la région. Par la suite, grâce aux progrès de la connaissance des conditions locales et des outils de travail, des éléments nouveaux furent mis en évidence et ont servi de guide pour les recherches ultérieures.

A la lumière de ces connaissances, l'auteur illustre les caractéristiques géotectoniques et phénoménologiques de la région, en décrivant la série stratigraphique des terrains.

Cette série exclusivement sédimentaire est formée par un socle régional (schistes phylladiques et quartzites permo-triasiques), par une série évaporitique triasique et jurasicoliasique surtout calcaire,

par quelques terrains du crétacé-éocène et de l'oligocène (schistes argileux, calcaires et grès).

Toute cette série est en grande partie recouverte (à l'exclusion de petites zones) par une formation flyshoïde allochtone constituée de calcaires et schistes argileux d'âges variés (surtout crétacé-éocène) en dispositions irrégulières et chaotiques.

Cette dernière formation est elle-même accessoirement recouverte par des sédiments récents, miocènes et pliocènes (argiles, sables et conglomérats).

Pour illustrer la situation tectonique régionale, l'auteur se réfère aux effets structuraux de la formation des Apennins, qui ont déterminé, dans cette région la formation d'une série de plissements anticlinaux (rides) de direction apenninique, avec de grandes fractures (failles) et charriages.

En même temps que ces plissements de surface, il s'est très probablement formé un gonflement en profondeur avec, comme conséquence, la descente progressive des masses rocheuses vers des zones de plus en plus chaudes, jusqu'à l'établissement des conditions requises pour leur transformation en granite.

Pendant les phases successives de vieillissement des rides, avec les phénomènes de distension de la croûte terrestre, les amas magmatiques potentiellement mobiles ont trouvé les conditions pour une remontée vers la surface, sinon pour un épanchement en surface proprement dit (intrusions).

Dans ces nouvelles positions plus superficielles, le magma se consolide par dispersion de chaleur et extromission de ses parties volatiles.

L'auteur parle ensuite de l'âge probable de la formation des principales fractures qui intéressent les terrains autochtones. Elles sont d'âges différents selon les divers mouvements tectoniques qui ont intéressé la région. Il pense que la formation des fractures les plus récentes est aussi la plus favorable à la remontée du flux thermique.

De l'examen des caractéristiques géotectoniques ci-dessus illustrées, émergent les faits les plus importants, qui sont :

La très grande fracturation des terrains du socle ancien (permien) suivant des directrices bien déterminées;

La présence, dans la série stratigraphique locale, de terrains hautement perméables (principalement la « série d'anhydrite triasique »);

L'existence de lacunes stratigraphiques qui mettent en contact direct la susdite formation avec la série argileuse de couverture;

La grande imperméabilité de la formation de couverture qui sert de « grand couvercle » à tout le système géohydrothermique.

Ce mémoire fait remarquer que les manifestations naturelles (vapeurs d'eau et gaz sulfo-carbonique) se libéraient ou se libèrent toujours en correspondance des zones où la couche argileuse est moins épaisse, dans les rares zones où les terrains plus perméables qui constituent leur substratum affleurent et enfin, quelquefois, le long des contacts par faille entre terrains de nature différente.

L'auteur décrit en outre les prospections et les études géologiques et géophysiques effectuées dans la région boracifère, pour avoir de nouveaux éléments pouvant servir de guide à la recherche.

Ces études ont consisté en des prospections géotectoniques de détail et des prospections géophysiques variées. Parmi celles-ci, certaines se sont montrées plus adaptées que les autres aux exigences de cette recherche, comme la méthode électrique (résistivité), la méthode thermométrique et la gravimétrie.

L'auteur donne ensuite quelques précisions sur 380 forages exécutés dans cette région. La production totale de vapeur des 160 sondages actifs est de 2 850 000 kg/h.

Une fois décrite la région boracifère, on passe à la description de la région du mont Amiata située, toujours en Toscane, à 70 km environ au sud-est de la précédente.

Cette région, bien que la série stratigraphique sédimentaire soit semblable à celle de la région boracifère, présente une différence substantielle due au fait qu'ici on trouve des effusions de roches volcaniques acides (ignimbrites).

On fait remarquer que dans cette zone la couche des argiles « scagliose » de couverture est très imperméable, si bien qu'on ne note en surface que de très modestes manifestations de gaz (surtout $CO_2$).

Les 11 sondages effectués dans cette région ont rencontré de grandes quantités de fluides constitués au début par 96 p. 100 de gaz et 4 p. 100 de vapeur d'eau, tandis que par la suite il y a eu une remarquable amélioration, jusqu'à obtenir maintenant un rapport de 23 p. 100 de gaz et 77 p. 100 de vapeur d'eau. La production totale des sondages actifs est de 160 000 kg/h avec une pression moyenne de production de 6 atmosphères.

La société Larderello poursuit avec succès la recherche des fluides endogènes dans les régions boracifère et Amiata depuis plus d'un siècle sur la première et depuis trois ans sur la seconde. Il y a en outre d'autres régions sur lesquelles la même société commence des recherches de même nature :

Région de Roccastrada en Toscane, à environ 30 km au sud-est de Larderello;

Région de Montecatini-Orciatico en Toscane, à 25 km environ au nord de Larderello;

Région de La Tolfa dans le Latium, à 150 km au sud-est de la région boracifère.

Dans toutes ces régions, les séries sédimentaires sont semblables à celles de la région boracifère, mais, différence notable, on y note la présence d'effusions de roches volcaniques acides (ignimbrites), comme dans la région du mont Amiata.

En outre, la société Larderello est en train d'effectuer des recherches à un stade très préliminaire dans la région des monts Berici dans l'Italie du

Nord (Vénétie), où existent des produits volcaniques acides d'âge assez récent.

Dans les régions ci-dessus mentionnées ont été exécutées des prospections géotectoniques de détail et des prospections géophysiques par méthodes électrique (résistivité), gravimétrique, thermométrique. Dans la région de La Tolfa et de Montecatini les premiers forages ont déjà été commencés.

En conclusion de cet exposé, nous rappelons les diverses conditions, indices et caractères particuliers qui peuvent être utiles pour la préparation d'une recherche de fluides chauds sur des zones diverses :

La présence dans la zone d'effusions de roches volcaniques n'est pas une condition indispensable pour le succès de la recherche (la région de Larderello en est un exemple classique);

Par contre, l'existence d'une anomalie thermique sensible est une condition indispensable;

Existence d'une couverture de terrains hautement imperméables;

Présence de niveaux très perméable à une profondeur économiquement accessible par forages;

Présence de fractures dans les terrains plus ou moins anciens qui constituent le socle régional.

Enfin, il est conseillé à ceux qui se proposent d'entreprendre une recherche de fluides chauds de prévoir une série d'études et de travaux préliminaires :

Prospections et études géologiques;

Prospections géophysiques (électrique, gravimétrique, thermique, etc.);

Quelques forages d'exploration.

# PROSPECTING OF GEOTHERMAL FIELDS AND EXPLORATION NECESSARY FOR THEIR ADEQUATE EXPLOITATION, PERFORMED IN VARIOUS REGIONS OF ITALY

*(Translation of the foregoing paper)*

*Renato Burgassi* *

Everyone who, for one reason or another, is to any extent concerned with the problems of geothermal energy, must have come across the name of Larderello at the very outset.

This is easy enough to explain. Larderello has been the only place — and I shall unavoidably have to discuss it at greater length than all the others mentioned in this paper — where exploration work, followed by actual utilization of geothermal energy on an industrial scale, has been going on for over a century.

It therefore seems quite natural to assign absolute priority to the Larderello region in a paper concerned precisely with prospecting for geothermal energy, and with its adequate utilization.

## The Larderello region

### General features

This region, often termed the Boraciferous region on account of the boron in its thermal waters and steam, is located at the centre of the Italian peninsula, a short distance from the coast of the Tyrrhenian Sea (30 km on the average). Its area is about 400 km$^2$, entirely in the Tuscan provinces of Pisa, Siena, Grosseto and Leghorn (figures 1 and 2).

Geographical co-ordinates: latitude 10° 45′ to 11° 03′ N, longitude 43° 09′ to 43° 18′ E.

The region is hilly, with peaks reaching a maximum altitude of 1 000 m. These peaks belong to a range about 50 km long, called Metalliferous Hills on account of their abundant mineral deposits (sulfides, oxides and carbonates of iron, copper, lead, zinc, and other metals). These deposits are in all probability associated with magmatic phenomena of relatively recent age (Mio-Pliocene and Quaternary) in Tuscany, and should thus be correlated with the endogenous fluids of the Boraciferous region.

Without wishing in the slightest to turn this paper into an historical narrative, I must still recall the origins of the search for endogenous fluids in this region, so that I can fully evaluate the facts and circumstances responsible for its development.

The first prospectors were guided exclusively by the numerous natural steam and gas jets, which very frequently caused violent ebullition in the natural basins known locally as "lagoni" (figure 3). These manifestations, sometimes on an impressive scale, were grouped in a number of centres, sometimes far apart (10 to 15 km) spread over an extensive area, each occupying, at most, half a square kilometre.

Those who first undertook rudimentary borehole drilling (figure 4) sank their wells to a depth of a few metres below the surface in the immediate neighbourhood of the natural geothermal activity. Consequently they succeeded in draining off the hot fluids, which came to the surface as a result of the abundant circulation through the cavities and discontinuities in the surface formations, which had become eminently permeable due to the very fact of that circulation.

The flow from these first bores was naturally very modest, of the order of several hundred kg/h, in the form of saturated steam, accompanied by meteoric water circulating practically at the surface, which had a marked downgrading effect on the hot fluid.

The subsequent information obtained on the local geothermal conditions thanks to the advances in the geological sciences, increased familiarity with the general background, and the improvement in drilling equipment became more and more complete.

This progress in exploration, which has led to the continuous improvement in our knowledge on this subject, may be illustrated by the following example. From the initial phases of the exploration proper, the centres of the natural springs or vents, and very often those outlets themselves, had been found to be aligned along very definite directional lines. We are able today to say that these lines correspond to the major structural and tectonic directions.

As already noted, the present state of our knowledge gives us a far clearer, if not perfect, view of the general geological background. We shall therefore briefly examine the main features of this background.

### The geological conditions

The "soffioni" region is characterized geologically by the presence of numerous small islands of ancient,

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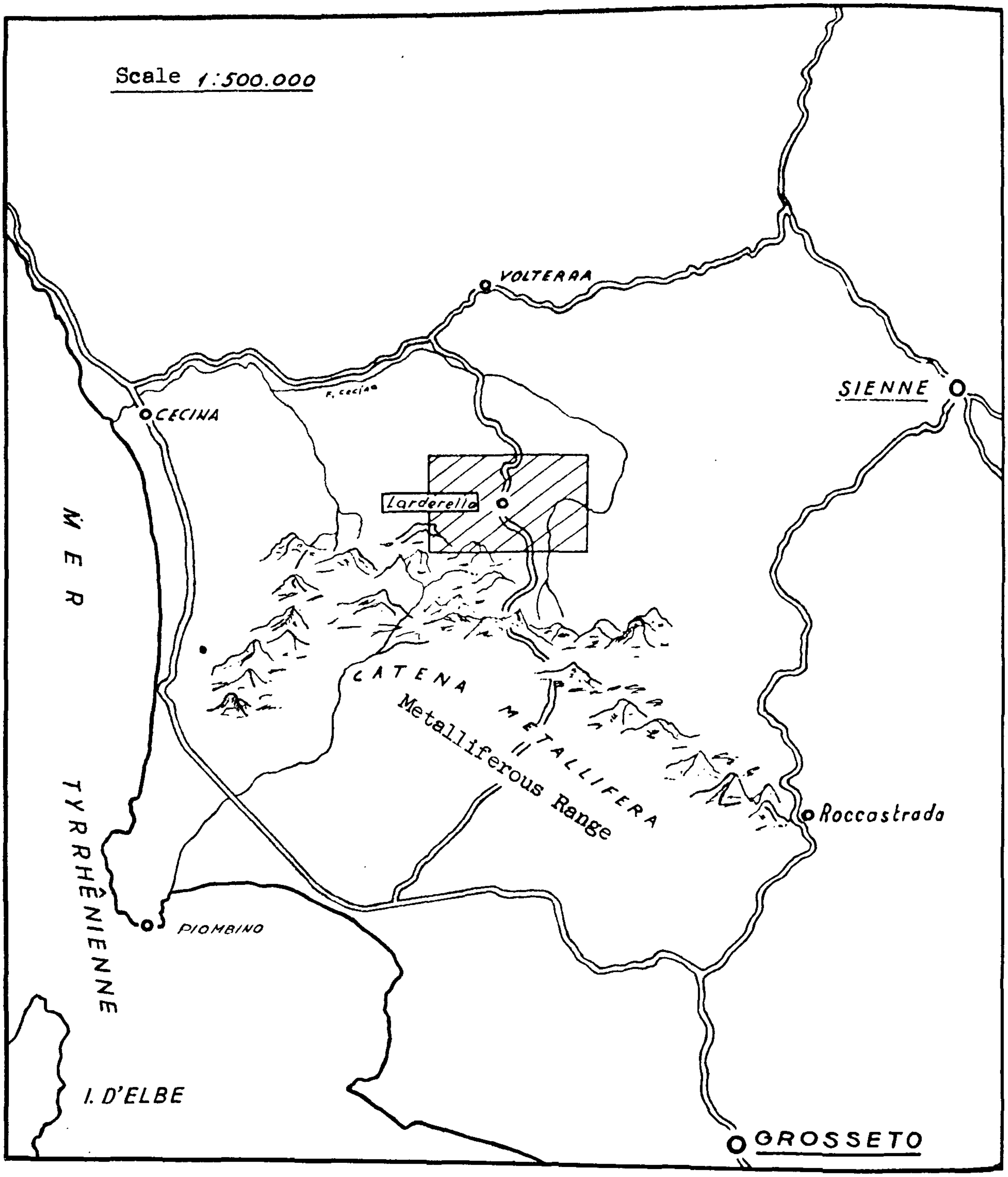


**Figure 1. Boraciferous region: planimetry**

tertiary, secondary and primary formations, composed of a Paleozoic crystalline basement (schists, phyllades and quartzites) and a predominantly limestone sedimentary series (Mesozoic-Cenozoic). These formations, which are certainly autochthonous, outcrop through an allochthonous cover formed by a tectonic coulee ("argille scagliose") displaced during Apenninean orogenesis.

After the phases of overthrust, formation and emergence of tectonic folds, renewed subsidence of the region occurred, followed by renewed marine transgression, leading to new sedimentation of strata which may thus be termed "neo-autochthonous".

The stratigraphic sequence of all these formations may thus be described in chronological order, from top to bottom (table 1).

REGIONAL TECTONICS

To have a good understanding of the characteristics of the tectonics of the "soffioni" region, the structural result of the Apenninean orogenesis must be recalled. As a result of the tangential compression of the earth's crust, it buckled upwards (and as a result increased in depth) to form a certain number of elongated folds with the strike of the Apennine range (or "anticlines", to use a more common term).

The folds are not all of the same age, for sound general reasons permit one to demonstrate that they are more and more ancient as one approaches the Tyrrhenian Sea, and that each of them antedates the one immediately adjoining it on the east and north-east.

Without going into the details here, we shall note merely that, owing to the relative rigidity of the formations constituting the upper portion of the

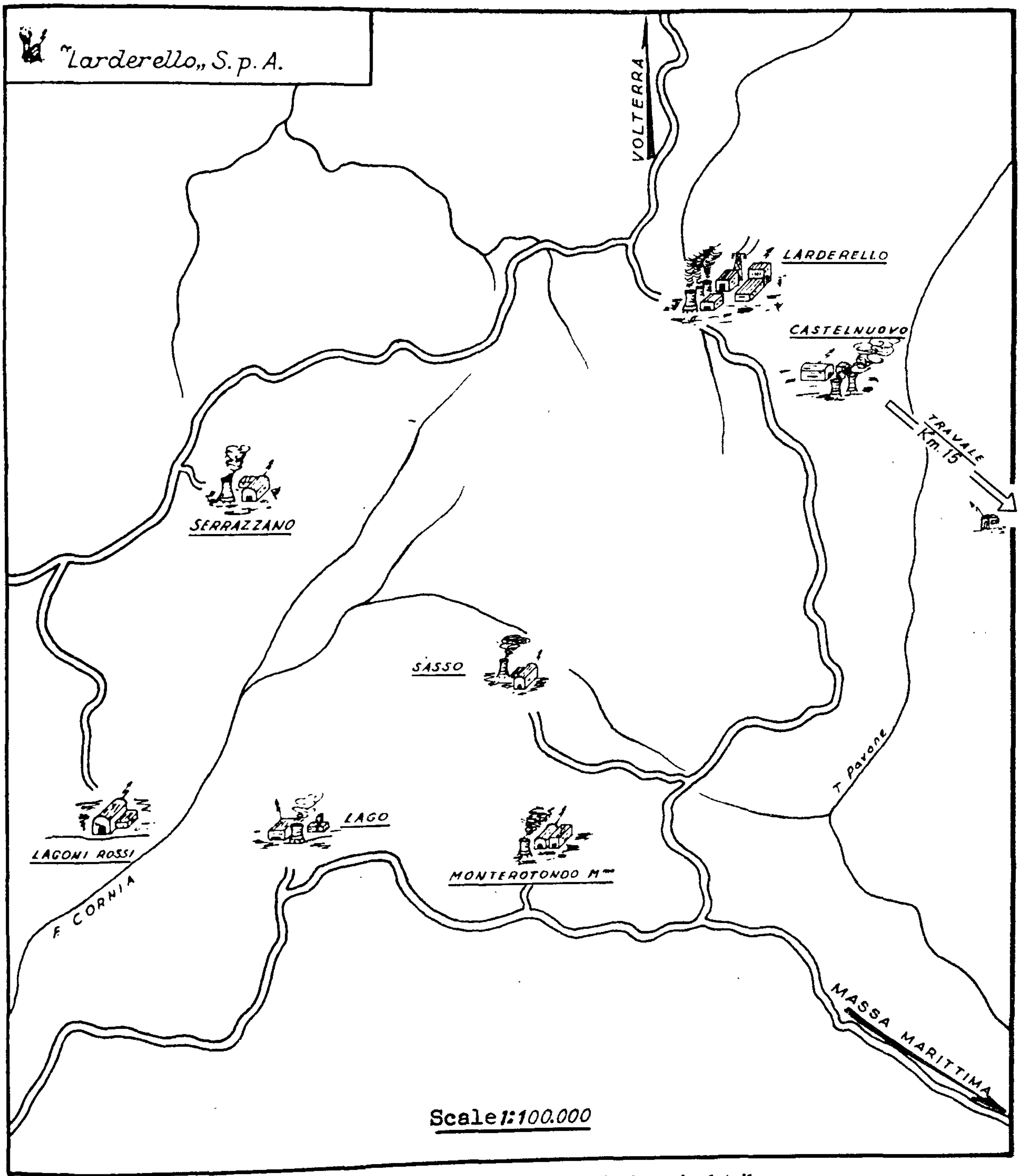


Figure 2. Boraciferous region: Planimetric detail

lithosphere (to a depth of about 10 km), anticlinal deformation occurred by means of fractures with displacement, that is, of faults, convergent in depth and with the strike of the fold. The portions super-elevated along the axis of the fold (axial culminations) are bounded by systems of faults transverse to the structure (NE-SW), and probably subvertical.

At the same time as the anticlinal folding on the surface (by means of faults converging downwards), and for the same general cause, in all probability a tangential compression of that section of the lithosphere affected by orogenesis, downwarping occurred.

The consequence was the progressive descent, to zones of higher and higher temperature, of considerable masses of rock, under the conditions requisite for their metamorphosis into granite.

The birth of each fold was thus, typically, accompanied by the formation of magmatic nodules in its deep root (mostly at a depth of 20-25 km or more).

During the ageing of the fold and its gradual subsidence, during one of the phases of crustal relaxation and bulging which must be assumed to have followed the phases of compression that give rise to the fold, the magmatic nodules, potentially mobile, found opportunities for ascent and even for effusion onto the surface (the phenomenon of intrusion). In this new position, nearer or at the surface, the magma became consolidated by cooling to the temperature of the surrounding medium, while expelling a large proportion of its volatile constituents.

At Gavarrano and near Campiglia, in fact, the granite is included in the massive limestone of the Lower Lias, in a series where all regional metamorphism is absent and there is only contact metamorphism. It is therefore probable that the magma ascended to above the limit of regional metamorphism, located between 4 000 and 7 000 m below the surface.

The regional background of the Boraciferous region, from the costal region and the Campiglia hills to the Monticiano-Roccastrada hills, corresponds to the domain of three tectonic folds — the first, second and third (figure 5).

Here, as in general in the northern Apennines, the folds have been partially covered and submerged, especially following the phase of subsidence, by the

**Figure 3. Natural manifestation of Boraciferous region ("lagone")**

Table 1. Stratigraphic sequence of the Boraciferous region
*after G. Merla* (1952)

| *Tectonic* | *Age* | *Formations* |
|---|---|---|
| NEO-AUTOCHTHONOUS . | Pliocene | Conglomerates, sands and clays |
| | Miocene | Conglomerates, sands, clays, marls |
| | *Surface of transgression* | |
| ALLOCHTONOUS . . . . | Various ages (from Lower Jurassic-Lower Cretaceous to Oligocene) | "Schistose clays", green rocks, "palombini" limestones, chaotically agglomerated |
| | *Surface of overthrust and tectonic denudation* | |
| AUTOCHTHONOUS *Mesozoic-oligocene sedimentary series* . . | Oligocene | "Macigno", sandstone and argillaceous strata |
| | Oligocene; Eocene-Cretaceous | Polychromatic schists, more rarely nummulitic sandstones intercalated upwards |
| | Lower Cretaceous; Upper Jurassic | Jaspers |
| | Middle Jurassic; Lias | Siliceous limestone, stratified |
| | Lower Liassic (Sinemurian) | Worn ammonitic limestones |
| | Lower Liassic (Hettangian) | "Waxy" massive limestone |
| | Rhetian | Dark limestones with intercalations of grey clays (Schists with Avicula contorta) |
| | Upper Triassic (Carnian-Norian?) | Anhydrite series (alternating anhydite-dolomite and dolomitic limestones), at the outcrops the gypsum is eliminated, leaving a residual breccia termed "cavernous limestone" |
| | *Surface of transgression* | |
| *Crystalline basement* | Permian | Quartzites and anagenites intercalated with schists |
| | Carboniferous? | Phylladic schists |

Note: Important breaks in the stratigraphic sequence are noted in numerous zones of the Boraciferous region. They are due to tectonic causes or erosion.

allochthonous cover of the "argille scagliose" (schistose clays), which was formed and spread by overthrusting along the flanks of the fold during their upheaval. The western folds are older, and will thus be seen to be strongly dislocated by subsidence, and the more so, the more ancient they are. Between one fold and the next, there is no outcropping of the autochthonous formations whatsoever through the "schistose clays". This is precisely because these are zones of subsidence, where still more masses of allochtonous overthrusts could accumulate. The boraciferous zone corresponds in its entirety to a tectonic culmination, and constitutes the second fold; this fold, like the others, has a whole system of faults, shearing surfaces of the rock masses accompanied by a relative displacement of the two jointed compartments. These faults have either longitudinal strikes (NW-SE), or strikes more or less transverse to the fold.

The various existing faults were not necessarily all formed at the same time. On the contrary, there are grounds and observational facts indicating that some of them may be more ancient and others more recent. The more ancient generation is that of the longitudinal and transverse faults that accompanied the upheaval of the fold; their age may be placed in the Lower and Middle Miocene.

At the same time, the conditions for the formation of trachytic magmas were realized in depth (but not yet for their migration to the neighbouring zone of the surface, and still less for their consolidation, accompanied by ejection of steam). Numerous other subsequent regional tectonic movements also took place subsequently, in connexion with the expansion of the root of the fold and with the corresponding subsidences, the marine transgression in the Upper Miocene and Pliocene, the final post-Pliocene emergence.

It is more than likely that these movements were accomplished by new faulting, and very often by reactivating the old ones, especially the subvertical faults. A considerable part of the movements following the upheaval of the fold were of the nature of bulging; the last movements are definitely of Quaternary age, that is, they date back only some hundred thousand years. It is precisely these latest movements and their recent age that seem to have favoured the ascent of the magma and the emission of steam. Indeed, the old faults, which played no further part in these successive movements, probably long ago became impermeable reservoirs for deposits of mineralizing fluids.

It seems logical to note that these generations of the most recent fractures are precisely the major passages by which the endogenous fluids ascend (figures 6 and 7).

## Discussion of the field

If we examine the geotectonic features of the Tuscan Boraciferous region, we shall see at once that there are certain fundamental indications for endogenous-fluid prospecting in this region. These features may be briefly described as follows.

The lowest formations in the stratigraphic sequence explored by drilling are composed of the same strongly siliceous rocks (schists, phyllades and quartzites) which constitute the ancient crystalline basement of this region. These formations have undergone major tectonic phenomena which have determined their folding, the formation of positive (dorsal) structures, and, in consequence, abundant faulting along clearly defined directional lines.

These formations are immediately overlain by the formation of anhydrites and limestones known as the "anhydrite series". The original thickness of this formation may be estimated, from the regional data, at 300-400 m, but it very often thins to 50-100 m on account of its plasticity. In this latter case (as in the Larderello area), its natural permeability is considerably increased as a result of the circulations of hot fluids that have been established for thousands of years, to the point where it might be compared to a sponge. The proof is that in such zones (which may cover several square kilometres) where these particular conditions exist, over 90 per cent of all the wells reaching the "anhydrite series" have been producing.

The stratigraphic sequence described above is often reduced to the point where all the strata that would normally overlie the "anhydrite series" are missing, so that this sequence is covered only by the "schistose clays", and sometimes by Neogene formations. Such zones correspond in general to the culminations of minor anticlines ("dorsal" anticlines, in the local terminology), and it is there that exploration has proceeded with most intensity and most success.

The zones whose stratigraphic sequence is more or less complete, that is, where the Triassic anhydrite series is overlain by the predominantly limestone formations of the Lias and Jurassic, followed by the successive horizons all the way up to the Oligocene, are generally synclinal zones in which the anhydrite series itself is very often less permeable than elsewhere, and therefore less productive, because, owing to its great thickness, the circulations concentrate near the roof and wall. In such zones the stratigraphic sequence includes another rather permeable series, the upper horizon of the Jurassic ("Malm"), consisting of highly fractured and permeable jaspers (95-98 per cent silica). In any case, the production from this horizon is much more modest than that from the "anhydrite series".

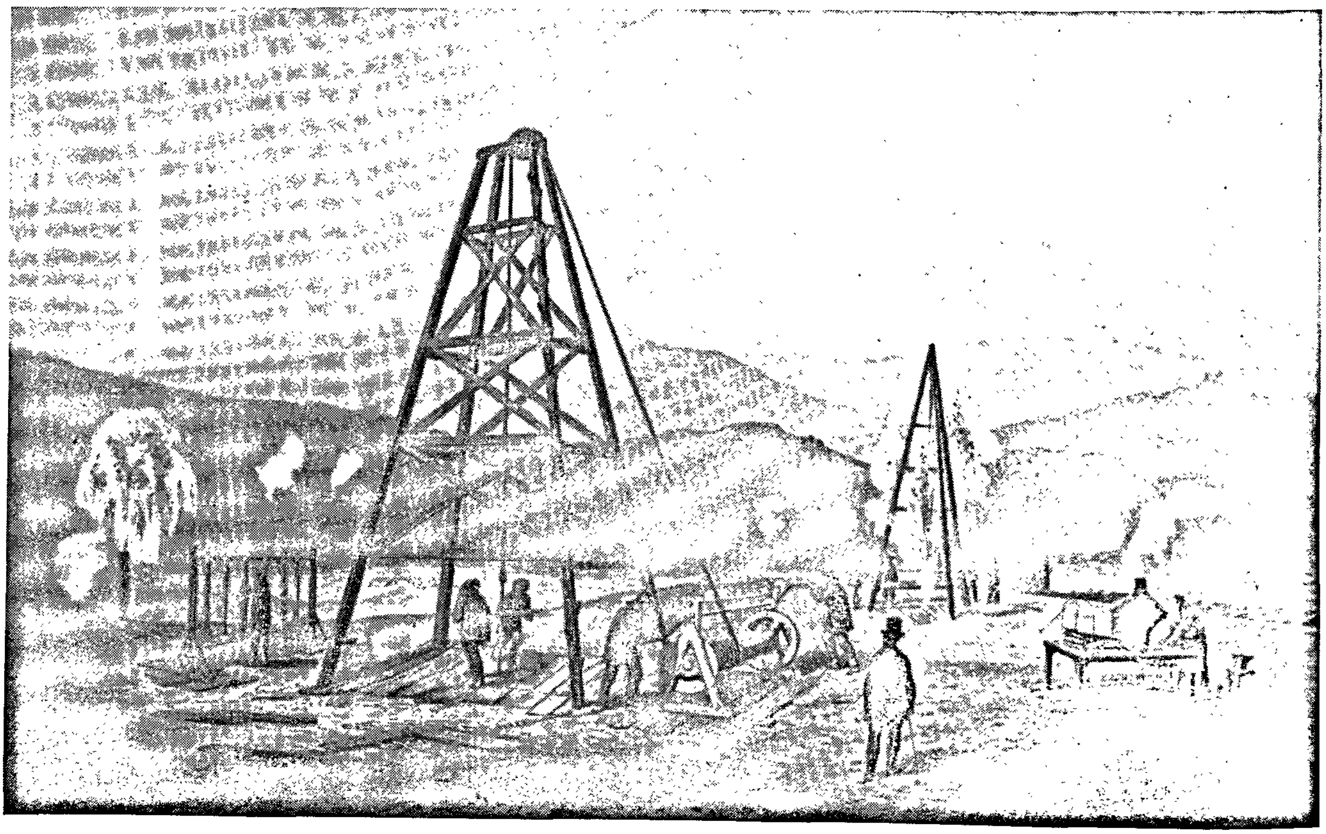

**Figure 4. First attempts at test drilling in the Boraciferous region**

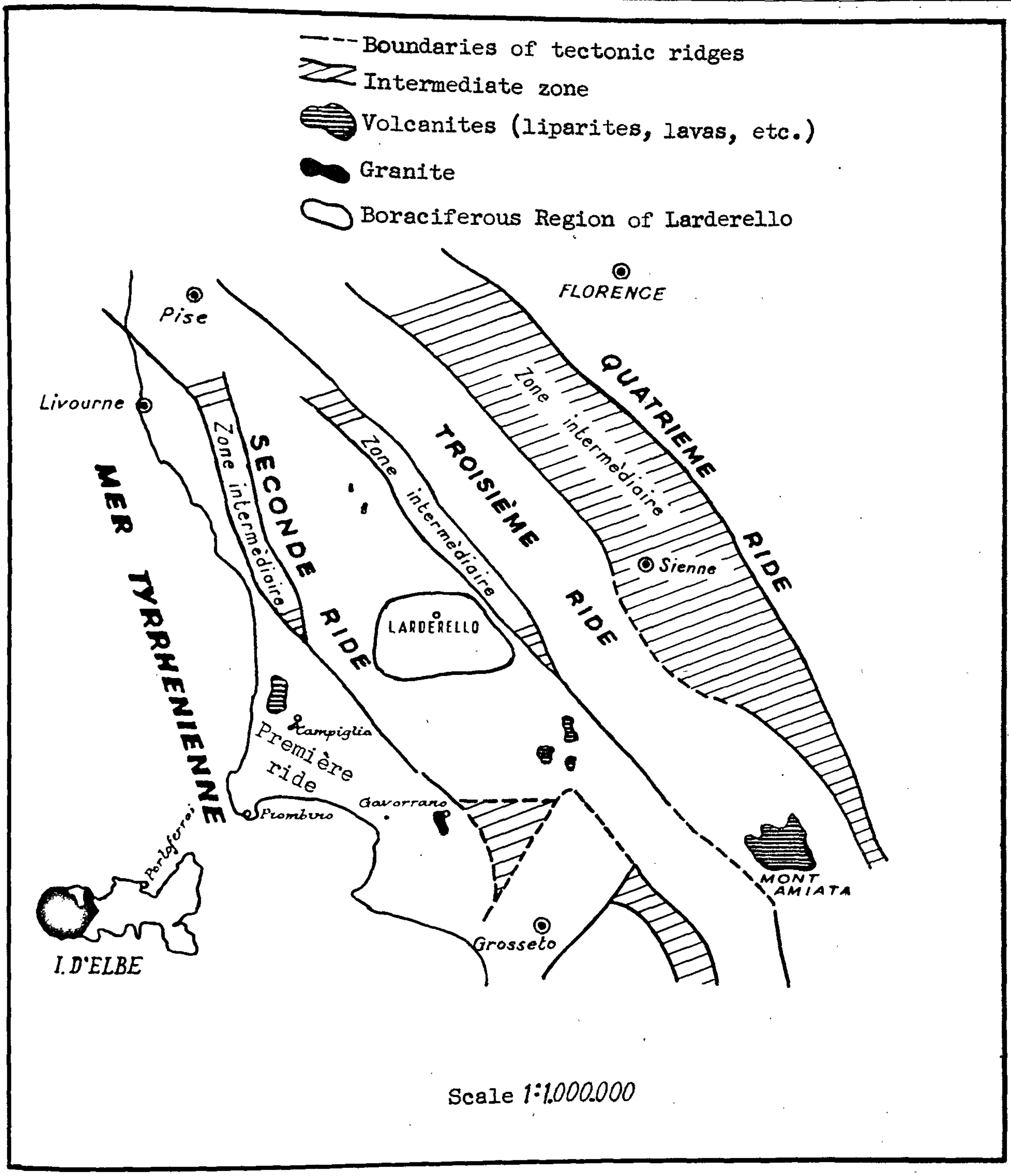


**Figure 5. Tectonic scheme of Tuscany**

The last series of the local stratigraphic sequence is the allochthonous cover of "schistose clays", whose thickness may range from 200 to over 2 000 m, and which consists essentially of argillaceous schists accompanied by limestones and other rocks. This formation, above which there are sometimes more recent layers (Neogene), themselves also essentially argillaceous, is impermeable and acts as a "lid" for the entire geo-hydrothermal system.

## Natural geothermal activity

It seems opportune to resume, at this point, the examination of the springs and vents mentioned at the beginning of this section. It was essential first to describe, at least summarily, the general background against which this activity occurs today (or occurred in the past), in order to deduce the causes for its existence.

Table 2. Old analyses of gases taken from natural vents of the Boraciferous Region

| *Locality* | *Hydrogen sulfide* | *Carbon dioxide* | *Nitrogen* | *Methane* | *Hydrogen* |
|---|---|---|---|---|---|
| Larderello . . . . . . . . . | 4.20 | 90.47 | 1.90 | 1.43 | 2.0 |
| Castelnuovo. . . . . . . . | 3.76 | 92.63 | 1.08 | 0.90 | 1.63 |
| Sasso. . . . . . . . . . . . | 5.43 | 88.33 | 1.55 | 2.01 | 2.55 |
| Serrazzano . . . . . . . . | 6.10 | 87.90 | 2.93 | 2.10 | 0.97 |

Most of these natural outlets have disappeared today, on account of the drainage of the most permeable horizons by the producing wells; they emitted steam and gases, or still emit them. As an example, we give an old analysis, performed about 1870 (table 2).

The data collected as a result of the expanding exploration work now enable us to say that natural hot springs and vents occur under specific local conditions, or, more exactly :

(*a*) Where the argillaceous cover ("schistose clays") is not thick (200-300 m) and directly overlies the "anhydrite series", coinciding with marked folding of the crystalline basement (zones of Larderello, Castelnuovo, Serrazzano, Lagoni Rossi);

(*b*) Where particularly permeable formations of the lower stratigraphic sequence outcrop through the "schistose clays", formations such as the anhydrite series or the jaspers of the "Malm" (Castelnuovo, Sasso, Monterotondo, Lago);

(*c*) To a lesser extent, along certain faulting contacts between different formations.

The natural outlets, especially where they were of greatest magnitude, may be assumed to have developed a direct channel for the discharge of the hot fluids to the surface, and thus to have allowed and determined the natural development of the phenomenon, perfecting the geo-hydrothermal cycle until the appearance of steam at the surface.

Moreover, by maintaining a dynamic regime of circulation, they were very probably the factors

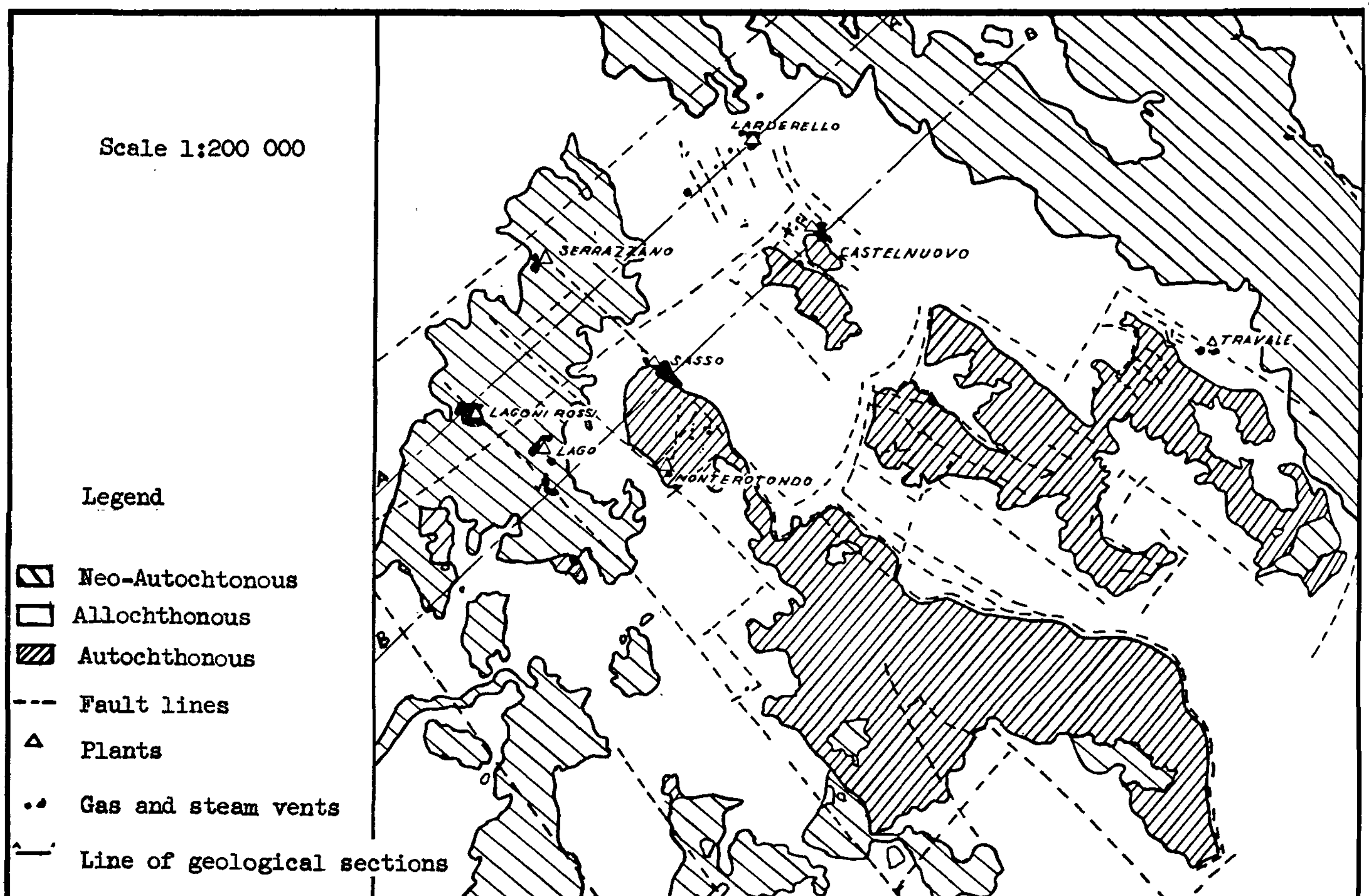


Figure 6. Geotectonic scheme of the Boraciferous region (Larderello "soffioni")

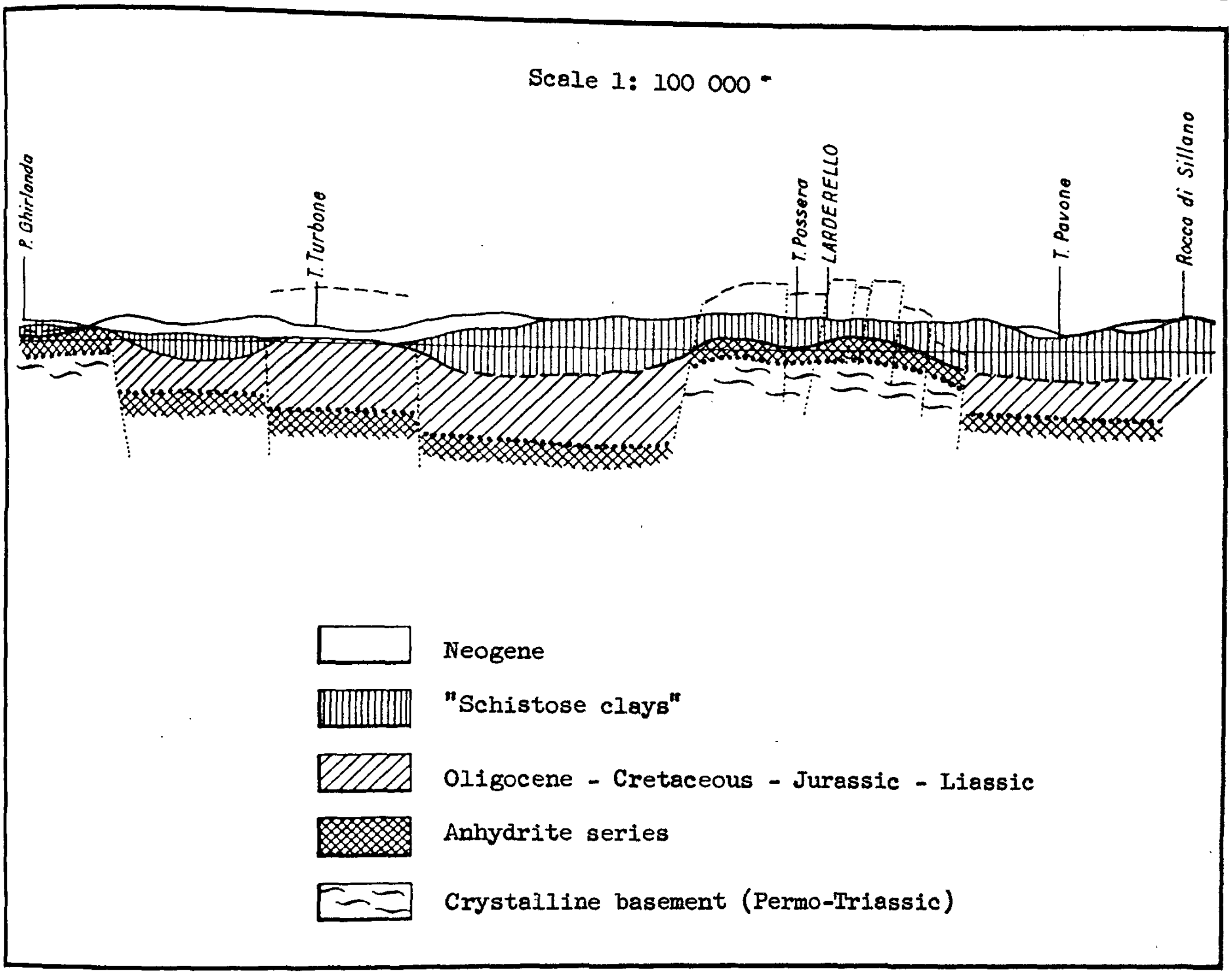


**Figure 7. Section of the geo-tectonic scheme of the Boraciferous region**

that permitted its development in the permeable horizons of the stratigraphic sequence, in particular the anhydrite series, and especially in the zones of its minimum thickness.

## Geological and geophysical exploration and prospecting

The criteria that guided exploration in the past were, as already noted, more than simplified, since the prospectors were concerned only with exploratory drilling as close as possible to the sites of surface activity; thus, these outlets long provided the sole guide for exploration.

Subsequently it was recognized, to an ever increasing extent, that a set of exploratory and prospecting operations had to be performed, in order to collect the largest possible amount of information that would provide new criteria for guiding the drilling.

Thus, *surface geotectonic surveys* were performed, based on very detailed topographic maps (scale 1/10 000 and 1/25 000), sometimes drawn specifically for that purpose. These surveys, together with auxiliary petrographic and paleontological studies, made it possible to draw detailed geological maps and structural sections. These documents indicate:

(*a*) The outcropping formations, and on the sections, the formations present in depth;

(*b*) The principal fault lines;

(*c*) The stratigraphic and structural features.

These surveys covered a total area of 450 km$^2$ in the Boraciferous region.

As already mentioned, the allochthonous series of the "schistose clays" covers the greater part of the Boraciferous region. This allochthonous cover, which is extremely heterogeneous and dislocated, has no stratigraphic correlation whatsoever with the underlying autochthonous formations. Thus, this fact substantially complicates the interpretation of the surface geology. This is why various *geophysical exploration* methods were tried in order to obtain information on the substratum under the argillaceous cover. The following methods were tried a number of times at various locations:

(*a*) Electrical, the spontaneous polarization method;

(*b*) Electrical, the resistivity method (quadripole);
(*c*) Magnetic;
(*d*) Gravimetric;
(*e*) Radioactivity measurements;
(*f*) Seismic method, by refraction and reflection;
(*g*) Geothermal method.

Some of these methods had to be eliminated for various reasons, primarily because they proved unsuitable for solving the specific problems involved, while others (gravimetric and temperature surveys) proved suitable for regional prospecting aimed at recognition of the great magmatic masses with deep-seated intrusions and the great basement structures (gravimetry), or important geothermal anomalies (geothermal measurements).

Finally, the electrical resistivity method could be intensively applied, and yielded a rather faithful representation of the shape of the substratum of "schistose clays", making it possible to reconstruct the structural pattern and trace the fracture lines in good approximation.

In the Boraciferous region, 4 900 electrical loggings were run over a total area of 495 km².

## Bores

Very numerous bores were drilled (figure 8) in various zones, sometimes far apart (as much as 15 km) and arbitarily termed "steam fields". Other holes were drilled in positions intermediate between fields; the total area of exploration by drilling has expanded until it covers an area of 70 km² to date. The total number of boreholes is 380, without counting those drilled before the introduction of mechanical drills in 1926. The average measurements of these boreholes are as follows:

| | |
|---|---|
| Average depth . . . . | 700 metres |
| Maximum depth . . . | 1 600 metres |
| Maximum diameter . . | 584 millimetres |
| Minimum diameter . . | 143 millimetres |

The boreholes are all tubed with cemented steel of diameter and depth varying according to the circumstances.

The depth of the boreholes varies with the thickness of the impermeable cover ("schistose clays") and the consequent depth of the steam-bearing permeable strata (anhydrite series, series of jasper and quartzites of the basement).

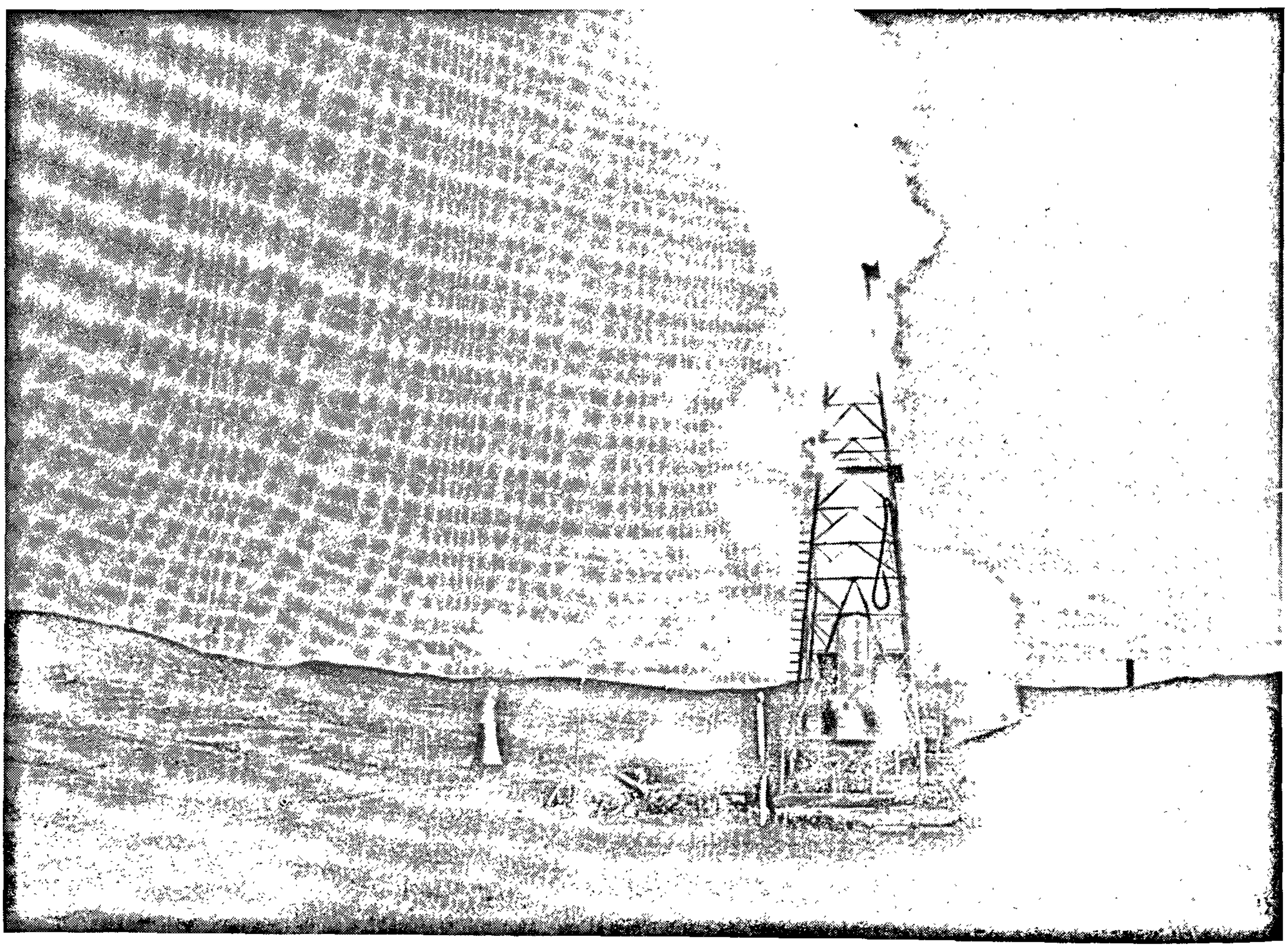

**Figure 8. Gusher test well in the Boraciferous region**

### Production

The production of the 160 wells now in production in the Boraciferous region, which feed the electrical and chemical plants of Larderello, S.p.A., is as follows:

| | |
|---|---|
| Steam flow . . . . . . . . . | 2 850 000 kg/h |
| Mean service pressure . . . . . | 5 atm abs |
| Shut-in wellhead pressure . | 10 to 32 atm abs |
| Mean temperature . . . . . . . . | 200°C |
| Maximum temperature . . . . . . . | 245°C |

The average chemical composition of the fluid produced is as follows:

| | *Grammes* |
|---|---|
| Steam ($H_2O$) . . . . . . . . | 955.0 |
| Carbon dioxide ($CO_2$) . . . . | 42.5 |
| Combustible gases ($CH_4$ and $H_2$) . . . . . . . . . . . . | 0.2 |
| Hydrogen sulfide ($H_2S$) . . . | 0.9 |
| Nitrogen ($N_2$) . . . . . . . . | 0.16 |
| Boric acid ($H_3BO_3$) . . . . . | 0.25 |
| Ammonia ($NH_3$) . . . . . . | 0.30 |
| Rare gases (He, Ar, Ne) . . . | 1.0 cc. |

As an example, figure 9 is a graph of the flow of a well, in kg/h, plotted as the ordinate, against the time in months and years as the abscissa. Examination of this graph, which is practically similar to those of all the steam wells of the region, shows clearly the sharp fall in production during the initial period of well life. This decline then gradually flattens out, and the production curve approaches an asymptotic value. Some wells have been producing for about forty years, with a flow now reduced to a tenth of its initial value.

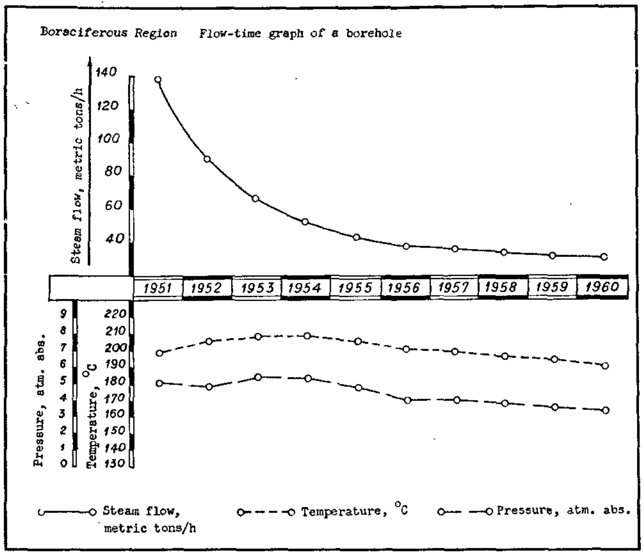


**Figure 9. Flow-time graph of a borehole in the Boraciferous region**

## The Monte Amiata region

### Introduction

The Monte Amiata region is likewise located a short distance (50 km) from the coast of the Tyrrhenian Sea, and about 70 km SE of the Larderello region, entirely in the Tuscan provinces of Grosseto and Siena (figure 10). It is a mountain massif rising abruptly above the surrounding area to an elevation of 1 738 m. Geographical co-ordinates: 42° 49′ to 42° 57′ Lat. N, 11° 31′ to 11° 41′ Long. E.

### Geology

The stratigraphic sequence of sedimentary formations in this region differs in no way from that in the Larderello region, discussed above, and omission of its description is therefore felt to be in order.

One substantial difference, however, is the presence here of volcanic formations, represented by "ignimbrites" (trachytes, in the old terminology), which make up the relief of Monte Amiata from the level of about 800 m to the summit.

These ignimbrites were produced by acid volcanism, which manifested itself largely in volcanic clouds.

The mass of ignimbrites also contains true lavas in the shape of domes and extrusion ridges formed along the fissures through which the magma was ejected.

### Tectonics

The tectonics of the Monte Amiata zone likewise partially repeats the theme dominant at Larderello. At many points the stratigraphic sequence is reduced and stratified, putting the "schistose clays" into direct contact with the anhydrite series. A further complication, however, has been introduced by the magmatic intrusion, followed later by a sharp volcano-tectonic collapse due to the eruption, and which has given rise to a new fault system.

### Manifestations

In the Monte Amiata area, near the volcanic shield, a series of modest outlets are noted. They consist of hot springs, ranging in temperature from 20 to 50°C, and mainly of vents of cold gas composed essentially of $CO_2$ and $H_2S$, aligned along the principal fissure systems. This activity, which is very modest, owing to the high impermeability of the argillaceous cover, distinctly differentiates the Amiata zone, in this respect, from the classical zone of Larderello.

### Geological and geophysical exploration and surveys

In this region, too, we carried out a series of preliminary surveys and exploration work, comprising a geo-tectonic detail survey consisting of analyses and studies relative to the problem, and geophysical exploration by the resistivity and gravimetric methods.

### Drilling

Twelve boreholes have been drilled in this region up to now, near Bagnore, where the preliminary work indicated a marked elevation of the substratum

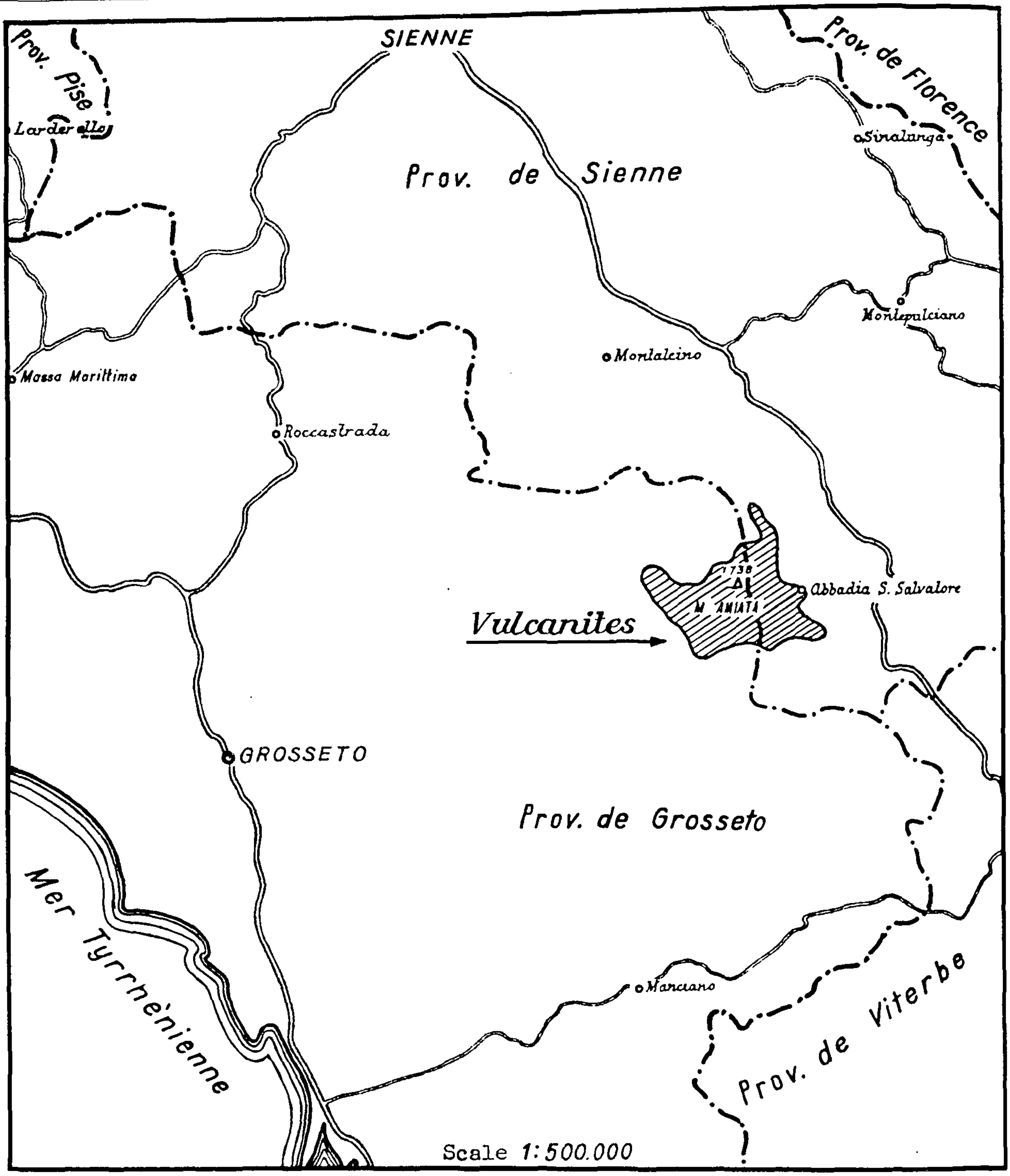


**Figure 10. Monte Amiata region: planimetry**

under the "schistose clay" cover. It was reasonable to assume, in this connexion, from the resemblance with other strongly uplifted zones, that the very permeable anhydrite series might also be found here in direct contact with that cover. The initial drilling has fully confirmed this hypothesis.

The boreholes in this region have characteristics identical with those of Larderello. They range in depth from 400 to 1 100 m.

### Production

As already mentioned, the natural geothermal activity in this region is rather on the modest side, and consequently there has been no natural evolution of the geo-hydrothermal cycle, as at Larderello, accompanied by spontaneous liberation of the major part of the gases and presence of steam at the surface.

The first boreholes yielded enormous flows of gas ($CO_2$ and $H_2S$) which was present in the veritable accumulations in the depths and may be in large part emulsified or dissolved in the water. The volume of the gas flow decreased markedly with time.

It will suffice as an example to mention the data on the gas/steam percentage ratio in the fluid discharged by Bagnore No. 1 well, the first to be drilled in this zone (table 3).

The total production today from the five production wells in the Monte Amiata region is 200 000 kg/h of a fluid with the following average characteristics:

| | |
|---|---|
| Gas/steam ratio . . . . . . . . | 30 per cent gas |
| Shut-in wellhead pressure . . . . | 8.5 atm abs |
| Pressure under production conditions. . . . . . . . . . . . . | 5.5 atm abs |
| Temperature . . . . . . . . . . . | 150°C |

## Various regions

Besides the regions described above, where Larderello, S.p.A., has been conducting industrial operations, for over a century in the first case, and for three years in the second, there are also other regions of Italy (figure 11) where it has undertaken important preliminary prospecting work to determine the possibilities of discovering endogenous fluids that can be industrially exploited.

Owing precisely to the preliminary status of these operations, it does not seem advisable to describe in detail the characteristics of each region. They are, incidentally, very similar to each other. These regions will therefore merely be mentioned by name, and we shall state as a whole the common features of the geological and hydrothermal conditions, as well as the work that has been undertaken.

### Roccastrada region

This region is located about 30 km SE of Larderello, in the southern part of the Metalliferous Hills, in the Tuscan provinces of Grosseto and Siena. Geographical co-ordinates: 42° 55′ to 43° 04′ Lat. N, 11° 02′ to 11° 16′ Long. E.

### Region of Montecatini-Orciatico (near Volterra)

This region is about 25 km N of Larderello, in the Tuscan province of Pisa. Geographical co-ordinates: 43° 24′ to 43° 27′ Lat. N, 10° 28′ to 10° 45′ Long. E.

### La Tolfa region

This region is likewise a few kilometres from the coast of the Tyrrhenian Sea, near Civitavecchia and Santa Marinella, in the province of Rome, in Latium. Geographical co-ordinates: 42° 01′ to 42° 12′ Lat. N, 11° 47′ to 12° 04′ Long. E.

### General features

The features common to all these regions is the existence of a series of sedimentary formations similar to that of Larderello, with very impermeable horizons covering deep formations, more or less permeable, and mainly the presence of a more or less great mass of recent volcanic acid products (ignimbrites), similar to, and perhaps contemporary with, those of Monte Amiata.

The tectonics is marked by structures strongly uplifted over the others, and by directrices of faults of varied orientation.

The natural outlets consist primarily of thermal springs whose temperature may reach 50-60°C, and of vents of cold sulfo-carbonic gases, similar in all respects to the outlets at Monte Amiata.

### Region of the Monti Berici

Larderello, S.p.A., is also doing prospecting work, on a very preliminary basis, in the region of the Monti Berici, in northern Italy, in Vicenza province, Venetia. Geographical co-ordinates: 45° 23′ to 45° 29′ Lat. N, 11° 27′ to 11° 36′ Long. E.

Important traces of fairly recent volcanism are found in this region, as well as natural geothermal activity in the form of hot springs and gas vents ($CO_2$ and $H_2S$) (figure 12).

### Geological and geophysical exploration and surveys

Detailed geological surveys and studies on a total area of 1 050 km² have been run on the above regions, and the following geophysical exploration work has also been carried out: gravimetry on 1 760 km² with 2 300 stations; electric (resistivity) logging on 650 km² with 1 150 bores.

### Boreholes

In the La Tolfa and Montecatini regions, the first drillings have already begun, and it is planned to initiate such work in the near future in the other regions.

**Table 3. Percentages of gas and steam from bore "Bagnore 1" (Monte Amiata region)**

| *April 1959* | | *October 1959* | | *April 1960* | | *October 1960* | | *March 1961* | |
|---|---|---|---|---|---|---|---|---|---|
| *Gas per cent* | $H_2O$ | *Gas per cent* | $H_2O$ | *Gas per cent* | $H_2O$ | *Gas per cent* | $H_2O$ | *Gas per cent* | $H_2O$ |
| 81.0 | 19.0 | 77.1 | 22.9 | 64.4 | 35.6 | 35.0 | 65.0 | 23.2 | 76.8 |

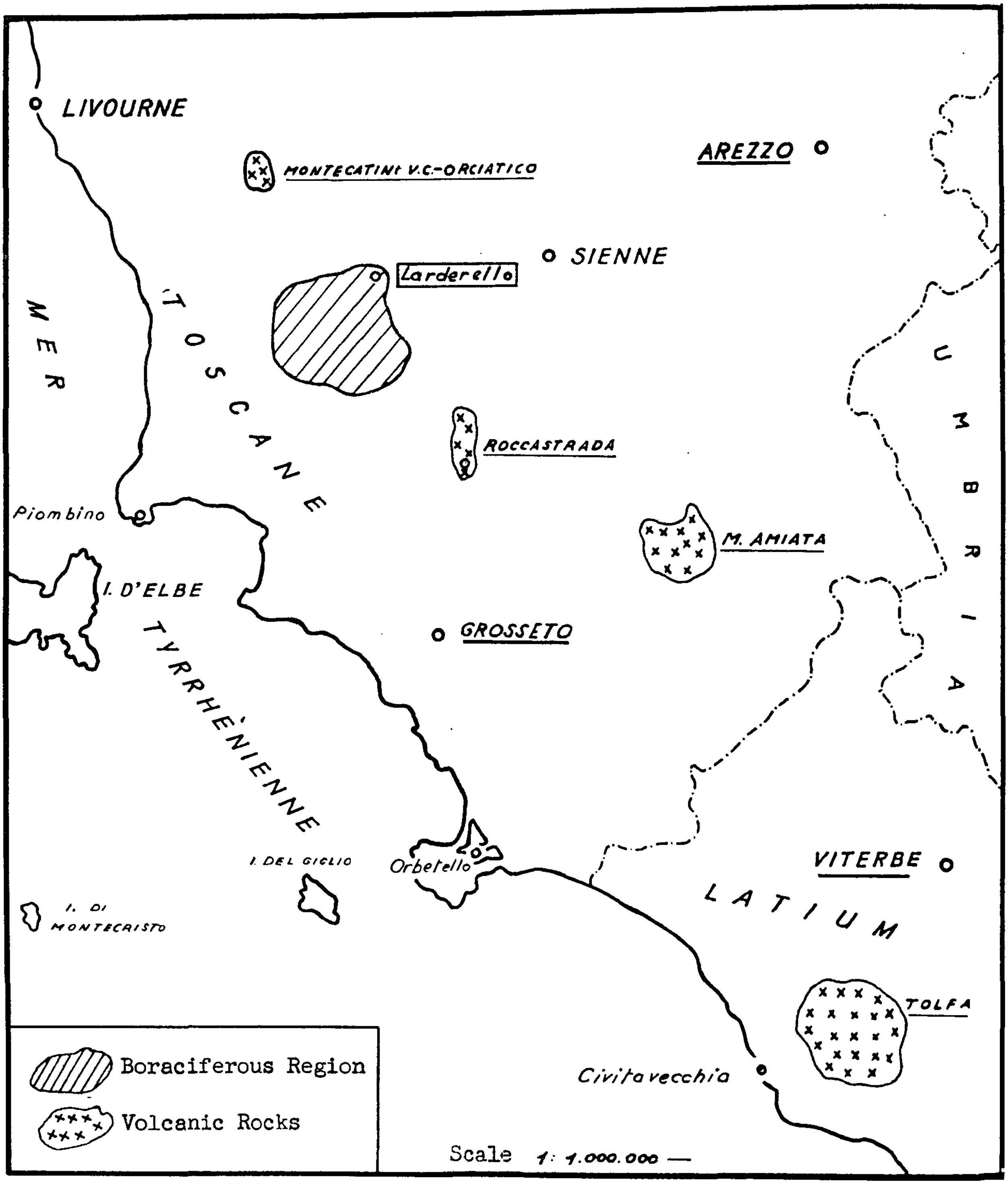


Figure 11. Roccastrada, Montecatini—Orciatico and La Tolfa regions

## Probable indications and peculiar features that may guide prospecting for endogenous fluids in new zones

We have already seen that neither in the Boraciferous Region of Larderello nor in its immediate vicinity is any outcropping of recent magmatic rocks encountered, and that even the bores, at least down to the depths of 1 500 to 1 600 m reached to date, have likewise not encountered such rocks. This fact justifies the assertion that the presence of magmatic effusions is not an essential condition for prospection work.

As for zones like Monte Amiata, where we do note the presence of magmatic effusions, it seems that the age of these phenomena should be the primary factor considered. Both at Monte Amiata and in the other regions mentioned in this paper

(La Tolfa, Roccastrada, etc.), the magmatism is invariably post-Pliocene.

One necessary condition is the existence of an appreciable geothermal anomaly in the zones under consideration. Such an anomaly may be disclosed, *inter alia*, by the presence of hot springs, and, under the most favourable conditions, by steam jets, but still better by regional temperature surveys with shallow boreholes (maximum depth of 50 m) arranged in a net with sides one to two kilometres in length.

The geothermal gradients found in the Larderello region boreholes may be as high as 9°C in 10 m, which seems highly significant. In addition to the presence of hot springs, vents of $CO_2$ and $H_2S$ gases (even cold) may furnish other symptomatic indications, for these gases are generally due to magmatic phenomena.

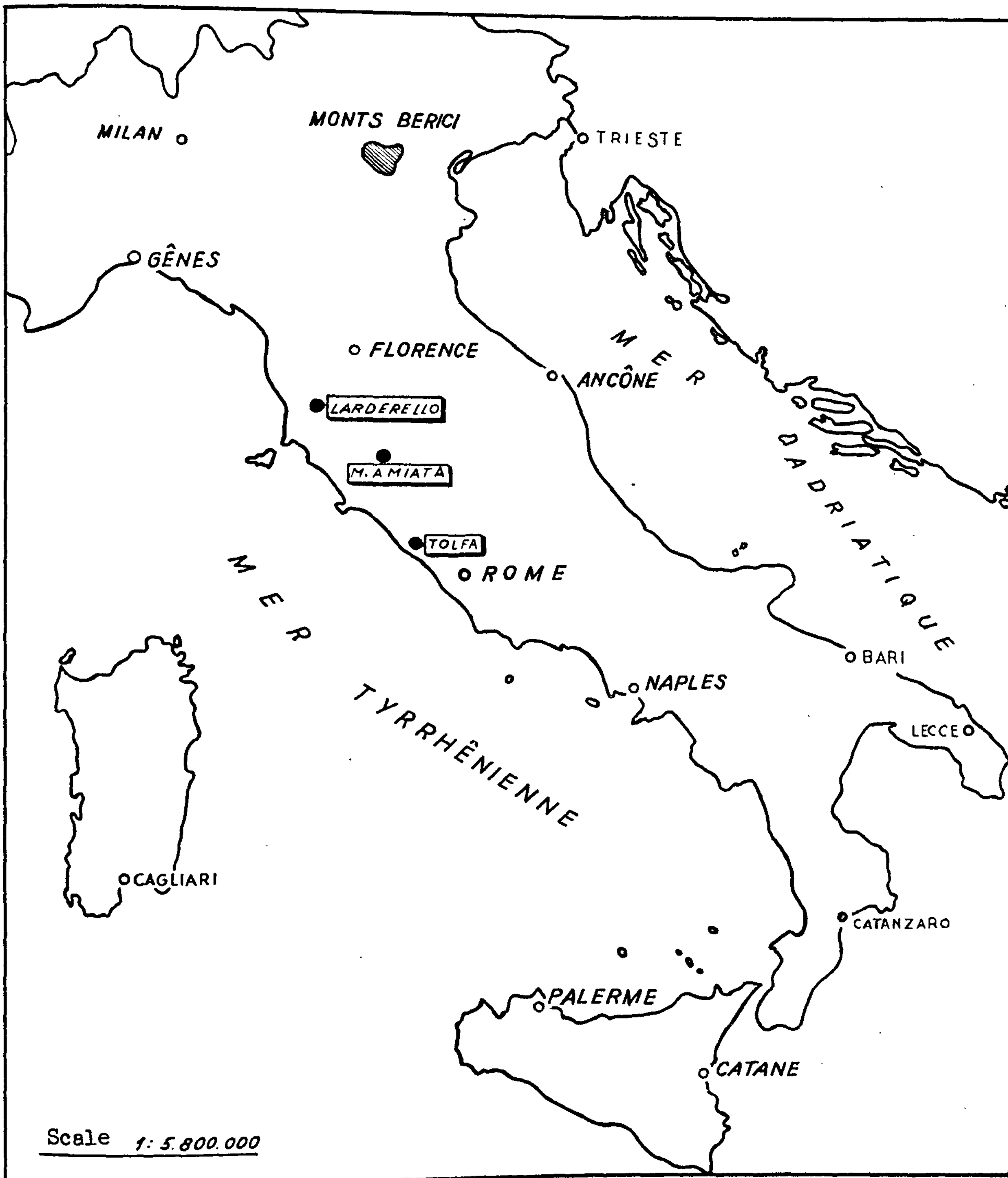


Figure 12. Map of Italy showing the Monti Berici region

Still another important indication is the presence of boron, which, in larger or smaller quantities, is always present in the fluids from the natural outlets found in the zones where the results of prospecting operations have been favourable (Larderello, Monte Amiata, La Tolfa, etc.).

As for the general geological background, the following conditions may be considered essential:

(*a*) Existence of an impermeable cover, to stop the upward diffusion or excessive dispersion of the fluids at the surface, and the rapid downward infiltration of cold meteoric water;

(*b*) Presence of permeable horizons in the local stratigraphic sequence at depths economically accessible to drilling. Consequently, another favourable condition is the phenomenon of folding, permitting the existence, in the zones in question, of certain high structures, which are obviously of greater interest for exploration and in the initial stage of prospecting;

(*c*) Sufficient fissuring of the regional basement formations to facilitate the ascent of hot fluids.

From what has been explained in this section, it would seem to be obvious that, in setting up a programme of prospecting for endogenous fluids, provision should be made for the following preliminary operations:

(*a*) Geo-tectonic detail survey of the entire region under consideration, based on topographic maps on a scale not smaller than 1/25 000;

(*b*) Survey of all the hydrothermal and gas outlets and analysis of the fluids;

(*c*) Regional temperature survey with shallow boreholes arranged in a regular net;

(*d*) Geophysical exploration by the most suitable method, to obtain the maximum information about the deep structures (gravimetric, electric, and other methods);

(*e*) Several exploration wells to collect data, in depth, about the stratigraphic sequence and the geothermal gradients.

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### *Summary*

In a brief introduction, the author indicates that exploration for geothermal energy in the Larderello region antedated such work in other regions of Italy and of the world. Work of this kind has been going on for a century at Larderello, and the endogenous fluids discovered are being industrially exploited. The author describes the characteristics of this region, beginning with its geographical position in the central part of Italy (Tuscany), only a short distance (averaging 30 km) from the coast of the Tyrrhenian Sea.

It is a hilly region which forms part of a range of heights called Metalliferous Hills on account of the metallic minerals they contain. These minerals are probably due to the Tuscan "magmatism" and should thus be associated with the Larderello phenomenon.

The first prospecting consisted of modest drilling operations, guided exclusively by the natural showings of steam and gas ($CO_2$ and $H_2S$) at various points of the region. The subsequent advances in the knowledge of the local conditions and in the mastery of the tools of the art disclosed new elements which served as guides for subsequent exploration.

In the light of this knowledge, the author illustrates the geotectonic and phenomenological characteristics of the region by describing the stratigraphic sequence of the area.

This sequence is exclusively sedimentary, and is formed by a regional basement (phylladic schists and Permo-Triassic quartzites), by a Triassic and Liassic evaporitic series consisting mainly of limestones, and by several Cretaceous-Eocene and Oligocene formations (argillaceous schists, as well as limestones and sandstones).

This entire sequence is covered (except for small zones) by an allochthonous flyschoid formation consisting of limestones and argillaceous schists of various ages (mainly Cretaceous-Eocene) in irregular and random arrangement.

The accessory cover of this formation consists of Miocene and Pliocene sediments (clays, sands and conglomerates).

To illustrate the regional tectonic situation, the author refers to the structural effects of the Apenninean orogenesis which have led, in this region, to the formation of a series of anticlinal folds in Apenninean direction, with great fractures (faults) and overthrusts.

Most probably a subsidence occurred simultaneously with the surface folding, leading to the consequent progressive descent of rock masses towards hotter and hotter zones, until the establishment of the conditions necessary for their metamorphosis into granite.

During the successive phases of ageing of the folds, with the phenomena of crustal bulging, the potentially mobile magmatic accumulations found the conditions necessary for an ascent towards the surface, if not for effusion onto the surface itself (intrusions).

In these new and more superficial positions, the magma became consolidated by dissipation of heat and ejection of its volatile portions.

The author then discusses the probable age of the principal fractures associated with the autochthonous formations. They are of varying age, according to the various tectonic movements that have taken place in the region. He believes the formation of the most recent fractures was the most favourable to the ascent of the heat flux.

Examination of the above geotectonic characteristics discloses the following facts of major importance:

The very great faulting of the ancient basement formation (Permian) along very well determined directional lines;

The presence, in the local stratigraphic sequence, of highly permeable formations (mainly the "Triassic anhydrite series");

The existence of statigraphic breaks putting this formation into direct contact with the argillaceous cover series;

The high impermeability of the cover formation, which serves as the "great lid" for the entire geohydrothermal system.

The author notes that the natural showings (steam and sulfido-carbonic gas) were liberated, or are still being liberated, in the zones where the argillaceous cover is not so thick, in the rare zones where the more permeable underlying formations outcrop to the surface, and, finally, in occasional cases, along the faulting contacts between formations of different nature.

The author also describes the prospecting operations and the geological and geophysical exploration work conducted in the Boraciferous region to obtain new elements that might serve to guide the exploration work.

This work consisted of detailed geotectonic studies and of various types of geophysical exploration. Some of these geophysical methods proved to be more suitable than the others for the requirements of this work, such as the electrical (resistivity) method, the geothermal method, and the gravimetric method.

The paper then reports on 380 boreholes drilled in this region. The total steam flow of the 160 active boreholes is 2 850 000 kg/h.

After describing the Boraciferous region, the author passes to the description of the Monte Amiata region, still in Tuscany, but about 70 km SE of the former field.

Although the sedimentary stratigraphic series of this region resembles that of the Boraciferous region, there is nevertheless a substantial difference between the two regions, since here we find effusions of acid volcanic rocks (ignimbrites).

The author points out that in this zone the layer of the "schistose clays" of the cover is highly impermeable, so that only very modest gas showings are found at the surface (mainly $CO_2$).

The eleven boreholes drilled in this region encountered large amounts of fluids, consisting at first of 96 per cent gas and 4 per cent steam. There was a remarkable improvement later, however, and the present ratio is 23 per cent gas to 77 per cent steam. The total production of the active holes is 160 000 kg/h at an average wellmouth pressure of 6 atm.

The Larderello company has been successfully prospecting for endogeneous fluids in the Boraciferous and Amiata regions, for over a century in the former case, and for three years in the latter. There are also other regions on which the company is now initiating similar exploration work:

The Roccastrada region of Tuscany, about 30 km SE of Larderello;

The Montecatini-Orciatico region of Tuscany, about 25 km N of Larderello;

The La Tolfa region of Latium, 150 km SE of the Boraciferous region.

In all these regions, the sedimentary series resemble those of the Boraciferous region, but there is an important difference. Effusions of acid volcanic rocks are noted in all of them, as in the region of Monte Amiata.

The Larderello company is also conducting exploration work, in a very preliminary stage, in the region of the Monti Berici in Northern Italy (Venetia), where there are acid volcanic products of very recent origin.

In the above regions, detailed geotectonic studies have been performed, together with geophysical exploration by the electrical (resistivity), gravimetric and geothermal methods. In the La Tolfa and Montecatini regions, the first drillings have already begun.

In concluding this report, we recall the varied conditions, indices and peculiar characteristics that may be of use in preparing an exploration project for hot fluids in various zones:

The presence of volcanic effusions in the zone is not an indispensable condition for the success of the prospecting operation (the Larderello region is a typical example of this);

On the other hand, the existence of an appreciable thermal anomaly does constitute an indispensable condition;

Existence of a cover composed of highly impermeable formations;

Presence of highly permeable horizons at a depth economically accessible to drilling;

Presence of faults in the more or less ancient formations that constitute the regional basement.

Finally, the author advises all who propose to undertake prospecting for hot fluids to provide for a series of preliminary studies and work including the following:

Geological prospecting operations and studies;

Geophysical exploration (electrical, gravimetric, geothermal, etc.);

Drilling of several exploration boreholes.

# PROSPECTION GÉOTHERMIQUE POUR LA RECHERCHE DES FORCES ENDOGÈNES

*R. Burgassi *, F. Battini * et J. Mouton †*

## Conditions géologiques et géothermiques du champ de Larderello

La vapeur exploitée dans la région de Larderello (Toscane) provient d'une série perméable constituée essentiellement par les calcaires caverneux et les anhydrites du Trias supérieur (rhétien), surmontant des schistes et quartzites du Permien. L'ensemble est recouvert par la série imperméable des « argille scagliose ».

La roche magasin peut également être constituée par des grès oligocènes (« Macigno ») et des blocs de calcaires « alberese » qui se trouvent parfois à la base des « argille scagliose ».

La couverture argileuse imperméable maintient sous pression dans la série calcaire un fluide surchauffé (lequel se détend et se vaporise dans les forages d'exploitation). La série calcaire est alors portée à la température du fluide (200-240 °C) et agit comme une source de chaleur provoquant une augmentation du flux et du gradient géothermique dans les terrains de recouvrement.

Dans les zones stériles où les calcaires ne contiennent pas de fluide surchauffé, soit par défaut d'alimentation, soit par défaut de perméabilité, flux et gradient doivent être beaucoup plus réduits.

La société Larderello, S.p.A., s'est proposé de mesurer les variations du flux de chaleur le long d'un profil perpendiculaire à la zone productive de Larderello-Castelnuovo et atteignant à ses deux extrémités des zones stériles (voir fig. 1 pour la position du profil).

Cet essai devait permettre de mettre au point la technique opérative, de juger de l'efficacité de la méthode géothermique et de préciser ses possibilités d'application à de nouvelles zones.

## Mise en œuvre de la prospection géothermique

Une série de sondages en petit diamètre de 30 à 35 m de profondeur, non tubés, ont été disposés le long d'un profil d'essai à des intervalles compris entre 300 et 600 m.

Des mesures systématiques de température ont été effectuées (avec des thermomètres à résistance) dans chaque sondage et à différentes profondeurs pendant une période qui a duré entre 10 et 50 jours suivant les sondages. Ces mesures ont permis de déterminer les éléments suivants :

*a*) La durée de stabilisation du sondage après la fin de la perforation (le mouvement de l'outil et la circulation de la boue perturbant notablement la répartition normale des températures dans les formations). La stabilisation définitive est extrêmement longue mais en pratique l'équilibre est atteint à moins de 0,1 degré après une période variable entre 3 à 7 jours suivant les sondages.

*b*) La durée de stabilisation de la température de la boue dans les sondages après descente des câbles de mesure (20 minutes).

*c*) La profondeur limite de l'influence des variations de la température superficielle (généralement 10 m).

La figure 2 indique l'allure successive des diagrammes de température au cours de la stabilisation d'un sondage. L'équilibre est atteint lorsque les diagrammes se superposent.

On a pu montrer d'autre part qu'à partir de 15 m de profondeur la variation saisonnière de température était nulle, ou tout au moins pratiquement négligeable. Une légère variation (de l'ordre de 0,2 °C pour 50 jours) a cependant été observée pour certains sondages : elle correspond probablement à la dernière phase de stabilisation des sondages, qui est fort longue.

Les gradients de température ont été déterminés, dans chaque sondage, une fois l'équilibre thermique atteint. Pour un flux donné, ce gradient varie avec la conductibilité thermique K des terrains (suivant la loi de Fourier, le flux $\Phi$ à travers une surface $S$ est $\Phi = K \times S \times$ gradient). Cela est bien mis en évidence dans les forages ayant traversé des terrains de natures diverses (fig. 3).

Pour que les valeurs des gradients mesurés soient proportionnelles aux valeurs du flux en chaque point, il faut donc que ces gradients soient rapportés à un terrain de même conductibilité thermique. Un coefficient de correction, fonction de la nature des terrains (reconnue par carottage électrique), a été évalué à partir des diagrammes de température. Dans la zone de Larderello, sa valeur passe de 1 pour les terrains très argileux à 2 pour les terrains très calcaires.

En tenant compte de la valeur de ce coefficient pour chaque sondage, l'ensemble des gradients mesurés a alors été rapporté à un terrain argileux à basse conductibilité thermique.

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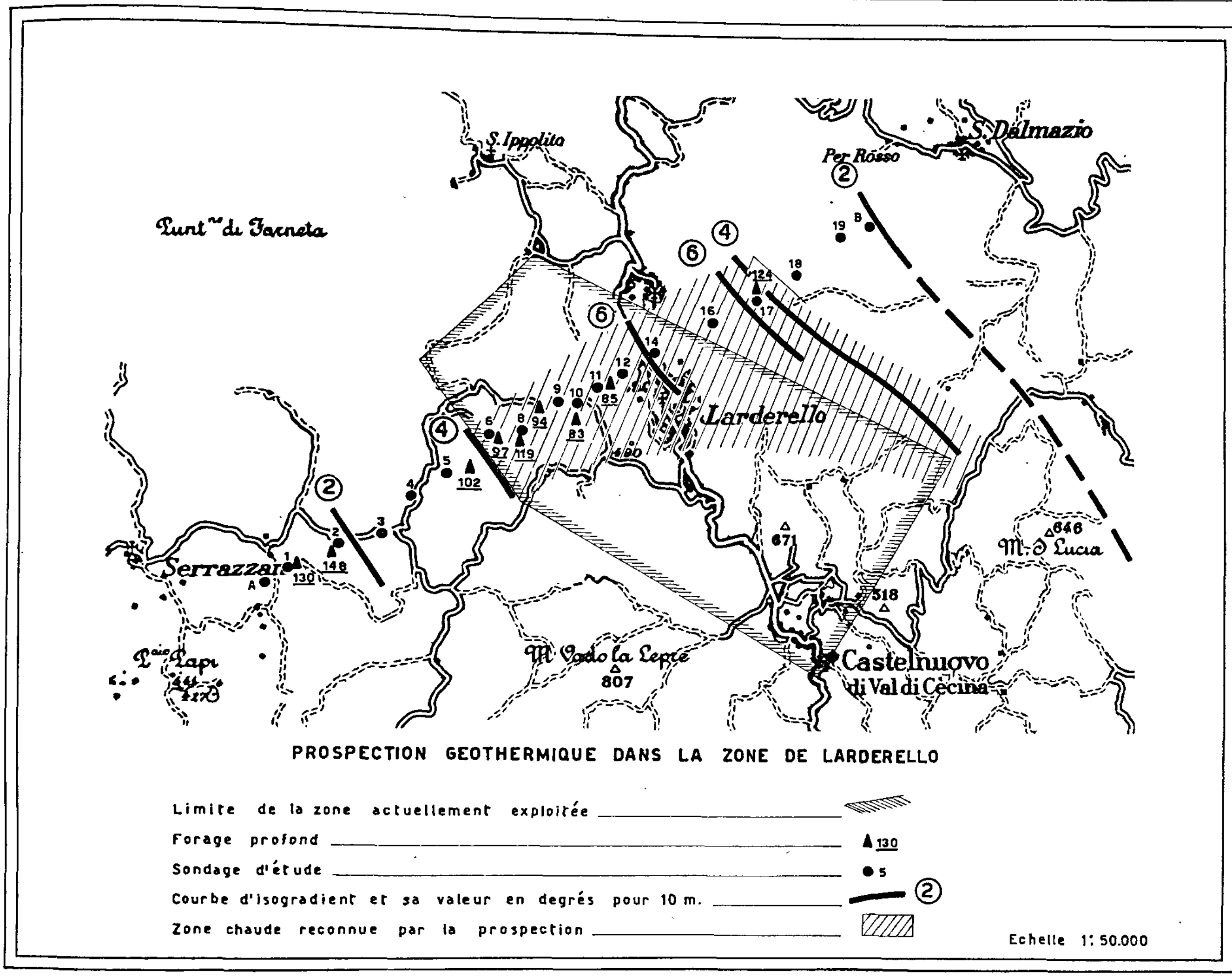


Figure 1

## Examen des résultats de la prospection

### Anomalie du gradient à l'aplomb de la zone productive

La courbe des gradients de température (le gradient indiqué correspond à l'accroissement de température sur 10 m) mesurés et corrigés a été reportée sur la figure 4. Sur la même figure est indiquée l'allure de la topographie superficielle et celle du substratum calcaire des « argille scagliose » (d'après les données des forages et de la prospection électrique).

Le gradient mesuré présente des valeurs fort élevées (plus de 5° pour 10 m) dans la partie centrale du profil, qui correspond à une zone chaude et structuralement haute, et des valeurs plus basses (1,5 à 2° pour 10 m) de part et d'autre de cette zone.

On a cherché à se rendre compte si cette diminution du gradient était due seulement à l'enfoncement des calcaires ou si elle correspondait également à l'absence de fluide surchauffé dans ces mêmes calcaires.

La surface topographique (ou plutôt la surface qui se trouve vers 10-15 m de profondeur à la limite d'influence des variations externes de température) et la surface des calcaires (s'ils sont imprégnés de fluide surchauffé) peuvent être considérées de manière approximative comme deux isothermes, la première à la température de 10°, la seconde à la température de 220°.

Le gradient géothermique aura une valeur variable suivant la distance de ces deux isothermes. La valeur moyenne approximative de ce gradient théorique a été indiquée sur la figure 4.

Si les calcaires sont effectivement imprégnés de fluide surchauffé, le gradient mesuré doit être supérieur au gradient théorique. En effet, la conductibilité moyenne du recouvrement augmente avec les nombreuses inclusions calcaires et avec la profondeur : elle se trouve alors toujours supérieure à la conductibilité du terrain argileux superficiel de référence.

La zone anomalique où se trouve vérifiée cette condition est indiquée en hachurés sur la figure 4. Elle se situe dans la partie médiane du profil de

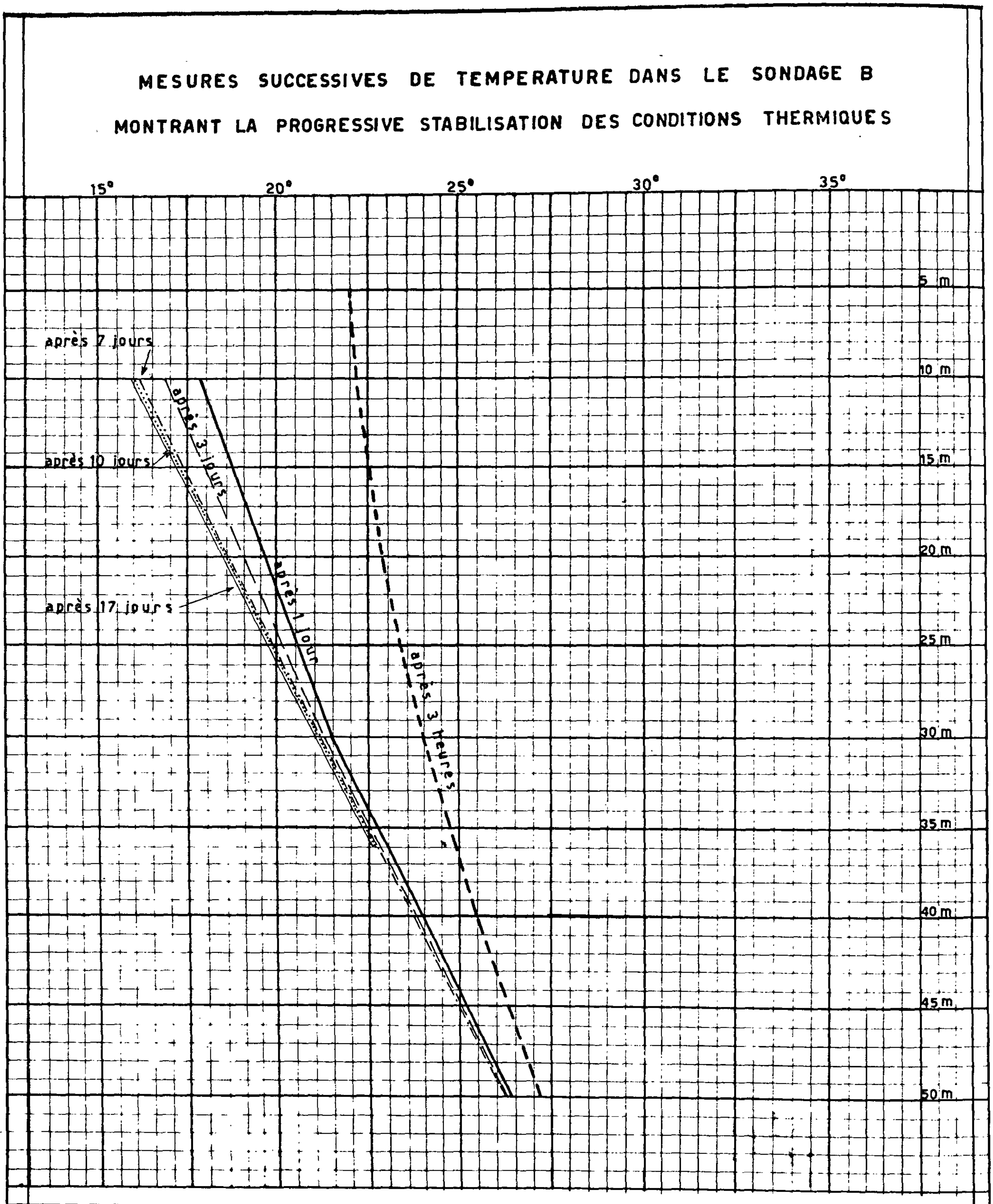
MESURES SUCCESSIVES DE TEMPERATURE DANS LE SONDAGE B
MONTRANT LA PROGRESSIVE STABILISATION DES CONDITIONS THERMIQUES
15°
20°
25°
30°
35°
5 m
10 m
15 m
20 m
25 m
30 m
35 m
40 m
45 m
50 m
après 7 jours
après 10 jours
après 17 jours
après 3 jours
après 1 jour
après 3 heures

Figure 2

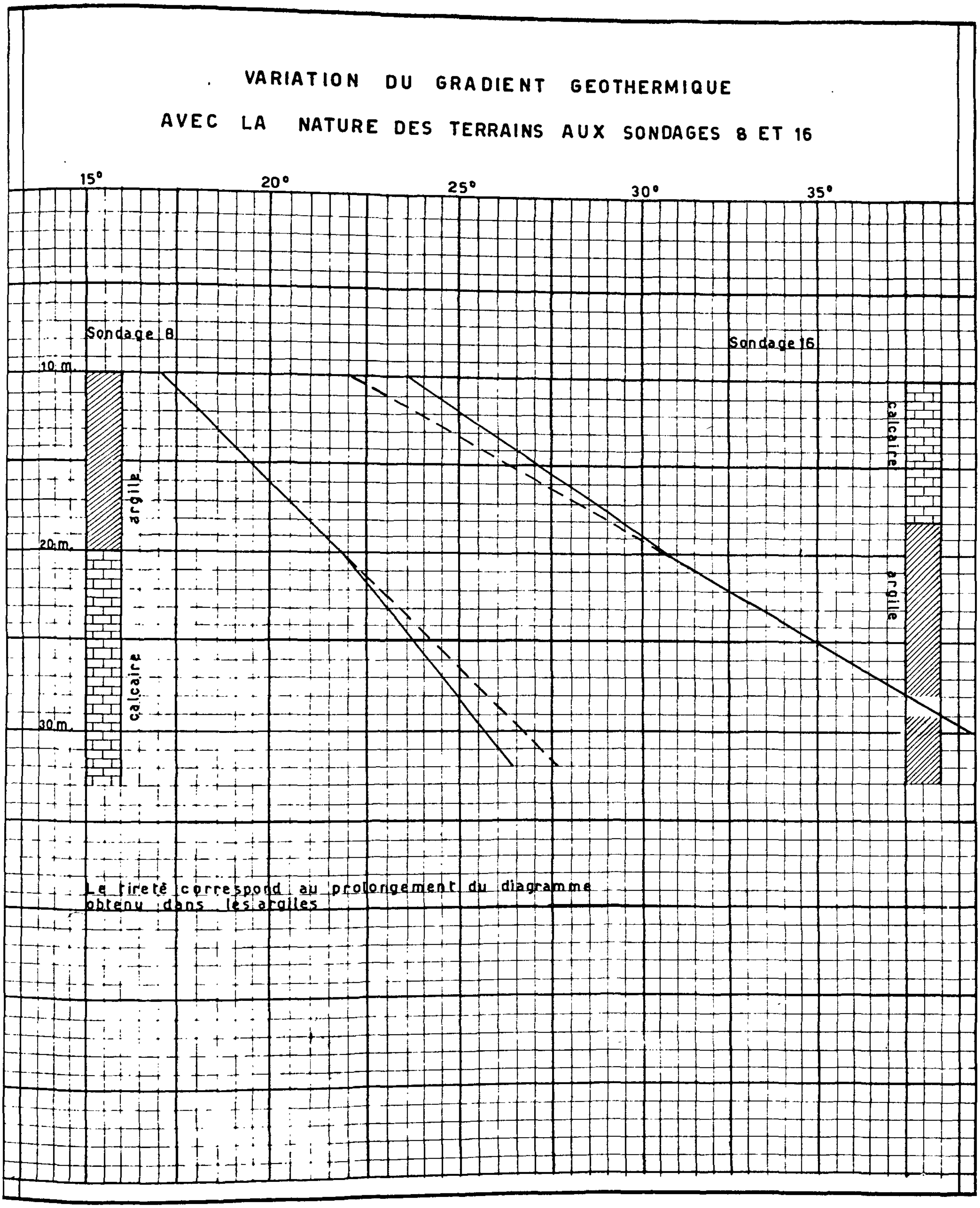
VARIATION DU GRADIENT GEOTHERMIQUE
AVEC LA NATURE DES TERRAINS AUX SONDAGES 8 ET 16
15°
20°
25°
30°
35°
Sondage 8
Sondage 16
10 m.
20 m.
30 m.
argile
calcaire
calcaire
argile
Le tireté correspond au prolongement du diagramme
obtenu dans les argiles

Figure 3

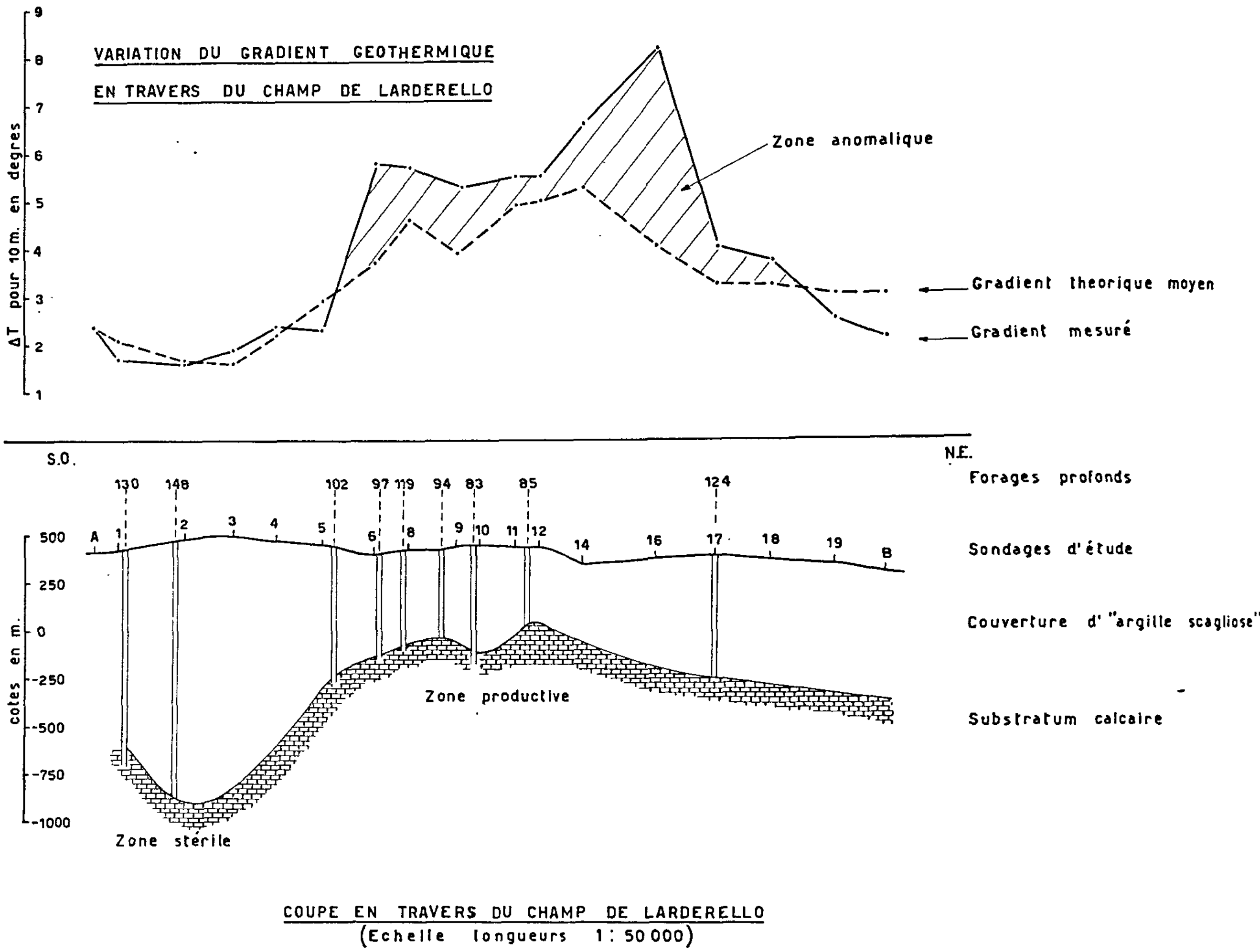


**Figure 4**

mesures et correspond exactement à l'extension du champ connu de Larderello.

On notera la valeur particulièrement élevée du gradient au sondage 16. Il s'agit probablement là d'une anomalie locale due à des montées superficielles de vapeur dans les inclusions calcaires des « argille scagliose ».

Les deux extrémités du profil où le gradient mesuré est inférieur ou égal au gradient théorique, correspondent au contraire à des zones stériles.

Les valeurs mesurées et corrigées du gradient sur le profil envisagé ci-dessus et sur un second profil d'étude qui lui est perpendiculaire ont été reportées sur la figure 2 où l'extension de la zone anomalique chaude a également été indiquée. Cette zone déborde légèrement au nord le champ actuellement exploité, et il paraît intéressant d'effectuer des forages dans cette direction.

### Anomalie régionale du gradient

On doit souligner que dans les zones reconnues stériles, le gradient a encore une valeur élevée (1,5 à 2° pour 10 m) notablement supérieure à celle du gradient géothermique normal (0,3° pour 10 m). C'est que toute la région de Larderello est probablement le siège d'une anomalie régionale du flux de chaleur, d'origine profonde (due par exemple à un magma en position anormalement haute). C'est ce gradient régional anormal qui provoquerait le réchauffement du fluide et sa montée par convexion le long des lignes de failles ou fractures jusqu'au toit de la série calcaire, où il est arrêté par la couverture imperméable des « argille scagliose ».

A cette anomalie régionale se superpose l'anomalie secondaire (que nous avons étudiée) due à la masse calcaire surchauffée, laquelle peut à son tour être masquée par de fortes anomalies locales dues à des remontées superficielles de vapeur dans les inclusions calcaires des « argille scagliose ».

## Critères pour l'emploi de la méthode géothermique dans de nouvelles zones

L'application de la méthode géothermique peut être envisagée sous deux aspects :

1) Un gradient régional anormalement élevé étant, semble-t-il, la condition de base pour la présence

de fluide surchauffé, il y a lieu de s'assurer, avant d'entreprendre des recherches détaillées et des forages profonds, que ce gradient anormal existe réellement. La détermination de la valeur régionale du gradient peut être exécutée à très large maille.

2) Dans les zones à gradient anormal et dans celles-là seulement, on peut dans un second temps rechercher les anomalies secondaires du flux, c'est-à-dire rechercher les zones susceptibles d'être effectivement productives, en associant la prospection géothermique à l'étude structurale du sous-sol par méthode géophysique classique (prospection électrique ou sismique). L'exemple du profil étudié à Larderello a montré que l'extension d'une zone productive pouvait effectivement être déterminée avec une bonne précision.


## *Résumé*

La vapeur exploitée à Larderello provient de calcaires triasiques protégés par une couverture imperméable d'argiles. Ces calcaires sont portés à la température du fluide (200-240°) qu'ils contiennent et constituent une source de chaleur qui provoque une augmentation notable du flux et du gradient géothermique dans les terrains argileux de recouvrement.

Des mesures du gradient de température ont été exécutées suivant un profil perpendiculaire à la zone productive dans des sondages d'une trentaine de mètres de profondeur. De nombreux essais ont permis de déterminer le temps nécessaire pour atteindre l'équilibre thermique des sondages après perforation et la profondeur limite à partir de laquelle les variations de la température superficielle n'ont plus d'influence sur les mesures.

Pour un flux donné, le gradient de température varie avec la conductibilité thermique des terrains, qui est plus élevée pour les calcaires que pour les argiles. Un coefficient de correction a donc été appliqué à chaque sondage, de manière à rapporter tous les gradients à un terrain argileux de basse conductibilité thermique.

La courbe des gradients de température corrigés présente des valeurs élevées dans la partie centrale du profil, qui correspond à une zone chaude et structuralement haute, et des valeurs plus basses de part et d'autre de cette zone.

Pour tenir compte des variations de profondeur des calcaires, on a établi une courbe des gradients théoriques, en admettant que le recouvrement est homogène et que la surface du sol et celle des calcaires constituent deux isothermes.

La conductibilité moyenne du recouvrement étant plus élevée que la conductibilité du terrain argileux de référence, le gradient mesuré et corrigé doit être plus élevé que le gradient théorique pour que les calcaires contiennent effectivement un fluide surchauffé.

Cela a été observé dans la partie centrale du profil, qui correspond à la zone productive de vapeur, mais ne l'a pas été dans les zones stériles extrêmes. La prospection géothermique permet donc de localiser avec une précision suffisante les zones favorables à la présence de fluide surchauffé.

La présence de ce fluide paraît d'autre part en relation avec un gradient régional anormalement élevé. Les sondages d'étude effectués à Larderello sont restés dans le secteur d'influence de ce gradient.

Dans de nouvelles zones, il paraît souhaitable, avant d'entreprendre des recherches détaillées et des forages, de s'assurer qu'un tel gradient régional anormal existe réellement. Dans l'affirmative et seulement alors, on pourra entrer dans une phase plus détaillée en associant prospection géothermique et prospection géophysique classique pour la détermination des zones les plus favorables à la recherche.


# GEOTHERMAL PROSPECTING FOR ENDOGENOUS ENERGY


## *Summary*

The steam utilized at Larderello originates in Triassic limestones protected by an impermeable cover of clays. These limestones, which are at the same temperature as the fluid they contain (200-240°C), constitute a heat source providing a considerable increment to the heat flux in the argillaceous cover, and causing a considerable increase of the geothermal gradient there.

Measurements of the temperature gradient have been made on a perpendicular profile in the producing zone in boreholes some 30 m deep. The time required after penetration of the drill for the borehole to attain thermal equilibrium has been determined by numerous experiments, and the limiting depth at which the variations of the surface temperature no longer affect the measurements has also been determined.

For a given heat flux, the temperature gradient varies with the thermal conductivity of the formations, which is higher for limestones than for clays.

A correction factor was therefore applied to each borehole to refer all the gradients to an argillaceous formation of low thermal conductivity.

The curve of corrected temperature gradients shows high values in the central part of the profile, corresponding to a hot and structurally high zone, and lower values outside this zone.

To allow for the variations in the depth of the limestones, a curve of theoretical gradients was plotted under the assumption that the cover was homogeneous and that the surface of the ground and that of the limestones were both isotherms.

The mean conductivity of the cover being higher than that of the argillaceous reference formation, the measured and corrected gradient should be higher than the theoretical gradient, because the limestones contain a superheated fluid.

This has been observed in the central part of the profile, which corresponds to steam production, but not in the non-producing extreme zones. Geothermal prospecting thus permits sufficiently accurate localization of the zones where the conditions favour the presence of superheated fluid.

The presence of this fluid may, on the other hand, be related to anomalous high regional gradient. The test borings at Larderello were in the zone of influence of this gradient.

It would seem desirable to make sure of the actual existence of such an anomalous regional gradient in newly developed zones before undertaking detailed exploration and drilling. In the affirmative case, and only in that case, should the more detailed phase be entered by combining geothermal prospecting with classical geophysical methods to determine the zones most favourable for study.

# CONTRIBUTION DES MÉTHODES GÉOPHYSIQUES A LA PROSPECTION DES CHAMPS GÉOTHERMIQUES

*J. J. Breusse* *

Pour bien comprendre les possibilités d'application des méthodes géophysiques à la recherche d'énergie géothermique, il convient tout d'abord de préciser la structure géologique que doit présenter un champ géothermique pour qu'il y ait production de vapeur sèche plus ou moins surchauffée ou d'un mélange de vapeur saturante et d'eau chaude.

Dans le cas de production de vapeur sèche surchauffée, cas le plus souhaitable évidemment, il est maintenant communément admis qu'un tel champ doit présenter les conditions suivantes :

*a*) Existence d'une batholite de roches acides en voie de refroidissement et de fractures importantes affectant les couches sédimentaires surincombantes, fractures plus ou moins ouvertes et qui seront en conséquence d'âge relativement récent, et comportant des chenaux de circulation pour le fluide endogène. Certaines de ces fractures pourront même atteindre la surface du sol et donner lieu à des « soffioni »;

*b*) Présence d'un ou plusieurs horizons perméables généralement fissurés ou caverneux jouant le rôle de magasin ou de réservoir;

*c*) Existence d'une couverture imperméable assurant la conservation du gisement;

*d*) Absence d'infiltrations, même latérales, d'eaux douces superficielles ou marines dans l'horizon magasin, lesquelles refroidissent le gîte et changent les conditions d'état physique du fluide endogène.

Pour la production de vapeur saturante et d'eau chaude, le champ devra avoir les caractéristiques suivantes :

*a*) Existence dans l'écorce terrestre d'une zone chaude, généralement d'origine volcanique;

*b*) Présence d'un horizon magasin, le plus souvent coulée de laves ou tufs volcaniques imprégnés de vapeur ou d'eau chaude;

*c*) Existence d'une couverture semi-perméable qui protège plus ou moins bien le gisement;

*d*) Un réseau de fractures peut également exister et favorise alors les circulations, mais il n'a pas ici le caractère impératif du schéma précédent.

Ces conditions étant posées, on a songé à utiliser différents paramètres physiques des roches et les méthodes géophysiques qui en dérivent pour la prospection géophysique des champs géothermiques. Par certains côtés, et en particulier d'un point de vue structural, cette prospection se rapproche de celle de la recherche des hydrocarbures. Ces paramètres sont : la température, la susceptibilité magnétique, la densité, la conductibilité électrique, la vitesse de propagation des ondes élastiques et la radioactivité.

## Température

L'énergie recherchée étant de nature géothermique, on a pensé tout d'abord à la mesure du gradient de température. Le but de l'opération est de mettre en évidence, au cours d'une reconnaissance générale, des anomalies qui seront produites par les zones chaudes. L'horizon magasin, à moins qu'il ne soit très profond, est porté à une température supérieure à celle que supposerait le gradient géothermique général, et il y a également l'influence des fractures superficielles. Dans ces conditions, les couches de terrain qui surmontent le magasin s'échauffent par conduction, et c'est ainsi qu'on a pu calculer que dans le cas d'un plan maintenu à une température $T$ et recouvert par exemple par des marnes, la température atteindra $T/2$ dans les marnes à 27 mètres au-dessus du plan au bout de 100 ans et à 270 mètres du même plan au bout de 10 000 ans.

Ce gradient de température pourra être déterminé, dans une première reconnaissance à large maille, à l'aide de mesures thermométriques exécutées au fond de simples trous de tarières disposés en quinconce, méthode assez rapide et peu coûteuse. Les zones anomaliques tant soit peu développées pourront ensuite faire l'objet de mesures identiques, mais au fond de forages d'une dizaine de mètres de profondeur, ou mieux en mesurant le gradient de température dans ces forages, afin de se libérer des fluctuations superficielles de la température.

Cependant, en règle générale, une région aura été retenue par le géologue spécialiste en raison des indices de surface qu'elle offre : émanation de vapeur et d'eau chaude, existence de geysers, de sources chaudes, solfatares, etc. Deux cas peuvent alors se présenter :

1) Si ces indices sont nombreux et suffisamment dispersés, on pourra ne pas avoir recours à une reconnaissance thermométrique, car ils constituent par eux-mêmes la réponse à ce qu'on peut attendre d'une première reconnaissance.

2) S'ils sont rassemblés ou quasi uniques, on peut recommander une telle prospection afin d'avoir une

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idée de la localisation et de l'extension des anomalies calorifiques produites par les zones chaudes.

## Susceptibilité magnétique

On a songé à utiliser les propriétés magnétiques des terrains, et en particulier leur susceptibilité, qui est l'intensité d'aimantation d'un petit volume de roche plongé dans un champ unitaire, en mettant en œuvre la méthode magnétique, soit au sol en mesurant (avec une balance de Schmidt, le plus fréquemment) les variations de la composante verticale du champ terrestre, soit en aéroportée en enregistrant le champ terrestre total à l'aide d'un magnétomètre.

L'horizon magasin et sa couverture seront le plus souvent constitués par des terrains sédimentaires, donc de très faible susceptibilité magnétique, et l'allure tectonique de ce magasin ne se traduira sur les mesures que d'une façon très floue, sinon même indiscernable. Ce qui peut s'inscrire sera l'effet, mais affaibli et étalé, de l'allure d'un substratum cristallin plus ou moins profond, effet qui sera difficile à distinguer des variations dues à l'hétérogénéité interne du socle. De plus, cet effet sera totalement masqué par les terrains volcaniques ou métamorphiques et plus ou moins ignorés qui peuvent exister dans la couverture.

Dans le cas présent, cette technique est la moins efficace et elle est certainement à écarter pour les prospections préliminaires tout au moins, malgré son faible prix de revient.

## Densité

Un autre paramètre qui peut être considéré est la densité, la méthode qui en dérive étant la gravimétrie. Elle consiste à mesurer les variations de l'intensité de la pesanteur entre les stations de mesure et une station de référence. Cette méthode est en général mieux adaptée que la méthode magnétique, néanmoins elle a l'inconvénient, tout comme cette dernière, d'inclure dans la mesure les effets de terrains superficiels et profonds. Certes, il peut se faire que l'horizon magasin et les couches qu'il surmonte soient plus denses que les terrains de la couverture, mais les anomalies résiduelles correspondantes pourront être masquées par l'effet d'hétérogénéités plus profondes, et la discrimination est loin d'être toujours aisée.

On pourra néanmoins déduire certaines informations sur la tectonique, mais l'interprétation reste délicate et les corrections sont importantes. En particulier, la méthode exige un relevé topographique précis des points où le gravimètre a été mis en station, ce qui rend la méthode coûteuse, surtout si le relief est accentué, et vu la grande généralité des renseignements apportés.

Aussi ne saurions-nous conseiller la gravimétrie au stade initial de la prospection, lorsque les conditions géologiques sont encore mal connues et en général ne sont pas simples.

## Conductibilité électrique

Nous arrivons maintenant aux méthodes basées sur la mesure de la conductibilité électrique des terrains. Nous avons exposé au début de ce mémoire les conditions géologiques requises par un champ géothermique. On est amené en quelque sorte à étudier l'allure d'un horizon perméable et chaud, et à préciser le réseau des failles qui l'affecte sous une couverture imperméable le protégeant d'échanges trop rapides ou trop brutaux avec l'extérieur.

Cette couverture sera en général argileuse ou marneuse, donc électriquement conductrice par rapport au magasin qui sera gréseux, calcareux, dolomitique ou constitué de laves. D'autre part, on va être amené à étudier le comportement de ces terrains dans une tranche superficielle du sous-sol de quelques centaines de mètres d'épaisseur et dépassant rarement un millier de mètres. Ces conditions, même en relief mouvementé, sont parfaitement du domaine de la prospection électrique basée sur la mesure de la résistivité, avec sa technique du sondage électrique pour la reconnaissance générale et les prospections de semi-détail et celle de la carte des résistivités pour les études de détail. Ces techniques offrent en outre le grand avantage de se classer parmi les méthodes dynamiques, à savoir qu'il est possible et très aisé dans ce cas de faire varier la profondeur d'investigation, puisqu'elle dépend de la longueur de la ligne d'envoi de courant utilisé. De plus, la résistivité est un paramètre qui varie dans de très larges proportions avec le faciès des terrains (1 à 10 ou même à 1 000). En résumé, ces techniques permettent en définitive d'établir des cartes en courbes de niveau de l'allure du toit de l'horizon magasin, ainsi que de tracer les accidents et fractures qui l'affectent.

Ce n'est pas tout. Il leur reste encore une propriété très intéressante qui se rapporte directement au problème de la recherche de l'énergie géothermique. Nous avons vu, lors de l'exposé sur les questions de température et des zones chaudes, que la chaleur émanant du magasin échauffait peu à peu la couverture. Or, la résistivité d'une formation dépend étroitement de sa température : c'est ainsi qu'un terrain porté de 17 °C à 150 °C voit sa résistivité divisée par 5, et elle est divisée par 9 si sa température passe de 17 °C à 280 °C. On a donc là un moyen efficace de déterminer s'il existe des zones chaudes à la base de la couverture en établissant une carte de résistivité à la profondeur correspondante, et de savoir par exemple si une fracture, cause de la structure géologique, est nourricière ou non.

Ce point est important en soi, sans compter que la méthode remplace et se substitue à la mesure directe en surface de la variation de la température lors d'une prospection de semi-détail. La prospection électrique garde cependant son utilité, même si les failles ne présentent qu'un très faible rejet ou s'il est nul par endroits.

### Vitesse de propagation des ondes élastiques

Il y a encore les méthodes sismiques, qui sont basées sur la mesure de la vitesse de propagation des ondes élastiques dans le sous-sol. Deux méthodes s'offrent à nous : la réfraction sismique et la réflexion sismique.

Au point de vue de la détermination de l'allure structurale, la réfraction sismique est assez voisine de la prospection électrique, puisqu'elles font appel toutes deux à des trajets d'énergie plus ou moins horizontaux, donc spécialement aptes à déceler les accidents verticaux. Par contre, la réfraction offre plusieurs inconvénients : elle est beaucoup moins sensible au faciès des terrains; sa mise en œuvre est plus complexe; elle exige un équipement important et lourd, si on désire atteindre une profondeur de plusieurs centaines de mètres, 500 m par exemple; et les calculs d'interprétation sont beaucoup plus longs. Elle utilise des explosifs qu'il faut garder, transporter, enfouir assez profondément, et il est nécessaire d'avoir les cotes topographiques des points d'explosion et des sismographes. En outre, elle ne fournit aucune indication sur les zones chaudes profondes. Bref, son prix de revient est beaucoup plus élevé que celui du sondage électrique.

Il y a encore la réflexion sismique, qui demande l'obtention de réflexions, donc l'existence de miroirs, ce qui n'est pas toujours le cas, surtout si on a affaire à des formations volcaniques. Sa mise en œuvre sera d'autant plus délicate que l'on sera en présence de terrains dont la topographie sera du type minier. De plus, cette méthode, mettant en jeu des trajets d'énergie verticaux, est peu indiquée pour déterminer les failles et leur rejet.

Elle offre en outre tous les inconvénients de la réfraction sismique en ce qui concerne l'utilisation des explosifs, l'enfouissement des charges, la lourdeur de l'appareillage et les difficultés de mise en œuvre. C'est une méthode coûteuse pour de résultats qui auront dans ce cas toutes chances d'être parcellaires et médiocres, et nous ne saurions absolument pas la conseiller pour de telles recherches.

### Radioactivité

On a pu songer aussi à la méthode radioactive, qui consisterait dans notre cas à mesurer les substances radioactives qui sont éventuellement véhiculées par les failles et fractures. Pour ce faire, il est certes nécessaire que les accidents recherchés traversent la couverture pour aboutir jusqu'à la surface. De toute façon, les résultats à attendre d'une telle méthode sont trop aléatoires, et elle restera entièrement muette sur les conditions structurales. Elle est donc à écarter comme méthode sérieuse de recherche.

### Conclusion

En conclusion, nous sommes formellement pour l'utilisation de la prospection électrique pour résoudre les problèmes posés par la recherche des champs géothermiques, ou tout au moins par leur mise en œuvre préalable, parce que les résultats obtenus seront les plus complets.

Lors d'une reconnaissance générale, nous recommandons d'exécuter des sondages électriques avec une maille de 500 × 500 mètres, soit 4 stations au km². Pour les études de semi-détail sur les zones retenues comme pouvant être intéressantes, on resserrera cette maille jusqu'à 250 × 250 mètres, et même moins. Enfin, pour implanter au mieux les premiers forages de reconnaissance, une carte de résistivité sera exécutée.

Nous insistons de plus sur le fait qu'outre sa parfaite adaptation technique à ces problèmes le prix de revient de la prospection électrique est le moins élevé parmi les méthodes dynamiques, ce qui permet pour une même dépense de réaliser des explorations et reconnaissances beaucoup plus complètes, plus rapides et plus étendues.

## *Résumé*

L'auteur rappelle tout d'abord les conditions auxquelles doit satisfaire la structure géologique d'un champ géothermique pour qu'il y ait production de vapeur sèche plus ou moins surchauffée, ou d'un mélange de vapeur saturante et d'eau chaude.

Pour reconnaître cette structure, on a cherché à utiliser différents paramètres physiques des roches : température, susceptibilité magnétique, densité, conductibilité électrique, vitesse de propagation des ondes élastiques et les méthodes géophysiques qui en découlent.

L'application de ces méthodes est ensuite examinée, tant au point de vue de leur opportunité d'emploi que des résultats à en attendre.

Il est ainsi discuté des différents modes d'exécution des mesures thermométriques et de leur utilité. Puis des mesures magnétiques et de leur contre-indication pour les prospections préliminaires. Les mêmes conclusions s'appliquent aux mesures gravimétriques, qui concernent surtout la géologie profonde, sont coûteuses et d'une interprétation délicate.

Il est ensuite démontré que la conductibilité électrique est le paramètre à retenir, étant donné les conditions structurales à déterminer, la facilité de mise en œuvre et d'adaptation et le faible coût des méthodes de prospection électrique et en particulier de la technique du sondage électrique, qui apporte de plus des renseignements précieux sur le

faciès des terrains. On est, d'autre part, en présence d'une technique dynamique qui offre en outre l'avantage de mettre en évidence les zones chaudes par suite de la baisse de résistivité des terrains par effet thermique.

La mesure de la vitesse de propagation des ondes élastiques et des méthodes qui en dérivent (réflexion sismique et réfraction sismique) est ensuite présentée et discutée. Ces méthodes, dont la mise en œuvre est importante et onéreuse, ne sauraient être conseillées dans le cas d'une reconnaissance générale.

La conclusion est nettement en faveur de l'utilisation préalable de la technique du sondage électrique pour la résolution des problèmes que pose la recherche des champs géothermiques.

## THE CONTRIBUTION OF GEOPHYSICAL METHODS TO THE SURVEY OF GEOTHERMAL FIELDS

### *Summary*

Conditions are listed which the geological structure of a geothermal field must satisfy in order to produce more or less overheated dry steam, or a mixture of saturating steam and hot water.

Different physical parameters of rocks have been used to determine this structure: temperature, magnetic properties, density, electrical conductivity, wave velocity. Geophysical methods have been derived from these parameters, and operations have been carried out.

The applications of these methods are then examined with respect to the choice of the proper method and the results to be expected.

Thermometric measurements are discussed, considering the different ways they may be carried out and their usefulness. Mention of magnetic measurements follows: they should not be used in preliminary exploration. This is also true of gravity data, which apply principally to deep formations; they are costly and difficult to interpret.

Electrical conductivity is then proved to be the most valid parameter, because of the tectonics to be determined and because it is easy to operate. Moreover, electrical prospecting methods are inexpensive, and electrical sounding, in particular, gives valuable data concerning the nature of the formations encountered. Furthermore, it is a versatile method offering the added advantage of indicating the warm areas through decreased formation resistivity by thermal effect.

Wave velocity measurements are then discussed, together with the corresponding methods: seismic reflexion and refraction. These methods, which are expensive to set up, are not advisable in the case of a general reconnaissance programme.

The author concludes that electrical methods should be used first when surveying geothermal fields.

# GEOCHEMICAL ASPECTS OF THERMAL SPRINGS IN EL SALVADOR

*Gerd Christmann* *

The following discussion is concerned with an interpretation of post-volcanic phenomena of the thermal areas Laguna Verde and Salitre, western El Salvador. Methods aiding in the precise identification of thermal waters are described and discussed.

In the thermal waters of Laguna Verde and Salitre, the following chemical differences may be recognized :

The moderately warm, nearly neutral, chloride-containing waters of Salitre are characterized by a normal $SO_4$-content.

The hot, strongly acid, sulfate-containing waters of Laguna Verde are marked by a normal Cl-content. The discharge from these springs is considerably smaller and is accompanied by a steam phase.

The chemical characteristics of these thermal waters markedly coincide with the data from Craig (1956), who analysed hundreds of samples from famous thermal regions such as Yellowstone Park, Wyoming, Lassen Park, California, Iceland, Kenya, New Zealand and Lardorello, etc. The thermal waters of El Salvador can be fitted into Craig's classification without much difficulty.

Moreover, Craig (1956) found that enrichments of certain isotopes are extremely helpful in classifying various thermal waters.

According to the composition of their isotopes, these springs correspond to the associated surface water, or they contain approximately the same deuterium concentration as the local meteoric waters, but they are enriched in $O^{18}$ with respect to these waters by amounts ranging up to approximately 0.4 per cent.

In the acid thermal waters the deuterium content attains values as high as 5 per cent, the $O^{18}$ content increases to 1.6 per cent in comparison to the local meteoric waters, and there is a general tendency for this enrichment to be associated with the progressive decrease in pH.

At first it may not be easy to explain these phenomena because it is difficult to extract oxygen for isotope analysis from many of the minerals composing the rocks. Therefore, the amount of variation in the $O^{18}/O^{16}$ ratio in silicates, carbonates, and oxides in igneous and metamorphic rocks is not very well known. The first to succeed in obtaining precise and reliable data on oxygen isotopes were Baertschi and Silverman (1951) and Silverman (1951). They analysed silicate rocks, generally finding that those rocks which contained the greatest percentage of free quartz were richest in $O^{18}$. The greatest concentration of $O^{18}$ was found in quartz that formed at relatively low temperatures. It is remarkable that the highest $O^{18}/O^{16}$ ratios were found in the more siliceous rocks and the lowest in the more basic rocks (Silverman, 1951). He attributes these variations in isotopic composition to diffusion processes.

Thus, if isotopic exchange takes place between water and rock, we expect that the oxygen of the water will become enriched in $O^{18}$ but the hydrogen content will not change significantly. Let us suppose that the exchange is an equilibrium phenomenon. This requires that the equilibrium constant at the temperature of contact be smaller than the difference in $O^{18}$ concentration between water and rock. Silverman's data indicate that this might be the case.

These data hold true particularly for the geologic relations in the Salitre field because here the most conspicuous occurrences are crusts of the siliceous evaporites. Loss of pressure and temperature are decisive above all in the precipitation of $SiO_2$.

Craig's explanation of the process of enrichment in acid waters is not at all satisfactory.

Urey (1947) and Tudge and Thode (1950) have shown that energy, entropy and free energy of isotopic substances depend largely on the vibrational frequencies of the molecules, which in turn depend on the masses of the atoms in the molecules.

The sulfur isotopes, $S^{32}$ and $S^{34}$, with a 6 per cent mass difference in geochemical processes involving a valence change of —2 to +6, such as that between sulfide and sulfate, are fractionated with the lighter. The heavier, less energetic isotope is concentrated in the more tightly bound sulfate (Ault, 1960).

In the more favourable relationship of mass differences of $H_2O$ and $D_2O$, the $D_2O$ enrichment occurs mainly through diffusion and exchange processes.

Krauskopf (1960) assumes the existence of various partial pressures for the different components of a magmatic gas phase. The thermal waters of Laguna Verde can be explained easily by these data, as well as the situation described by Grange (1955) for the Waiora Valley in New Zealand.

Industrial utilization of these phenomena is very significant for El Salvador. In the following, a method is described which makes possible quick determinations of $D_2O$.

Richards (1898) and Richards and Wells (1903) listed a temperature of 32.383°C at which anhydrous

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sodium sulfate stands at equilibrium with the decahydrate, the saturated solution and its vapour. According to Taylor (1934), the point of inflection is raised by 2.10°C, when $H_2O$ is supplanted by $D_2O$. These physical data should be very useful and suffice at least for qualitative determination of coefficients of enrichments.

The ordinary indicators are useless in a precise indication of the point of inflection. However, it is possible to obtain a specific indicator by marking use of the application of an exact form of the law of mass action upon dissociation of weak electrolytes.

For an electrolytic dissociation of the type

$$AB \rightleftarrows A^+ + B^-$$

the law of mass action yields

$$K^c = \frac{c_{A^+} \cdot c_{B^-}}{c_{AB}} \tag{1}$$

In this form the law can, however, be used only with some precaution. The reason for this lies in the fact that the undisturbed anomalous molecular movement does not occur any more because of the mutual attraction of the ions. One obtains a real constant if one substitutes the concentration of the reactants and products for their activities in the law of mass action. If one writes $a_A$ and $a_B$ for these, then for a commonly formulated chemical equation the state of equilibrium becomes:

$$K^a = \frac{a_{B_1}{}^{n_1} \cdot a_{B_2}{}^{n_2} \cdot \ldots\ldots}{a_{A_1}{}^{m_1} \cdot a_{A_2}{}^{m_2} \cdot \ldots\ldots} \tag{2}$$

or $K^a = Q_a$, when $Q_a$ is the quotient of the activity products. $K^a$ signifies the thermodynamic equilibrium constant, its value remaining invariable under all circumstances at a given temperature.

The activities, more precisely their logarithms, are indicative values for the tendency of reaction of the particles. With a substance in solution, the activity is defined best by indicating the approach of its value to the molar concentration of the substance with increasing dilution of the solutions, i.e., the activity $a$ is normed to the molarity of volume $c$, whereby the condition of norming mathematically is expressed as:

$$\lim_{\Sigma c \to 0} a/c = 1 \tag{3}$$

The relationship $a = c$ is valid only for extremely dilute solutions. The exact handling of the ratios of the solutions of finite concentration is made possible by the introduction of the so-called "coefficient of activity". These are factors which combine activities and molarities in the following manner:

$$a = c \cdot \mu_c \text{ or } \mu_c = a/c \tag{4}$$

According to (3), the relation

$$\lim_{\Sigma c \to 0} \mu_c = 1,$$

i.e., in extremely dilute solutions the coefficients of activity of the dissolved substances = 1. They also depend on the kind and concentration of other particles.

If one considers a homogenous reaction in a solution one obtains from (1) by the substitution of (4):

$$K^a = \frac{c_{B_1}{}^{n_1} \cdot c_{B_2}{}^{n_2} \cdot \ldots\ldots}{c_{A_1}{}^{m_1} \cdot c_{A_2}{}^{m_2} \cdot \ldots\ldots} : \frac{\gamma_{B_1}{}^{n_1} \cdot \gamma_{B_2}{}^{n_2} \cdot \ldots\ldots}{\gamma_{A_1}{}^{m_1} \cdot \gamma_{A_2}{}^{m_2} \cdot \ldots\ldots} \tag{5}$$

or $K^a = Q_c \cdot Q\mu$, $Q\mu$ = quotient of the products of activity. Because $Q_e = K^c$, therefore:

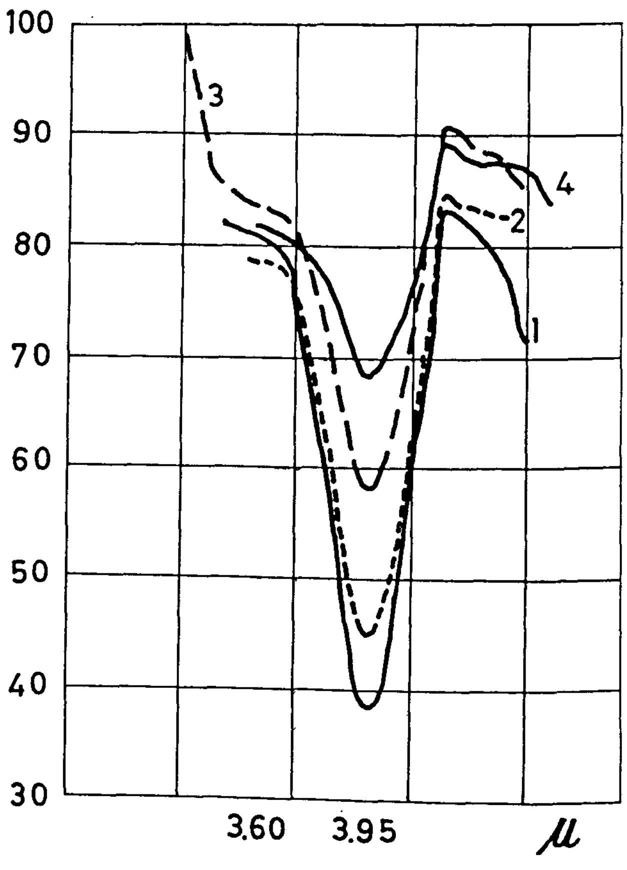
$$K^c = K^a/Q\mu \tag{6}$$

The ionic coefficients of activity may deviate from (1) at relatively small ionic concentrations, the result being that under certain circumstances the constant of equilibrium $K^c$ differs greatly from the thermodynamic constant of equilibrium $K^a$. Variations in the ionic concentrations and therefore in the coefficients of activity lead consequently to appreciable qualitative effects.

Thus the dissociation of $Fe(SCN)_3 \rightleftarrows Fe^{3+} + 3\ SCN^-$

$$K^c = K^a/Q = K^a \frac{\gamma Fe(SCN)^3}{\gamma Fe^{3+} \cdot \gamma SCN^{-3}} = \frac{K^a}{\gamma Fe^{3+} \cdot \gamma SCN^{-3}}$$

If one increases the ionic concentration of a solution by adding an arbitrary salt, the ionic coefficients of activity decrease, and $K^c$ increases.



If the added salt contains neither ions of $Fe^{3+}$ nor ions of $SCN^-$ the concentration of undissociated $Fe(SCN)_3$ is lowered by the increase of dissociation constant $K^c$. In this process a change in colour is noted. A solution of such a desired concentration is obtained by dissolving 1.5 m-mol $FeNH_4(SO_4)_2$ . . 12 $H_2O$ and 4.5 m-mol KSCN in 1 litre of water.

Through a careful application of the described theory it should be possible to use this process as a simple field method.

An outstanding, yet simple, laboratory technique in analysing mixures of $H_2O$-$D_2O$ is described by Oostens and Fripiat (1959). For the examinations, a Beckman spectrophotometer with double beam, model IR-4, was employed. The precision of the results is independent of the optics (NaCl or $CaF_2$). The apparatus marks the degree of permeability in per cent which depends upon the wave length. The figure gives an example for these analyses made for weight concentration of heavy water: (1) 4.73 per cent, (2) 3.10 per cent, (3) 2.46 per cent and (4) 1.19 per cent. In the graph (previous page) the permeability was plotted along the ordinate, the wave length along the abscissa.

The occurrence of characteristic isotope enrichments in thermal water can be explained only theoretically. The difficulty lies not in the problem itself, but in the fact that up till now one is still uncertain of the degree of purity of strictly "juvenile" water in samples. Epstein (1960) proposes a solution to the problem pointing out characteristic $O^{18}/O^{16}$ ratios in coexisting minerals.

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## *Summary*


According to Craig, Boato and White (1956) two main types of thermal springs may roughly be distinguished:

Chloride, tepid waters with pH in the range of 5-9. They are generally discharged from a large body of ground water.

Acid hot springs, relatively high in sulfate, with a pH from 1-5 and much smaller rates of discharge.

In this model the thermal springs in the western part of El Salvador can be classified without much difficulty. With the aid of recent publications this paper attempts to explain the characteristic enrichment of isotopes.

Regarding industrial utilization, the described situation is very significant for El Salvador. Perhaps an answer can be found in the specific composition of the different isotopes. The question is up for discussion, whether or not there is a correlation between characteristic isotopic enrichments and the chemistry of the thermal springs.

A simple method is described which can probably be used in the field for determining the deuterium enrichment. An extremely efficient laboratory technique was developed by the application of IR-spectroscopy.

# ASPECTS GÉOCHIMIQUES DES SOURCES THERMALES DU SALVADOR


## *Résumé*

D'après Craig, Boato et White (1956), on peut, d'une façon générale, faire la distinction entre deux types principaux de sources thermales :

1. Les eaux tièdes chlorurées, dont le pH varie entre 5 et 9. Elles sont généralement alimentées par une masse d'eau souterraine importante.

2. Les sources chaudes acides, qui ont une teneur en sulfates relativement élevée, dont le pH s'échelonne entre 1 et 5, caractérisées par un débit beaucoup plus faible.

Il n'est pas particulièrement difficile d'inscrire les sources chaudes de la région occidentale de la République du Salvador dans le cadre de cette classification. On s'efforcera d'interpréter l'enrichissement observé dans leur composition isotopique.

En ce qui concerne les applications industrielles, la situation qui vient d'être décrite est très significative pour le Salvador. On pourra peut-être donner une réponse à la question en examinant la répartition spécifique des divers isotopes en cause. Il conviendrait d'établir s'il existe une corrélation entre certains enrichissements caractéristiques en isotopes et la composition chimique des sources chaudes.

On décrit une méthode simple, qui pourra probablement s'employer sur place, pour déterminer l'enrichissement des eaux en deutérium. L'application de la spectroscopie dans la région de l'infrarouge a permis la mise au point d'une technique de laboratoire extrêmement efficace.

# GEOTHERMAL ENERGY IN MEXICO

*Luis F. de Anda,* * José Isita Septien* † *and Jesús Ruiz Elisondo* ††

Before 1955, when exploration drilling was begun in Mexico, there were a number of known places with hydrothermal springs, some of which were used for recreation and bathing. Studies before 1955 by Isita Septién (1) and de Anda (2, 3) were among the first to show the urgent necessity of studying the geothermal resources of Mexico scientifically.

The Comisión Nacional de Energía Geotérmica established a department in 1955 to study possibilities and developments in the new source of geothermal energy; it was sponsored by the Comisión Federal de Electricidad, the Banco de México, S.A. and Nacional Financiera, S.A. The reasons which prompted its creation were based mainly on available data, which were considered favourable from the geological point of view for conducting exploration in the subsurface by drilling in search of natural steam for the production of electrical energy. The conventional sources of energy in Mexico had been the subjects of careful study, in order to schedule consumption of available energy because of the ever-growing demands of the country.

Most recent information indicates that total energy consumed in Mexico for different uses comes from the following sources :

| *Source* | *Per cent of total* |
|---|---|
| Natural gas | 20.0 |
| Crude oil | 72.0 |
| Coal | 6.2 |
| Water | 1.8 |

Mexico is probably the only country in the world which depends largely on oil to provide for its energy requirements. It is estimated, on the basis of actual consumption, that coal reserves are sufficient to fulfil growing demand for more than one country; the hydroelectric resources of Mexico which remain unexploited offer an appreciable amount of energy to be utilized for future development. The growing pace of energy consumption in Mexico indicates that its oil reserves have only a thirty-year period of life expectancy.

For the past three years, some geologically favourable zones have been explored systematically for radioactive minerals, mainly within the states of Chihuahua, Sonora, Coahuila and Durango. The results so far promise Mexico an indigenous supply of uraniferous raw material in the near future, sufficiently large so that production of nucleo-electric energy may, at the proper moment, at least in part, complement the energy from conventional sources, aided by the accelerated extraction of Mexican hydrocarbons.

The new sources of energy, known as solar, wind, geothermal, tidal and thermotalassic, present a new and singular field in Mexico. Of the five sources mentioned, only geothermal energy has been explored, with the results mentioned in this report.

The development which may be obtained as a result of the exploration of geothermal energy in Mexico points to its future importance in the energy pattern of the country.

The experimental geothermoelectrical power plant at Pathé,[1] in the State of Hidalgo, shows an approximate cost of $53 per installed kilowatt, indicating that the connexion of geothermoelectrical plants with electrical systems provided by thermoelectric or hydroelectric plants in the Bajio and Mexicali zones will have an advantage in cost of electrical energy, of benefit to both the people and the Government. It is important to note that the cost of the experimental Pathé plant was exceptionally low; the Ansaldo turbo-generator group of 3 500 kilowatts was sold by Larderello to the Comisión Federal de Electricidad at a very low price, with co-operation in research work. The power house and the frequency converter were recovered from old installations.

## General geological aspects of Mexico

In Mexico there are rocks from Cambrian, in Sonora, to Recent. Mesozoic predominates in the central part of the country, greatly masked by acid effusive rocks. This zone and the west central zone are rich in minerals.

Figure 1 shows the approximate location of the following zones :

(i) Between the western part of the central portion, mentioned above, and the coastal plain of the Gulf of Mexico, there is a north-to-south mountainous chain, intensively folded, known as the Sierra Madre Oriental. The Mexican geosyncline includes such a chain, which is formed mainly by Mesozoic, Paleozoic and Cenozoic rocks. The Sierra Madre Oriental has been subjected to an alpine type

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[1] See figures 6 and 7 below.


Figure 1. Physiographic zones of Mexico

of deformation and contains limestone, shales, sandstones, conglomerates and marls; it extends from the centre of Mexico to the north, comprising part of the states of Chihuahua, Tamaulipas, Nuevo León, Hidalgo, Coahuila and Zacatecas.

(ii) The north and central plateaux are regions situated in the former Mexican geosyncline. They contain Paleozoic and Mesozoic rocks, which are covered in large part by volcanic flows of variable composition, from acid to basic.

(iii) The Sierra Madre Occidental is a continuation to the south of the Basin and Range System and is formed in great part by rocks of igneous origin, both intrusive and extrusive, with greater abundance of the latter. It is believed that the predominant age of these rocks is Tertiary; their basement is unknown, but in the light of the few data available, and considering their correlation with Arizona, it is not difficult to suppose that the gross section of volcanic rocks is sublaid in large part by old terrains of Paleozoic, and even older layers. The structure which predominates in the Sierra Madre Occidental is block faulting. This wide region of the country is for the most part inaccessible; and many mineral deposits which undoubtedly are lodged in fractures have not yet been discovered in the region. The zone, of variable width, which represents the transition between Sierra Madre Occidental and the western limit of the Mexican geosyncline, constitutes the more important mineralized region of the country, extending perceptibly in a north-west to south-east direction.

(iv) The neovolcanic zone is composed fundamentally of volcanic rocks, from Tertiary to Recent age, transversal to the general trend of Sierra Madre Oriental and Sierra Madre Occidental, being located approximately between parallels 19 and 21, north latitude. This is a region of intensive geyserian activity, in which the Pathé and Ixtlán fields, which are being studied, are located.

(v) The Baja California peninsula is formed by a batholith, mainly integrated by intrusive igneous rocks of granitic composition, the age of which is believed to be pre-Cretaceous. In the same part of the peninsula there are likewise volcanic rocks from the Tertiary, located in isolated basins which contain sediments from Tertiary to Recent.

(vi) The Pacific coastal plain is formed by the western slopes of the Sierra Madre Occidental; it is a zone within the limits of the continent, towards the Pacific, with intensive seismic activity, especially in the Acapulco region.

(vii) The zones known as Sierra Madre del Sur, Sierra de Chiapas, the Gulf coastal plain and the Yucatán plateau form the remaining zones conventionally recognized in Mexico; they are shown in figure 1.

Schematically, Mexico exhibits a marked tilt towards the Gulf of Mexico, where recent sediments occur, whereas the Pacific coast exhibits a crystalline basement, made up of intrusive Paleozoic rocks.

Two great stresses occur in Mexico: one is projected from North America and exerts pressure towards the south, mainly along meridian 100 W; the other proceeds from South America and acts through Central America, pressing Mexico towards the north-west.

The combination of these two stresses produces an important zone of transversal dislocation, from the Gulf of Mexico to the Pacific Ocean. Such a zone is the new volcanic region, in which a basaltic plurivulcanism predominates, with intercalations of felsites, even with faneritic intrusives in dikes. It might also be considered that the Gulf of California is a consequence of this dislocation, as well as the San Andrés fault zone, which reaches San Francisco, California, in the United States.

## Distribution of geothermal zones in Mexico

To repeat, the zone of transversal dislocation known as the new volcanic region corresponds to a line of weakness in which it is supposed that the best results of geothermal energy may be encountered, not excluding the fault zone of San Andrés, which is considered a consequence of the dislocation that gave rise to the new volcanic zone (figures 2 and 5).

In Mexico, the presence of manifestations that might lead to obtaining steam are intimately connected, up to a certain point, with a favourable structure, mainly through fractures and zones of weakness that in one way or another have constituted the conduits along which a considerable volume of volcanic materials has come to the surface. Therefore, the geothermal fields of Mexico investigated to date — Pathé, Ixtlán, Mexicali and a few others considered as potential — are found within an important structural region.

Experience gained in this field has demonstrated that calorific energy contained in steam might be utilized for industrial and economic purposes. Such energy comes from the heat accumulation of igneous rocks in the subsurface, which remain at sufficient depth to dissipate heat during a longer or shorter period of time. Fluids of meteoric character which have circulated to the depths have absorbed heat coming out at the surface as steam.

It might be thought that a certain amount of steam which appears on the surface may in fact have a magmatic origin, a matter which might better be studied by means of nuclear geochemistry through studying a good number of samples.

It is interesting to note that in the locality known as Aconchi, Sonora, there are hydrothermal manifestations with temperatures at the surface up to 70°C. The spring deposits precipitated from such waters are highly radioactive. There is a question whether the abnormal temperature results from energy provided by the disintegration of radioactive minerals or from hot water circulating in the depths of the crust that has taken heat from an igneous body still in the process of cooling and carrying radioactive materials in solution.

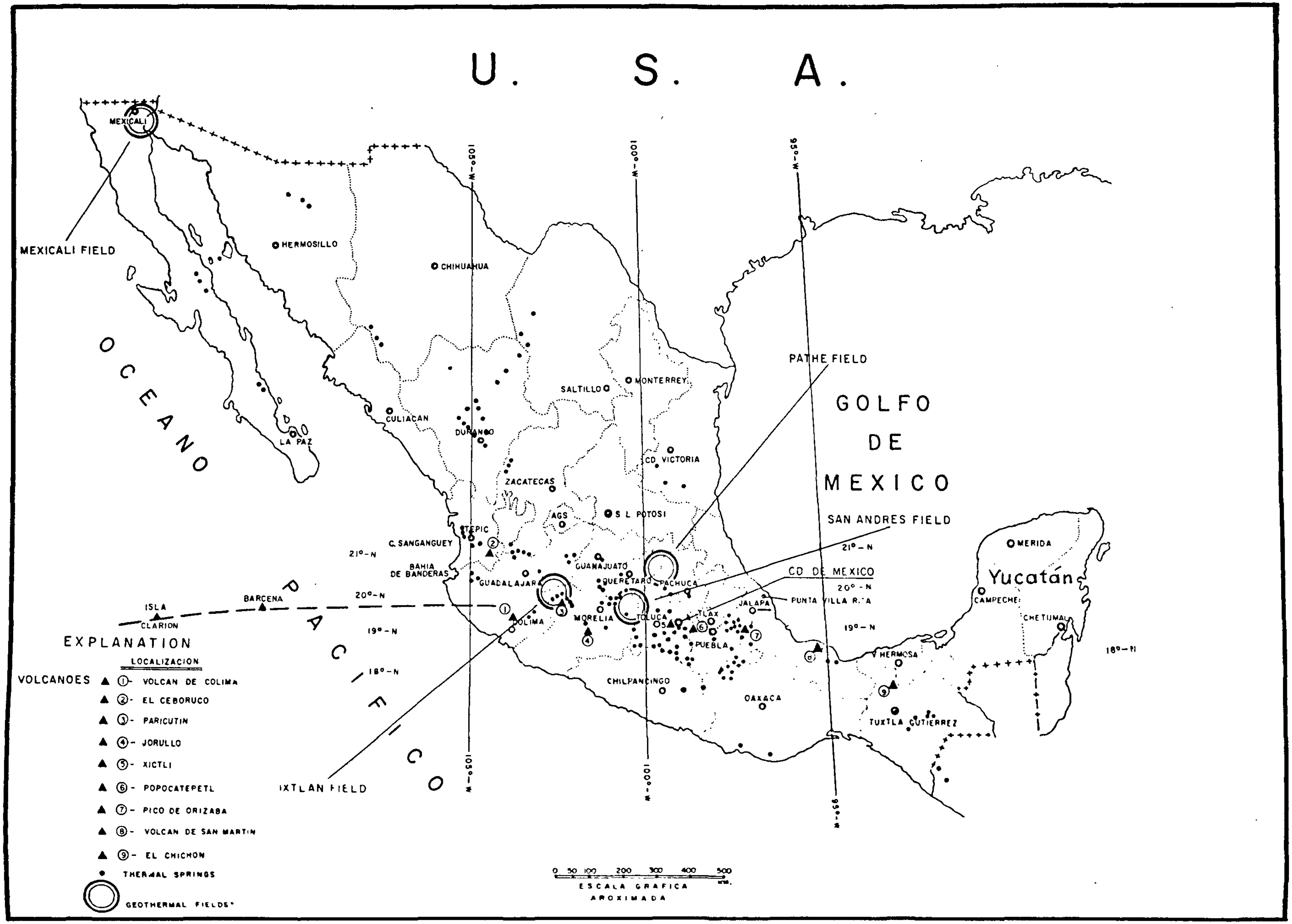



Figure 2. Location of hydrothermal springs, principal volcanoes and geothermal fields, Mexico

The new volcanic zone mentioned earlier is a part of the earth's crust in which favourable structures, volcanism and steam make Mexico a zone of great interest to explore.

## Geothermal fields actually drilled and studied

Three zones have been studied in Mexico to date for the purpose of recovering steam : Pathé, Hgo.; Ixtlán, Mich. and Mexicali, B. C. (see figure 2).

At Pathé and Ixtlán, the chemical analyses show that the hydrothermal manifestations are sodium chloro-sulphated, but in Mexicali they are sodium-chloride waters.

The characteristics that have influenced the decision to choose these zones are the following :

Widespread manifestations of hydrothermal fountains with superficial boiling temperatures;

Favourable structure, so far as was shown by surface geology; and

Hydrothermal activity in relation to volcanic phenomena.

The prospecting methods included :

Superficial geologic examinations;

Systematic measures of temperatures;

Chemical sampling of hydrothermic fluids;

Drilling by diamond drills, churn drills and rotary drills.

Geologic observations were conducted to connect the occurrence of hydrothermal fountains with structural aspects, stratigraphy and volcanism from Tertiary to Recent.

There is not sufficient data available to permit evaluation of the productive capacity of the geothermal zones mentioned. A theoretic study of the Pathé field which follows discusses some of the characteristics of the field.

### Pathé

Pathé (figures 2, 3 and 4) was originally chosen because it presented evidence of attractive geothermal activity—that is, thermal springs and fumaroles at boiling point, a great amount of geyseritic rock, mineralized rocks with sulphides, alteration of primary rocks giving place to important deposits of caolinite, veins of gypsum and profound erosion in preferential directions with fractures. Some chemical analyses were made of the water of various springs, and it appeared opportune to start an exploratory perforation.

At 1 552 metres above sea level, Well No. 1 was started on 17 August 1955. The choice of location was not based on a spring or fumarole, but rather on the position of fractures, and the possible crossing of several. For this well, percussion drill equipment was used in order to permit a more complete record of rocks and temperatures.

At a depth of three and a half metres, the water table was cut out, and the temperature was 28°C; at four metres the temperature rose to 40°C; and at 69 metres it was 100°C, exploding the steam trapped in the mud brought out in the spoon. At a depth of 238 metres the well exploded, and the temperature was around 150°C.

The temperature at the bottom of the well decreased when it reached the pyrite zone and, as it penetrated, the temperature increased abruptly. In the vicinity of the pyritic beds, the spoon brought out pieces of eponded rock, several centimetres in size, as if they had been in a surface exposed to wear produced by a strong current of water.

These facts, and the experience acquired in the perforation of other wells for the procurement of water in these places, high enough above sea level, make it appear that the circulation of underground water is an important factor in geothermal exploitation; it acts unfavourably, by cooling and dissipating ascending thermal energy.

It has been proposed that the Pathé wells should be deepened, at least to reach the bottom near sea level to avoid the adverse effect of fast underground water currents.

After Well No. 1 exploded, however, eleven wells were drilled, to the north, south and east of Well No. 1, at relatively shallow depths. Well No. 12 will be drilled to 1 500 metres in spite of the technical difficulties encountered.

Figure 4 presents a geologic correlation of the wells actually drilled at Pathé.

In 1956, a modified formula from the equation of Carlslaw (4) was applied to results found in the drilling of Well No. 1, and a notable correspondence was found between the temperature encountered with further drilling and the theoretic curve drawn using the formula :

$$T_1 = T_0 - a \int_{br^2}^{\infty} \frac{e^{-u}}{u} \cdot du$$

in which :

$T_1$ = temperature that must exist at depth, $r$.

$T_0$ = 374.61°C = limit of temperature for this theoretic curve, being the critical temperature for water steam

$a$ = constant = $\frac{\lambda}{4\pi K}$ (varies from one place to another)

$b$ = constant = $\frac{1}{4\,k\,t}$ (varies from one place to another)

$\lambda$ = intensity of the sending source

K = Kelvin coefficient of thermal diffusibility (constant in each place, but varying from one place to another)

$t$ = time elapsed since the thermal body started to lose heat towards the surface (constant in practice if the extent of the geological elapsed time since the emission of heat started is considered)

$$u = \frac{r^2}{4\,k\,t}$$

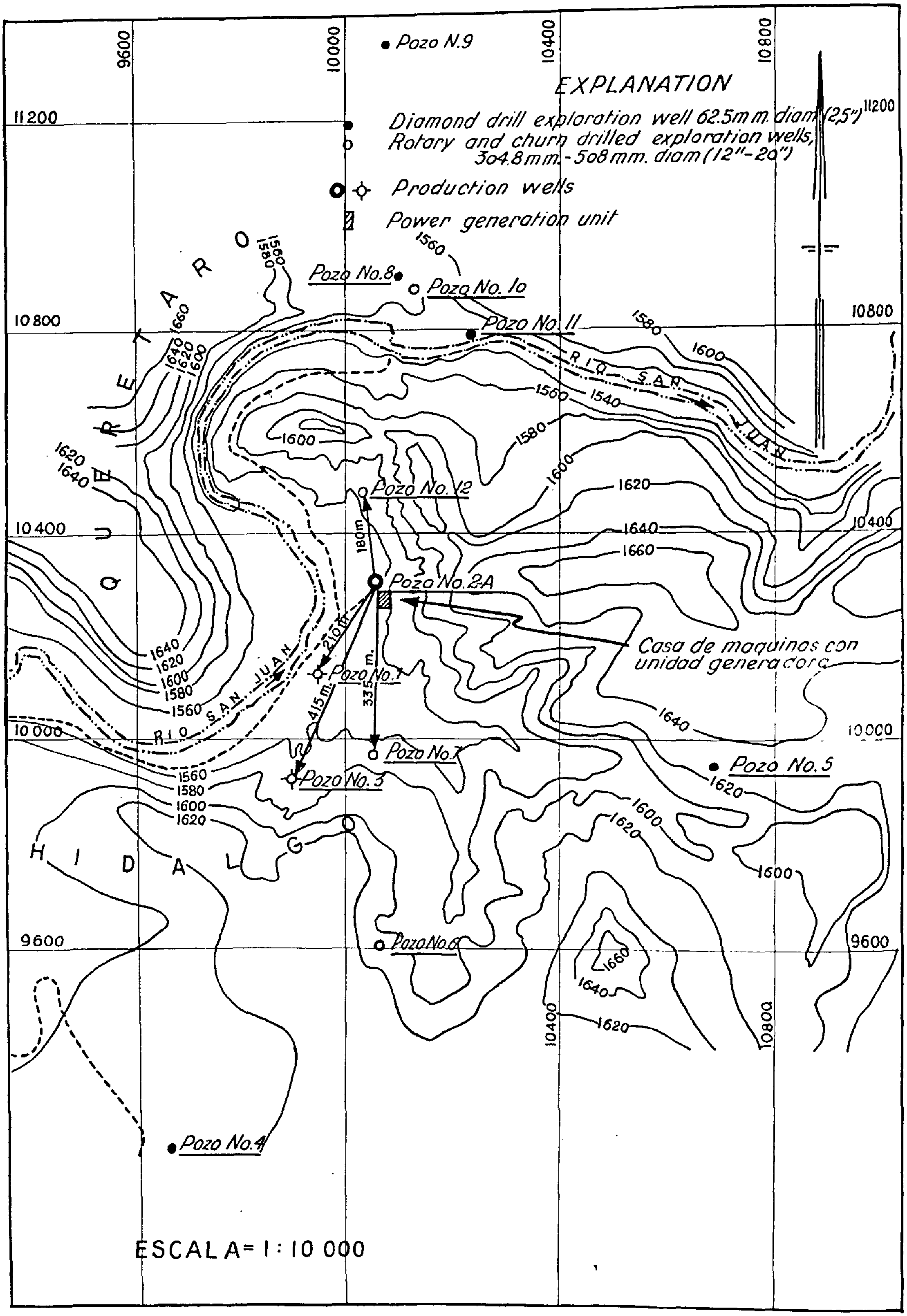



Figure 3. Location of wells in geothermal zone, Pathé, Hidalgo

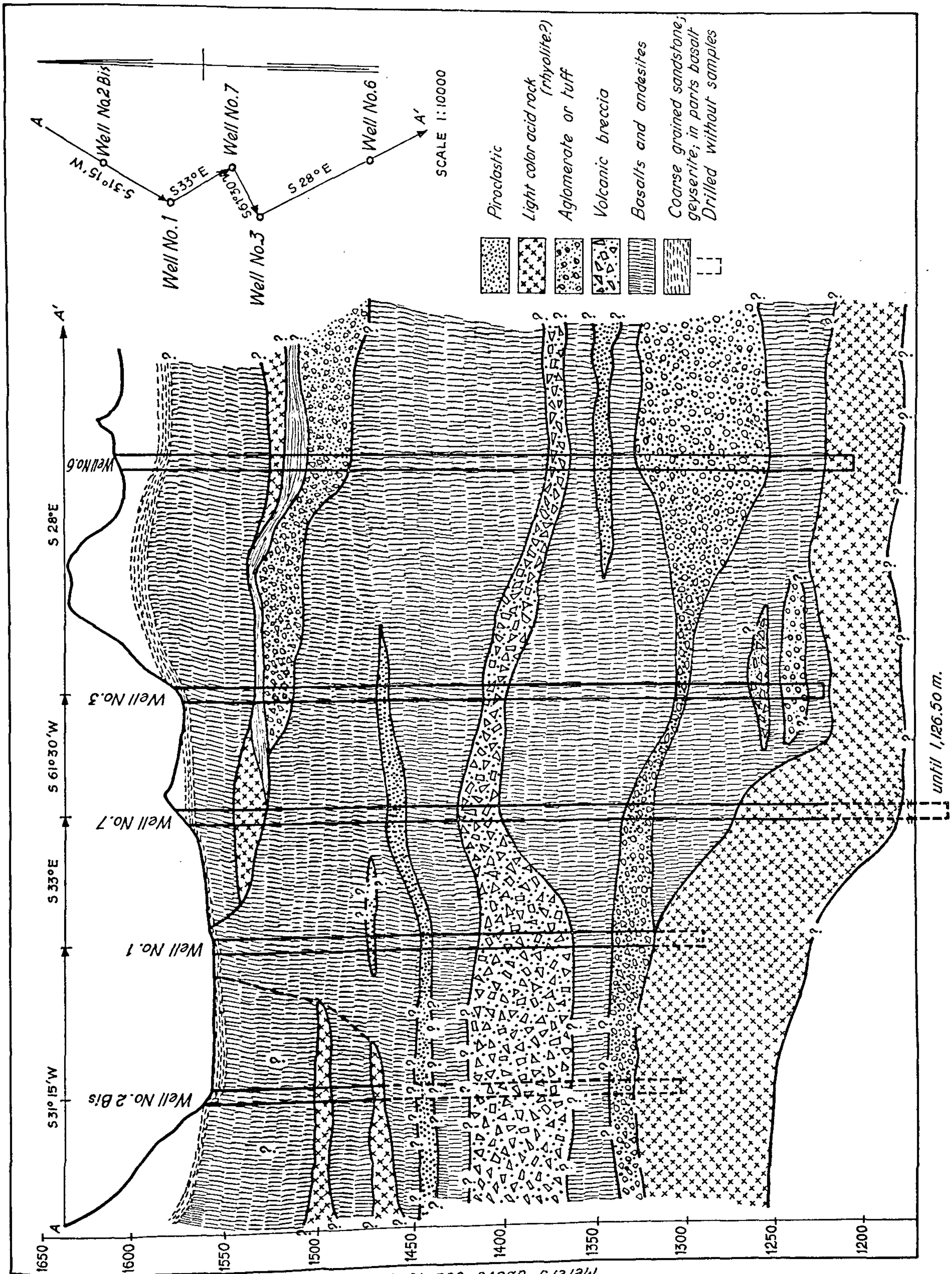



**Figure 4.** Subsurface geology of the geothermal zone, Pathé, Hidalgo

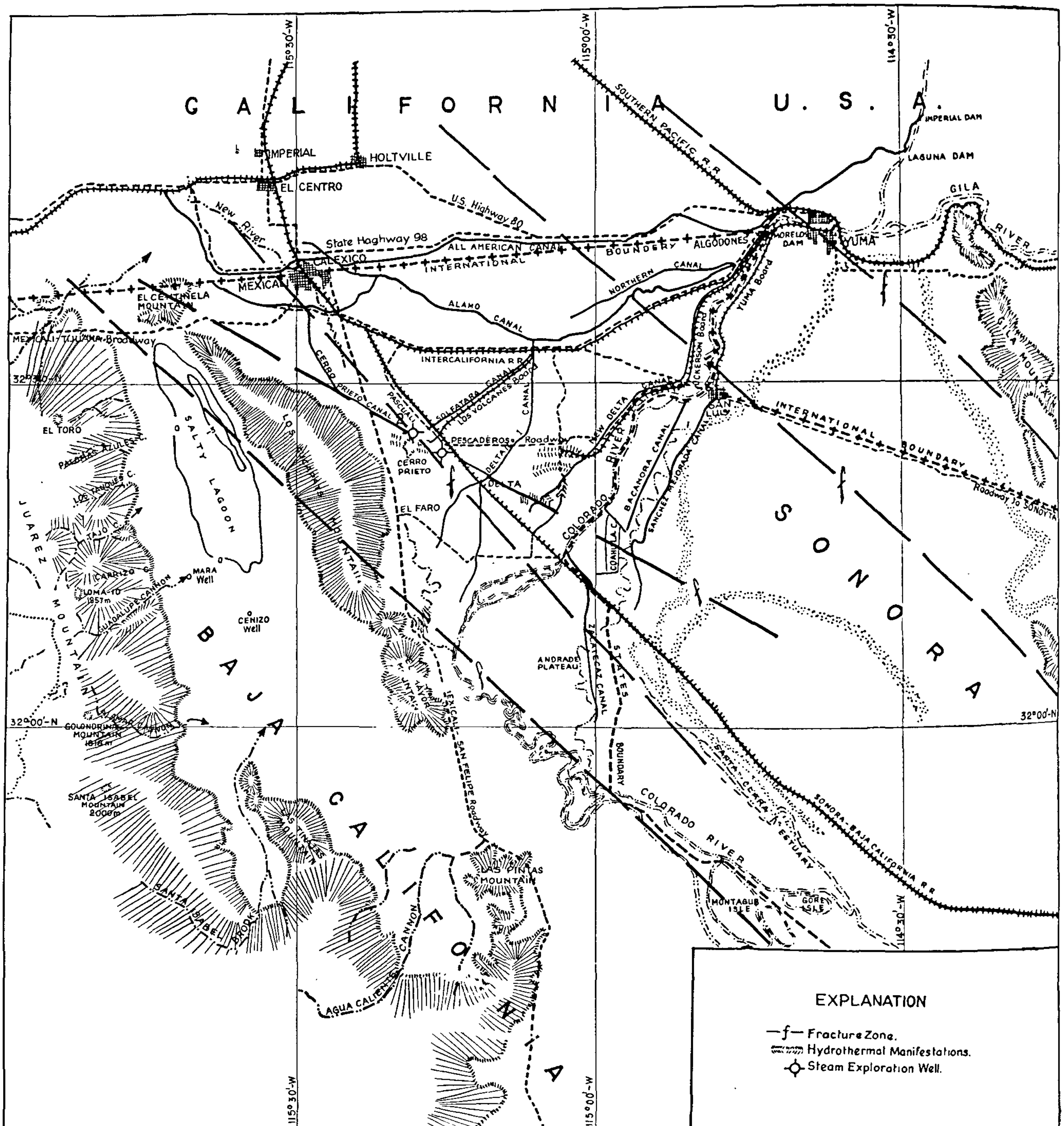



**Figure 5. Mexicali zone, showing trends of fracturing, hydrothermal springs and location of exploratory steam wells**

The integral

$$\int_{br^2}^{\infty} \frac{e^{-u}}{u}\, du$$

is a form of the exponential integral:

$$\int_{x}^{\infty} \frac{e^{-u}}{u} \cdot du = f(u),$$

whose development is:

$$f(u) = -0.577216 - \log_e x + x - \frac{2.2!}{x^2} + \frac{3.3!}{x^3} - \frac{4.4!}{x^4} - \ldots$$

in which 0.577216 is the constant of Euler; for each value of $u$, the corresponding value of $f(u)$ has been calculated by several authors and published by the Federal Works Agency of the United States.

The parameters $a$ and $b$ are fixed in each case, providing two readings as the drilling proceeds, and since:

$$a = \frac{T_0 - T_1}{f(u_1)} = \frac{T_0 - T_2}{f(u_2)}; \qquad b = \frac{u_1}{r_1} = \frac{u_2}{r_2}$$

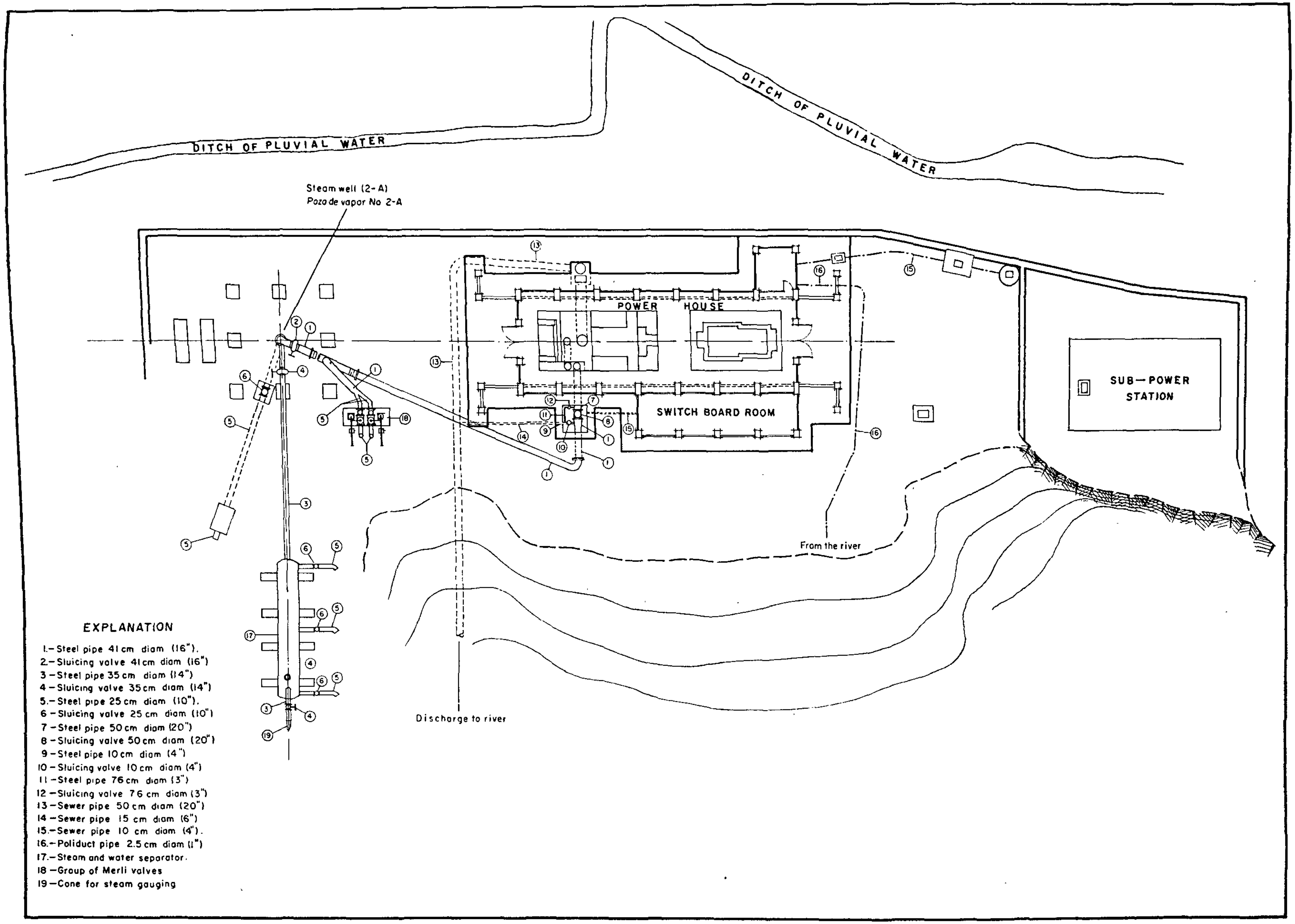



**Figure 6. Equipment used in providing natural steam at geothermal pilot plant, Pathé, Hidalgo**

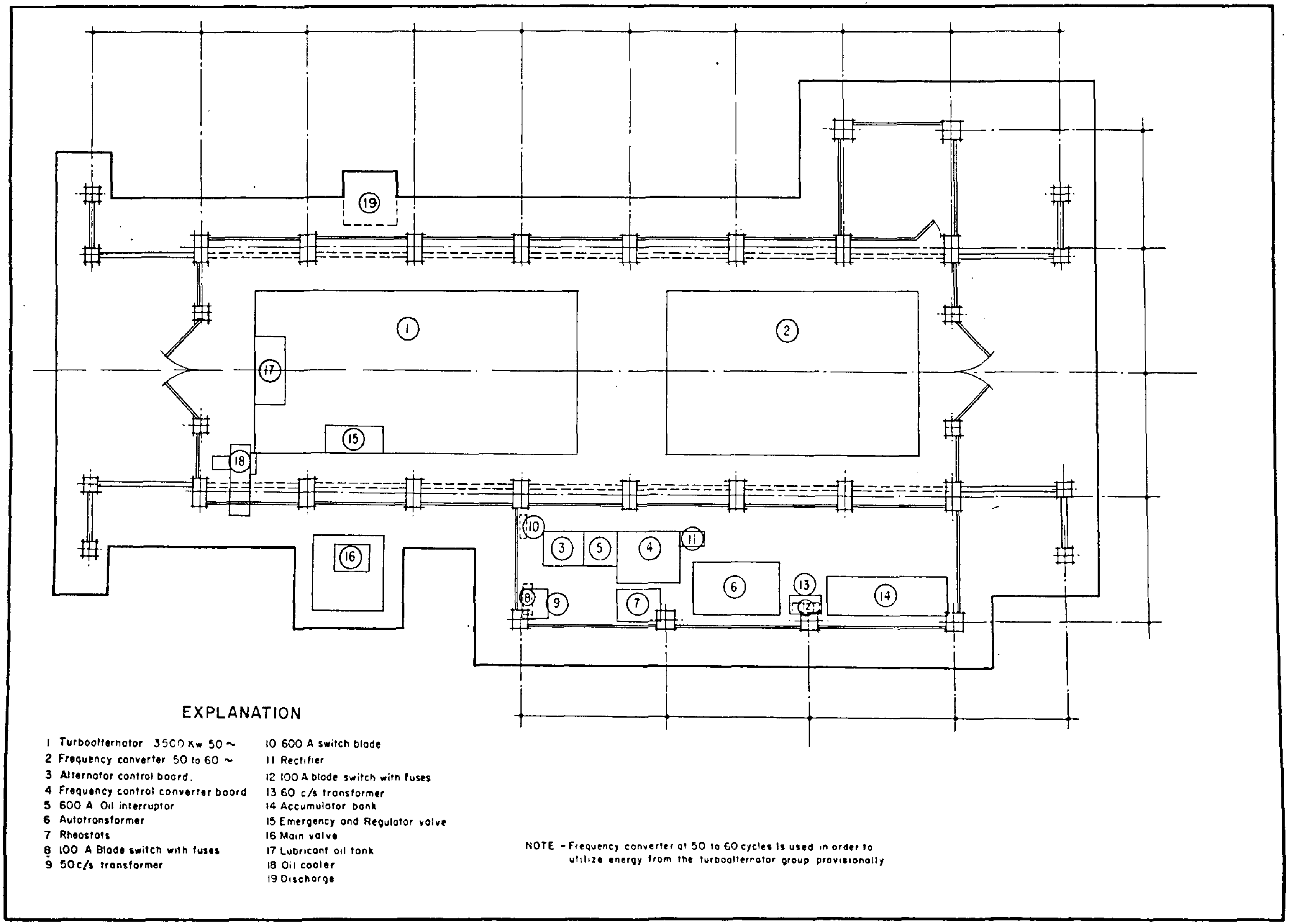
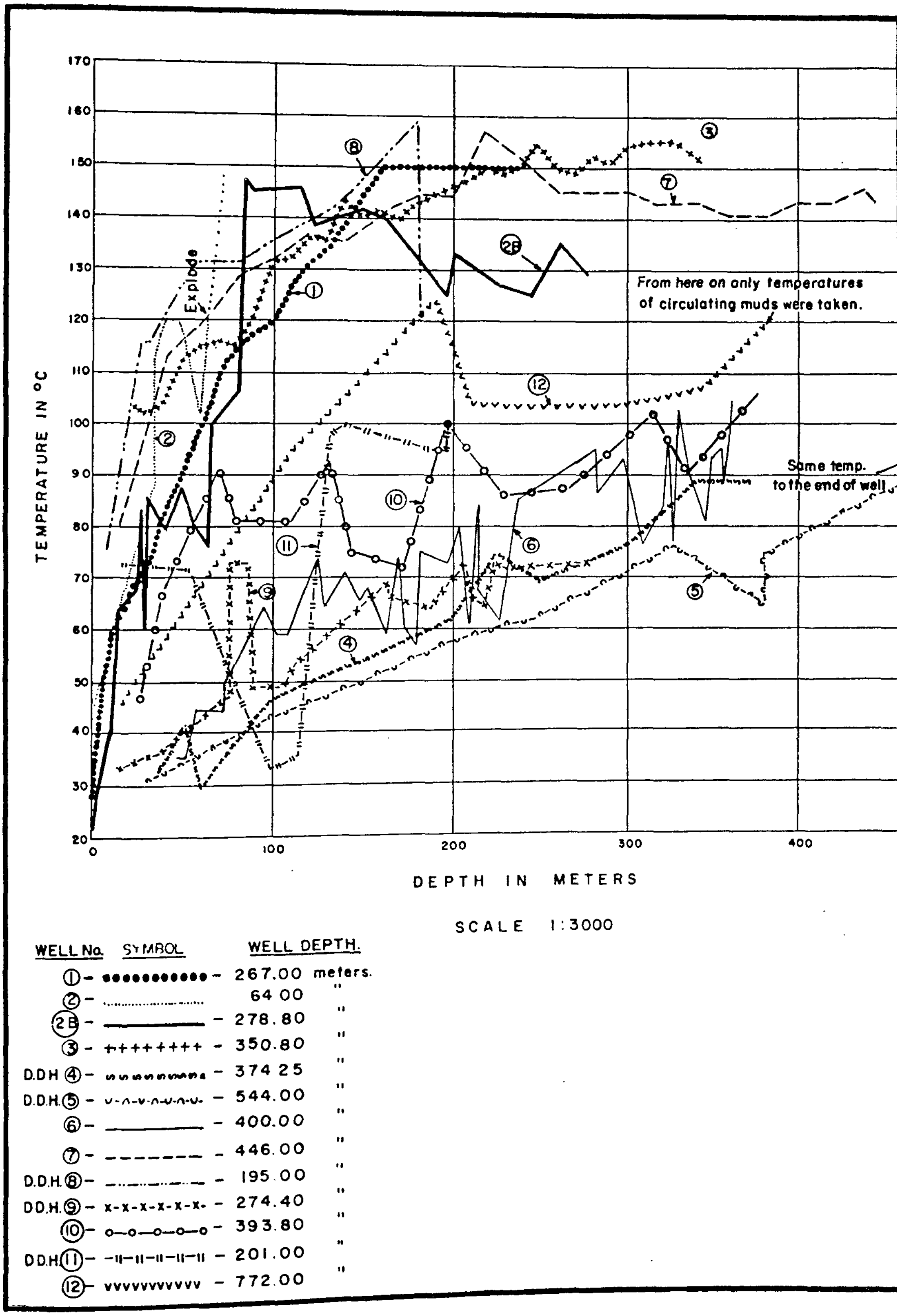



**Figure 7. Geothermoelectric pilot plant at Pathé, Hidalgo, operated by the the Comisión Federal de Electricidad**




D.D.H = Diamond Drill Hole

Figure 8. Temperatures at varying depths in geothermal wells, Pathé, Hidalgo

There is a system of two equations:

$$f(u_2) = \frac{T_0 - T_2}{T_0 - T_1} \cdot f(u_1); \qquad u_1 = \frac{r_1^2}{r_2^2} \cdot u_2$$

Since $T_0$, $T_1$, $T_2$, $r_1$, $r_2$ are known, with the aid of the table, the curve that relates $u$ with $f(u)$ can be drawn on logarithmic paper.

Any given value may then be assumed for $u_2$, and by replacing it in the former equation, a corresponding value for $u_1$ may be obtained. With the aid of the appropriate table, the corresponding value is found for $f(u_1)$; by replacing it in the first equation, a value of $f(u_1)$ is found; it will be false in general, and it will not coincide with the true

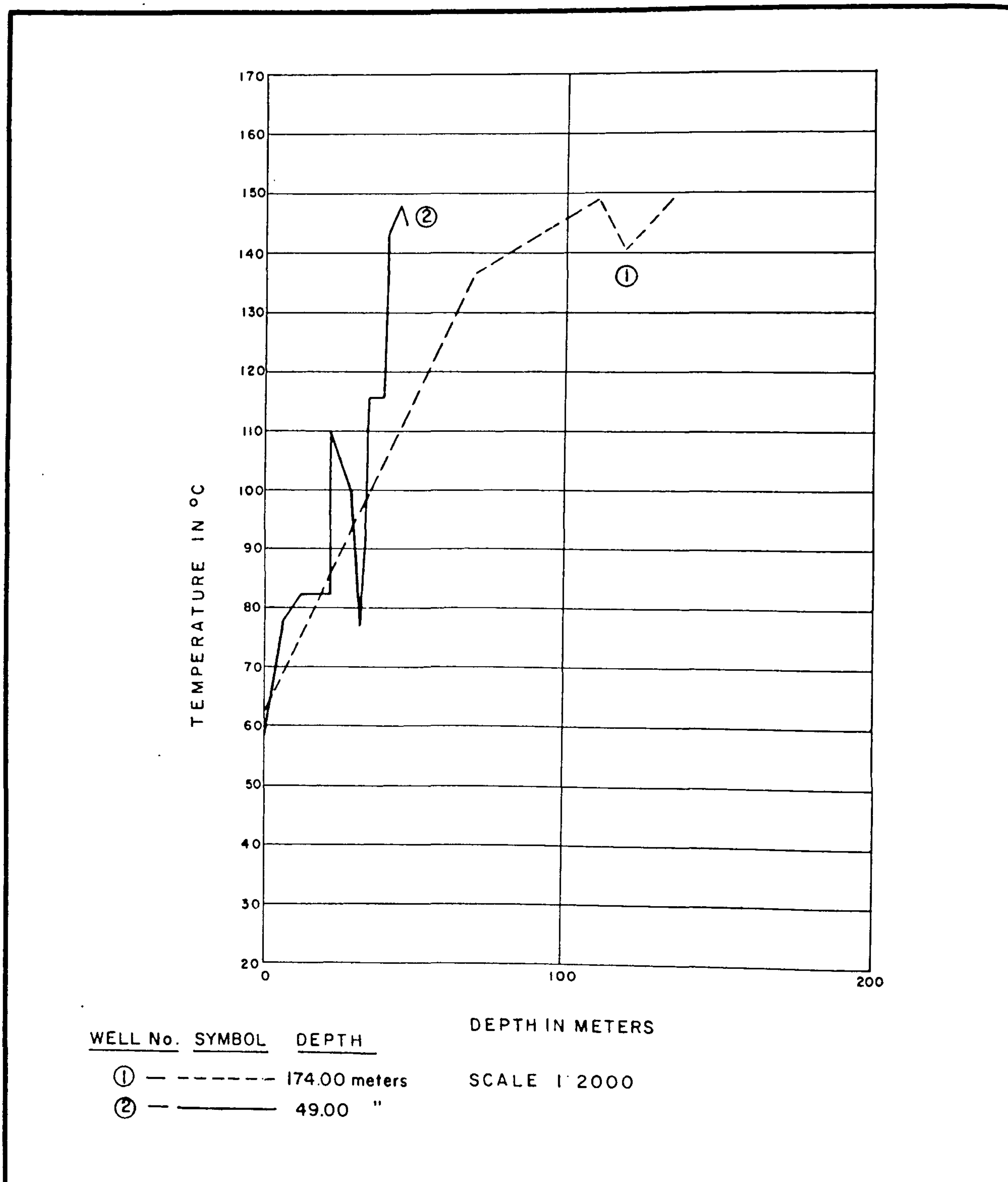



Figure 9. Temperatures at varying depths in geothermal wells, Ixtlán

value that $f(u_2)$ ought to have when a predetermined value is assigned to $u_2$ and the corresponding value of the function is found on the tables. Nevertheless, that value is placed on the graph.

Other values are calculated in the same way, and will have a curve that will intersect the true curve of the relation of $u$ with $f(u)$ at one point. This point marks the value that must be chosen for $u_2$, replacing it in the equation :

$$b = \frac{u_2}{r_2}$$

This is the value that has been sought for $b$. In the same way the table provides the value of $f(u_2)$, which corresponds to the last value chosen for $u_2$, that is substituted in :

$$a = \frac{T_0 - T_2}{f(u_2)}$$

Having the values sought for the two parameters $a$ and $b$ for the well mentioned, the theoretic curve applicable to the geothermal well in question can then be drawn.

Estimates of the productive capacity of a geothermal field can be determined by following a similar procedure, drilling three wells close enough so that the operation of two of them appreciably affects the pressure readings on the third. In a similar way the permeability of an aquiferous body can be determined, using pumping methods, applying the formulas of Muskat (Flow of Homogeneous Fluids Through Porous Media), Theis (Determination of the Permeability of Water Bearing Materials) or Wenzel or others.

This estimate has not yet been made because it is thought that the first well does not have the necessary depth, and the readings are therefore inadequate.

There is a possibility of an underground sedimentary trap in the Pathé field. This opinion is based on the observations made on the Mesozoic limestone outcrops around Pathé, which, roughly, follow a semi-ellipse. To the north-west of this locality, near León, Gto., such limestones are unconformably overlying crystalline schists. There are plans to conduct detailed geological surface mapping in the near future, and an electrical resistivity exploration, as well, in order properly to locate the volcanic sediments contact underneath.

## Ixtlán

Ixtlán field (figures 2 and 9) is situated in the state of Michoacán, near Chapala Lake (1 400 metres above sea level) and at an elevation above the lake surface of more than 100 metres. Both surface and subsurface drainage ape towards such a lake, and the Duero River is the surface expression of this drainage. Ixtlán valley is structurally a graben; on the left margin of the river there are several thermal springs, some of which function as geysers of reduced flow. Saline deposits of hydrothermal origin are not very abundant.

Two shallow drillings have been made at Ixtlán (figure 9) for geothermal purposes : one at 220 metres and the other at 180 metres below the surface of the terrain. At the beginning, temperatures increased more rapidly than at Pathé for the same depths, but below approximately 150 metres, temperatures were practically stabilized, and did not increase further.

All these circumstances lead to the inference that Chapala Lake makes the thermal springs behave as geysers; the assumption is that the influence of Chapala on Ixtlán goes as deep as 150 metres below the surface; actually, this lake regulates and holds back the water to a certain depth. The geyser phenomena perhaps would not be apparent if underground hydraulic flow were rapid enough. This situation seems to occur in other parts of Mexico.

There are no substantial saline deposits as a result of hydrothermal activity in Ixtlán, perhaps because the salts are intercepted on their way up by the rapid flow of underground water. Only dissolved salts can reach the surface and be precipitated.

There are definite plans to carry on drilling to a depth of 1 500 metres below the surface. It will then be known whether or not these considerations are sound.

## Mexicali

Mexicali field (figures 2 and 5) is located in the meridional continuation of the San Andrés fault system, which perhaps gave origin to the Gulf of California.

There is a basaltic promontory near Mexicali, called Cerro Prieto (figure 5), around the margins of which there are several hydrothermal springs; sulphur deposits of non-economic importance and a few salts precipitated from the springs are exploited locally in a rudimentary way.

West of Cerro Prieto lies the Sierra of Kukapás, formed by the granitic batholith of Baja California. Its western and eastern margins show clear evidence of faulting. Incipient mineralization is exploited in the interior of the range, and there are some hydrothermal springs at the eastern margin, especially in its northernmost portion.

Geothermal exploration was initiated near the eastern part of Cerro Prieto in order to reach the granitic batholith below the overlying sediments and try to find a favourable steam trap between the two main types of formation.

To the present time, more than 600 metres have been drilled in alluvial deposits without reaching the batholith. Temperatures seem to have been increasing very favourably, although it has not been possible to determine the maximum temperature so far reached owing to a mechanical difficulty at the depth mentioned (see figure 10).

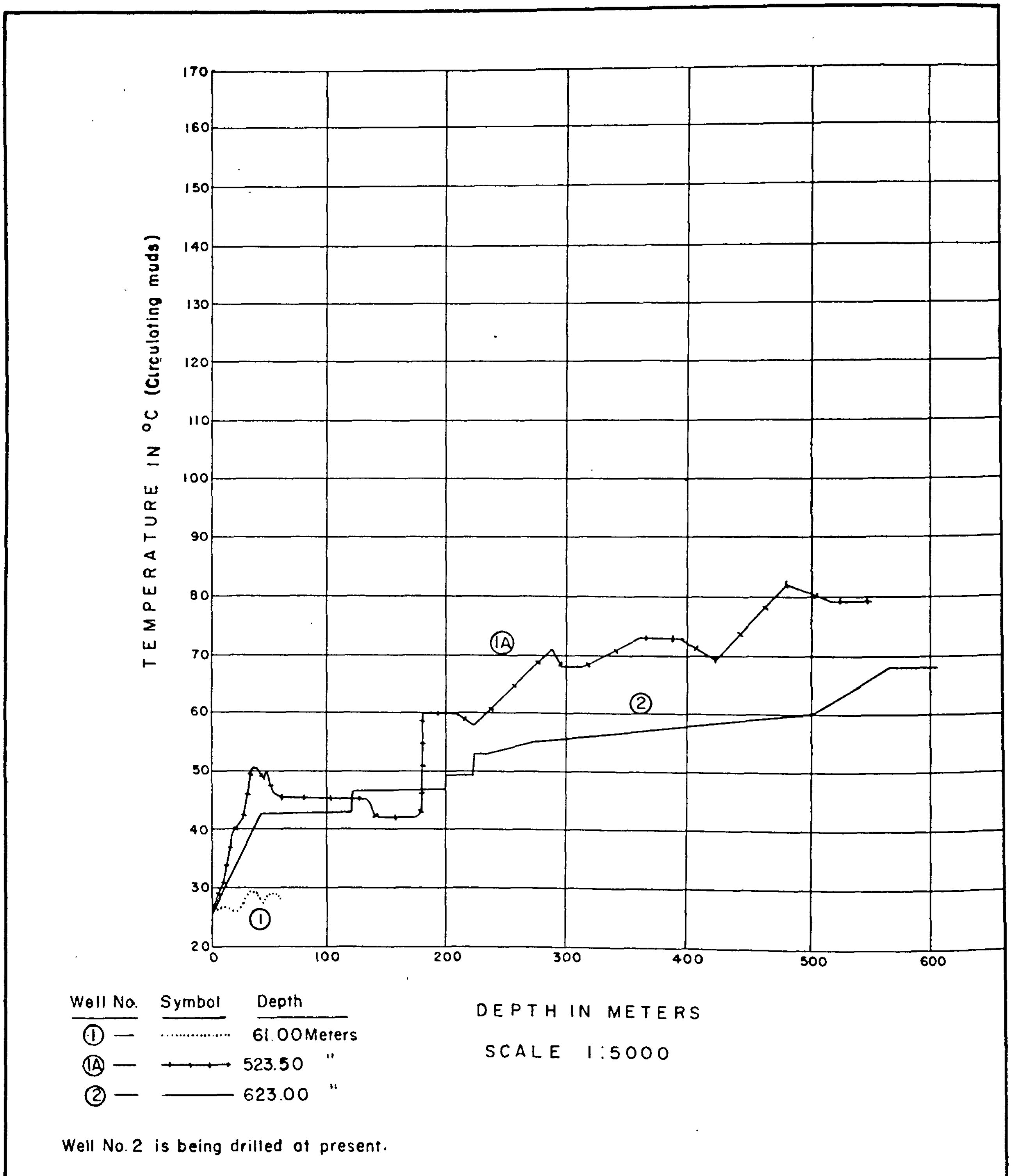



Figure 10. Temperatures at varying depths in geothermal wells, Mexicali

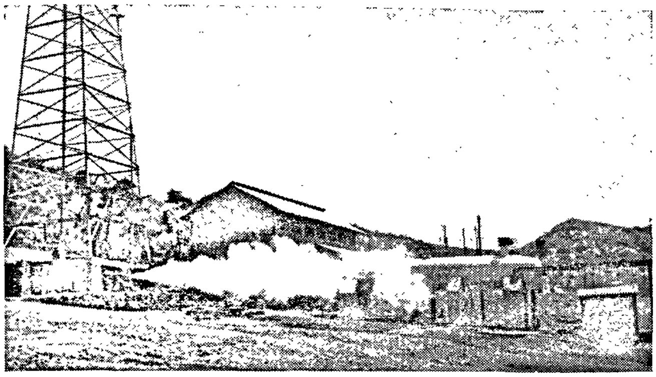


Figure 11. Geothermal electric pilot plant, Pathé, Hgo., Mexico

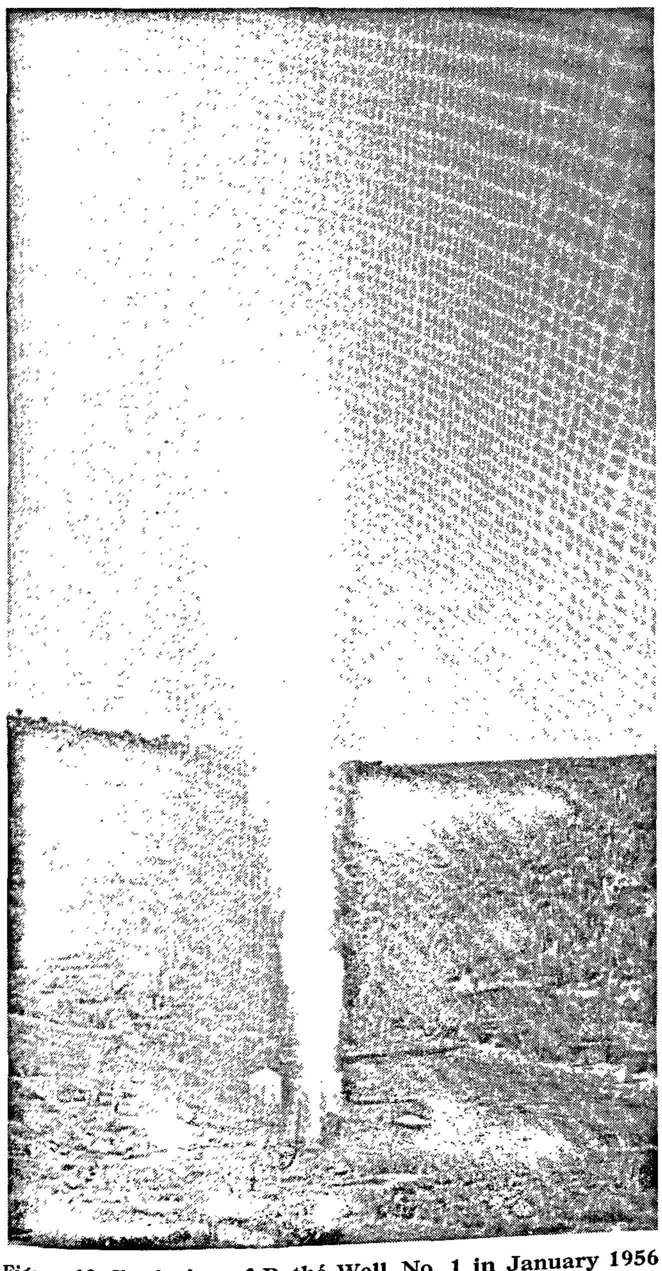


Figure 12. Explosion of Pathé Well No. 1 in January 1956

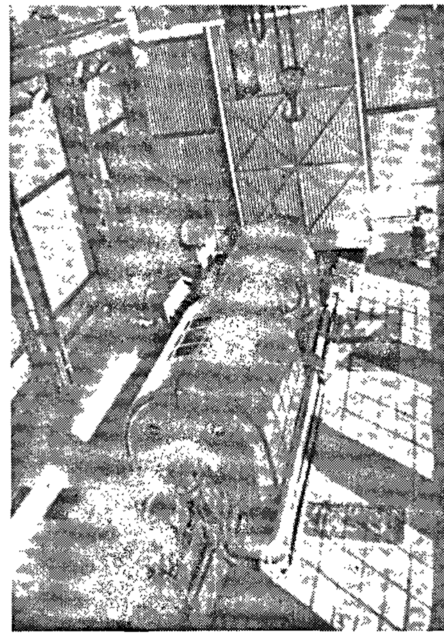


Figure 13. Geothermoelectric 3 500 kW group in pilot plant, Pathé, Hgo., Mexico

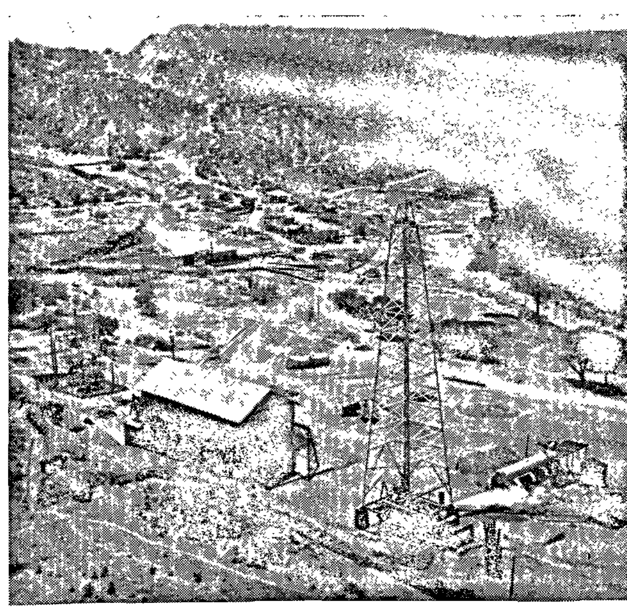


Figure 14. Pathé field development, Mexico. Foreground, Well No. 2A and pilot power house; middleground, Well No. 1; background, Well No. 3

## Conclusions

In the light of experience obtained at Pathé, Ixtlán and Mexicali, the utilization of geothermal energy in Mexico will probably result in cheaper energy in the central and north-western parts of the country.

Corroboration of success in the three fields mentioned will permit and encourage general enterprises to work at the development of this new field of energy, thus helping the local economies of some parts of the country.

At the beginning of 1961, about 8 million pesos (about U.S. $640 000) had been invested for the purpose of investigating geothermal energy in Mexico; this included drilling a total of sixteen wells. This is a small amount, considering the size of the country and the possibilities offered by geothermal development.

## Acknowledgements

On their own behalf, and on behalf of the institutions they represent, the authors wish to express their gratitude to the United Nations Conference on New Sources of Energy for the opportunity of presenting to the Conference the achievements, as well as the unsolved problems, of the fascinating field of geothermal energy in Mexico.

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## *Summary*

Evidences of geothermal activity related to structural and tectonic features were considered in choosing three sites for investigation and drilling in Mexico : Pathé and Ixtlán, in the neovolcanic zone, and the fault zone of San Andrés, near Mexicali, B.C. This paper includes general information on the progress of investigations in these zones.

Information is given in connection with methods used in the explorations conducted so far, including technical problems of drilling, as well as costs and results obtained in the wells drilled (twelve in Pathé, two in Ixtlán) at depths between 250 and 760 metres, in areas partly consisting of basalts, much altered and fractured, at a general elevation of 1 550 metres above sea level.

Consideration is given to the possible effects of elevation above sea level on production and to the advantage of drilling deep, to sea level, in order to learn the influence of subsurface water on steam production at different elevations.

Results obtained to the present time with one well drilled to 600 metres in the steam field at Mexicali, B.C. are given in the text.

Experience with the turbo-generator pilot plant installed at Pathé, utilizing one of the dry steam wells, demonstrates that production characteristics are affected by the operation of some near-by wells, whose production of water and steam has varied with time. Mention is also made of the costs of production of geothermal-electric energy.

Observations on incrustations of the Pathé wells indicated that a chemical change from carbonates to silica had occurred. It is supposed that the amount of incrustation material will diminish with the increasing depth of the wells, and that at the same time there will be an increase in the discharge pressure.

To complement the drilling, a geological survey is now planned to cover a wide surrounding area at the steam fields of Pathé and Ixtlán. In exploring the geological structure, the discontinuity of volcanics and older underlying rocks is considered important as a trap for steam in the subsurface area. Geophysical methods and techniques will likewise be used for this purpose.

# ÉNERGIE GÉOTHERMIQUE AU MEXIQUE


## *Résumé*

Les indications d'activité géothermique en rapport avec des caractéristiques structurelles et tectoniques ont été étudiées pour choisir trois emplacements en vue de recherches et de forages dans la République mexicaine : Pathé et Ixtlán dans la zone néovolcanique, et la zone à failles de San Andrés, près de Mexicali, en Basse-Californie. Ce document fournit des renseignements généraux sur ces zones qui jusqu'à présent, ont fait l'objet de recherches.

Les auteurs donnent des renseignements sur les méthodes de recherche déjà utilisées, mentionnant notamment les problèmes de forage, ainsi que le coût et les résultats obtenus dans les puits forés (12 à Pathé, 2 à Ixtlán) à des profondeurs variant entre 250 et 760 mètres, dans des zones formées partiellement de basaltes, très altérés et fracturés, à une altitude générale de 1 550 mètres au-dessus du niveau de la mer.

Ils examinent les résultats possibles en matière de production à diverses altitudes et les avantages que présenteraient des forages atteignant le niveau de la mer, afin de déterminer l'influence des eaux souterraines à diverses altitudes, en rapport avec la production de vapeur. Ce mémoire présente les résultats obtenus jusqu'à présent avec un puits du champ de vapeur de Mexicali (profondeur actuelle : 600 mètres).

L'expérience acquise avec l'installation pilote turbo-génératrice de Pathé, en se servant de l'un des trois puits de vapeur sèche, démontre que les caractéristiques de production sont affectées par l'exploitation de certains des puits voisins, dont la production d'eau et de vapeur a varié en fonction du temps. Il est fait mention du coût de production d'énergie électrique géothermique.

En observant les incrustations des puits de Pathé, on a constaté un changement de leur nature chimique : les carbonates se sont transformés en silicates. On présume que la quantité de matière d'incrustation sera d'autant plus faible que les puits seront plus profonds, la pression de décharge augmentant parallèlement.

Pour compléter le forage, on prévoit maintenant une étude géologique qui portera sur une vaste zone entourant les champs de vapeur de Pathé et d'Ixtlán. En étudiant les structures géologiques, on attache une grande importance aux discontinuités des roches volcaniques et des autres roches plus anciennes, qui forment des pièges de vapeur dans le substratum. On emploiera également des méthodes et des techniques géophysiques à cette fin.

# GEOLOGICAL ENVIRONMENT OF HYPERTHERMAL AREAS IN CONTINENTAL UNITED STATES AND SUGGESTED METHODS OF PROSPECTING THEM FOR GEOTHERMAL POWER

*L. C. Decius* *

The purpose of this paper is to classify occurrences of thermal emanations in the continental United States with the view of determining what characteristics recommend specific areas as reasonable prospects in attempting to develop geothermal power. None of the published literature that has come to the attention of the writer has treated of the prospective economic value of geothermal energy as related to the development of power. Literature relating thermal springs to human health and welfare, however, is abundant, and has been of great value for this study. Private geologic studies with the object of producing geothermal power were made by the writer starting in the year 1924 and at later dates by others, but so far as is known such studies have been very limited.

Including two presently drilling, there have been forty-three wells drilled in the western United States in the attempt to discover and develop geothermal power. Important discoveries have resulted in several areas, and manufacture of electrical energy is presently in operation at one. It has been the privilege of the writer to observe the drilling or the findings of all but two of these wells, as well as to conduct geologic investigations in eight of the total of ten areas in which exploration drilling has been conducted.

## Sources of geothermal heat

The occurrence of thermal springs—that is, springs having temperatures noticeably higher than the mean average temperature of the atmosphere in the area in which they are located, may be ascribed to several causes. Temperature gradient of the earth's crust must be recognized as a possible primary cause of thermal springs and as a beneficial factor in aiding retention of heat in springs which may owe their abnormal thermal state to other causes. Estimated averages of geothermal gradients vary from one degree Fahrenheit per 60 feet of depth to one degree Fahrenheit per 100 feet of depth. Even in the lesser case, water or gas at depths of 12 000 feet should have temperatures near the boiling point of water. Deep oil wells have generally substantiated such figures. In extremely deep wells, one at a depth of 20 600 feet, temperatures as high as 454°F have been encountered, and at least 500°F is expected in deep wells to be drilled in the near future.

It may be assumed from the above that in areas where there are no avenues of rapid escape or ascent for waters or gases that have their habitat in high-temperature depths, a state of relative hydraulic and thermal equilibrium exists. Waters existing in these zones may be either connate, meteoric or, possibly to a minor degree, juvenile waters which have had their source in magmas. For the purpose of this study they may all be designated under the term, "interstitial water".

Movement of interstitial water may be induced by the addition of meteoric water, causing it to escape in springs or broad areas of evaporation. Water so escaping from the deep zones of saturation should not exhibit abnormal temperature differences. The introduction of an equilibrium-disturbing phenomenon therefore appears to be requisite to the creation of changes in temperature from the established normal.

Various geological phenomena may play roles in disturbing the normal thermal equilibrium. Such phenomena may be due to any of the following: (*a*) the presence of intrusive magma ascending to zones near enough to the earth's surface to impart their abnormal heat to surrounding rocks and consequently to interstitial water in such rocks; (*b*) extrusive igneous rocks which because of their recent date of activity still retain abnormal heat; (*c*) active volcanism; (*d*) expiring volcanism where escaping heat is found in rocks adjacent to collapsed volcanic cones or calderas; (*e*) disintegration of radioactive elements. The latter phenomenon more likely occurs over too broad an area to act as a localized source of heat. Heat generated by faulting is also evident in some cases, but few if any faults are believed to generate sufficient heat to create hyperthermal waters. In such cases the probability is always present that the fault merely affords an avenue of escape for waters that have received their heat from deep sources entirely separate from faulting.

Of all the probable sources of geothermal heat cited above, intrusive and extrusive masses of magma must be recognized as a requirement in affording hyperthermal conditions of economic value. Intrusive magma of whatever form may act as a source of heat from which thermal waters and gases are derived. Batholiths, laccoliths or lesser bodies, such

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as dikes, stills and stocks, carry original heat sufficiently high to impart hyperthermal qualities to waters and gases coming within their sphere of influence. Many of such intruding bodies, presently exposed by erosion, may be studied. Questions persistently arise as to the depth at which still hot bodies of intrusive igneous rocks may exist in areas of present hyperthermal activity. The depth, of course, may be anything from zero to many thousands of feet. The only probable limiting factor is the greatest depth at which they may have sufficient capacity to impart conducted heat to water and gases having avenues of escape to the surface. This means that such intrusive magmas are within the zone of interstitial water or sufficiently close to it so that their heat components, which must be much higher than the normal earth temperature gradient, can, by conductivity, start and maintain convection currents. By convection currents so built up, the heat-bearing media find their way to the surface. It might be better stated to say that the heat-bearing water and gas are forced to the surface by hydraulic processes so developed.

It is not probable that convection currents within the interstitial water zone and within the scope of this problem resemble convection currents operating in a free surface vessel to which heat is applied. Resistance to the upward movement of heated water and gas is offered in varying degrees by the differences in permeability of the rocks through which they must travel. It is further probable that ascending heated water and gas may be confined to relatively narrow channels along fracture planes in the rocks.

In figure 1, a striking example of intrusive magma is seen in the occurrence of Devils Tower in Crook County, Wyoming. The photograph is copied from United States Geological Survey, *Bulletin 1021-I*. The author, Charles S. Robinson, believes Devils Tower was formed by the intrusion of magma into overlying sedimentary rocks. The tower at present rises some 600 feet above the talus slope at its base. It is about 800 feet in diameter at its base and 180 to 300 feet across its relatively flat top surface. The author estimates that at the time of intrusion the tower was probably covered by several hundred feet of sedimentary rock. A well drilled 1.5 miles from Devils Tower in search of oil encountered rock similar to that of Devils Tower at a depth of 1 400 feet in a location normally occupied by Mesozoic rocks of far greater thickness than 1 400 feet. No other extrusive rocks occur in the vicinity of Devils Tower. It appears that a family of intrusive stocks may possibly have risen from a very extensive body of magma underlying the vicinity of Devils Tower.

Speculation as to thermal activity that may have existed during the intrusion and cooling stage of Devils Tower may well include the expulsion of thermal water and gas to the earth's surface. It intruded rocks well within the zone of interstitial water. The Tower is a phonolite porphyry. Heat necessary to allow this rock to become fluid and intrude overlying rocks would approximate 1 800°F. One cubic mile of this rock cooling from 1 800°F to 100°F would liberate sufficient heat to operate a 4 000 kW generator plant for 7 000 years. Study of igneous bodies of earlier geologic ages than those concerned here show that one cubic mile would be but a small part of the great masses that have been exposed by erosion or that have flowed from vents.

Hot water and gas reaching near enough to the earth's surface to be exploitable by drilled wells constitute the media by which heat may be captured and employed in driving engines. Steam at superheat temperatures together with steam that may be flashed from water above the boiling point, as well as heat that may be transferred from water at less than the boiling point, all become usable products. Areas where wells may successfully recover the above products are within the desirable range for prospecting. Such areas as may afford superheated steam and water above the boiling point must be recognized as those exploitable within our present economic limitations.

## Prospecting methods

A search of the literature leads to the conclusion that springs of hyperthermal characteristics, that is, springs with emanation of water at or near the boiling point, are limited to that part of the United States lying west of the easterly front of the Rocky Mountains. Figure 2 shows that boundary by dash and dot line. Widespread volcanic activity during Tertiary and Quaternary time occurred across nearly all parts of the westerly United States. Within the area west of the east front of the Rocky Mountains, excluding the Yellowstone Park area, there are about 700 known thermal springs. Of the foregoing number there are some eighty or ninety springs of hyperthermal character. Investigation of geologic surroundings in the vicinity of the hyperthermal springs indicates that in almost all cases these springs are situated within, adjacent to, or within a short distance of, late Tertiary of Quaternary volcanic rocks. The evidence, while not wholly complete, nevertheless strongly associates the very hot areas with Pliocene, Pleistocene or Recent effusive or explosive volcanics.

Figure 2 also shows the area within which the eighty or ninety hyperthermal springs are situated. It is to be noted that all prospecting of geothermal products to date has occurred within this area. From available data and evidence it would therefore appear that geologic prospecting for geothermal products, at least in the United States, should be conducted within areas of late Tertiary and Quaternary volcanism.

In prospecting for favourable areas in which to attempt development of geothermal products of sufficient volume to justify development of power, it is the opinion of the writer that at the present time the most dependable and possibly the only practical method lies in an interpretation of thermal emanations as related to their geologic environment. Measurements of heat flow, principally from run-off waters, have been suggested and are no doubt usable in specific cases. Such measurement methods, however, may not be applicable to other cases in other areas. Any attempt to measure heat by means of temperature and volume of run-off thermal waters at the Big Geysers in Sonoma County, California, would fall far short of finding total amounts. This is an area of superheat, comprising sixty or seventy acres, giving up heat to the atmosphere by radiation while affording only a small run-off of hot water. Measurement of heat radiated from the rock surface to the atmosphere would involve exhaustive investigations that seem unwarranted because it is obvious from observation that attempts at economic development are highly justified.

Similar conditions prevail in several of the hyperthermal areas where prospect drilling has been conducted in the western United States. In some of them it appears that only a small part of the

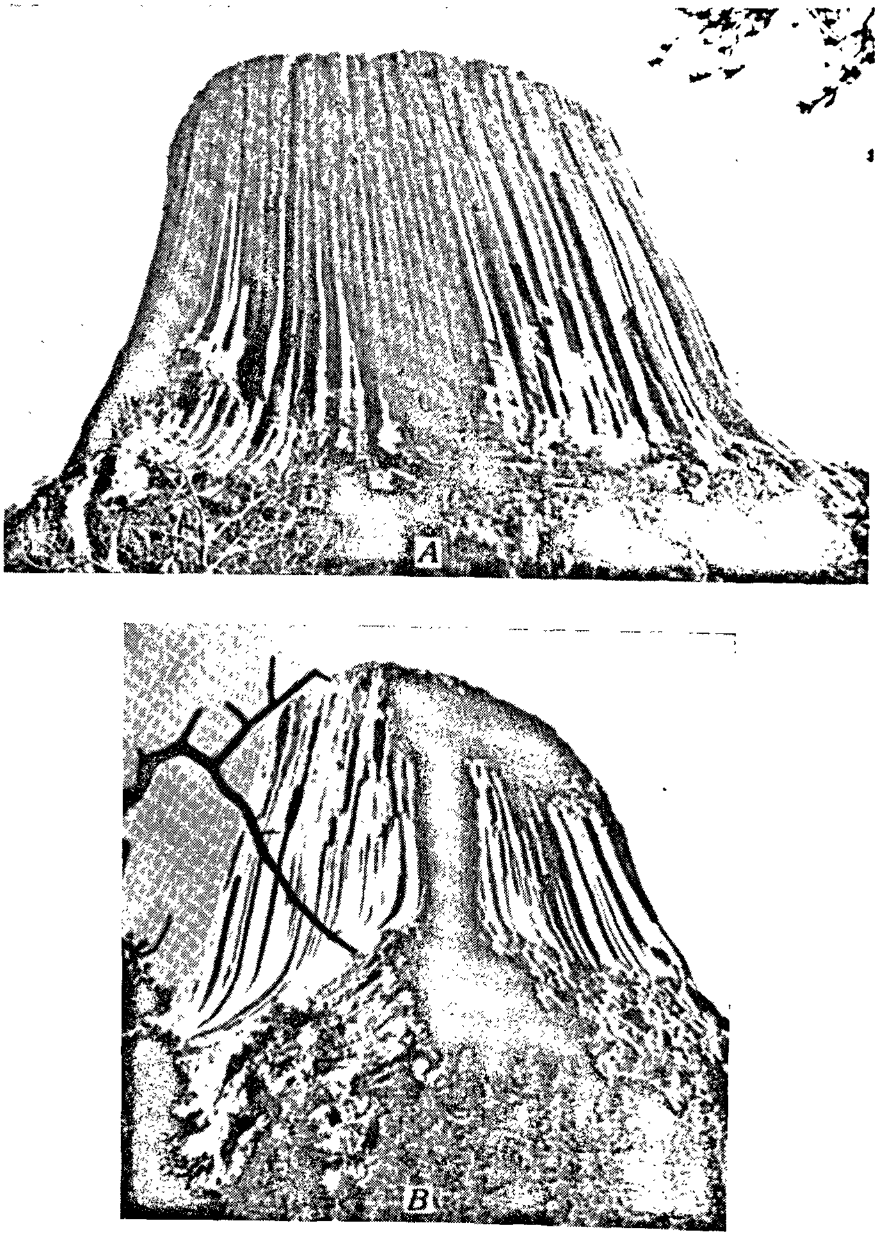
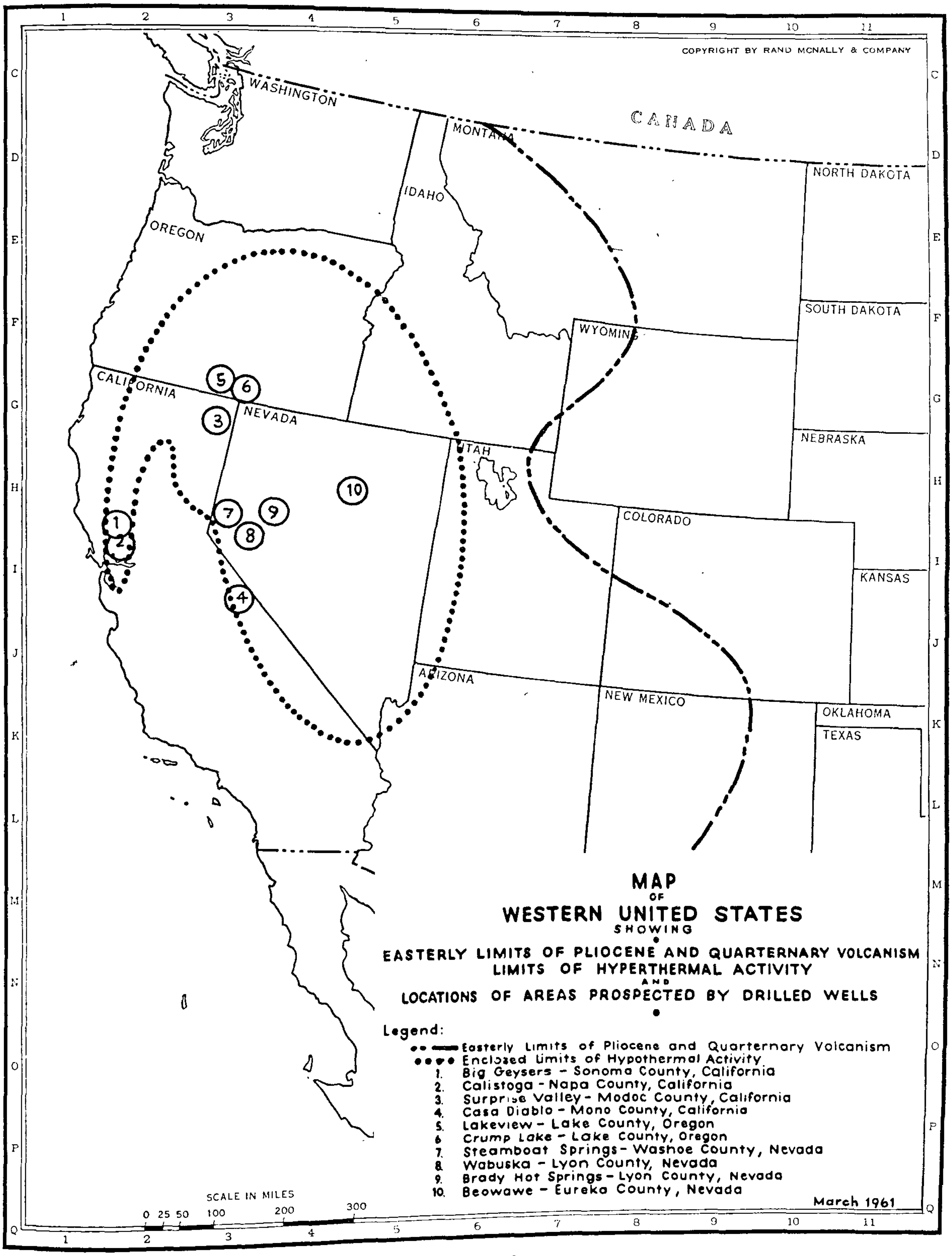



**Figure 1. Devils Tower, Crook County, Wyoming**

A. North-west side of Devils Tower showing how the columns taper or converge and in places unite near the top and are cut by numerous cross-fractures.

B. South side of Devils Tower showing the columns flaring out and merging to form the massive base.

(After *United States Geological Survey*, Bulletin 1021 I)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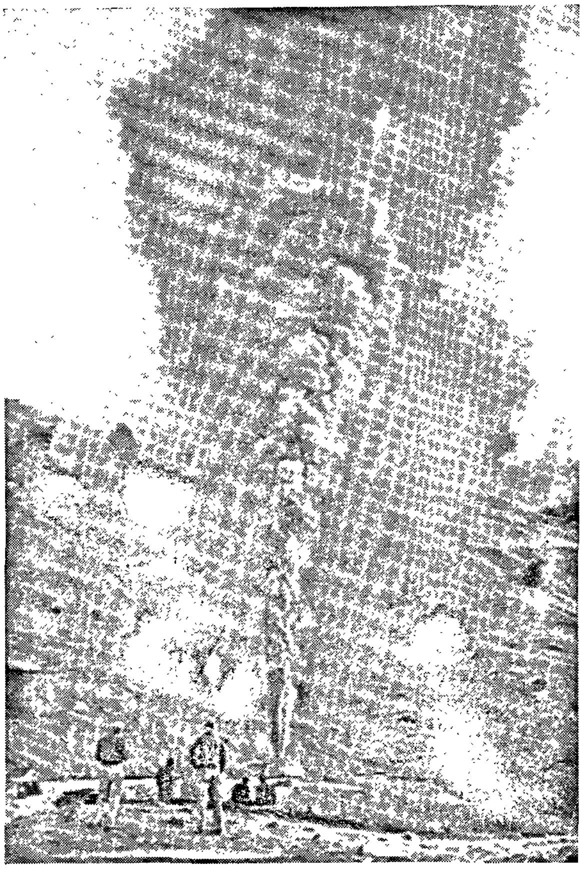
ARIZONA
NEW MEXICO
OKLAHOMA
TEXAS
MAP
OF
WESTERN UNITED STATES
SHOWING
EASTERLY LIMITS OF PLIOCENE AND QUARTERNARY VOLCANISM
LIMITS OF HYPERTHERMAL ACTIVITY
AND
LOCATIONS OF AREAS PROSPECTED BY DRILLED WELLS
Legend:
Easterly Limits of Pliocene and Quarternary Volcanism
Enclosed Limits of Hypothermal Activity
1. Big Geysers - Sonoma County, California
2. Calistoga - Napa County, California
3. Surprise Valley - Modoc County, California
4. Casa Diablo - Mono County, California
5. Lakeview - Lake County, Oregon
6. Crump Lake - Lake County, Oregon
7. Steamboat Springs - Washoe County, Nevada
8. Wabuska - Lyon County, Nevada
9. Brady Hot Springs - Lyon County, Nevada
10. Beowawe - Eureka County, Nevada
March 1961
SCALE IN MILES
0 25 50 100 200 300

Figure 2



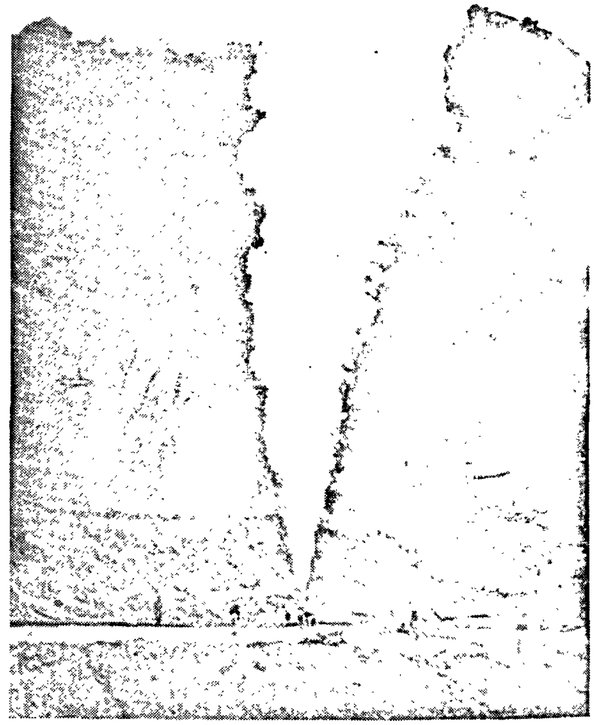


**Figure 3**

Magma-Thermal Power Company well number 1, September 1955, at Big Geysers, Sonoma County, California. At left, well at completion blowing drilling mud, formation rock and steam. At right, after a few hours of cleaning up, well blowing clean steam. Total depth 603 feet, surface pipe cemented at 180 feet. Shut-in pressure 240 psi. Temperature at bottom 600°F. This well is typical of operation by Magma-Thermal Power Company at Big Geysers.

*(Photographs by Redwood Empire Association)*

thermal emanation reaches the surface. Because of the porosity of surface overburden there is undoubtedly a subsurface run-off of thermal water into deep basins adjacent to the area of thermal activity. None of such subsurface run-off is observable or measurable. In many cases understanding of geologic control points to the advisability of testing by prospect drilling.

What improvements in prospect well locations the future may develop rests with information to be developed by close observation of subsurface data gained from well logs, including principally core records and the various types of electric and other logs, together with temperature surveys by thermocouple instruments. At present, prospecting in the western United States has not gone outside areas of thermal activity observable at the surface. Recognizing the probability of subsurface zones of heat saturation into porosity zones adjacent to the avenues of ascent of the geothermal products, prospect drilling with the purpose of extending the productive areas will follow exploitation of proved productive areas. What assistance geophysical surveys may render is also to be proved in the near future.

## Areas prospected by drilled wells

Figure 2 shows the locations of ten areas within the hyperthermal region of western United States that have been prospected by drilled wells. The first area, location 1, is the Big Geysers in Sonoma County, California. The first geological observations in this area were by William Brewer in 1861. Since that time various reports have been published by geologists of the State of California. Private geologic investigation with the purpose of producing geothermal steam for generation of electric power was made in 1924 by the writer, and investigations by other geologists followed in 1955.

The Big Geysers area is one of five emanations of hyperthermal springs occurring along a straight five-mile alignment immediately on the north side of Sulphur Creek in Sonoma County, California. None of these emanations exhibits true geyser characteristics.

Sulphur Creek has cut the deep trench of Sulphur Canyon in a north 60° west direction into rocks of the Franciscan, Jurassic group. These rocks include principally well-indurated medium to fine grained sandstones with minor thin dark shale members, cherts, greenstones altered from basalt and serpentines derived from ultra-basic intrusive masses. The total thickness of the Franciscan group in the Sulphur Canyon area is not determinable. It unquestionably aggregates several thousand feet and may total as much as 15 000 or 20 000. The lowest exposed member of the Franciscan in Sulphur Canyon is the sandstone series. It is through this member that all five of the thermal emanations have found exit to the surface.

Structurally the Sulphur Canyon area presents a northward dipping monocline extending from the bottom of the canyon northward to the summit of the mountain ridge some 6 000 feet distant and 1 700 feet higher. Elevation at the Big Geysers is 1 700 feet above sea level.

Regionally it appears that Sulphur Canyon is cut into a great fault rift which may be moving in sympathy with the movement of the San Andreas Rift paralleling Sulphur Canyon approximately 30 miles to the south-west. Along the San Andreas Rift the westerly block is drifting northerly. Some evidence suggests a northerly drift of the block on the south side of Sulphur Canyon. There is also unquestionable evidence of overthrusting of the block of rocks on the north side of Sulphur Canyon towards the south.

The fault zone of what may here be called the Sulphur Canyon fault appears to have a width of about 1 000 feet at the area of the Big Geysers within which zone the rocks are shattered and displaced to the extent of developing chaotic structural conditions. This feature combined with cascading boulders from higher elevations and crushed landslide material precludes exact interpretation of fault conditions in the immediate area. Similar conditions are found one mile westerly at Sulphur Bank, another area of hyperthermal activity, and again

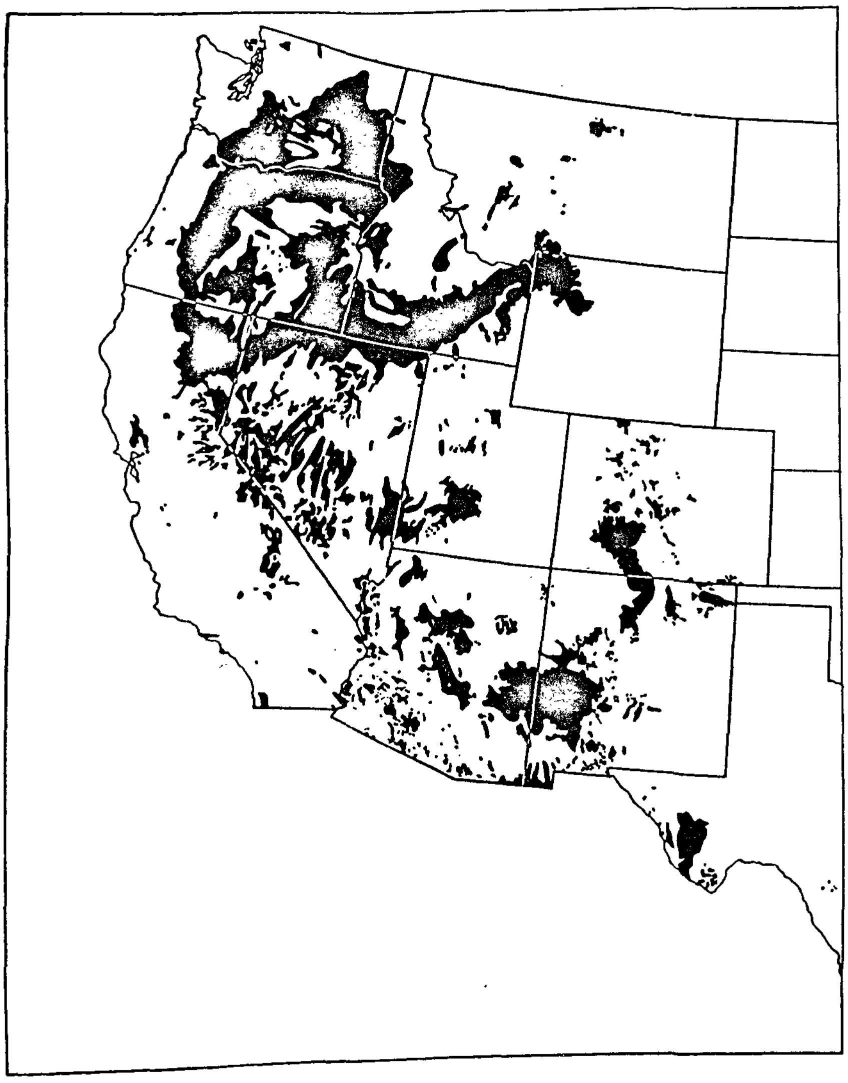


**Figure 4**

This map, copied from United States Geological Survey *Water Supply Paper Number 489* by Oscar Edward Meinzer, should be read in conjunction with figure 2. Within these areas of volcanics, Pliocene, Pleistocene and Recent volcanics afford the great majority of hyperthermal emanations.

the suggestion is of a broad fault zone. Two miles south-east of Big Geysers near the thermal activity at Duchy Creek, the Franciscan sandstones are at vertical angles and indicate extreme compression. At the easterly extremity of the fumarole district in the Little Geysers area, overthrusting towards the south is strongly evidenced.

Temperatures across the five-mile extent of the fumarole areas in Sulphur Canyon were taken at the surface, specifically at Sulphur Bank, Big Geysers and Little Geysers. Each of such areas demonstrates thermal emanation at the boiling point of water. Fumaroles appear at various points over an area of approximately 100 acres at Sulphur Bank, over approximately 70 acres at Big Geysers and about 20 acres at Little Geysers. The temperatures noted are of course all within the influence of cooling by atmospheric conditions. During drilling operations temperatures of 350°F were encountered at depths of only 20 to 30 feet, and at 900 feet temperatures were in excess of 400°F.

In searching possibilities of the source of heat issuing from the various points along the Sulphur Canyon fault zone, the following features may be considered. The faulting is probably of late geologic age and may well be active today, as is the paralleling San Andreas Rift. The degree of compression developed along the Sulphur Canyon fault is no doubt relatively great since the rocks involved should withstand great forces before failing. If faulting can develop heat of the intensity and volume in evidence in Sulphur Canyon, then such phenomenon may be considered as a possible source. It should be emphasized that the Franciscan sandstones from which the Sulphur Canyon fumaroles issue are of Jurassic age, and the igneous members associated with them undoubtedly reached final cooling in the far distant geologic past.

The much more probable source of heat, and the writer believes it the only logical source compatible with available evidence, lies in an intrusive magma along the zone of weakness created by the Sulphur Canyon fault. The region immediately north and east of Sulphur Canyon is in part occupied by extensive volcanic flow and eruptive rocks. Cobb Mountain, only two miles distant from the Little Geysers, is composed of a group of volcanic eruptives, and only a few miles farther north volcanic craters are found. This volcanism is Quaternary, with numerous explosive and extrusive vents from which molten rocks reached the surface. It is therefore logical to postulate intrusive magmas which failed to reach the surface in the vicinity of this volcanic field. The depth below the surface at which such magmas may exist is beyond justifiable speculation, but the fact that some of them reached the surface in the near vicinity of Sulphur Canyon allows the belief that they may possibly be only a few hundred or a few thousand feet deep. It is further probable that possible existing buried magmas in the Sulphur Canyon region may be of quite recent geologic time since there is no requirement that they be contemporaneous with activity in the near-by Quaternary volcanic field.

## Prospect drilling

While prospect well drilling commenced in 1922 at the Big Geyser area it was not until 1955 that modern methods were used in the operations. During the summer of 1959 drilling was recommenced with the object of developing adequate steam to justify expensive equipment necessary to generate electricity. This last drilling programme was highly successful, and the electricity generating project is in full operation.

During the drilling in 1959 careful attention was directed to subsurface conditions. Rotary drilling machinery was employed with capacity loads and drilling depths well beyond anticipated requirements, and coring equipment was available during the entire operation. Since this last stage of drilling was designed to obtain necessary data with respect to geological conditions as well as to secure production, it may be described as a prospecting programme.

Wells were programmed with a short conductor string of 20-inch casing. Drilling continued with a $17\frac{1}{2}$-inch hole and continuous coring below approximately 200 feet in order to select the best formation in which to land and cement $13\frac{3}{8}$-inch surface casing. These depths varied from 285 to 398 feet. Drilling continued with a $12\frac{1}{4}$-inch hole to completion varying from depths of 745 to 952 feet. All wells of this group were brought in without perforated pipe below the $13\frac{3}{8}$-inch casing. Six wells were completed under the above programme.

A composite picture from the above list indicates that a sound and successful development drilling operation resulted. The pipe sizes employed in this operation were greater than a purely exploratory operation would require since there was reasonable assurance that all wells would be commercially productive and the greater sizes were believed advisable to obtain maximum production. From the information gained, an ideal prospect well could be planned as follows: Using similar rotary drilling equipment, set and cement 60 feet of 20-inch conductor pipe, drill and core a $17\frac{1}{2}$-inch hole selecting the landing point for the shoe of a $13\frac{3}{8}$-inch surface string opposite firm non-caving formation; land and cement pipe back to the surface; drill ahead with spot coring to a depth to be selected from appearance of cores—i.e., through zones demonstrating vein porosity or through rocks visibly subjected to high thermal activity and recording high temperature. Some reduced cost would result by setting $11\frac{3}{4}$-inch or even $9\frac{5}{8}$-inch surface pipe with successively smaller hole diameters below the surface pipe. At the Big Geysers, coring disclosed zones of porosity with open veins $\frac{1}{2}$-inch wide occurring in highly indurated Franciscan sandstone, also zones in which interbedded shales had been highly altered and partially broken down from their original normal state of cementation and induration. Zones of iron sulphides, pyrite and marcasite indicated a possibility of subsurface correlation, but more data are required if they are to become usable for such purpose. A tendency towards lost circulation was noticed particularly in areas where cores showed open seams. The above data were all useful in determining the productive steam zones.

Incertainty of the subsurface attitude of the Sulphur Canyon fault has so far required that surface locations of wells be made within the areas demonstrating thermal activity on the land surface. One well was located and drilled to 1 400 feet depth with the thought that it might intercept a northward dipping fault plane. It resulted in small production and otherwise gave no evidence of establishing the position of the fault plane. Cores from the six wells drilled in the Big Geysers area during 1959 together with the action of the thirteen wells drilled prior to that year established the producing zone as a sandstone body highly disturbed and shattered by faulting and altered by hydrothermal activity. To assign it any other than an originally northward dipping attitude would not be justified. The rock is a dense indurated grey sandstone with minor interbedded shale. In its unaltered and unfractured condition the sandstone body would by estimate, no tests having been made, have a porosity of less than 10 per cent and a permeability of less than one millidarcy. The high productivity from drilled wells therefore must result from porosity due to fracturing. The zone demonstrating hyperthermal activity as stated is approximately 1 000 feet wide. Wells drilled into any part of this zone produce heat through the medium of steam or other gases and hot water. There is no adequate term in the literature that defines such a body of rock, and the writer therefore suggests the name Thermifer be used to designate a body of rock or reservoir from which such heat products as here described may be produced.

Owing to steam temperatures which approximate 350°F and to some high pressure zones, all drilling must be conducted with a blowout preventer installed on the surface casing. Footage drilled from the surface to the landing point for the shoe of the surface casing may be conducted with reasonable safety if there is an adequate supply of heavy drilling fluid ready at all times with which to control any tendency of the well to flow within the first three or four hundred feet of depth. A blowout with 350°F steam could cause serious injury to persons and has already resulted in substantial property and reservoir damage.

Casa Diablo Hot Springs (location 4 on figure 2) is situated in southern Mono County, California, at the southern edge of the Mono Volcanic Field. The surface is occupied by recent rhyolite and obsidian masses of the so-called Mammoth Embayment, a physiographic feature of some 200 square miles immediately east of the bold front of the Sierra Nevada Mountains.

The Mammoth Embayment is a subsidence area resulting from complementary equalizing adjustment due to the expulsion of large volumes of flow and explosive materials through vents and craters of the Mono Volcanic Field. Subsidence of both regional and local character is too recent to permit of close time dating. The general subsidence has been accompanied by a group of normal faults with the regional northwest-southeast trend. Displacement along the fault planes is small, individual cases showing from only a few feet to possibly one or two hundred feet.

Thermal emanations directly upon the fault lines are numerous. Some occurrences of thermal activity in the area cannot be directly related to the faults, but these particular cases are in areas of obscured exposures so that they, as well as the obvious emanations that occur directly on fault planes, may owe their location to the same cause.

During the years 1959 and 1960, five wells were drilled in the Casa Diablo area. The first was located on the down side of a normal fault having a displacement of 200 feet or more. Location was made with the object of intersecting the fault plane at a depth of a few hundred feet. The well was drilled to 1 063 feet. No cores were taken, but ditch samples indicated that drilling was still in volcanics at its total depth. It failed to flow and was temporarily abandoned. Some months later the well was easily brought into production by applying compressed air at the surface.

Three wells were drilled in 1960 on a fault plane from which the Casa Diablo Geyser has been known active for over a hundred years. These wells were drilled to 630, 810 and 570 feet. All are productive; combined they indicate a total capacity of 1.18 million pounds of steam per hour at 35 pounds per square inch pressure. A successful operation seems assured from the above volume, and the entire field of geothermal production is only partly explored.

History of the drilling operations in the Casa Diablo area, as shown in the case of the first well which was thought to be non-productive, indicates the necessity of obtaining reliable temperature surveys before abandonment. If such surveys show sufficient heat, the well should be relieved of the hydrostatic head standing above points of high heat intervals since pressure exerted by a hole full of water or drilling mud may hold back production.

Calistoga, Napa County, California, location 2 on figure 2, has had three prospect wells drilled in search of geothermal power. Two of these wells were drilled within a few hundred feet of a geyser. Both the first two wells were started in the central part of a mile-wide alluvial filled valley. Core records indicate that the wells drilled into Franciscan, Jurassic sandstone at a few hundred feet of depth. Their location is eighteen miles from the Big Geysers area (location 1 on figure 2) and in structural trend with the Big Geysers area although they do not appear to be in the same fault zone. The fact that these wells drilled into Jurassic sandstone makes them analogous, to this extent at least, with the Big Geysers area. Since the sandstone body is covered by several hundred feet of valley alluvium, however, its condition and structural attitude at the drilling location are unknown. It is probable that thermal products are ascending through the sandstone at some near-by location, but it is also quite possible that these thermal products, chiefly hot water, are being spread laterally through the unconsolidated alluvium of the valley. For a successful prospect in this area it will be necessary to locate the trace of any faulting in the Jurassic sandstone on its surface at the base of the alluvium. It is believed that the hot water produced by the two wells above mentioned, which was recorded as 260°F, enters the wells from the valley alluvium. Neither well would flow of its own pressure.

A mile farther south, on the eastern border of the town of Calistoga, a well was drilled to 518 feet at the foot of a small hill standing about 100 feet above the valley floor and having a diameter of about 400 feet at its base. The hill is composed of a highly weathered tuffaceous volcanic rock. The volcanic is related to the Pliocene rhyolite and andesite series that borders both sides of the alluvial valley which at this location is one mile wide.

No coring was conducted in this third well, but drill cuttings to 340 feet, where the well lost circulation, are all volcanic material. Thirteen-inch casing was landed and cemented at 200 feet. On one test which was not observed by the writer, the well is stated to have blown dry steam through two-inch tubing which had been run to 510 feet, almost to the bottom of the well at 518 feet. The well is uncased below 200 feet.

Since tubing was pulled the well stands with fluid level at approximately 20 feet. Introduction of dry ice starts the well flowing 230°F water with some vapour. It will flow steadily until manually shut in. Hot water production was estimated at 1 500 gallons per minute, but tests later observed by the writer appeared considerably less.

Since this well blew dry steam under the conditions stated above, it appears of great importance that technical information which was not taken or recorded during the drilling be obtained before further procedure. The writer has recommended the following: (*a*) Take side well core samples from 200 feet to bottom in order to determine whether or not the well drilled through the volcanic flow rocks and into Jurassic sandstone. At the point of lost circulation, 340 feet, it could have drilled into alluvial material on an old land surface. (*b*) Run an electric log to locate zones of porosity which, combined with the core records, may locate zones from which hot water enters the hole. (*c*) Run temperature survey for location and confirmation of hot water zone. (*d*) If the above data indicate the advisability of excluding cold water entry into the hole, run a caliper log survey to locate optimum point at which to land and cement an intermediary string of casing.

The above example is given to point up the necessity of taking and keeping all possible technical information during the drilling of any prospect well. This is but another case proving that it is less costly to keep current technical records than to be required to take them under disadvantageous conditions at a later time.

Four wells were drilled in north-eastern California and south central Oregon, all on the down side of profound faulting on the east and west fronts of the Abert-Warner fault blocks. These blocks are approximately 30 miles wide and extend some 150 miles in a north-to-south direction. They comprise late Tertiary and Quaternary volcanic flows. Mountains of the blocks rise to an average of 8 000 feet and stand 3 500 feet higher than the grabens on the east and Modoc lava beds on the west. Profound faulting outlines the eastern and western borders of the entire feature.

One well drilled to 650 foot depth at Lakeview, Oregon (location 5, figure 2), in an area of thermal springs registering temperatures as high as 180°F, was abandoned as non-productive. The springs issue from valley alluvium immediately on the west front of the Abert fault block. One well drilled at location 6, Crump Lake, Oregon, reached 1 684 feet. It recorded temperature of 170°F and encountered high head artesian water. Location was on the east front of the Abert fault block and very near the surface entered volcanic rocks on the up side of the fault. The high head hot water must be interpreted as issuing from highly porous volcanics.

Two wells were drilled at the east front of the Warner fault block (location 3, figure 2), Surprise Valley, California. The first of these two, near the mountain front, passed out of valley fill into volcanic rocks in place at 290 feet. It was abandoned as non-productive at 2 150 feet. A second well was drilled 3 375 feet east of the first, in the flat Surprise Valley graben. At its total depth of 1 968 feet it was still apparently drilling in valley alluvium with no evidence of having entered volcanics of the Warner Range. The well was abandoned as non-productive. This last well was drilled in the immediate vicinity of the famous mud volcanoes which erupted with violent explosive force in 1951. Temperature recorded in the thermal springs following eruption was at the boiling point, though the highest temperature recorded in the drilled well was 156°F. It is difficult to reconcile the differences in temperature with any other probability than that ascending hyperthermal water issuing from a deeply buried fault rises vertically through the alluvial valley fill in a very narrow zone.

The Abert and Warner fault blocks are situated in the Basin and Range Province of western America, a structural province characterized by profound faulting and numerous mountain blocks separated by deeply filled alluvial valleys. The Abert-Warner blocks are also situated within the central portion of the extensive Modoc and Cascade lava flows of Pliocene and Quaternary age. The great lava plateaux of this area occupy north-eastern California, south central and south-eastern Oregon and southerly portions of Idaho. They extend over, and occupy the surface of, approximately 60 000 square miles with accumulated thicknesses of lava of several thousand feet. It has been suggested above that favourable areas for geothermal prospecting might be found within these regions of geologically late volcanism. The Modoc-Cascade and adjacent volcanic plateaux provide the essential features wherever structural conditions may coincide to localize prospecting areas. The vast Columbia lava plateau of northern Oregon and south-east Washington, occupying some 85 000 square miles, is of Miocene age and significantly exhibits few, if any, thermal springs of hyperthermal characteristics.

Locations 7, 8, 9 and 10 all occur within the Basin and Range Province in Nevada. Here Pliocene and Quaternary volcanics on the surface are limited to isolated small areas as compared with the vast extensive flows of the Modoc-Cascade-Columbia plateaux. The association of thermal activity with faulting in Nevada is, however, especially noticeable.

At Wabuska, Nevada (location 8 on figure 2), an area of extensive thermal springs occurring in a valley one-half mile from outcropping Tertiary lava, three wells were drilled to a greatest depth of over 2 000 feet. Well logs indicate valley alluvium to at least 1 500 feet depth. No structural geologic features were in evidence to aid in well locations, and it is extremely doubtful that geophysical instruments would have been usable. Production of 140°F water highly charged with sodium sulphate similar to water of the natural springs was obtained. The venture was considered unsuccessful.

Steamboat Springs, location 7 on figure 2, ten miles south of Reno, Nevada, exhibits thermal activity over several hundred acres. The geologic setting involves a basement of Mesozoic granodiorite, Tertiary volcanics, a thin mantle of Tertiary basalt and extrusive Quaternary rhyolite.

Four wells were completed in the area. The first, located on the east down side of a normal fault, was drilled to 1 771 feet. The log indicated alluvium to 350 feet, Tertiary volcanics to 1 050 feet, and from this depth granodiorite and volcanics to bottom. The log further suggests that drilling below 1 500 feet was in a fault zone. It was abandoned as non-productive.

A second well on a conspicuous sinter area along a suggested fault zone was drilled to 973 feet, the top 190 feet being logged as sinter material and then granodiorite to bottom. Initial tests rated 125 000 pounds of steam per hour. Producing pressure through an 8-inch orifice was 40 pounds per square inch.

Two additional wells approximately a mile west of the active thermal area on the sinter cone found steam production, probably from granodiorite; no log is available. The near-by occurrence of Quaternary rhyolite suggests a ready source of heat, but the escape through such dense rocks as granodiorite is not readily explained by other than local faulting within the thermal field; in this case productive wells may be limited to the near proximity of such faults.

At Brady Hot Springs, Nevada (location 9, figure 2), three wells have been drilled, one a failure and two successful producers. The wells are located in the midst of a series of thermal springs having a north 30° east alignment. The surface formation is valley alluvium on which the springs have built up sinter material. Quaternary volcanic flow rocks outcrop a few hundred feet south of the springs.

Drill cuttings bailed from well number one, which was drilled with standard tools, indicate that the drilling was in very coarse, mostly sub-angular, fragments averaging approximately one-eighth inch in diameter with some fragments of one-half-inch diameter. The material is characteristic of rapid outwash from a near-by source. No evidence of having drilled into older rocks in place was exhibited by the drill cuttings.

That the thermal springs on which the wells were drilled are situated on a fault line that can be seen from the air has been reported by reliable authority. Most amazingly, following the completion of producing wells number two and three, a series of small fumaroles exuding vapor ten or fifteen feet into the air have become actuated; they were not known to exist prior to the drilling. The fumaroles are confined to a narrow belt that has now spread to a length of approximately three miles in the alignment of the fault line.

Wells presently producing encourage the thought that the area will afford commercial production of steam and hot water. Drilling to date, combined with the unusual activation of new fumaroles, indicates a prospective narrow zone controlled by faulting.

At location 10, figure 2, near Beowawe in north central Nevada, there is a group of small geysers and fumaroles on a sinter area against the foot of a north-facing bold escarpment of Tertiary lava. The sinter area stands about 200 feet higher than the broad alluvial valley north of the lava escarpment. In turn, the lava flow mountains rise 600 to 700 feet above the valley floor.

Evidence suggesting that the escarpment of the volcanics is due to faulting is found in the physiographic features, the almost rectilinear alignment of the north front of the mountains and the occurrence of springs and sinter terrace at the contact of valley alluvium with the volcanics.

Beowawe is a hyperthermal area of springs issuing along the top of a sinter terrace sixty or seventy feet across its relatively flat top and extending half a mile along the base of the escarpment. Geysers, fumaroles and springs issue from more than a hundred pot holes and vents across the top of the sinter area. One thousand feet to the north in the flat valley a group of five or six fumaroles exhibiting weak geyser action roughly parallel the sinter terrace.

Three wells have been completed in the exploration for geothermal products at Beowawe. The first, drilled to 1 919 feet, was located on the valley floor about 600 feet north of the fumarole area on top of sinter terrace. The well logged sinter material, opal and coarse sand grains derived from volcanic material to 150 feet. Below this depth it logged andesite, basalt and weathered volcanics as well as occasionally some rounded sand grains and pebbles indicating erosion surfaces between flows. At 1 580 feet slickenside material is suggestive of a fault plane. The well was whipstocked south in an attempt to bottom under the sinter terrace, but failed to reach that subsurface area.

Two wells located directly on top of the sinter area have been completed as excellent producers at depths of 500 to 700 feet. No log record has been obtained for these wells, but it is believed they drilled almost entirely in a faulted zone. The Beowawe project has possibilities of becoming a very successful geothermal development.

## Conclusions

Thermal emanations with temperature near the boiling point of water indicate prospective areas in which to drill wells in exploration for geothermal energy.

In the United States, prospective areas appear to be limited, with extremely few or even no exceptions, to zones upon or relatively near post-Miocene volcanism.

Quantitatively, areas warranting prospect drilling are, at the present stage of exploration, best judged by details of immediately surrounding lithologic and structural geologic features. The outstanding example supporting this opinion is the above-described phenomenon at Brady Hot Springs, Nevada. Here, two completed wells on a group of hot springs approximately one-quarter mile long created new fumaroles for a distance of three miles along a fault zone on which the hot springs were located.

Avenues of escape to the surface for geothermal products are provided by faulting. Normal faults occurring in areas of subsidence following the extrusion of lavas are the most common types associated with hyperthermal emanations. Faulting of any nature, however, may provide the means of ascent for hot water and gas.

The quality and quantity of heat required for economic exploitation of geothermal energy must rest with the available market, value per kilowatt-hour of electrical energy in the particular market area and the collective exploitation and production costs of the natural energy. Depending on local conditions, it is probable that energy capable of generating two or three thousand kilowatt-hours could afford a successful operation. From results of exploratory drilling during the past two years, it seems reasonable to expect at least six and possibly more of the areas prospected in the western United States to result in successful and profitable operations.

Drilling methods and technique must of course be determined by the operator. Experience shows, however, that where there is probable high temperature and pressure near the surface full caution must be exercised to avoid creating blowouts before safety equipment can be installed. The choice of the casing programme should include at least one size that can be sacrificed and the well still completed at the intended depth. Simply stated, the programme should provide a conductor, a surface string, an intermediate string, if it becomes necessary, and a production string.

If drilling equipment is adequate to handle the casing and hole size conveniently, excessive oversize and power may be avoided.

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## Bibliography

Citation of references to the geology over the very extensive areas discussed would occupy far too much of the space allowed in this paper. Published work of especial value to the subject has been that of Gerald A. Waring, Norah D. Stearns and Harold T. Stearns of the United States Geological Survey. The publications of Frank Wigglesworth Clarke and Oscar Edward Meinzer of the United States Geological Survey and the occasional papers of Donald E. White were of much value. The publications of E. T. Allen and Arthur L. Day are particularly well directed to the subject.

## *Summary*

Geothermal heat, to be of economic value, must be contained in gases or fluids as mobile carriers. If it is contained in gases, such gases must be under pressures sufficient to produce from wells and transmit to engines with adequate remaining pressure to drive the engines. If it is contained in water, the temperature must be sufficiently high to flash off steam or permit heat transfer to some other media

more adaptable for driving engines. For convenience, springs and thermal areas meeting the above requirements are referred to as hyperthermal.

Occurrence of hyperthermal springs and areas in the United States is limited to that region lying west of the easterly front of the Rocky Mountain system. It is significant that late Tertiary and Quaternary volcanism is likewise limited to the same area and that nearly all hyperthermal activity is closely associated with such volcanic areas.

Excluding the spectacular occurrences in Yellowstone National Park, there are about 700 known thermal springs in westerly United States and approximately eighty or ninety that may be classified as hyperthermal. The latter occur in Oregon, Idaho, California and Nevada and within approximately 10 per cent of the total area of the United States.

All but five of the above-noted hyperthermal springs and areas are situated within, or near enough to, Pliocene or Quaternary volcanism to justify the conclusion that they are directly associated with such phenomena. Injected magmas which still retain much of their initial heat are believed to be the principal, and possibly the sole, source of hyperthermal emanations.

Avenues of escape for gases and liquids from the magma or from the zone of abnormal heat created by an injected magma are afforded principally by faults and fractures in overlying rocks. Zones of high porosity and permeability in rocks adjacent to the heat zones may also have an important role in the process.

Prospecting for hyperthermal areas may well be confined to superficial observations in areas of geologically late volcanism. Structural features, principally faulting of any type, are important. Geophysical surveys may become valuable adjuncts to areal and structural geological studies.

Prospecting for production in areas of hyperthermal activity must be done by drilled wells. Most of the techniques employed in oil-well drilling, particularly those employed in obtaining subsurface information of lithology, porosity, permeability and temperature, are required for a successful operation. All such drilling should be conducted under constant competent geological and engineering direction.

## MILIEU GÉOLOGIQUE DES RÉGIONS HYPERTHERMIQUES DES ÉTATS-UNIS CONTINENTAUX SUGGESTIONS EN VUE DE LEUR PROSPECTION POUR LA FOURNITURE D'ÉNERGIE GÉOTHERMIQUE


### *Résumé*

Pour présenter une valeur économique, la chaleur d'origine géothermique doit être emmagasinée dans des gaz ou fluides qui lui servent de vecteurs. S'il s'agit de gaz, il faut que leur pression soit suffisante pour que les puits soient producteurs et que les gaz parviennent aux moteurs avec une pression restante qui suffise à entraîner ceux-ci. S'il s'agit d'eau, sa température doit être assez élevée pour permettre une vaporisation instantanée ou pour que sa chaleur se transmette à d'autres vecteurs convenant mieux à l'entraînement des moteurs. Pour plus de commodité, on qualifiera d'hyperthermiques les sources et zones géothermiques satisfaisant à ces exigences.

Aux États-Unis on ne trouve de sources et de régions hyperthermiques que dans la région située à l'ouest du flanc oriental du système montagneux que constituent les Rocheuses. Il est significatif que toute l'activité volcanique appartenant à la fin du tertiaire et au quaternaire se limite également à la même région et que la quasi-totalité de l'activité hyperthermique présente des rapports étroits avec ces régions volcaniques.

Exception faite des manifestations impressionnantes du parc national de Yellowstone, il existe environ 700 sources d'eaux thermales connues aux États-Unis, dont environ 80 ou 90 peuvent être classées comme étant hyperthermiques. Ces dernières se présentent dans l'Oregon, l'Idaho, la Californie et le Nevada, soit sur environ 10 p. 100 de la surface totale des États-Unis.

Toutes les sources et régions hyperthermiques mentionnées ci-dessus, sauf cinq, se trouvent dans des zones d'activité volcanique appartenant au pliocène ou au quaternaire, ou à proximité de ces zones, si bien que l'on est en droit de conclure qu'elles sont directement liées aux phénomènes en question. On estime que les magmas injectés qui conservent encore une grande partie de leur chaleur initiale représentent la source principale, voire unique, des émanations hyperthermiques.

Les voies d'échappement des gaz et des liquides du magma ou de la région où règne une chaleur anormale créée par un magma injecté sont fournies principalement par les failles et les fractures des roches qui se trouvent au-dessus de lui. Les régions très poreuses et très perméable dans les roches voisines des zones chaudes peuvent également jouer un rôle important dans le processus.

La recherche de zones hyperthermiques peut fort bien se limiter à des observations superficielles dans des zones de volcanisme géologiquement récent. Les caractéristiques structurelles, particulièrement

les failles de tous types, sont importantes. Les relevés géophysiques peuvent compléter utilement les études géologiques des régions et des structures.

La prospection en vue de la mise en production de certaines zones d'activité hyperthermique doit se faire par le fonçage de puits. On doit faire appel, si on veut réussir cette opération à la plupart des techniques auxquelles on a recours dans le forage des puits pétrolifères, particulièrement à celles qui servent à se procurer des renseignements sur la lithologie, la porosité, la perméabilité et la température du sous-sol. Tous ces forages doivent être menés sous la direction constante de géologues et d'ingénieurs compétents.

# INVESTIGATIONS FOR GEOTHERMAL POWER AT WAIOTAPU, NEW ZEALAND

*N. D. Dench* *

## Preliminary investigation

Before drilling began, useful background information was available on the Waiotapu area. The general geology of the area, as well as detailed chemical analyses and temperatures of the springs, has been described in a number of publications.[1] Aerial photographs and a contour map, which are essential for engineering planning, were available.

The unpublished report on a detailed investigation made by the New Zealand Department of Scientific and Industrial Research (DSIR) in 1957, towards the close of the period of shallow drilling, was of considerable help in siting and drilling the deep bores. It is clear, however, that the value of such a survey is enhanced if it precedes all drilling.

It is considered that a sufficient scientific appraisal, to be made before investigation drilling starts, should include the following:

(*a*) Geological report, including faults recognized from ground or aerial photographs;

(*b*) Natural heat escape survey: approximate, but showing the distribution of flow and the boundary of warm ground;

(*c*) Chemical analyses of springs, particularly chloride analysis, in areas like Waiotapu.

A map such as figure 2, supported by written information under the above headings, may be expected to result in logical siting of bores.

In the Waiotapu heat survey, the two areas of greatest surface heat flux were the one north-east of Bore 4 and the one around and south of the Champagne Pool. Spring-water chloride concentrations (indicative of a deep-seated source) were also highest in the Champagne Pool. The surface evidence, then, is that the main deep heat source at Waiotapu, or at least the main escape through the Waiotapu ignimbrite formation, is in the southern end of the thermal area.

Much of the thermal area is pitted by small surface-explosion craters, suggesting a fine balance between surface rock weight and hot water pressures beneath. In general, the ground-water table is close to or at the surface, and the use of considerable areas is limited because of lakes, streams or swamps.

## Shallow bores

The bores are described in the following paragraphs in the order in which they were drilled. The shallow bores were limited by drilling-rig capacity to a nominal 1 500 feet (450 m) and the deep bores, for the same reason, to 3 000 - 4 000 feet (900 - 1 200 m). Drilling aspects are discussed later under "Engineering".

### *Bore 1*

Bore 1 was sited in a closely faulted area near a concentration of fumaroles and steaming ground. Drilling fluid losses were frequent in broken country down to 1 189 feet. The combination of low temperatures in the upper part of the bore (figure 4) and of low water-level (or high bore siting), did not allow the bore to discharge, even with artificial attempts. Calculations of downhole pressures, versus saturated steam pressure corresponding to bore temperatures, showed that it was necessary to lift off the top 300 feet of water before the bore would blow.

### *Bore 3*

Bore 3 was drilled next, owing to expected similarity between Bores 1 and 2. Losses of drilling fluid, indicating moderate fissures, were experienced below production casing level at 1 369-foot and 1 439-foot depths. Temperatures during drilling were higher than in Bore 1, and a drilling fluid weight of 78 pounds per cubic foot (specific gravity 1.25) was carried to combat formation pressures. A shut-in wellhead pressure of 22 psig allowed the bore to discharge naturally.

The output from Bore 3 was small in total quantity and had a steam fraction of only 5½ per cent (table 2). When first blown, the bore ejected fragments of calcite. Deposition on the casing was so rapid that geysering due to choking of the flow occurred after only one month's blowing, and flow stopped altogether after a further 45 days. Since being cleaned out with the drilling rig, which found 25 cu ft of calcite between 190 and 440 ft, the bore has been left closed.

### *Bore 4*

Bore 4 was sited much closer to the areas which the later survey showed to be those of major natural heat escape. When its final depth, 1 508 feet, was reached, temperature runs made to help decide production casing depth led to the decision to drill

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* Investigations Engineer, Wairakei, Ministry of Works, New Zealand.

[1] See bibliography contained in reference 2.

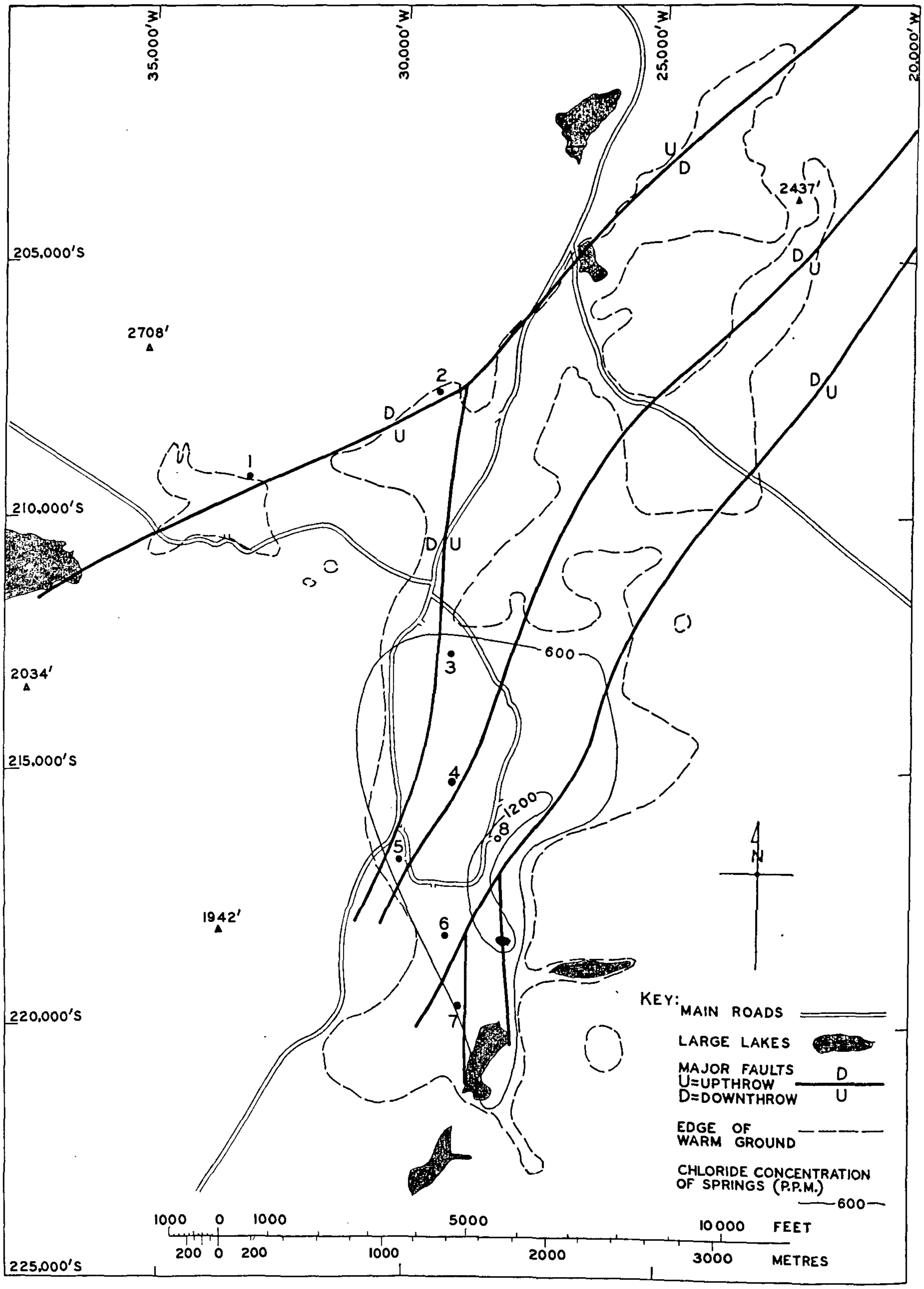


Figure 1. Topography of Waiotapu thermal area

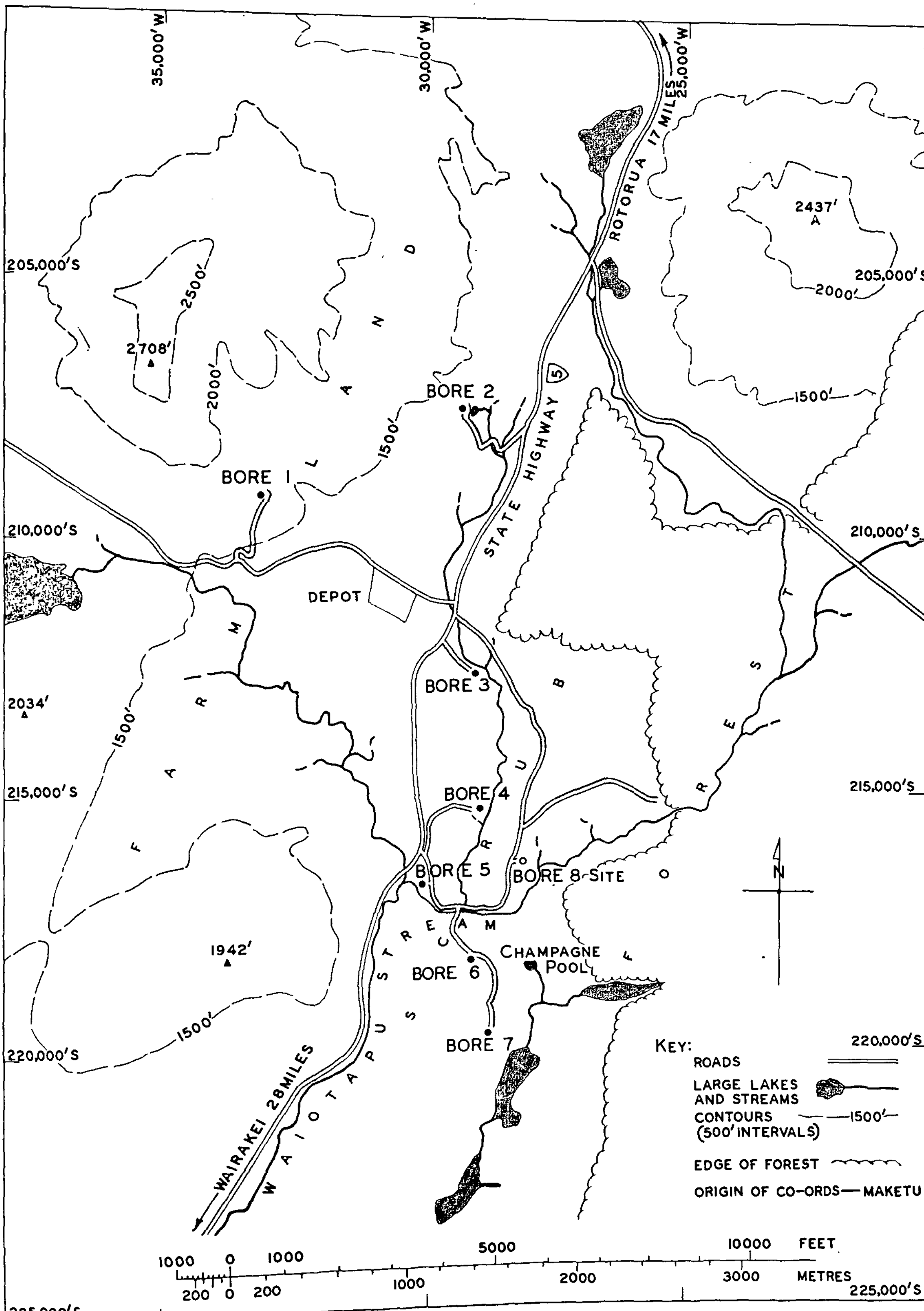


Figure 2. Waiotapu: preliminary investigations

**Table 1. Waiotapu: bore details**

| *Bore number* | *1* | *2* | *3* | *4* *Shallow* | *4* *Deepened* | *5* | *6* | *7* |
|---|---|---|---|---|---|---|---|---|
| *Dates* | | | | | | | | |
| Drilling began | 26 May 1957 | 23 Oct. 1957 | 30 Nov. 1956 | 16 May 1957 | 21 Jan. 1958 | 31 July 1957 | 13 June 1958 | 21 Aug. 1958 |
| Drilling finished | 1 Nov. 1956 | 6 Dec. 1957 | 1 Apr. 1957 | 17 July 1957 | 4 June 1958 | 29 Aug. 1957 | 6 Aug. 1958 | 4 Nov. 1958 |
| *Casings* | | | | | | | | |
| Surface | | | | | | | | |
| Outside diameter (inches) | 11¾ | 8⅝ | 11¾ | 11¾ | 11¾ | 8⅝ | 16 | 16 |
| Depth (feet) | 52 | 65 | 61 | 67 | 67 | 65 | 79 | 122 |
| Anchor | 8⅝in 303ft | 6in 376ft | 8⅝in 348ft | 8⅝in 369ft | 8⅝in 369ft; 7⅝in 316ft | 6in 363ft | 11¾in 348ft | 11¾in 385ft |
| Production | 6in 985ft | 4½in 844ft | 6in 985ft | — | 4½in 1 175ft | 4½in 885ft | 8⅝in 1 013ft | 8⅝in 988ft |
| Slotted liner | — | — | | — | (6in O.D. to 47ft) | — | 6⅝in 941ft — 2 980ft | 6in 949ft — 3 282ft |
| *Drilled hole* | | | | | | | | |
| Diameter | 5⅜in | 5⅜in | 5⅛in | 7⅝in; 5¾in | 7⅝in | 5⅛in | 7⅝in | 7⅝in |
| Depth | 1 593ft | 1 494ft | 1 489ft | 700ft; 1 508ft | 3 643ft | 1 491ft | 3 001ft | 3 282ft |
| *Reduced levels* | | | | | | | | |
| Casing head | 1 647ft | 1 401ft | 1 212ft | 1 154ft | 1 154ft | 1 082ft | 1 078ft | 1 135ft |
| Production casing shoe | + 662ft | + 557ft | + 227ft | (+ 785ft) | — 21ft | + 197ft | + 65ft | + 147ft |
| Hole bottom | + 54ft | — 93ft | — 277ft | — 354ft | — 2 489ft | — 409ft | — 1 923ft | — 2 147ft |

NOTES:

*Casing details* (API refers to American Petroleum Institute Standards):

16 in. H-40 × 65 lb/ft API, short threads
11¾ in. H-40 × 42 lb/ft API, short threads
8⅝ in. J-55 × 36 lb/ft API, short threads (Bores 6,7)
8⅝ in. H-40 × 28 lb/ft API, short threads (Bores 1-5)
7⅝ in. H-40 × 24 lb/ft API, butt welded
6⅝ in. J-55 × 24 lb/ft flush jointed
6 in. H-40 × 18 lb/ft API, short threads
4½ in. J-55 × 12.6 lb/ft flush jointed

*Slotted liners:*

*Bore 6:*
Hung from production casing on slips.
28/2½″ × 3/16″ slots per lineal foot.

*Bore 7:*
Liner is set on bottom.
16/3″ × 0.15″ slots per lineal foot.

*Bore 4 deepening time:*
The over-all time quoted includes 1 month regrouting the site.

*Bore depths and levels:*
These are quoted relative to casing head flange and Moturiki datum.

deeper, and the bore was left, therefore, without running the casing. During this initial drilling, fluid temperatures were quite high, and losses occurred at depths of 610 and 777 feet.

*Bores 5 and 2*

Bores 5 and 2 were drilled before the larger rig became available. Their purpose was to extend the area of upper formation investigated.

Bore 5 found formations and temperatures similar to those in Bore 4. A small fissure, found at 991 feet, is the probable steam production level. When opened and tested, the bore discharged greater quantities than Bore 3 in spite of its smaller diameter casing. Calcite deposition is less rapid than in Bore 3 but is nevertheless serious enough to rate the bore as unusable.

Bore 2, sited lower in elevation than Bore 1 but adjacent to the same fault, found generally similar but rather better temperature/pressure conditions in comparison with Bore 1 (figure 4), but still not sufficient for natural or artificial blowing. A marked temperature inversion at 600 feet shows that cross flows of hot and colder water are occurring at different levels. Fissures were found while drilling at 870 and 1 320 feet.

*Pressures*

Downhole pressures have not been quoted, but in the shallow Waiotapu bores they may be calculated accurately from wellhead pressures and hot water densities.

**Deep bores**

*Bore 4*

Bore 4 was deepened from 1 508 to 3 643 feet when drilling difficulties forced completion. The bottom of the hard ignimbrite was found at 1 805 feet, and mainly softer formations were found below. Temperatures during drilling increased considerably, but no major fissures were found. The prediction of higher temperatures was confirmed, with a maximum of 279°C being recorded in one run. In the closed state, stable gas pressures at the wellhead of up to 630 psig have been recorded (the highest in the field).

When opened and tested, Bore 4 discharged greater quantities than did Bores 3 and 5, and it operated at much higher pressure (table 2). Little or no calcite deposition has occurred in the year and a half of the discharge period.

*Bore 6*

Bore 6 was sited closest to the concentration of natural activity centred on the Champagne Pool. Since no major mud losses were experienced during drilling, it is apparent that permeability was low. Between 2 000 and 3 000 feet, gas inflow to the bore was large, and mud weight was raised to 85 lb/cu ft (sp gr 1.37) to prevent the well from flowing. Drilling temperatures were high. Maximum temperature recorded was 285°C at 2 500 feet, only 21 hours after water cooling ceased at that level, and while 200 gallons of cold water per minute were still pumped from the surface. The significance of this very early maximum, found similarly in Bore 4, is not clear.

When blown and tested, Bore 6 appeared as a typical Wairakei 8-inch-diameter bore with a total power potential of 7.3 megawatts at 130 psig (table 2 and figure 6). When left discharging, the wellhead pressure (and correspondingly the output quantity) decreased to 10 psig in four months because of calcite deposition in the casing above 1 400 feet. The bore has now been cleaned out twice and shows a recovery to approximately the same flow characteristics as when first blown.

*Bore 7*

Bore 7 was sited farthest south, but still close to the area of large natural heat flow. Permeability was low, drilling temperatures quite high from 3 000 feet, gas quantities small. The highest temperature recorded in any New Zealand steam bore, 295°C, was found at the bottom of Bore 7 after heating six weeks.

Discharge quantities were smaller and operating pressures much lower than in Bore 6. In eight months of blowing, the wellhead pressure changed little, and only a small quantity of calcite was then removed from 1 044-feet to 1 148-feet depths.

*Proposed Bore 8*

Before drilling operations were suspended, site preparations were partly completed for a proposed Bore 8 (figure 2).

*Pressures*

No satisfactory downhole pressure runs have yet been made in the Waiotapu deep bores, and, since fluid states and densities are not known with certainty, no calculations of pressures are possible.

**Engineering**

In general, the equipment and techniques used in drilling at Waiotapu differed little from those at Wairakei. These have been described in other papers and are not detailed here. Applications peculiar to Waiotapu are mentioned in this paper.

*Shallow drilling*

Main site equipment used in the shallow drilling was the following:

Drilling rig: truck mounted, with 38-ft mast and rated lifting capacity of 15 000 pounds.

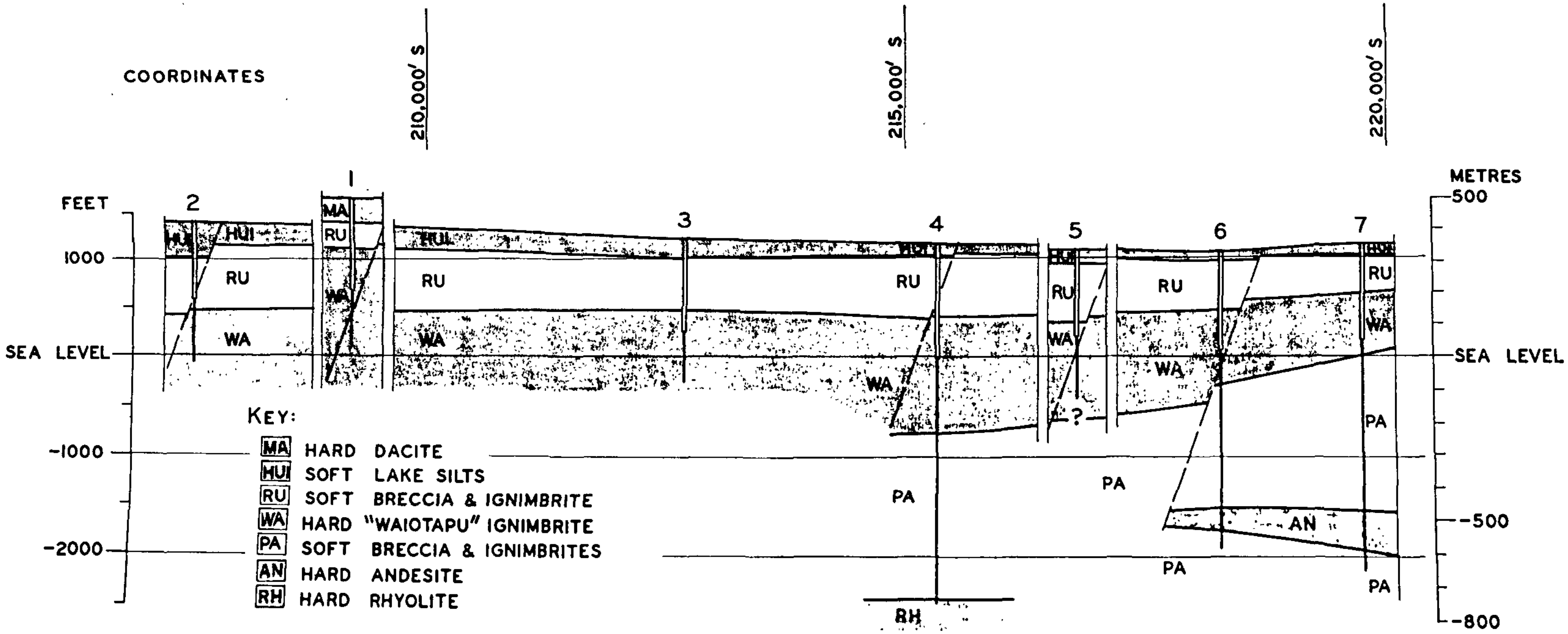


Figure 3. Waiotapu: north/south geological section

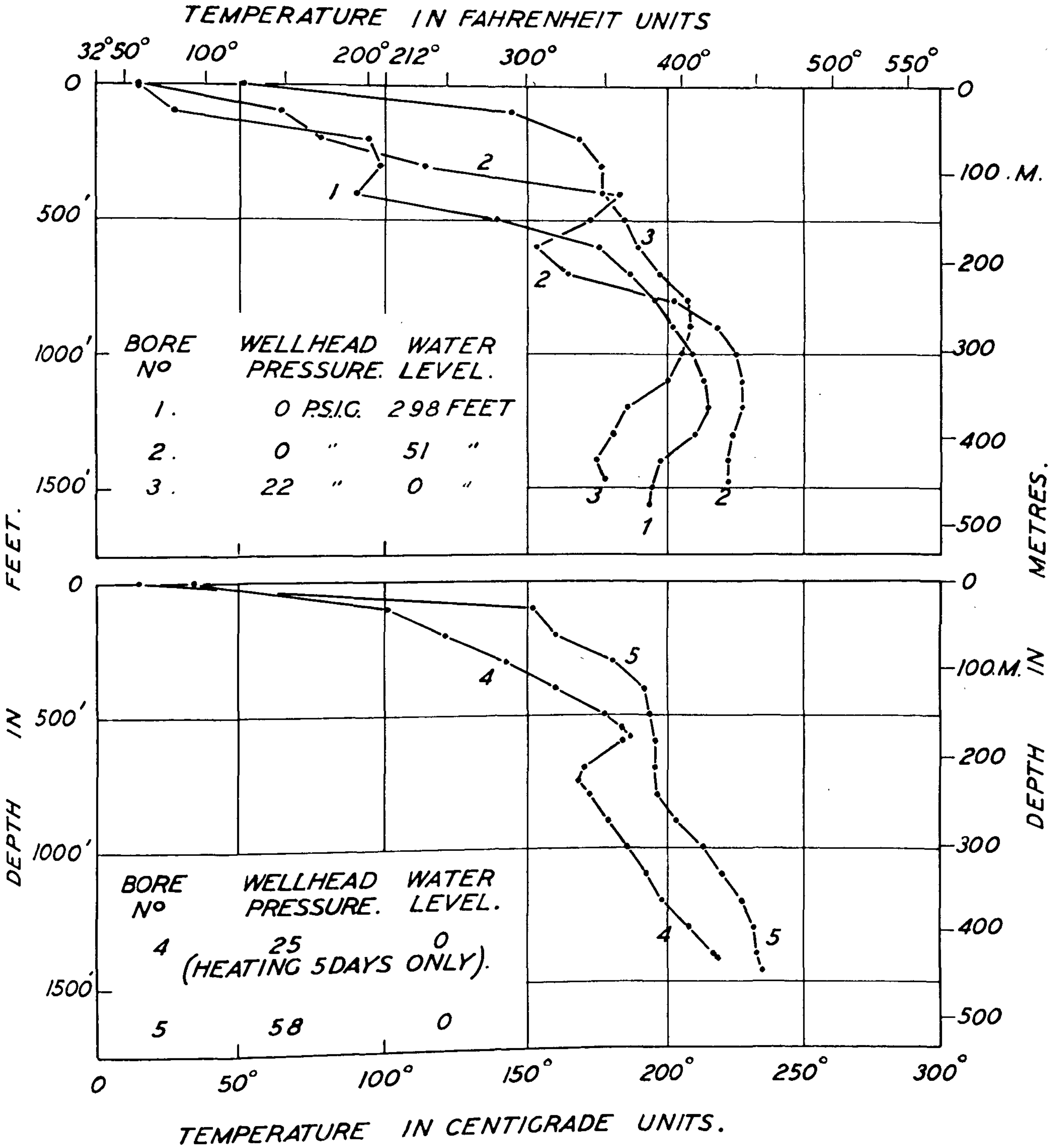


**Figure 4. Temperatures in shallow bores**

Pumps: 5 × 10-inch duplex; 4 × 6-inch duplex, mounted on rig truck.

Generator: 6 kilowatts, for lighting and mud shaker screen.

Tanks: 2/3 000 gallons, for mud storage, plus cooling tower.

The plant items were diesel engined.

A $2\frac{3}{8}$-inch outside diameter drill pipe was used, flush jointed in the near surface lengths to allow drilling through a steam gland. Current practice replaces the gland by a small blowout preventer with suitable high-temperature-resistant rubber. Drilling and completion wellhead equipment was to American standards (ASA), series 300, rated in New Zealand at 515 psig maximum working pressure for steam. Conventional roller drilling bits were used.

The initial programme, using $11\frac{3}{4}$-inch, $8\frac{5}{8}$-inch, 6-inch OD casings, was found too severe for the light drilling rig used because (*a*) production casing length was limited by mast capacity; (*b*) rotary torques were too great in hard, broken rock with the large bit diameters necessary. In the surface dacite rock in Bore 1, the 15-inch-diameter hole was begun at $7\frac{5}{8}$-inch diameter and opened out to $10\frac{5}{8}$ inches before running the full-sized bit.

The second casing programme — $8\frac{5}{8}$-inch, 6-inch, $4\frac{1}{2}$-inch OD — was easily within the rig capabilities, but had the following disadvantages :

(*a*) Clearances between bit and casing outside diameters were too small. Excessive time was spent in reaming to avoid stuck casing (table 3), and satisfactory casing cementings with 100 per cent fill-ups could not be guaranteed.

(*b*) The flush joints on the $4\frac{1}{2}$-inch casing had insufficient strength in compression to transmit the thermal loading when the bore heated. Telescoped joints occurred in Bore 4 production casing.

Preferred programmes would be $9\frac{5}{8}$, 7, $4\frac{1}{2}$ inches or $10\frac{3}{4}$, $7\frac{5}{8}$, $4\frac{1}{2}$ inches, using integral joints of strengths similar to standard American Petroleum Institute couplings, but of smaller outside diameter.

A water-based bentonitic mud was used throughout as a drilling fluid. Normal specific weight carried for both shallow and deep drilling was 75 lb/cu ft (sp gr 1.2). In fractured country below the production casing, water circulation can be advantageous, but drilling times at Waiotapu would not have been materially reduced. The 10-ft high timber mud cooling tower was inadequate for the highest drilling rates, and either ponds or forced draught (fan) coolers would have been better. It is now considered unwise to continue drilling with return fluid temperatures consistently above 70°C.

Drilling rates are given of two typical, well-controlled, shallow bores (table 3). Shorter hole time would have resulted from (*a*) reduction of core lengths; and (*b*) reduction of reaming time by the adoption of casing strings with greater clearances. Drilling was carried out continuously except for occasional weekends off when hole conditions were favourable.

**Table 2. Waiotapu : bore flows**

| *Bore number* | *3* | *4* | *5* | *6* | *7* |
|---|---|---|---|---|---|
| Diameter (inches) | 6 | 4 | 4 | 8 | 8 |
| Production depths (feet) | 985-1 489 | 1 175-3 643 | 885-1 491 | 1 013-3 001 | 988-3 282 |
| Highest blowing pressure (psig) | 72 | 270 | 128 | 315 | 114 |
| At pressure 65 psig : | | | | | |
| Steam flow (Klb/hr) | 4.4 | 16 | 11 | — | 40 |
| Water flow (Klb/hr) | 77 | 27 | 89 | — | 140 |
| Heat (MBtu/hr) | 27 | 27 | 38 | — | 87 |
| Enthalpy (Btu/lb) | 332 | 620 | 380 | — | 480 |
| Power from steam (kW) | 270 | 1 000 | 700 | — | 2 500 |
| Power from water (kW) | 330 | 100 | 400 | — | 600 |
| At pressure 130 psig: | | | | | |
| Steam | — | 13 | — | 54 | — |
| Water | — | 29 | — | 600 | — |
| Heat | — | 25 | — | 260 | — |
| Enthalpy | — | 600 | — | 400 | — |
| Power from steam | — | 900 | — | 3 800 | — |
| Power from water | — | 200 | — | 3 500 | — |
| At pressure 200 psig: | | | | | |
| Steam | — | 9 | — | 22 | — |
| Water | — | 23 | — | 405 | — |
| Heat | — | 19 | — | 170 | — |
| Enthalpy | — | 595 | — | 405 | — |
| Power from steam. | — | 700 | — | 1 600 | — |
| Power from water | — | 200 | — | 3 000 | — |
| Test equipment | Separator | 1 000 gal. calor. | 3 000 gal. calor. | Steam sampler (calorimeter) | |

All values are from most recent tests.

Estimated power figures assume condensing turbines and 75 per cent over-all set efficiency. Power from hot water assumes use of steam flashed at atmospheric pressure. Transmission losses are not considered.

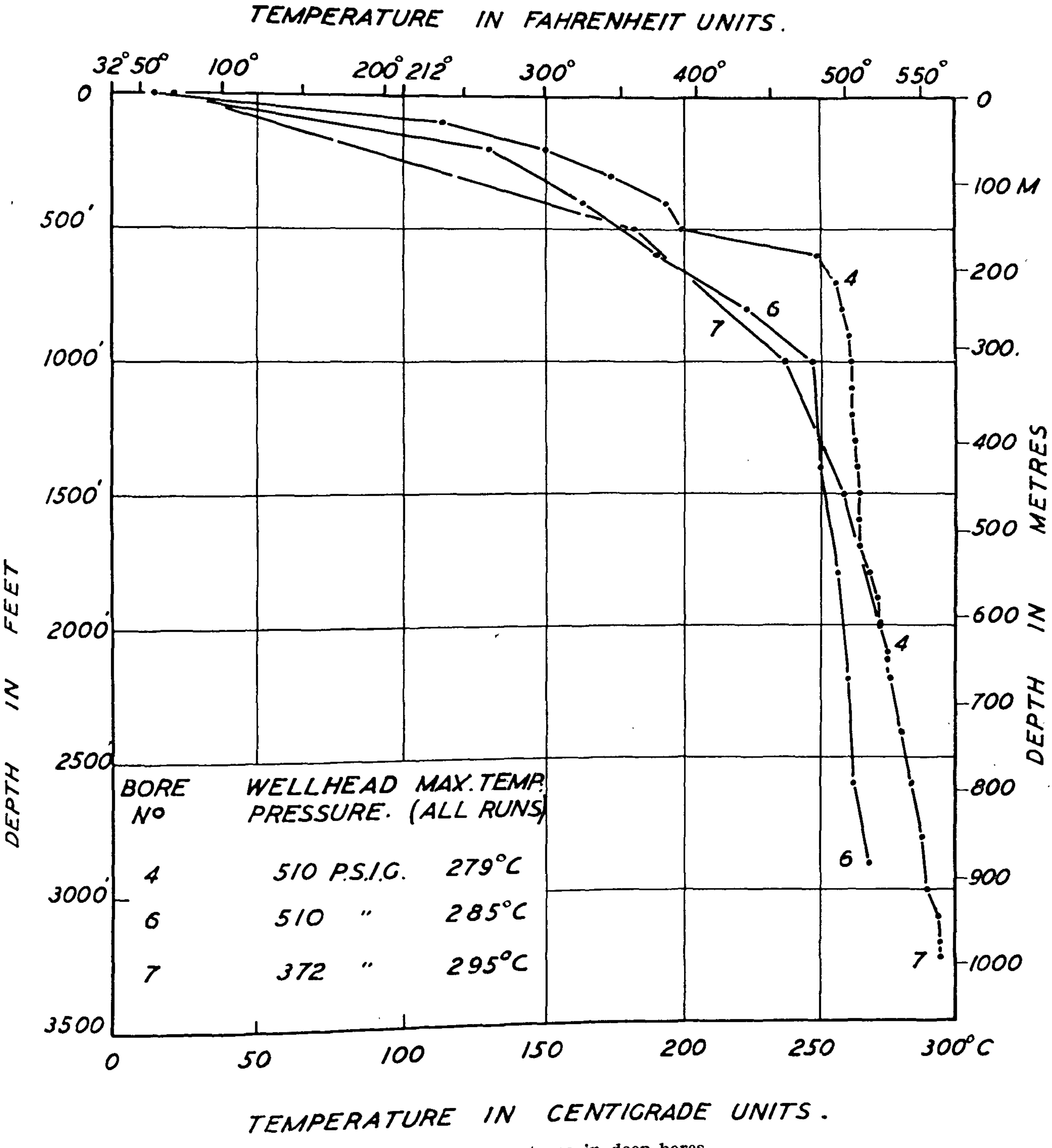


**Figure 5. Temperatures in deep bores**

*Deep drilling*

The major equipment for the deep drilling was like that used for Wairakei production drilling.[2] Except for insufficient mud cooling, it was adequate for the programme accomplished. Wellheads were rated at series 900, to withstand maximum pump pressures and a peak bore pressure of 900 psig at Bore 4.

Casing programmes are also the subject of a separate paper, but it is pertinent to mention here that a minimum of four cemented strings is considered necessary for exploration drilling to 3 000-feet depth. Possible sizes are 18, 13$\frac{3}{8}$, 9$\frac{5}{8}$, 6$\frac{5}{8}$ inches, with 4$\frac{1}{2}$-inch slotted liner.

[2] See other papers in this volume contributed by members of the staff of the Ministry of Works.

The list of drilling performances (table 3) needs no further comment except under Bore 7, "Circulation losses". Flowing lake muds at 97 ft. were finally sealed off by cementing the surface casing in two separate operations — from bottom, then later back-filled from the top.

*Bore 4 blowout*

With 8⅝-inch casing set to 369 feet, Bore 4 was deepened at 7⅝-inch diameter to 3 643 feet — without additional casing, due to equipment limitations. Mud return temperatures had been high — 75° to 85°C — and while pulling out a core, the bore came under a wellhead pressure of 40 psig. This was sufficient to cause a large eruption of surface formations 100 feet from the wellhead, and also smaller mud eruptions under pumps and pipe racks.

Over a period of a day or so the activity was controlled, then stopped, by pumping heavy mud

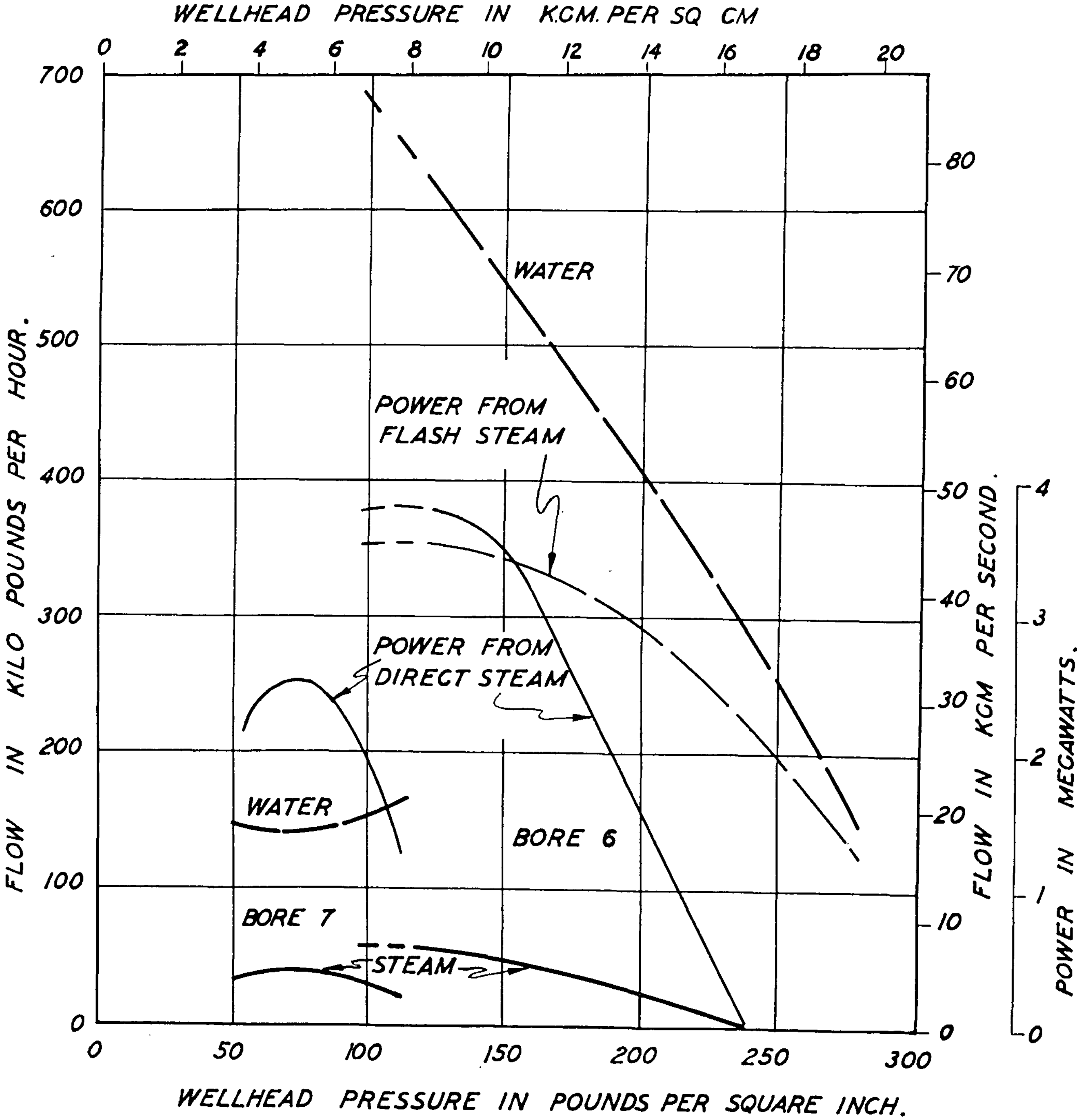


**Figure 6. Flow quantities of 8-inch, deep bores**

**Table 3. Waiotapu : drilling performances**

| *Hole rating* | *Shallow* | | | *Deep* | | |
|---|---|---|---|---|---|---|
| *Bore number* | *2* | *3* | *Average* | *6* | *7* | *Average* |
| Diameter (inches) | 4 | 6 | — | 8 | 8 | 8 |
| Depth (feet) | 1 494 | 1 489 | 1 492 | 3 001 | 3 282 | 3 142 |
| Elapsed time, including shifting (days) | 53 | 73 | 63 | 58 | 81 [a] | 70 |
| Number of cores | 25 | 18 | 22 | 34 | 54 | 44 |
| Average length (feet) | 8 | 7 | 7.5 | 4 | 2.5 | 3 |
| *Time:* | *Hours* | | *Per cent of total* | *Hours* | | *Per cent of total* |
| Drilling | 339 | 349 | 35 | 574 | 623 | 41 |
| Coring | 145 | 167 | 16 | 162 | 231 | 14 |
| Casing, reaming | 149 | 85 | 12 | 32 | 66 | 3 |
| Casing, running, cementing | 158 | 167 | 17 | 180 | 134 | 11 |
| Circulation losses | 53 | 77 | 7 | 65 | 425 | 17 |
| Cooling hole | 0 | 35 | 2 | 75 | 75 | 5 |
| Breakdowns | 105 | 108 | 11 | 139 | 120 | 9 |
| Total | 949 | 1 000 | 100 | 1 200 | 1 674 | 100 |
| *Average penetration rates (feet per hour):* | | | *Average* | | | *Average* |
| Upper breccias etc. | 10 | 6.5 | 8 | 22 | 18 | 20 |
| Waiotapu ignimbrite | 3 | 2.5 | 3 | 3 | 8 | 5.5 |
| Lower formations | — | — | — | 1.5-22 | 2-18 | — |

[a] Approximate.

and cement slurries from the surface. Casing fractures were found and sealed, the site was regrouted, and production casing was set into the ignimbrite.

It is probable that high temperature flow from deep levels broke out of the hole into faulted country at 470 feet, and flashed into steam with eruptive force below the surface siltstones. The pressure at 470 feet cannot have exceeded 270 psig (wellhead pressure plus mud weight). It is likely that the smaller eruptions originated from the casing breaks.

At Waiotapu it is imperative to set casing into the main ignimbrite formation before penetrating the hotter zones beneath. It is now standard practice in investigation drilling to set production casing as soon as sufficient depth is reached. This was not done in any of the shallow bores. In the more recent investigations elsewhere a 200-300-ft depth core hole has been drilled alongside the cellar position, to assist in programming the main bore where near-surface formation conditions are in doubt. In suitable ground, this has allowed surface casing to be set as deep as 250 feet and anchor casing to 650 feet.

## Sites, services and establishment

Site access and levelling were straightforward except that the thermal clays, when wet, delayed operations drastically. Timber mattressing was necessary on Bore 7 site and approach road. Reinforced concrete drilling cellars, 10 × 8 ft on plan, 8 ft and 10 ft deep, were used in conjunction with timber substructures.

Water for drilling the shallow bores, required at up to 100 gallons per minute, was pumped from streams through 3-inch or 4-inch galvanized pipes. Owing to the strongly acidic quality of the spring-fed streams, piping was up to 2 miles in length. For the larger rig, and a maximum requirement of 400 gpm, a 6-inch-diameter gravity supply line was installed from high up on a stream, over a distance of 3 miles.

Consolidation grouting was carried out at all sites. Normally 20-ft depth standpipes were used, and grouting was done in 30-ft stages. At Bores 4 and 6, where steam blew from some holes, 100-ft standpipes were cemented in to avoid cracking the weak surface silts when grouting. The following tabulation summarizes the site grouting :

| *Bore No.* | *Number of holes* | *Area (feet)* | *Max. depth (feet)* | *Total cement (tons)* |
|---|---|---|---|---|
| 1-5, 7 | av. 21 each | 30 (radius) | 100 | av. 40 each |
| 4 (repeat) | 42 | 180 × 120 | 120 | 320 |
| 6 | 47 | 45 (radius) | 125 | 189 |

If the area is to be developed later for power station construction, the temptation to drain the valley to achieve more usable land area must be resisted. Blowouts from shallow depths due to the formation of steam under the silts would almost inevitably result.

The investigation was serviced from the Geothermal Project at Wairakei, where base stores, repair shops and offices are located. At the Waiotapu depot, 4 000 square feet of covered space contained storage for bentonite, cement and general stores, a small workshop and an office. There was frequent delivery of stores from Wairakei — daily at times during the deep drilling. A 5-ton truck was based at the rig. A 100-horsepower crawler tractor was stationed at Waiotapu for site and road preparation and rig shifting, but additional transport and a crane were drawn from Wairakei for the latter work.

### Accommodation, staffing

Living quarters at the depot comprised three small houses, forty single men's huts, cookhouse and washroom; all except the last were easily transportable.

During drilling, three eight-hour shifts were employed, the small rig needing three men per shift, the large rig, five. A toolpusher, locally in charge of drilling, and five or six other employees were stationed permanently at Waiotapu. Men required for site preparations, surveys and bore measurements were drawn from Wairakei. Most of the consolidation grouting was done by the rig crews between drilling holes. Altogether, personnel living at the camp varied between twenty and forty employees.

Detailed planning and direction of the work were undertaken from Wairakei. Communication from drilling site to depot and base was by radio, supplemented by telephone between the two offices.

### Investigation time

The over-all time involved in the investigations described here, including setting up the camp, was approximately three years. The start of the work was slow, owing to acute labour shortage and to inexperience in drilling the first hole. Time was also lost by using the rig crews to do most of the grouting. With adequate resources available in manpower and equipment, the same programme could be carried out in two years. If the additional bores thought necessary to complete the investigation are added, and the preliminary survey is included, the minimum period required is three years.

## General observations

Cores were taken in the early bores at 100-ft intervals, later at 50-ft intervals throughout, and finally, as the formations became more clearly recognized, at 50-ft intervals in the lower sections of the holes only. Petrological study of all cores provides basic information for understanding the field and planning further bores.

Chemical analyses of the bore discharges have shown constituent proportions generally similar to those found at Wairakei. Chlorides, however, appear rather lower, and bicarbonates rather higher, than at Wairakei, suggesting, respectively, greater distance from the primary source, and greater tendency to deposit calcite.

Since the bores wêre drilled, continued measurements have been made, on both bores and natural phenomena, in order to find any trends and to gain more information on discharge characteristics. Measurements include :

(*a*) Fortnightly inspections plus readings of bore wellhead pressures, stream temperatures and flows.

(*b*) Downhole temperature and pressure readings, in which no appreciable changes have occurred.

(*c*) Bore flows.

Occasional cleanouts and surface maintenance have been carried out.

Wellheads have been protected by timber covers, and the deep bores, which can produce poisonous hydrogen sulphide gas, are fenced off. The 8-inch bores discharge into 6-ft diameter horizontal concrete silencers, and Bore 4 discharges into the adjacent stream.

In the Waiotapu field it was found that bores sited close to major natural heat escape produced the most steam. They also happened to be sited on low ground and therefore had the highest pressures. No major feeding fissure was found in any bore.

The hot water reservoir above the main ignimbrite sheet has only a very weak cap, and there is consequently little pressure differential to produce strongly flowing bores. The high temperature reservoir below the Waiotapu ignimbrite has a strong impermeable cap and produces acceptable quantities of steam from the relatively impermeable formations so far found in the only three holes drilled into it.

## Acknowledgements

The writer wishes to thank the Commissioner of Works, New Zealand Ministry of Works, for permission to publish this paper, and to acknowledge the help received from the Project Engineer and from my colleagues on the staff at Wairakei. Thanks are also due staff of the New Zealand Department of Scientific and Industrial Research for information.

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2. Lloyd, E. F. The Hot Springs and Hydrothermal Eruptions of Waiotapu. *New Zealand Journal of Geology and Geophysics*, Wellington, vol. 2, No. 1, Feb. 1959.

*Summary*

The Waiotapu Thermal Area lies, roughly, at the centre of the main thermal belt, 150 by 30 miles, in the North Island of New Zealand. The natural heat flow from the area was estimated as being of the same order as at Wairakei, where over 60 000 kilowatts of power from geothermal steam is currently produced. Values were :

Wairakei : 1 860 million Btu/hour (relative to 0°C).

Waiotapu : 1 400 (100 000 kcal/sec).

In addition, geological and engineering considerations made this area appear suitable for electric power production from geothermal steam. The Power Division of the Ministry of Works was directed to carry out an investigation to this end in 1955. In the period May 1956 to November 1958, seven bores were drilled to a maximum depth of 3,643 feet (1,110 metres).

The Waiotapu Thermal Area lies 30 miles (50 kilometres) to the north-east of Wairakei, in a valley dominated by two dacite volcanoes to the north and a volcanic dome to the south-west (figure 1). A number of faults cross the area, the most prominent being that in the north-west, along which Bores 1 and 2 are sited (figure 2). The sequence of rocks found in the greater part of the field investigated was, in simplified form (figure 3), as follows :

Surface siltstones : 100-200 feet thick.

Soft breccias etc. : 300-600 feet thick.

Hard ignimbrite ("Waiotapu" formation) : 600-1 200 feet thick.

Softer breccias etc. : more than 1 000 feet thick.

*Shallow investigation*

All bores were sited close to major faults and along obvious thermal ground. Bores 1 and 3 (and later Bore 2), drilled to approximately 1 500 feet (450 metres) displayed decreasing temperatures towards the bottom (figure 4). Of these three bores, only Bore 3 had sufficient pressure to produce a steam flow to the surface. Although downhole pressures at sea level in all three bores were similar, it was evident that Bores 1 and 2 were sited too high on the flanks of the mountain (height 2 708 feet) to allow steam production. Therefore, no deeper prospecting has been done in the northern part of the field.

Bores 4 and 5, located farther south and drilled to similar depths, showed steeply rising temperatures in the Waiotapu ignimbrite below (approximately) 750 feet. From these results it was inferred that a higher temperature reservoir lay beneath the main ignimbrite, and deeper investigation was begun when a larger drilling rig became available.

*Deep investigation*

Bore 4 was deepened to 3 643 feet (1 110 metres) and Bores 6 and 7 were drilled to over 3 000 ft. (table 1). These bores all encountered much higher temperatures (figure 5) — 295°C maximum compared with 235°C maximum in the shallow bores. All had high shut-in wellhead pressures and blew freely when opened. The softer formations met below the ignimbrite were not highly permeable, and none of the deep holes struck large fissures.

As in the Wairakei field, the Waiotapu formations generally contain hot water rather than steam. Some steam is formed under blowing conditions as the pressure is reduced during the flow up the bore. The proportion of steam at atmospheric pressure at Waiotapu varies between 15 and 45 per cent (derived from table 2). These values are of the same order as those generally found at Wairakei.

The two deep bores with 8-inch (20-cm) diameter production casings produce a total of 90 000 pounds per hour of steam and 830 000 lb/hr of hot water at a wellhead pressure of 100 psig (figure 6). These quantities represent estimated power figures of 5 400 kilowatts, using only the directly separated steam, and 10 000 kW using the secondary steam from the hot water flashed to atmospheric pressure as well.

*General observations*

Most of the Waiotapu bores deposit calcite on their casings at a faster rate than at Wairakei. The shallow bores block so rapidly that they may be disregarded for power production.

Drilling was stopped in 1958, partly in order to assess the results to that stage, and partly to renew investigations elsewhere with the equipment used at Waiotapu. It is considered, however, that not sufficient drilling has yet been done to support any decision to accept or abandon the field as a large-scale steam-producing area. Only two large-diameter, deep bores were drilled, the considerable thermal area in the east was not investigated by drilling, and only shallow bores were drilled in the north.

A detailed scientific investigation of the area was carried out in 1957 by the New Zealand Department of Scientific and Industrial Research (DSIR). This is commented on in this paper, which also describes the engineering aspects of the drilling programme — necessary organization, technical features and drilling times.

# RECHERCHES EN VUE DE LA MISE EN ŒUVRE DE L'ÉNERGIE GÉOTHERMIQUE A WAIOTAPU (NOUVELLE-ZÉLANDE)

## *Résumé*

Le gîte thermique de Waiotapu se trouve à peu près au centre de la principale région géothermique, qui mesure 150 sur 30 miles (environ 240 sur 50 km), de l'île du Nord de la Nouvelle-Zélande. Le débit naturel de chaleur de cette région a été évalué comme étant du même ordre que celui de Wairakei, où des centrales fonctionnant à la vapeur géothermique fournissent actuellement plus de 60 000 kW. Les chiffres notés sont les suivants :

Wairakei : 1 860 millions de Btu/heure (valeur rapportée à 0 °C);

Waiotapu : 1 400 millions de Btu/heure (100 000 grandes calories/seconde).

En outre, certaines considérations géologiques et techniques viennent confirmer l'impression que ce champ se prête bien à la production d'énergie électrique à partir de la vapeur géothermique. Le Service de l'énergie du Ministère des travaux publics a été chargé en 1955 de procéder à des recherches dans cette voie. Pendant la période de mai 1956 à novembre 1958, sept puits d'une profondeur maximum de 3 643 pieds (1 110 mètres) ont été forés.

La région thermique de Waiotapu se trouve à 30 miles (50 km) au nord-est de Wairakei, dans une vallée dominée au nord par deux volcans constitués de dacite et au sud-ouest par un dôme volcanique (fig. 1). La région est sillonnée d'un grand nombre de failles, dont les plus visibles se trouvent au nord-ouest, le long desquelles on observera les puits 1 et 2 (fig. 2). En gros, les formations rocheuses rencontrées dans la majeure partie du champ étudié sont les suivantes, comme l'indique la figure 3 :

Grès fins de surface, riches en éléments boueux : 100 à 200 pieds d'épaisseur (30 à 60 m);

Brèches molles, etc. : 300 à 600 pieds d'épaisseur (90 à 180 m);

Ignimbrite dure (formation dite de Waiotapu) : 600 à 1 200 pieds d'épaisseur (180 à 360 m);

Brèches plus molles, etc. : plus de 1 000 pieds d'épaisseur (300 m).

### *Examen superficiel*

Tous les puits ont été forés près de failles principales et en bordure de terrains d'activité géothermique nettement caractérisée. Les puits 1 et 3 (et plus tard le puits 2), foncés jusqu'à environ 1 500 pieds (450 m), ont indiqué une baisse de température vers le fond (fig. 4). De ces trois puits, seul le 3 accusait une pression suffisante pour donner un écoulement de vapeur en surface. Bien que les pressions de fond réduites au niveau de la mer dans les trois puits aient été analogues, il était évident que les puits 1 et 2 étaient situés trop haut sur les flancs de la montagne (à 2 708 pieds d'altitude) pour permettre la production de vapeur. En conséquence, on n'a pas fait de forages de prospection plus profonds dans la partie nord de la région.

Les puits 4 et 5, situés plus au sud et foncés à des profondeurs du même ordre, ont manifesté des températures en montée rapide dans l'ignimbrite de Waiotapu, à des profondeurs dépassant environ 750 pieds. On a déduit de ces résultats qu'il existait un réservoir à plus haute température sous l'ignimbrite principale, et on a commencé la prospection aux plus grandes profondeurs dès qu'on a pu disposer d'une installation de forage plus importante.

### *Recherches en profondeur*

Le puits 4 a été approfondi à 3 643 pieds (1 110 m) et les puits 6 et 7 ont été foncés à des profondeurs dépassant 3 000 pieds (tableau 1). On a trouvé, dans tous ces puits, des températures beaucoup plus élevées (fig. 5) — maximum de 295 °C contre 235 °C — que dans les puits moins profonds. Dans tous les cas, la pression qui régnait à la bouche des puits fermés était très élevée, et les échappements étaient continus dès qu'on les ouvrait. Les formations plus molles que l'on a trouvées au-dessous de l'ignimbrite n'étaient pas très perméables, et aucun des forages profonds n'a rencontré de fissures importantes.

De même que dans les champs de Wairakei, les formations de Waiotapu contiennent généralement de l'eau chaude, plutôt que de la vapeur. Il se forme un peu de vapeur, dans des conditions permettant son éruption, à mesure que la pression baisse au cours de la montée le long du puits. A Waiotapu, la fraction vapeur, à la pression atmosphérique, varie entre 15 et 45 p. 100 (d'après le tableau 2). Ces valeurs sont du même ordre que celles que l'on trouve habituellement à Wairakei.

Les deux puits profonds qui avaient des tubages de production de 8 pouces (20 cm) de diamètre ont débité un total de 90 000 livres de vapeur à l'heure, et 830 000 livres à l'heure d'eau chaude à une pression à la bouche du puits de 100 livres par pouce carré au manomètre (fig. 6). Ces quantités représentent des puissances installables évaluées à 5 400 kW, en ne se servant que de la vapeur séparée directement, et 10 000 kW en se servant également de la vapeur secondaire obtenue en faisant bouillir rapidement l'eau chaude à la pression atmosphérique.

### *Remarques générales*

La majorité des puits de Waiotapu souffrent d'une accumulation de calcite sur le tubage plus

rapide qu'à Wairakei. Les puits peu profonds s'obstruent si rapidement qu'il vaut mieux ne pas y songer pour la production d'énergie.

Les forages ont été suspendus en 1958, en partie pour pouvoir évaluer les résultats acquis, et en partie pour reprendre les recherches ailleurs, avec le matériel utilisé à Waiotapu. On estime cependant qu'il n'a pas encore été foncé assez de puits pour justifier une décision d'accepter ou d'abandonner le champ en tant que gîte capable de produire de la vapeur sur une grande échelle. On n'a foré que deux puits profonds de fort diamètre, et la région thermique étendue qui se trouve à l'est n'a pas encore été explorée par forage. Dans le nord, on s'en est tenu à des puits peu profonds.

Des recherches scientifiques détaillées sur cette région ont été effectuées en 1957, sous les auspices du Service des recherches scientifiques et industrielles de Nouvelle-Zélande (DSIR). Le présent mémoire donne certaines précisions à ce sujet. Il décrit également les aspects techniques du programme de forage — l'organisation nécessaire, les caractéristiques techniques et les temps de forage.

# SCIENTIFIC FACTORS IN GEOTHERMAL INVESTIGATION AND EXPLOITATION

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Geothermal work should always be regarded as experimental because the character of the hydrothermal system varies so greatly from one field to the next. The problems of each must be approached individually, and too great a reliance must not be placed on experience gained elsewhere. Practically all the New Zealand fields are of the aquifer type; therefore experience in New Zealand may not apply in many overseas fields. Nevertheless, it may be useful to examine the philosophy underlying the New Zealand work and the organisation by which it is accomplished.

The scientific factors discussed here are concerned with prospecting, with assessing the capacity of the field, and with locating exploration and production drill holes; they are involved in choosing the form of utilisation (whether for heating, chemical processing, power generation, etc.) and utilisation techniques (for example, whether heat exchangers, gas extractors or chemical inhibitors are required). In brief, the scientific appraisal forms the basis upon which utilisation is planned by the engineer. For this reason, the services of competent scientists and well-equipped laboratories are essential to any large geothermal project. Finally, it is necessary to study the response of the field to exploitation, to predict future trends, and to assist in formulating the best management policy. Therefore it is necessary for scientific services to remain available throughout the development phase, and to continue during the productive life of the field.

Problems of the origin of hydrothermal fields are not considered here. It is undoubtedly true that a better understanding of the underlying causes of hydrothermal systems would greatly assist prospecting and development, but research along these lines cannot justly be charged against any one project.

## Suggested practice based on New Zealand experience

### Prospecting stages

The scale of prospecting must obviously be governed by the demand for power, the availability and economics of alternative resources, and the information already available. In the simplest case, a single hole will meet all requirements, and this might be located by inspection alone. A brief reconnaissance might suffice to evaluate a slightly larger project, or to compare the relative merits of geothermal, hydroelectric and diesel power stations in a particular area; but a much more extensive investigation, combined with test drilling, is desirable before an attempt is made to bring a large geothermal field into production.

For this reason, it is often advantageous to prospect in stages:

I. Regional survey;
II. Preliminary reconnaissance;
III. Comprehensive survey;
IV. Proving.

Together, these four prospecting stages lead to utilisation:

V. Development;
VI. Production.

Stage I shows the geological background; stage II may be regarded as a qualitative assessment of a particular field; and stage III a quantitative assessment upon which the broad outline of a suitable project may be based. In stage IV, test holes are drilled to confirm or amend the previous assessment, and the details of the project are settled. As each stage of prospecting is completed, the results to date should be examined and, if satisfactory, used in planning the succeeding stage. In practice, the stages frequently overlap one another, and one or more may be omitted in the smaller projects; nevertheless, the procedure remains one of periodic reappraisal and replanning.

### Regional survey

At the commencement of prospecting, it is likely in many cases that information is already available from regional surveys which form part of a national programme (e.g., topographical, geological, geophysical). If this is not so, it is very desirable that such surveys should be made and taken well beyond the visible limits of the hydrothermal field. This is necessary not only because there may be unseen extensions of the field, but also because the regional survey may greatly assist the interpretation of local phenomena.

### Preliminary reconnaissance

Initially this will cover questions of accessibility, terrain, and proximity to established centres of

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population and industry; also the manner in which a geothermal project can best meet the requirements of the community. Field work will be done by small, versatile parties, using aerial photographs as a basis for mapping.

Geologists will note the structural setting, volcanic associations, permeability of the rocks, possible aquifers, alignment of fumaroles, or hot springs along faults, and so on.

Hydrologists will study the hot springs, fumaroles and areas of steaming ground. Highly superheated steam vents may suggest that steam alone will be tapped from fractures in the rocks; in such a field, problems of separation of steam and water will not arise; but there may be a high gas content, and a large contribution of heat from storage should not be expected. Slightly superheated steam vents and copious boiling springs or geysers suggest a boiling water system in which considerable stored heat may be available, and the elevation of the springs above the natural cold water table may give an indication of the presence of thermo-artesian pressure. Absence of pressure and of boiling springs may indicate high permeability in the host rocks, in which case to attempt to draw more than the natural flow of hot water may induce cold water into the field.

Typical samples will also be taken for chemical analysis, to indicate the presence of valuable or injurious by-products, and to distinguish between steam-heated, perched ground water and deep circulating hot water.

Most important is a knowledge of the extent of the field and an estimate of the natural mass and heat output. The contribution of hot springs and pools is relatively easy to gauge; that of steaming ground and fumaroles may be less so. In New Zealand, a rapid survey of vegetation, or even a study of air photographs, gives sufficiently accurate preliminary figures for steaming areas; fumaroles are compared by noting the relative dimensions of the steam clouds.

All this work will be directed towards establishing the approximate capacity of the field, its suitability for various forms of utilisation, and its economic value compared with alternative resources. It does not, however, by any means exhaust the usefulness of surface surveys, and if the verdict at this stage is favourable, these surveys will be extended. If drill holes are already in existence, full use will be made of any information they provide, but as a rule no drilling will be done at this stage.

### Comprehensive survey

This will be undertaken by specialist field parties, using such techniques as give promise of adding to the knowledge of the hydrothermal system. Aerial photographs may now be found inadequate as a basis for mapping, and some surveying may be required.

Detailed geological mapping will be carried out, and extended well beyond the limits of the hydrothermal field. This will be assisted by geophysical surveys, designed to clarify the structure, rock sequence and hydrology. Gravity and aeromagnetic work may be used to build up the broad picture, and seismic profiles to provide local detail. Electrical surveys may be used to map the distribution of hot or saline water, and surface magnetic surveys to show those areas which have been subject to hydrothermal alteration.

A careful survey will be made of the temperature distribution near the surface, since this indicates the area over which stored heat may be available, and a new estimate will also be made of the mass and heat output, which permits assessment of the power potential of the field for continuous production. These surveys also form a basis for comparison after utilization has begun, when the work is repeated in order that the efficiency of extraction may be gauged and the response of the field to the draw-off studied. Changes in hot spring discharge are easily seen, but more important changes in steam escape are less apparent, and it is advisable to establish a number of fixed traverses at which these can be measured.

Exploratory drilling may begin at this stage if required to assist the interpretation of the surface work—e.g., for additional geological or hydrological information, or to aid the interpretation of the geophysical data; but the holes should be located to assist this work rather than to test possible steam or hot water production. Core samples will be taken for petrological examination, especially for the rank and intensity of the hydrothermal alteration, and also for the measurement of physical properties, such as density, porosity, permeability, and magnetic polarisation. Temperature, pressure, and water level will be measured in the hole, and if it is capable of discharging steam or hot water, this will be metered as for production holes.

These exploratory holes may be of small depth and diameter, so long as they provide the information required, and they need not be elaborately equipped for full-scale production, which is not their purpose. In some cases, however, it may be possible to combine the two functions in the same hole. This then forms part of the proving programme also and is drilled and equipped accordingly. On the other hand, the scientist will frequently desire information from below the optimum producing horizon, and some of the exploratory holes may therefore be drilled to much greater depth. This is particularly important in certain types of field where hot aquifers lie one above the other. Such deep holes provide useful information about the lower limits of a hot aquifer, and at later stages they may be used to give early warning of adverse changes at depth.

Chemical sampling of springs and fumaroles may help to indicate the type of condition likely to be met in the drill holes, but many of the chemical features are quite superficial. Chemistry becomes more important when holes are drilled, and their discharges can be sampled and trends followed over a reasonable period. Dissolved solids and gases will be estimated, in order that mineral deposition and corrosion troubles can be anticipated, or the need for heat exchangers, gas extractors, etc., assessed. Commercially valuable by-products will be looked for, and the economics of their extraction studied. The concentration of various constituents, or their ratios, or isotope ratios, may be examined for clues to the location of feed zones, and the radioactive isotopes $C_{14}$ and tritium may be estimated in order to establish an apparent age or turnover time for any meteoric water contributing to the output.

### Proving

As a result of the foregoing surveys, a fairly accurate idea of the most important features of the field should be obtained, so that its suitability for a specific project can be judged. Some idea of productivity may have been afforded by exploratory holes, but the final proof of the field's capacity can only come through systematic test drilling. All available information will therefore be used to select the drilling sites most effective for this purpose. The number of holes in this programme depends on the size and complexity of the field, and also the reliance which can be placed on the interpretation of the scientific work. Under favourable conditions, the holes may be widely spaced, but where the interpretation is not clear, or where the field is complex, the spacing must be closer.

Although these holes are designed for production, they will also yield much information not previously available. Therefore each is carefully studied in comparison with predictions based on previous work, and the interpretation of that work is amended where necessary. In fact, the picture must be constantly brought up to date as new information comes to hand, so that it is at all times as complete as possible.

Cores will be taken at intervals specified by the geologist and examined in the same manner as those from the exploratory holes. Drillers' logs will be examined and pumping tests made; temperature, pressure and, if possible, electric logs will be made and repeated as the hole warms up after drilling. This will indicate impermeable caps and permeable aquifers or fracture zones from which production may subsequently come.

As each proving hole reaches equilibrium, or when it has yielded sufficient data to permit extrapolation to equilibrium conditions, it will be opened. If there is sufficient gas pressure, or thermo-artesian pressure, the hole will discharge spontaneously; if not, it may be possible to induce eruption with the help of air lift, gas bomb, or swabbing. In some cases, where hot water alone is required, continuous air lift may be installed.

On first opening, there is often considerable erosion underground and the discharge may carry rock fragments. It is of interest to have these examined petrologically to determine their point of origin in the rock sequence. There is also a tendency to rapid change in discharge characteristics in the early stages, and it is therefore wise to allow a substantial "settling down" period before attempting to meter the output.

The mass output at various wellhead pressures will be measured and compared with previous pumping and permeability tests; the enthalpy of the discharge will be compared with the formation temperature to show whether free steam is present in a water system, or whether cold water has easy access to the hole. After testing, the hole may be deepened, or the casing may be perforated, and similar tests repeated at lower or higher levels.

A close watch should be kept on shut-in wellhead pressures; a general decline will accompany draw-down in an aquifer, whereas a rapid rise will show the accumulation of free steam or gas. Output testing should also be repeated at intervals to disclose long-term trends. There is usually a slow decline in mass output, but in a boiling water system this may be accompanied by increasing enthalpy. This may suggest an increasing proportion of free steam in an aquifer, or blockage by mineral deposition. Decreasing enthalpy will suggest the exhaustion of a steam pocket, or the approach of cooler water.

Chemical sampling will also form a part of this programme of metering the proving holes. It will follow the lines set out for exploratory holes. Changes observed since the earliest drilling may help to indicate the size of the reservoir being drawn upon, and possibly the location of the channels through which it is fed.

### Final assessment

At this point, the decision to proceed with a geothermal project may have been made, and the form it should take decided; but the size of the project will remain to be settled.

As a result of all investigations, the following should be known with reasonable accuracy:

(i) Type of field—e.g., steam, water;
(ii) Capacity of field, in continuous flow and in storage;
(iii) Location of productive fissures, aquifers, etc., and the enthalpy to be expected from them;
(iv) Productivity of drill holes at various wellhead pressures in various parts of the field;
(v) Chemistry of the discharge; gas and mineral content;
(vi) Pressure and temperature distribution; susceptibility to boiling, cold water invasion, etc.

At the same time, certain purely engineering problems should have been studied—for example, access routes, plant siting, foundation tests, pipeline routes, cooling water supplies, and, of course, suitable drilling techniques.

With the help of all this information, it should now be possible to choose an appropriate rate of extraction and write plant specifications. In some low-pressure fields, the contribution to the output which is drawn from storage must be carefully regulated; otherwise there is risk of cold water invasion. In small fields, especially, it will be wise to set the initial draw-off not much higher than the pre-existing natural flow. It is well known that the yield of some New Zealand and overseas fields is several times this flow, and provision may therefore be made for later expansion, but the advisability of this cannot be settled at this stage and is best indicated by the results of the initial development.

### Development

The remaining production holes will now be drilled. If previous work has been satisfactory, the drilling technique will be well established, and since no coring is required at this stage progress should be rapid. With the completion of each hole, however, tests will be made as before. Increasing detail is thus added to the knowledge of the field, and in some cases this detail may suggest desirable modifications of the programme.

As the power house or other plant is put into operation, *ad hoc* scientific assistance will be given, for example, in examining the chemical balance at all stages of the flow sheet, and in metallurgical "trouble shooting".

### Behaviour of the field during production

A hydrothermal system is dynamic, and the changes induced by production may in some cases gradually lead to conditions quite different from those found in the proving stage. It is most important, therefore, that scientific study should be continued during the productive life of the field. This will enable trends to be recognised and their causes determined, and it will permit changes in management policy to take advantage of favourable developments and circumvent unfavourable effects.

There will usually be a drop in pressure in the field as a result of the draw-off. In some fields this simply causes a drop in output from the holes; in others it will cause boiling and accumulation of free steam, and it may be both prudent and profitable to drill holes to tap this; in others again, it may lead to invasion of part of the field by colder water, and it may be necessary to curtail production where this threatens and to concentrate production where there is the least sign of pressure drop. Mineral deposition may also be less troublesome in some sectors than in others, and production may be concentrated accordingly.

The measurements necessary to enable this strategy to be adopted include the following:

(i) Periodical remeasurement of surface temperatures and residual heat escape. This will indicate the efficiency of extraction, and it is also useful for detecting leakages through fractured drill hole casing;

(ii) Integrated mass and heat output from all holes, indicating trends in the field as a whole;

(iii) Mass and heat output from individual holes, which will show the more local trends;

(iv) Chemical sampling; this is often a useful indicator of changing hydrology;

(v) In holes which have to be shut down for one reason or another, temperature and pressure logs should be made;

(vi) In holes which require cleaning or servicing, pumping tests will show changes in permeability due to mineral deposits or to erosion;

(vii) Before reconnecting such holes to the pipelines, the rate of heating and build-up of pressure will be studied, and output characteristics will be measured.

The importance of obtaining this type of information is such that it may justify the drilling of special holes if the normal production holes do not become available often enough. In addition, precise level surveys and tiltmeters may be found useful. Extraction of hot water from an aquifer will lead to ground subsidence, just as with cold water; on the other hand, the accumulation of large bodies of steam may lead to raising of ground levels.

## Organisation and costs

All major electric power stations in New Zealand are owned and operated by the New Zealand Electricity Department. Construction of power schemes is the responsibility of the Ministry of Works, either using its own forces or operating through design consultants and contractors. The role of the Department of Scientific and Industrial Research is normally confined to the use of geology and geophysics in prospecting and site testing. Owing to the novelty and complexity of the problems of utilising geothermal power, a wider range of scientific methods is employed than is necessary to investigate a hydroelectric or coal-fired project, and frequently new techniques have had to be developed. As a result it has been found desirable to set up a fairly elaborate scientific organisation. This organisation has naturally varied from time to time as the project has progressed through the various stages discussed above.

### Organisation for typical surveys

Actual examples of the organisation adopted for each type of investigation are given in the following paragraphs.

*Type I: regional survey*

Prior to 1937 a broad survey of the whole Rotorua-Taupo region was carried out over several years by the New Zealand Geological Survey (1); geophysical techniques were also tested in typical localities (2, 3) and a comprehensive survey of chemical aspects of the hot springs was undertaken (4). These surveys were conducted by small parties of two to five, based at their normal headquarters, which were outside the area under investigation.

A recent example is the survey by the Geophysical Survey, Wellington, of geothermal gradients throughout the North Island of New Zealand, designed to study the thermal setting of the whole volcanic belt.

*Type II: preliminary reconnaissance*

By 1945 some shallow drilling had demonstrated the practicability of small-scale use of natural heat and suggested a much greater potential. As a result, the scientific work was reoriented to study the possibility of utilization on a larger scale. Between 1945 and 1949 the Geological Survey and the Geophysical Survey made detailed studies of the Rotorua field (5, 6), and of the characteristics of discharging holes (7). Preliminary surveys were later made in other promising localities. At this stage a regional office was opened in the area with a nucleus of a professional staff of four; and about eight assistants were attached for varying periods. A light drill rig operated by the Geophysical Survey was available for experimental drilling.

The investigation of the geothermal resources of Fiji (8) furnishes another example of a Type II survey. The purpose of this survey was to cover all potential areas, without prior definition of method of utilization, and to select fields justifying more detailed work. A geologist familiar with New Zealand conditions spent two months in the territory, water samples were brought to New Zealand for analysis, and recommendations were made for geophysical measurements to provide confirming information.

*Types III and IV: comprehensive survey and proving*

Early in 1950 it was decided to concentrate the investigations on the Wairakei area. Additional scientific field parties were made available, and the Ministry of Works took over the drilling and engineering investigations. In order to integrate the activities of scientists belonging to different organisations and to co-ordinate with the engineers of the Ministry of Works, it was found desirable to appoint a scientific co-ordinator within the Department of Scientific and Industrial Research (DSIR).

The DSIR team averaged twenty-five; it covered geology and petrology, hydrology and chemistry, and utilised the following survey methods : thermometric, seismic, gravimetric, electric, magnetic, and aeromagnetic. Considerable effort had to be devoted to the development of techniques, especially for the measurement of the heat output of the various forms of natural activity.

During this period the Ministry of Works drilled some fifteen bores averaging 1 000 feet, thus gaining experience in overcoming the difficulties of drilling for steam in permeable rocks. The existence of these holes enabled further scientific work to be done in the fields of stratigraphy, hydrothermal alteration, physical bore logging, and the measurement of two-phase bore discharges.

A survey of this type was carried out at Waiotapu (9); smaller-scale examples are those made at Rabaul in New Britain (10) and Kawerau, New Zealand (11). In all these cases the work covered only a limited area in connection with a clearly defined economic objective.

*Type V: development*

The close co-operation between the scientists and engineers established at Wairakei during previous phases has continued. As methods have been developed it has proved possible to transfer responsibility for many of the observations to a measurements group set up within the Ministry of Works. The aim of the observations, both on the natural activity and the bores themselves, is to build up and maintain a picture of the state of the hydrothermal system as a whole. This forms a basis for decisions on siting new holes and the possibility of further extension of the size of the project.

The power house and steam collection system has been built under contract. Scientific assistance on corrosion and similar problems has been given as required to the consultants and contractors.

The scientists at present stationed in the thermal area number five professionals and seven assistants, covering the fields of geology, chemistry, and geophysics; in addition there are approximately ten others based at headquarters. It should be pointed out that work on neighbouring fields at earlier stages of investigation is covered by the same staff.

*Type VI: production*

Wairakei is now at the stage of production, but extensions are in process of construction. It is intended to continue the study of the state of the hydrothermal system, both because of the unique opportunity of observing the dynamic reactions of the system to utilisation, and as an aid in formulating management policy.

## Costs

The annual cost of DSIR geothermal activities over the last ten years has varied from £20 000 to £50 000. This is equivalent to about £2 000 per man-year on an average, for professional staff and assistants for salary and overhead. As explained above, the staff is engaged in simultaneous work on a number of fields at differing stages of investigation or development; DSIR is not called upon to meet drilling costs, nor those of the Ministry of Works measurement group.

The 1960 cost of DSIR investigations, £44 000, should be compared with the cost of one 3 000 - ft. investigational bore, which may be about £50 000. Similarly, if the total DSIR expenditure in the whole region is taken as £350 000, this is only a small part of the cost of one medium-sized geothermal power station (12).

The geothermal workers have been fortunate in being able to call upon a wide range of headquarters services, such as X-ray, optical and mass spectrometry, radioactivity measuring facilities, seismic prospecting teams, etc., which have been built up over a number of years to service the great variety of investigations conducted by the department. Only rarely has it proved necessary to send samples overseas or call upon outside experts.

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## *Summary*


Hydrothermal fields vary greatly in character and heat output. There is a wide range of applications to which they can be put, and there are various techniques for doing this. For this reason a diversity of information is required before the practicability of any proposed installation can be assessed. Investigations must necessarily be commensurate with the scale of project envisaged; in the simplest case, a single drill hole will meet all requirements and this might be located by inspection alone, but where larger projects are contemplated extensive investigations are required.

As a result of New Zealand experience, it is suggested that the scientific investigations should pass through six phases. Information from regional surveys — topographical, geological, geophysical, etc. — is valuable, since it assists the understanding of the setting. Preliminary reconnaissance will cover a study of heat flow, geology, hydrology, and chemistry. Attention will also be given to such matters as access and proximity to established centres of population and industry. If justified, this will be followed by a more comprehensive survey made by specialist field parties with more elaborate equipment. With data thus obtained, it should be possible to select sites to obtain the maximum information from such exploratory drill holes as are justified by the circumstances of the project. Core samples will be examined for physical and petrological properties, especially hydrothermal alteration. Tests will be made to determine temperature and pressure distribution, permeability and rate of heating. This will be followed by discharge tests and the taking of chemical samples.

The holes to be drilled in the proving phase will depend on the size of the project and the complexity of the field. Examinations similar to those suggested for the previous phase will be carried out, particular attention being devoted to mass and heat output determined for various wellhead pressures. The output from geothermal drill holes is apt to change in the initial stages; consequently the holes must be allowed to discharge for a period and measurements must be repeated from time to time to allow trends to be followed and possible interactions to be detected.

At this stage the information should be sufficient to build up an over-all picture of the field from which the scale of initial development and the best method of utilisation can be selected. In many cases it may subsequently be possible to extend the development, but the practicability of doing this is best decided from a study of the behaviour of the field after production has commenced. It is therefore essential that measurements, both of output and of conditions at depth, should be continued throughout the productive life of the field. The information thus gained will also enable appropriate variations in field management to be made as soon as changes in underground conditions become apparent.

As interest in geothermal utilisation developed in New Zealand, the programme of scientific study in the principal fields passed successively through the above stages. The main work is centred at Wairakei, and other fields are being investigated in the light of Wairakei experience. The organisation has been varied from time to time as circumstances have altered.

The cost of the scientific work in the whole region has varied since 1950 from £20 000 to £50 000 per year.

# ÉLÉMENTS SCIENTIFIQUES DANS LES RECHERCHES ET L'EXPLOITATION GÉOTHERMIQUES


## *Résumé*

Les champs hydrothermiques varient beaucoup quant à leur caractère et leur débit de chaleur. Ils se prêtent donc à nombre d'applications, avec diverses techniques en vue de leur exécution. Pour cette raison, il faut disposer de nombre de renseignements avant de pouvoir juger de la valeur pratique d'une installation éventuelle. Les recherches doivent, de toute nécessité, être menées à l'échelle du projet envisagé. Dans le cas le plus simple, un puits unique permettra de faire face à tous les besoins et on pourra en choisir l'emplacement par une simple inspection. Mais quand on envisage des projets de plus grande envergure, il faut procéder à des recherches étendues.

A la suite de l'expérience acquise en Nouvelle-Zélande, il est recommandé que les recherches scientifiques soient menées en six étapes. Celle des renseignements fournis par des *études régionales* — d'ordre topographique, géologique, géophysique, etc. — est précieuse, car elle aide à connaître le milieu physique où doivent se dérouler les recherches. Les *reconnaissances préliminaires*, qui portent sur le régime de l'écoulement de la chaleur, la géologie, l'hydrologie et la chimie, viennent ensuite. On se penchera également sur les questions telles que les voies d'accès et la proximité des centres de population et d'industrie déjà établis. Le cas échéant, on procédera alors à des *recherches plus étendues*, à mener par des groupes de spécialistes travaillant sur le terrain et dotés d'un matériel plus complet. Sur la base des données ainsi fournies, il devrait être possible de choisir les emplacements de manière à tirer le maximum de renseignements des puits d'exploration qui sont justifiés par les circonstances dans lesquelles se déroule le projet. On examinera les carottes pour juger de leurs propriétés physiques et pétrologiques, particulièrement de l'altération hydrothermique. On fera des essais pour déterminer la répartition des températures et des pressions, la perméabilité des formations et le régime des apports de chaleur. Cela sera suivi de mesures du débit et de la prise d'échantillons chimiques.

Les puits à foncer dans la *phase des essais* dépendront de l'importance du projet et de la complexité du champ. Des examens analogues à ceux qui ont été suggérés ci-dessus seront exécutés, en prêtant tout spécialement attention au débit de masse et de chaleur déterminé pour diverses pressions en tête de puits. Le débit des puits géothermiques peut varier aux stades initiaux, si bien qu'on doit laisser les puits débiter pendant un certain temps et répéter les mesures de temps à autre pour qu'il soit possible de discerner des tendances et de juger des actions mutuelles possibles.

Quand on en est arrivé à ce point, les renseignements disponibles doivent être suffisants pour mettre au point un tableau d'ensemble du champ, dont on pourra se servir pour déterminer l'échelle initiale de la *mise en œuvre* et la meilleure méthode d'utilisation. Dans nombre de cas, on pourra pousser le développement par la suite, mais la praticabilité de cette manière d'opérer sera décidée au mieux à la suite d'une étude du comportement du champ après sa mise en *production*. Il est donc essentiel que des mesures, tant du débit que des conditions trouvées en profondeur, se poursuivent pendant toute la durée de production du champ. Les renseignements ainsi obtenus permettront également des modifications appropriées de l'exploitation dès que des changements dans les conditions souterraines se manifesteront.

Avec le développement de l'intérêt porté à l'utilisation de l'énergie géothermique en Nouvelle-Zélande, le programme d'études scientifiques dans les principaux domaines est passé successivement par les stades mentionnés ci-dessus. Le centre principal est celui de Wairakei, et d'autres champs font l'objet de recherches à la lueur de l'expérience acquise dans ce champ. L'organisation a été modifiée de temps à autre avec l'évolution des circonstances.

Le coût des travaux scientifiques pour toute la région, depuis 1950, a oscillé entre 20 000 et 50 000 livres par an.

# REVIEW OF GEOTHERMAL ACTIVITY IN EL SALVADOR

*Fritz Durr* *

Geologically, El Salvador is an extremely young country. About one-fourth of the national territory is of Pleistocene age, and about three-quarters is covered by Tertiary formations, belonging mainly to the Pliocene. Cretaceous formations, which crop out in approximately 5 per cent of the country, are of less importance. Only the Cretaceous rocks are of sedimentary origin; all the others are volcanic. The Quaternary volcanism is limited to two volcanic belts, about twenty kilometres apart; associated with these are steam vents and thermal springs.

## Northern volcanic belt

This volcanic structure consists of about ten heavily eroded strato-volcanoes, which started their activity at the end of the Pliocene and continued into the early Pleistocene. All the volcanoes are aligned in a WNW direction, where tectonic elements in some places gave origin to the formation of a graben.

Geothermal activity in that area (known at about twenty places) consists of a few steam vents, but mainly of hot springs. These thermal manifestations seem to be independent of the volcanoes proper, since the volcanoes themselves do not show any geothermal activity, but the thermal springs are situated along tectonic lines between the volcanoes. Thus it seems that they may be due to deep water circulation rather than to heating in relatively high volcanic levels.

The thermal springs of this belt have not yet been studied in detail, but extrapolation of some calorimetric measurements suggests that their combined natural heat loss amounts to about $5 \cdot 10^4$ kcal/sec (above 25°C).

## Southern volcanic belt

In the southern part of El Salvador there is an important tectonic structure striking WNW, which gave origin to the so-called "Central Graben". This Central Graben traverses the entire country, with few interruptions, and continues to the east into Nicaragua. Within this graben there are a great many Quaternary volcanoes, some continuing active into historic times.

Geothermal activity along this belt is much more pronounced than along the northern one. The chief element consists of steam vents (at two places, dry steam), whereas real hot springs are of less importance. All these manifestations are clearly limited to the volcanoes themselves, being generally situated on their lower slopes. Such activity occurs at about forty different places.

Most of the geothermal studies so far undertaken have been limited to this belt. Calorimetric measurements in these manifestations indicate a natural heat loss of at least $15 \cdot 10^4$ kcal/sec (above 25°C), more than 50 per cent pertaining to the geothermal fields near Ahuachapán in the western part of El Salvador.

## Ahuachapán geothermal field

The geological setting consists of a WNW striking graben (part of the Central Graben), about 20 km wide, with vertical displacements up to 1 000 m. The faulting occurred at the end of Pliocene. Along the southern border of the graben a basaltic volcanism became active during the Pleistocene, flooding the graben with a cover of pyroclastics about 300-500 m thick. Later displacements affected the interior of the graben. A system of faults striking NNE affected the basement above all, whereas a system striking NNW seems to be limited mainly to the cover. One of the NNE lines gave origin to an explosive volcanism (several thousand years old); it consists of several individual volcanoes traversing the entire graben.

In the Ahuachapán region there are two types of geothermal activity: acid steam-fed manifestations on the slopes of the Pleistocene volcanoes along the southern border of the graben, and neutral or slightly alkaline thermal springs within the graben proper. The former are characterized by a high $SO_4''$ content and relatively small discharges, whereas the springs within the graben proper have high discharges rich in $Cl'$.

Groundwater movement occurs from the Pleistocene volcanoes down into the graben. Thus the thermal springs rich in $Cl'$ could be considered as heavy discharges (2 200 l/sec) of this mass of groundwater at places where the water table reaches the surface. In that case the chemical differences of the two types of natural manifestation would be due only to near-surface changes, and the acid waters of the manifestations situated higher should be underlain by a hot water mass rich in $Cl'$, so far not touched by prospection drilling. Diminishing temperatures of thermal springs to the north—i.e., in the direction of groundwater movement would support this assumption. Thus it is supposed that both types of geothermal activity are due to the same groundwater horizon within the Pleistocene tephra cover, and that this water is fed by hot fluids coming through fissures

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within the basement, mainly in the region of Pleistocene volcanoes.

Detailed determinations of the natural surface heat losses of the Ahuachapán geothermal field (taking into account discharge of springs and steam vents, evaporation losses from hot water surfaces and heat conduction to the atmosphere) lead to a figure of $8 \cdot 10^4$ kcal/sec (above 25°C) within a total area of $8 \cdot 10^{-7}$ m², 90 per cent of these heat losses pertaining to the Cl′ rich thermal springs. This gives an average heat flow of $100 \cdot 10^{-6}$ cal/cm² sec for the Ahuachapán geothermal field, compared to the normal heat flow in El Salvador, which amounts to about $2.5 \cdot 10^{-6}$ cal/cm² sec.

Some prospection drillings were conducted from 1956 to 1958 in two geothermal areas within the "acid" region, the deepest hole having a depth of 1 224 ft. Production from these holes consists of wet low-pressure steam, with a slightly different chemical composition compared to the natural manifestations. Monthly discharge measurements did not show any changes, nor have changes been observed in the chemical composition of the waters or the condensates. These drillings proved that in all cases steam was obtained from fissures within the Pleistocene cover.

## Geothermal energy and future energy supply

The hydroelectrical potential of El Salvador amounts to about $1 \cdot 10^6$ kW, nearly one-tenth of which is actually being used. The natural development in consumption of electric energy (not taking into account future industries with high energy demands) will require an increase of approximately 7 000 kW per year. Because of volcanic and generally permeable subsoil, leakage beneath dams is often high. Climatological conditions (rainy and dry seasons) lead to wide fluctuations in the discharge of the drainage systems, and the lack of vegetation leads to heavy erosion of the soil, with consequent deposition near the dam sites.

The geothermal potentials of El Salvador, as known so far, seem to be economically promising, and their energy utilization would avoid the above-mentioned difficulties. Furthermore, it seems that the geological setting of the existing thermal fields is not too complicated, making it possible to exploit geothermal steam at a reasonable cost. It is hoped that within the next few years the existence of enough steam can be proved to warrant a geothermal power plant with a capacity of 50 000 to 100 000 kW.

### *Summary*

El Salvador, has a Tertiary volcanic basement and is partly covered by Quaternary volcanic rocks. The Quaternary volcanism is limited to two volcanic belts; associated with these are steam vents and thermal springs, having a total heat loss of about $2 \cdot 10^5$ kcal/sec (above 25°C).

Most of the investigations have so far been confined to one of the main geothermal fields (Ahuachapán, western El Salvador). Ahuachapán lies within a WNW trending graben (20 km across) partially flooded by Pleistocene volcanic rocks. There are two different types of geothermal activity : acid water and steam issuing from the slopes of volcanic structures; and, at a lower level, nearly neutral thermal waters rich in Cl′. It is supposed that both types are derived from the same hot groundwater horizon.

Prospection holes proved the existence of wet steam at shallow depths within the region of the acid steam vents, where the steam is clearly confined to fissures. Natural surface heat losses of this field amount to $8 \cdot 10^4$ kcal/sec (above 25°C), having an average heat flow of nearly $100 \cdot 10^{-6}$ cal/cm² sec. It is hoped to prove enough steam to warrant a 50 000 to 100 000 kW plant.

## NOTES SUR L'ACTIVITÉ GÉOTHERMIQUE AU SALVADOR

### *Résumé*

La République du Salvador présente une plateforme volcanique appartenant au tertiaire, laquelle est partiellement recouverte par des roches, volcaniques elles-aussi, qui sont du quaternaire. L'activité volcanique du quaternaire est réduite à deux zones volcaniques, associés auxquelles on trouve des jets de vapeur et des sources thermales, dont les pertes totales de chaleur sont de l'ordre de $2 \times 10^5$ kilocalories par seconde (au-dessus de 25 °C).

La plupart des recherches se sont limitées à l'un des principaux champs géothermiques (Ahuachapán, Salvador occidental). Le gîte d'Ahuachapán est enclavé dans un massif effondré à orientation d'ensemble ouest-nord-ouest, large de 20 km, partiellement recouvert par des roches volcaniques appartenant au pléistocène. On observe deux types différents d'activité géothermique : des eaux et de la vapeur acides qui jaillissent des pentes des massifs volcaniques et, à des niveaux inférieurs, des eaux thermales presque neutres et riches en Cl′. On suppose que les deux

types de sources proviennent l'une et l'autre de la même zone d'eau souterraine.

Les puits de sondage ont démontré l'existence de vapeur humide aux faibles profondeurs dans la région des échappements de vapeur acide, où celle-ci se limite nettement aux fissures. Les pertes de chaleur superficielles naturelles, dans ce champ, se montent à $8 \times 10^4$ kilocalories/s (au-dessus de 25 °C) avec un débit de chaleur moyen voisin de $100 \times 10^{-6}$ cal/cm$^2$/s. On espère qu'il sera trouvé assez de vapeur pour justifier l'aménagement d'une centrale dont la puissance s'inscrirait entre 50 000 et 100 000 kilowatts.

# OPERATIONS RESEARCH AND POSSIBLE APPLICATIONS TO GEOTHERMAL EXPLORATION PROGRAMMING

*Fritz Durr* *

Though a generally accepted definition of Operations Research (OR) still does not exist, the great value of this branch of research has been proved by its amazing results. Whereas the methods of OR can be considered very promising in the field of geological exploration, not much is known so far on its practical application. Even simple examples and the mere formulation of problems may be helpful in speeding development in this field. Although this paper is intended to serve for geothermal exploration programming, the suggested methods apply equally to any geological exploration.

## Principles of Operations Research applied to geothermal exploration

Model building is a well-known concept of OR; extended in scope, it may be of significant help in analysing a situation. As an illustration, figure 1 gives a very simplified model of a geothermal exploration programme. Such models may be approached mathematically, and here, as often, the great number of salient factors makes solution difficult or, to the OR practitioner, interesting. This does not mean that solution is impossible if OR is not available, since a useful insight into the problems can be attained by listing the factors of influence and arranging them in order of importance.

Optimum distribution of effort is another important concept of OR. Applied to geothermal exploration, the problem is how to use limited funds to obtain maximum results. Two ways of spending available means are, for instance : (*a*) geological surface mapping and (*b*) exploration drilling. The final result may be considered the product of these two approaches; if one factor is zero, a tangible result can hardly be expected. The problem is therefore to find the most promising distribution of effort among the different approaches.

## Methods of OR and some suggested applications

Numerous mathematical methods have been developed since OR was introduced. They include Boolen Algebra, Decision Theory, Experimental Design, Game Theory, Information Theory, Linear Programming, Probability Theory, Sampling Theory, Search Theory, Sequential Analysis, Statistical Inference Theory, Systems Analysis and Transportation Technique.

Modern or mathematical logic can be used in drawing conclusions from qualitative statements, for instance, on the geological age of strata if certain findings are available. Frequency analysis of the intensity of earthquakes is helpful in seismic research; experimental design and game theory are the "new look" at nature in order to find out its secrets; so far geological exploration programmers have not made full use of the potential which sampling theory offers.

Among many other possibilities, four methods of OR are suggested here for their possible application to geothermal exploration :

| | |
|---|---|
| Search theory . . . . | Locating steam deposits |
| Information theory . . | Drilling a steam fissure |
| Probability theory . . | Drilling programmes |
| Transportation technique. . . . . . . | Steam delivery |

### Search theory

The basic concepts of Search Theory, developed especially for the location of U-boats, deal with problems very similar to geological exploration for underground deposits. The main difference is that submarines are moving targets, which is not the case with geological targets. Thus the kinematic problems of naval warfare may be reduced to static ones if applied to geological cases.

There may be a case where nothing is known about the position of a steam deposit within a certain region. With equal probability it might be situated at any place within this area. On the other hand, former studies may indicate different probabilities for finding it at certain locations; of course, one should take advantage of such knowledge when conducting a geological exploration. Methods of geological search should therefore be adapted to such differing conditions, and thus they may be roughly divided into two main groups : (*a*) random search and (*b*) probability search.

The mathematical concepts of military search can be adapted to such problems with relative ease, so that it will be possible to arrive at optimum solutions. For the probability of detection will generally result in some exponential form; the most promising distribution of effort can be obtained graphically.

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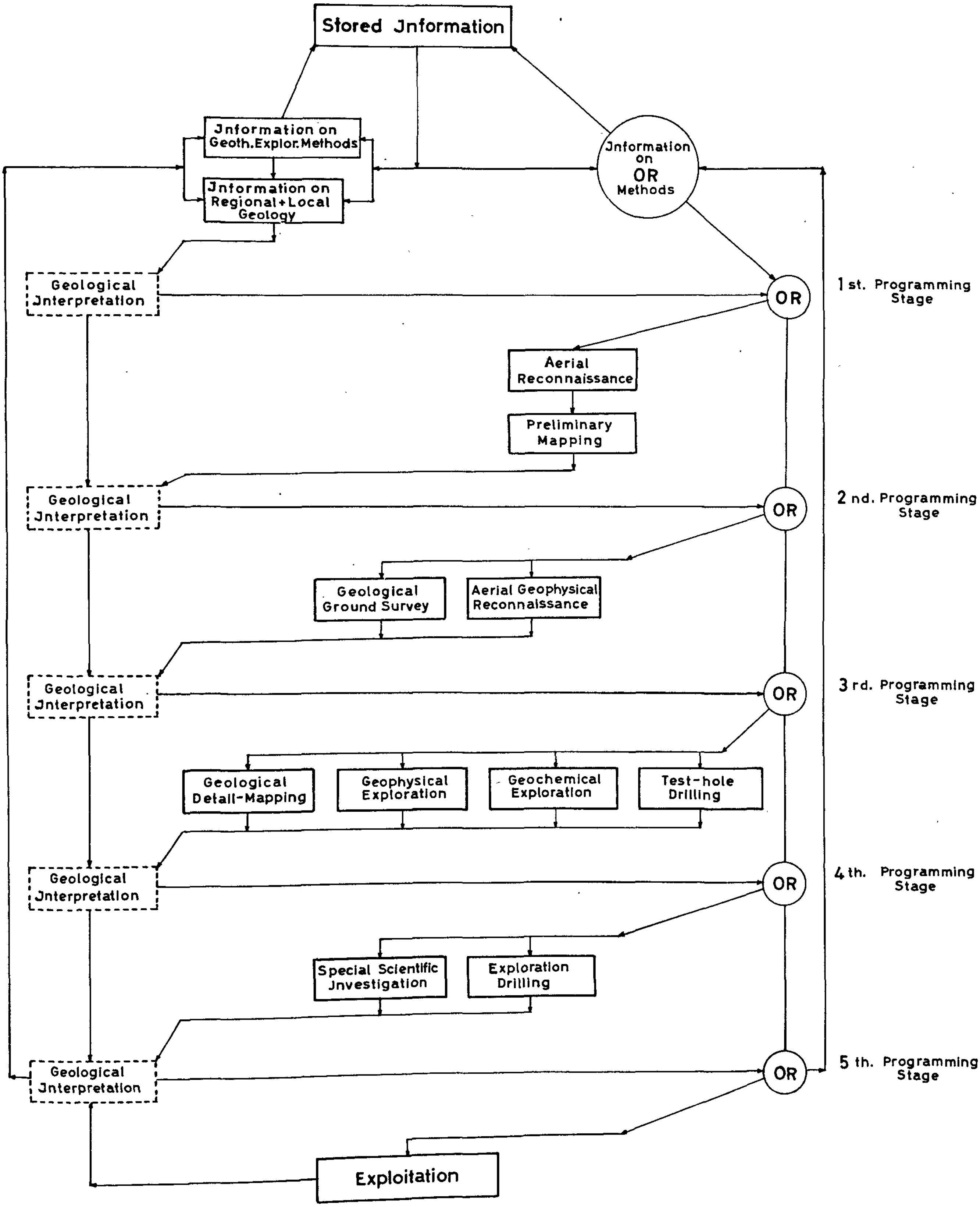
Stored Jnformation
Jnformation on Geoth. Explor. Methods
Jnformation on Regional + Local Geology
Jnformation on OR Methods
Geological Jnterpretation
OR
1 st. Programming Stage
Aerial Reconnaissance
Preliminary Mapping
Geological Jnterpretation
OR
2 nd. Programming Stage
Geological Ground Survey
Aerial Geophysical Reconnaissance
Geological Jnterpretation
OR
3 rd. Programming Stage
Geological Detail-Mapping
Geophysical Exploration
Geochemical Exploration
Test-hole Drilling
Geological Jnterpretation
OR
4 th. Programming Stage
Special Scientific Jnvestigation
Exploration Drilling
Geological Jnterpretation
OR
5 th. Programming Stage
Exploitation

Figure 1

### Information theory

Although the Information Theory has so far been applied mainly to solve problems connected with communication, there appears to be a wide and practically unexplored field for its application to other problems.

In geothermal exploration it could be used, as a simple example, in order to arrive at an optimum drilling programme in case it is desired to learn the maximum distance from a known point that a steam fissure is still steam bearing. Its entropy can be evaluated according to the precision required; with use of concepts of Information Theory, it will be possible to calculate the necessary number of holes, as well as their location.

Concepts of Information Theory could be very useful in a case where it is desired to get a clear picture concerning the thoroughness of investigation of certain regions; this can be of prime importance in deciding to reject or accept a zone for further studies.

### Probability theory

The Probability Theory is an extremely useful OR tool, since most of its mathematical methods are based on data of probabilities and statistics.

If there is already some information on the probability of finding a steam deposit within a certain area, but only limited funds are available to carry out further explorations and production drilling, then concepts of Probability Theory can lead to optimum plans. Influencing factors here are available funds, the costs of exploration and production drilling, and probability. If further funds should become available later on, the original plan would remain an optimum programme. Using concepts of Probability Theory would thus lead to a solution of the problem mentioned in the earlier section dealing with the optimum distribution of effort.

### Transportation technique

As a special form of linear programming, the Transportation Technique was developed especially for transportation problems such as the effective distribution of freight cars. Delivery of steam from productive holes to power plants is a very similar problem, and it seems quite desirable to make use of this method in such cases. Furthermore, in a case where there are different power plants, e.g., Larderello, and where geological evidence may make it possible to arrive at more or less exact figures regarding the additional potentials of different steam areas, the Transportation Technique could solve the problem of where to drill in order to minimize costs of delivery. It is evident that problems of this kind could easily come up during a steam drilling programme.

## Conclusions

The preceding sections illustrate some basic concepts of OR and suggested applications to geothermal exploration programming. The potential applications of OR to geothermal exploration cover a much wider range, as indicated by the few examples given; eventually all the different phases of exploration might be subjected to OR.

Not only may the clear-cut possibility of getting more value for money when optimizing operational programmes promote future interest in OR methods, but it may become necessary to take advantage of them, because from day to day the variety of exploration tools increases, and this leads to growing difficulties in synthesizing them into optimum plans. Parallel to this development is the fact that the so-called "best" deposits are discovered first; the more complicated cases thus remain, a situation which will necessarily lead to theoretical and therefore mathematical approaches. The more complicated the situations become, the more necessary to substitute quantitative mathematical analysis for such intangibles as "experience" or "intuition".

One of the great advantages of OR lies in the fact that the relative importance of different parameters of a system can be determined quantitatively over a wide range of conditions within a short time by means of mechanical or electronic computers. Thus it is possible to make a great number of calculations in advance or, in other words, to simulate a multitude of operations in order to study the sensitivity of a system to changes in the different parameters involved. New data can easily be incorporated by recalculating the corresponding programmes with the new values.

The prime necessity for any future geothermal exploration using OR is a better knowledge of the initial probabilities, since the success of any such programme will depend largely on statistical data regarding geological conditions or the efficiency of different search methods, as well as on costs of exploration; that is, data should be collected and, where necessary, experiments should be made.

It must be understood that OR is not intended as a panacea to operational problems, but rather to help an executive reach optimum decisions. It should also be appreciated that any improvement in the tools employed in geothermal exploration will, of course, also improve the explorations themselves, but it seems quite possible that OR efforts regarding the synthesized use of such tools may eventually pay off better.

### Summary

Methods of Operations Research (OR) were developed during the Second World War and were later adapted to industrial operational problems. These methods furnish tools for optimizing programmes, and it is suggested that advantage also be taken of them in programming geothermal explorations.

In order to make possible the more complete OR of geothermal exploration programmes, there is urgent need for collecting and evaluating data regarding geothermal explorations already performed, since the methods of OR are based principally on statistics and probability.

Field experience will prove or disprove the usefulness of different geological and geophysical methods for geothermal exploration, and may eventually lead to an improvement of their tools; whereas OR concerns the co-ordinated use of these tools, leading to an optimum output at a minimum cost. It seems quite possible that OR efforts will be more effective than investigation in improving the methods themselves.


## PROGRAMMES D'EXPLORATION GÉOTHERMIQUE


### Résumé

Les techniques de recherche opérationnelle (RO) mises au point pendant la guerre de 1939-1945 ont été adaptées, par la suite, à la résolution de problèmes posés par les besoins de l'exploitation de certaines industries. Ces techniques fournissent les outils permettant de mener les programmes dans les meilleures conditions possibles, et leur application à l'organisation des programmes d'exploration géothermique est recommandée.

Pour permettre des recherches opérationnelles plus complètes sur ces programmes, il est essentiel et urgent de recueillir et d'évaluer des données portant sur les explorations géothermiques déjà exécutées, car la technique de la RO repose principalement sur les statistiques et le calcul des probabilités.

L'expérience sur le terrain permettra de confirmer ou d'infirmer la validité de l'emploi des diverses méthodes géologiques et géophysiques d'exploration géothermique et aboutira peut-être au perfectionnement des outils auxquels elles font appel, tandis que la RO porte sur l'utilisation coordonnée de ces outils de manière à réaliser un maximum de production aux moindres frais. Il semble tout à fait possible que les efforts ainsi orientés soient plus efficaces que les enquêtes pour améliorer les méthodes elles-mêmes.

# GEOTHERMAL DRILLHOLES : CHEMICAL INVESTIGATIONS

*A. J. Ellis* *

The chemical work on geothermal drillholes in New Zealand has been limited to hydrothermal systems with heat stored in permeable strata as high temperature (200-280°C) chloride water. In the three New Zealand areas where deep drilling has been carried out (Wairakei, Waiotapu, and Kawerau), water was found at maximum temperatures ranging from 265° to 295°C, containing in solution about 0.3 per cent sodium chloride, and silica and calcium carbonate close to saturation.

Hydrothermal systems of this type are common to many parts of the world (Japan, Kamchatka, Iceland, Italy), and an examination of the techniques and results of drillhole sampling in New Zealand may be of assistance to other countries.

The field work necessary to make a preliminary assessment of a hydrothermal area is covered in companion papers of this series. On such evidence, test drillholes may be sited in a pattern related to natural activity, faulting, or on a grid system covering areas of highest heat output. Chemical evidence (1) from analyses of natural waters and steam provides important assistance in this first siting.

The structure of the Wairakei hydrothermal system was outlined by Studt (2) and Smith (3). A brief summary may aid in interpreting the results given below.

From the surface the country consists of porous beds of volcanic tuffs (Wairakei breccias), followed at about 500 feet by two mudstone beds, each of 100-200 feet thickness, and separated by breccias. Below about 500-1 500 feet considerable depths (1 500 feet in the west, over 3 000 feet in the east) of Waiora pumice breccias act as a reservoir bed for hot water, and are capped by the mudstone bands. The breccias

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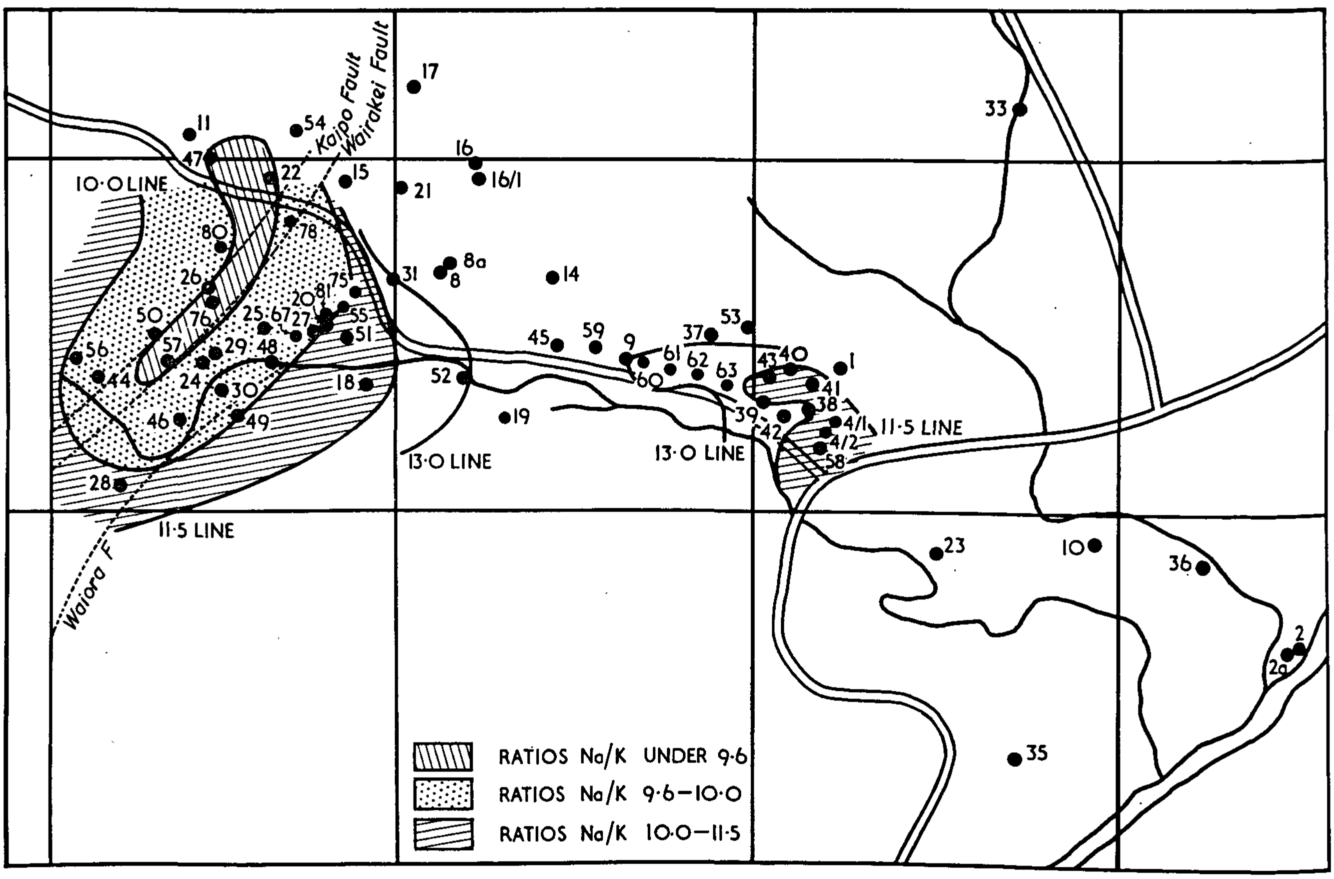


**Figure 1. Sodium/potassium atomic ratios for waters from major drillholes at Wairakei**

rest on an ignimbrite base of unknown thickness (over 2 000 feet) which is down-faulted in the area east of about Hole 45 (figure 1).

Through fissures in the ignimbrite, water at about 260°C rises into, and almost fills, the Waiora breccias and thence flows to the natural hot springs in Geyser Valley to the north-east. Steam rising from the hot water in the breccias is concentrated beneath the impermeable mudstone layers and is responsible for natural fumaroles, the largest of which is Karapiti fumarole. Some shallow drillholes have also tapped these reservoirs of dry steam.

## Chemical analyses of discharges from drillholes

### Sampling and analysis

The methods of collection and analysis of drillhole discharges are described in this series by Mahon (4) and by Ritchie (5), respectively.

A drillhole, when first discharged, takes at least several hours to rid itself of drilling mud and debris. In case the discharge is only of short duration, samples of water should be collected regularly. Suggested periods are after several hours, daily for a week, weekly for a month, then monthly.

At the first opportunity, complete samples of the discharges should be obtained, using one of the methods given by Mahon for separating the steam and water phase in a reproduceable manner for analysis.

The following determinations on the water phase should be made regularly : lithium, sodium, potassium, ammonium, magnesium, calcium, chloride, fluoride, boric acid, silica; also the pH and total concentrations of both sulphide and carbonate. From time to time, bromide, iodide, rubidium, caesium, strontium, and arsenic concentrations should be estimated.

On steam samples it is suggested that the carbon dioxide, hydrogen sulphide and ammonia contents be determined for each drillhole every two months. The minor constituents, such as hydrogen, hydrocarbons, and nitrogen, could be estimated once a year.

### Water analyses

*Early prospecting results*

The time taken for the water discharged from a drillhole to reach stable concentrations and ratios is an indication of the proximity of the hole to a major feeding source in the country. Three early Wairakei drillholes that tapped hot water are compared in table 1.

**Table 1**

| | | | | | |
|---|---|---|---|---|---|
| *Hole 9, 563 feet deep:* | | | | | |
| Time after opening | 1 month | 1 year | 3 years | 4 years | 6 years |
| Na+ (ppm) | 820 | 872 | 950 | 1 160 | 1 290 |
| Atomic ratio Na/K | 24 | 23 | 25 | 25 | 27 |
| *Hole 11, 886 feet deep :* | | | | | |
| Time after opening | 2 months | 1 year | 4 years | 8 years | |
| Na+ (ppm) | 1 100 | 1 192 | 1 260 | 1 235 | |
| Atomic ratio Na/K | 16.5 | 14.1 | 13.8 | 13 3 | |
| *Hole 20, 2 005 feet deep :* | | | | | |
| Time after opening | 4 months | 8 months | 3 years | 6 years | |
| Na+ (ppm) | 1 310 | 1 320 | 1 320 | 1 310 | |
| Atomic ratio Na/K | 9.0 | 9.5 | 9.8 | 9.7 | |

The sodium ion concentrations and the atomic ratios of sodium to potassium in the waters illustrate three different types of behaviour. In the undisturbed natural system, there was, at shallow depths in the permeable breccias, thermal water which had been diluted to some extent with ground water. Hole 9 tapped a rather homogeneous supply of this type in the first year before less diluted water was drawn from a deeper source. The water now tapped by this hole is almost undiluted (compare Hole 4/1, table 2) but travels a considerable distance from a feeding fissure, losing potassium into the country on the way.

Hole 20, the deepest of the three, was drilled to the top of the ignimbrite and immediately produced high-chloride water, the composition of which was unchanged after six years. Its high output, low Na/K ratio, and constant concentrations show that this hole is close to a point where hot water enters the breccias through the ignimbrite.

Hole 11, from present knowledge, is close to a feed zone, but was not deep enough to receive a supply of undiluted water immediately. The water also loses potassium in travelling upwards through about 1 300 feet of breccia.

Shallow prospecting holes may give, at least in the early stages, a misleading idea of many of the chemical characteristics of the main hydrothermal system. Only by continuous observations and comparisons can an accurate picture be obtained. At Wairakei, this has taken about five years.

A comparison of waters from prospecting holes with those of neighbouring hot springs enables a decision to be made on whether one or several bodies of hot water exist in a hydrothermal area.

**Table 2. Early analyses of waters from shallow prospecting holes, and from natural springs at Wairakei**

| *Drillhole No. or spring* | *Depth (ft)* | *Cl* | *Cl/B* | *Cl/F* | *Cl/As* | *Cl/Br* | *Cl/SO₄* |
|---|---|---|---|---|---|---|---|
| 23. . . . . . . . . . . | 1 350 | 1 910 | 22.5 | 110 | — | 900 | — |
| 13. . . . . . . . . . . | 1 402 | 1 970 | 23.5 | 155 | 920 | 880 | 160 |
| 4/1 . . . . . . . . . . | 1 494 | 1 765 | 22.5 | 175 | 900 | 850 | 150 |
| 9 . . . . . . . . . . . | 563 | 1 250 | 22.0 | 180 | 850 | 890 | 180 |
| 15. . . . . . . . . . . | 828 | 1 955 | 21.5 | 150 | 1 100 | 800 | 115 |
| 11. . . . . . . . . . . | 886 | 1 675 | 24.0 | 145 | 1 000 | 860 | 155 |
| 16/1 . . . . . . . . | 994 | 2 030 | 23.0 | 200 | 960 | — | 176 |
| Champagne Pool, G.V.[a] | — | 1 770 | 24.5 | 165 | 1 030 | 1 000 | 188 |
| Devil's Ink Pot, G.V.[a] | — | 1 265 | 24.5 | 140 | 1 020 | 800 | 127 |
| Spring N94/4/18, G.V.[a] | — | 1 840 | 25.0 | 160 | 1 020 | — | 19 |
| Devil's Eyeglass, W.V.[b] | — | 655 | 20.7 | over 5 000 | 1 400 | 440 | 6.9 |

[a] G.V. = Geyser Valley.
[b] W.V. = Waiora Valley.

Tables 2 and 3 give an impression of the differences that may be encountered in the chloride waters of two different hydrothermal areas of the one region. Table 2 gives some early analytical information from Wairakei drillholes and makes a comparison with results for some natural chloride-containing springs in the area. The drillholes cover about two square miles.

Apart from one or two anomalies, the ratios in the waters from drillholes and from the high-chloride springs are essentially constant over the whole area. It is important to note that the best production holes at Wairakei were subsequently sited in the Waiora Valley, where acid, low-chloride springs (e.g., Devil's Eyeglass) existed previously. They were perched pools of surface water heated by steam rising from the hot chloride water below. See Wilson (1) for discussion of various acid spring types.

Table 3, in giving comparable information for Waiotapu, shows that ratios and concentrations in waters tapped by the holes vary widely over the area. The geological environment is described in a *Bulletin* (6) of the New Zealand Department of Scientific and Industrial Research (DSIR). At least two different sources of water exist here, and the two most southern (and most successful) holes, 6 and 7, draw on water most similar to that supplying the Postmistress Pool.

### *More recent results*

Some recent complete analyses of waters from drillholes in three hydrothermal areas, Wairakei, Waiotapu, and Kawerau, are given in table 4. Results for ten of approximately 60 deep 8″ production holes at Wairakei are followed for comparison by two analyses of waters (Holes 13 and 23) on the outskirts of the area where temperatures are too low for steam production. Two examples each from 8″ holes at Waiotapu, and from the 2 000 feet, 8″ diameter holes at Kawerau, are included. The latter results are taken from Western (7).

Concentrations shown in table 4, as elsewhere in this paper, are expressed in ppm for water separated from the mixed steam/water discharges at the local atmospheric pressure (boiling point about 99°C). Values for total ammonia ($NH_4^+ + NH_3$), total carbon dioxide ($CO_2 + HCO_3' + CO_3'$) and total hydrogen sulphide ($H_2S + HS'$) are given, but these vary with the conditions of steam separation. The bicarbonate concentration cannot be interpreted as the quantity in the underground water (8) if the pH is above about 7.2. Boric and silicic acids are appreciably ionized at higher pH values, but in the deep water in the presence of carbon dioxide the ions are replaced by bicarbonate ions.

**Table 3. Waters from prospecting holes and natural springs at Waiotapu**

| *Drillhole No. or spring* | *Depth (ft)* | *Cl* | *Cl/B* | *Cl/F* | *Cl/As* | *Cl/Br* | *Cl/SO₄* |
|---|---|---|---|---|---|---|---|
| 1 . . . . . . . . . . . | 1 593 | 280 | 24.5 | 50 | — | — | — |
| 3 . . . . . . . . . . . | 1 489 | 675 | 29 | 65 | — | — | 22 |
| 4 . . . . . . . . . . . | 3 643 | 1 995 | 31 | 190 | — | 740 | — |
| 5 . . . . . . . . . . . | 1 491 | 950 | 27 | 130 | — | — | — |
| 6 . . . . . . . . . . . | 3 001 | 1 060 | 39 | 65 | 990 | 690 | 32 |
| 7 . . . . . . . . . . . | 3 282 | 1 140 | 24 | 92 | — | 800 | — |
| Postmistress Pool . . . | — | 685 | 32 | 54 | 1 300 | 770 | 20 |
| Champagne Pool . . . | — | 1 880 | 21 | 250 | 720 | 620 | 37 |
| Pool, Lake Ngakoro . | — | 1 785 | 22 | 176 | 480 | 670 | 82 |

## Table 4

| Hole No. | pH | Concentrations in water (ppm) | | | | | | | | | | | | | | | | | | Molecular ratios | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | | | | | | | | | | | | of chloride to | | | | | of sodium to | | | | |
| | | *Li* | *Na* | *K* | *Rb* | *Cs* | *Ca* | *Mg* | *F* | *Cl* | *Br* | *I* | $SO_4$ | Total $HBO_2$ | Total $SiO_2$ | *As* | Total $NH_3$ | Total $CO_2$ | Total $H_2S$ | *B* | *F* | *As* | *Br* | $SO_4$ | *Li* | *K* | *Rb* | *Cs* | *Ca* |
| *Wairakei:* | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 4/1 | 7.9 | 12.6 | 1 300 | 192 | 2.9 | 2.2 | 19 | 2 | 7.0 | 2 140 | 5.7 | 0.2 | 33 | 112 | 590 | 4.3 | 0.25 | 25 | 4 | 23.6 | 165 | 1 050 | 850 | 175 | 31.0 | 11.5 | 1 650 | 3 400 | 120 |
| 20 | 8.4 | 13.8 | 1 300 | 220 | 3.1 | 2.6 | 11 | 3 | 8.3 | 2 215 | 5.5 | 0.4 | 35 | 109 | 590 | 4.7 | 0.20 | 17 | 3 | 25.0 | 145 | 1 000 | 910 | 170 | 28.5 | 10.0 | 1 550 | 2 900 | 210 |
| 26 | 8.2 | 14.8 | 1 340 | 245 | 3.3 | 3.1 | 10 | 3 | 7.7 | 2 300 | 5.8 | — | — | 122 | — | 4.5 | 0.25 | 15 | 2 | 23.4 | 160 | 1 080 | 890 | 200 | 27.5 | 9.3 | 1 500 | 2 500 | 230 |
| 27 | 8.5 | 13.5 | 1 300 | 215 | 3.3 | 2.9 | 10 | 4 | 8.3 | 2 210 | 6.1 | 0.6 | 31 | 112 | 690 | 4.8 | 0.15 | 23 | — | 24.4 | 145 | 970 | 890 | 195 | 29.0 | 10.3 | 1 450 | 2 600 | 230 |
| 28 | 8.4 | 13.4 | 1 320 | 220 | 2.9 | 2.7 | 10 | 3 | 8.0 | 2 240 | 5.2 | 0.6 | 34 | 115 | 660 | 4.7 | 0.15 | 31 | 2 | 24.2 | 150 | 1 000 | 970 | 180 | 30.0 | 10.2 | 1 700 | 2 800 | 230 |
| 41 | 8.5 | 12.5 | 1 250 | 185 | 2.6 | 2.3 | 15 | 2 | 7.6 | 2 130 | 5.9 | 0.3 | 30 | 112 | 580 | 4.5 | 0.15 | 20 | 3 | 23.5 | 150 | 1 000 | 810 | 195 | 30.0 | 11.5 | 1 800 | 3 100 | 150 |
| 43 | 8.2 | 12.4 | 1 250 | 175 | 2.7 | 2.6 | 17 | 3 | 7.8 | 2 130 | 5.1 | — | 31 | 110 | 490 | 4.1 | 0.15 | 16 | — | 24.0 | 145 | 1 100 | 940 | 185 | 30.5 | 12.0 | 1 700 | 2 800 | 130 |
| 44 | 8.6 | 14.2 | 1 320 | 225 | 2.8 | 2.5 | 9 | 3 | 8.3 | 2 260 | 6.0 | 0.3 | 36 | 117 | 640 | — | 0.15 | 19 | 1 | 23.8 | 145 | — | 850 | 170 | 28.0 | 10.0 | 1 750 | 3 100 | 260 |
| 49 | 8.5 | 13.4 | 1 250 | 210 | 2.9 | 2.4 | 12 | 2 | 7.7 | 2 185 | 5.5 | 0.3 | 40 | 114 | 620 | 4.2 | 0.20 | 38 | 3 | 23.5 | 150 | 1 100 | 890 | 150 | 28.0 | 10.1 | 1 600 | 3 000 | 180 |
| 58 | 8.6 | 13.3 | 1 250 | 195 | 2.9 | 2.4 | 16 | 2 | 7.1 | 2 145 | 5.8 | 0.3 | 34 | 111 | 560 | 4.6 | 0.15 | 32 | 3 | 24.0 | 160 | 990 | 830 | 170 | 28.5 | 10.9 | 1 600 | 3 000 | 135 |
| 13 | — | 11.6 | 1 170 | 135 | 1.0 | 2.1 | 42 | — | 6.9 | 2 025 | 5.2 | 1.2 | 34 | 106 | 300 | 4.6 | 0.65 | 20 | 1 | 23.5 | 155 | 930 | 880 | 160 | 30.5 | 14.5 | 4 300 | 3 200 | 49 |
| 23 | 8.3 | 11.5 | 1 250 | 130 | 0.9 | 1.9 | 21 | 2 | 9.8 | 2 005 | 5.0 | 0.3 | — | 110 | — | — | — | 45 | 1 | 22.5 | 110 | — | 900 | — | 33.0 | 16.3 | 5 200 | 3 800 | 105 |
| *Waiotapu:* | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 6 | 8.9 | 6.6 | 860 | 155 | 2.4 | 0.8 | 14 | 4 | 6.0 | 1 450 | 4.7 | 0.2 | 52 | 56 | 470 | 3.1 | 0.9 | 65 | 15 | 32 | 130 | 990 | 690 | 76 | 39.0 | 9.4 | 1 350 | 6 200 | 105 |
| 7 | 8.8 | 6.4 | 790 | 90 | 0.7 | 0.9 | 4 | 3 | 7.5 | 1 310 | 3.7 | 1.0 | — | 63 | — | — | — | 90 | 7 | 25.7 | 95 | — | 800 | — | 38.0 | 14.9 | 4 200 | 5 100 | 350 |
| *Kawerau:* | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 7A | 6.5 | — | 210 | 34 | — | — | 5 | 0 | — | 305 | — | — | 9 | 32 | 194 | — | 7.0 | 120 | 3 | 11.8 | — | — | — | 92 | — | 10.5 | — | — | 75 |
| 11 | 8.9 | — | 658 | 6.6 | — | — | 3 | 0.5 | — | 689 | — | — | 48 | 67 | 345 | — | 3.0 | 650 | 30 | 12.7 | — | — | — | 39 | — | 180 | — | — | 400 |

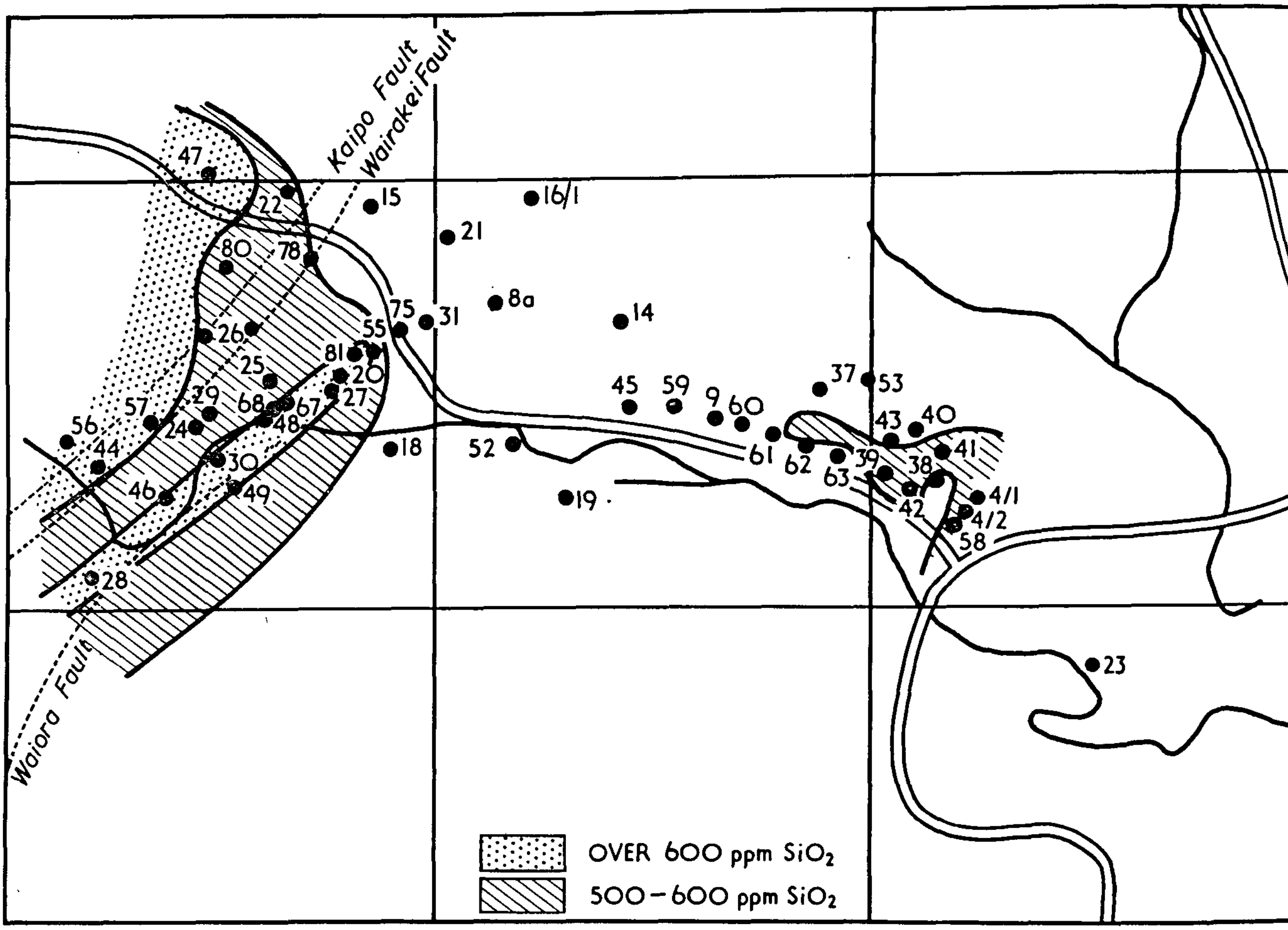


**Figure 2. Silica concentrations in waters from major drillholes at Wairakei**

The waters at Waiotapu and Wairakei are similar in general character, the Waiotapu waters being more dilute. The ratios of Na/Li and Cl/B, and the bicarbonate concentrations, are higher at Waiotapu, though the Cl/Br ratios are rather lower.

Kawerau waters are notably low in calcium concentrations and in Cl/B ratios. The concentrations of bicarbonate are much higher than in the other two areas.

The pH values for atmospheric pressure separation are similar for all three areas. The addition of a steam phase containing carbon dioxide to re-form the original deep water at about 250° results in a solution slightly more acid than neutral water for the temperature (9).

Tables 2 and 4, when compared, show how, at deeper levels at Wairakei, variations in water concentrations are much less than was found for waters from shallow holes early in the project.

*Interpretation of major features*

Steiner (10, 11, 12) showed that waters rising from the ignimbrite interacted with the country rock to form various zones of hydrothermal alteration. Ellis and Wilson (13) correlated the chemistry of alkali and alkali earth ions in the hot waters with the formation of hydrothermal minerals at different levels. Some essential changes include the loss of some potassium and rubidium from solution into the country, very slight loss of lithium, caesium, and magnesium, and a gain of calcium by leaching of rock. It is therefore possible to follow the movement of water through the country by means of ion ratios such as Na/K, Na/Rb, Na/Ca, Li/Ca.

In permeable country the drillholes which discharge waters with the lowest Na/K and Na/Rb ratios, or highest Na/Ca and Li/Ca ratios, are closest to a point where waters enter the system from greater depths. Ellis and Wilson (13) gave maps showing the variation in alkali ratios in waters over the Wairakei field, and showed that waters entered the breccias in at least two positions.

Figure 1, based on recent results from major drillholes, is a revised Na/K ratio map of Wairakei showing two centres where ratios are lower than for surrounding holes, thus indicating points of water inflow at depth. The drillholes in the east have, in general, higher Na/K ratios because of the greater thickness of breccias the waters must travel through from the ignimbrite base. The depth of the holes in relation to the country rock strata must always be kept in mind when comparing these ratios.

**Table 5**

*Group 1:* Range, 2 110-2 160 ppm

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Hole No. . . . | 4/1 | 4/2 | 31 | 39 | 41 | 43 | 58 | 59 | 60 | 62 |
| Cl (ppm). . . . | 2 140 | 2 140 | 2 120 | 2 140 | 2 130 | 2 130 | 2 145 | 2 160 | 2 115 | 2 160 |

Average = 2 138 ppm

*Group 2:* Range, 2 200-2 270 ppm

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Hole No. . . . | 18 | 20 | 24 | 27 | 28 | 30 | 42 | 44 | 46 |
| Cl (ppm). . . . | 2 230 | 2 215 | 2 250 | 2 210 | 2 240 | 2 230 | 2 200 | 2 260 | 2 225 |
| Hole No. . . . | 55 | 61 | 63 | 67 | 81 | | | | |
| Cl (ppm). . . . | 2 270 | 2 250 | 2 220 | 2 200 | 2 230 | | | | |

Average = 2 231 ppm

*Group 3:* Range, 2 275-2 340

| | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Hole No. . . . | 22 | 26 | 47 | 48 | 50 | 56 | 57 | 75 | 76 | 78 | 80 |
| Cl (ppm). . . . | 2 290 | 2 300 | 2 320 | 2 300 | 2 300 | 2 300 | 2 285 | 2 300 | 2 300 | 2 340 | 2 275 |

Average = 2 301 ppm

The concentrations of silica in the waters are also good indicators of water movement. The waters at Wairakei are close to saturation with respect to quartz, as they leave fissures in the ignimbrite.

The cooling of the water by steam separation as it moves in the breccias away from the entry zone (see the section on steam analyses below) causes quartz to be deposited into the country. Figure 2 shows the variation in silica concentrations in the waters from deeper drillholes over the Wairakei field. There are two areas in the west where waters discharged into the atmosphere contain above 600 ppm $SiO_2$. This suggests two separate inflows through the ignimbrite, probably related to the Waiora and the Wairakei and Kaiapo faults shown on the map. A third separate inflow in the east is indicated.

The most reproduceable samples of water are obtained from the weir-boxes of vertical tower silencers, which are fitted to production drillholes at Wairakei. The chloride concentrations can be relied upon to about ± 5 ppm. Table 5 shows that the chloride concentrations in waters from major holes fall, in general, into the same three groups (very high enthalpy discharges are omitted for simplicity).

These figures illustrate how simple concentration determinations may show individual points of hot water entry into a hydrothermal system. At Wairakei, water from a single primary source becomes diluted, or loses heat to surroundings, to varying extents as it flows up three separate channels.

Encroachment of ground water on the borders of a hydrothermal area at the levels tapped by the drillholes is also best estimated by chloride determinations.

An indication of the volume of hot water held in storage beneath the levels explored by drilling may be obtained by constant surveys over the years of the concentrations and ratios in the waters from bores of high output. When drillholes greatly increase the hot water flow from the area, a small reservoir would be revealed by changes in the dynamic chemical equilibria deep below, involving the reaction of

[1] Compare the figures in table 4, corrected for the concentration caused by loss of steam from 260°, with the values for quartz solubility given by Kennedy (14).

**Table 6**

*Hole 20 :*

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Date . . . . . . . . . | 10/53 | 2/54 | 7/55 | 8/56 | 4/57 | 8/58 | 8/59 | 6/60 |
| Cl (ppm) . . . . . . . | 2 318 | 2 250 | 2 200 | 2 195 | 2 255 | 2 260 | 2 230 | 2 230 |
| Atomic ratio Na/K. . . | 9.0 | 9.5 | 9.5 | 9.8 | 9.2 | 9.7 | 9.7 | 10.0 |
| Atomic ratio CL/B . . . | 24.5 | 24.0 | 23.0 | 23.0 | 23.5 | 25.0 | — | 25.0 |
| Atomic ratio Cl/As . . . | 1 050 | 950 | 1 080 | — | — | — | 1 000 | — |
| Atomic ratio Cl/F . . . | 145 | 140 | 170 | 180 | 150 | 145 | 145 | — |

*Hole 4/1 :*

| | | | | | | |
|---|---|---|---|---|---|---|
| Date . . . . . . . . . | 1/53 | 6/55 | 8/56 | 10/58 | 8/59 | 8/60 |
| Cl (ppm) . . . . . . . | 1 960 | 2 090 | | 2 130 | 2 150 | 2 140 |
| Atomic ratio Na/K . . | 19 | 11.9 | 10.8 | 11.5 | 11.8 | 11.8 |
| Atomic ratio Cl/B . . . | 23.0 | 23.0 | 22.0 | 23.5 | — | 23.5 |
| Atomic ratio CL/AS . . | 900 | 1 040 | — | 1 050 | — | — |
| Atomic ratio Cl/F . . . | 220 | 160 | 165 | 170 | 160 | — |

**Table 7**

| Hole No. | Date | Depth (ft) | Enthalpy of discharge (Btu/lb) | Gas content of total discharge (moles/100 moles $H_2O$) | Gas composition (per cent) | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | $CO_2$ | $H_2S$ | HCS[a] | $H_2$ | $N_2$ |
| 4/2 Wairakei. . . . | 7/53 | 1 490 | 515 | 0.018 | 92.7 | 3.7 | 0.4 | 0.2 | 3.0 |
| 8A Wairakei. . . . | 5/52 | 635 | 1 200 | 0.077 | 95.8 | 1.5 | 0.5 | 1.2 | 1.0 |
| 9 Wairakei . . . . | 10/53 | 563 | 530 | 0.060 | 94.4 | 3.2 | 0.6 | 0.9 | 0.9 |
| 20 Wairakei . . . . | 2/54 | 2 005 | 477 | 0.021 | 96.8 | 2.5 | 0.4 | 0.1 | 0.3 |
| 22 Wairakei . . . . | 6/59 | 2 036 | 455 | 0.011 | 89.5 | 4.9 | 1.8 | 1.2 | 2.5 |
| 58 Wairakei . . . . | 6/59 | 1 619 | 410 | 0.008 | 90.1 | 6.3 | 1.2 | 0.4 | 2.0 |
| 81 Wairakei . . . . | 7/59 | 1 883 | 475 | 0.009 | 92.8 | 4.2 | 0.9 | 1.8 | 0.3 |
| 6 Waiotapu . . . . | 9/58 | 3 001 | 430 | 0.032 | 88.0 | 10.3 | 0.2 | 1.0 | 0.5 |
| 7 Waiotapu . . . . | 7/59 | 3 282 | 450 | 0.103 | 92.3 | 5.3 | 0.5 | 2.0 | 0.0 |
| 7A Kawerau. . . . | 1959 | 1 985 | 480 | 0.32 | 97.2 | 2.8 | 0.0 | 0 | 0.2 |
| 11 Kawerau . . . . | 1959 | 2 046 | 480 | 0.37 | 95.5 | 2.5 | 2.0 | 0 | 0 |

[a] HCS = Total saturated hydrocarbons.

ground water with magmatic liquids and the country rock. Tritium estimations (15) assist by giving the minimum time for ground water circulation.

Table 6 shows the small variations in some chemical characteristics of discharges from two typical major drillholes at Wairakei (Hole 4/1 was, in 1953, still tapping stagnant and somewhat diluted water). The general constancy over a period of time is favourable for a long production life for the field.

## Steam analyses

### *Composition*

The gas contents and gas compositions of the steam separated from the discharges give detailed information on the movements of steam and water underground.

Table 7 gives examples of analyses of steam from Wairakei, Waiotapu, and Kawerau. Values for the last area were taken from Western (7). The gas contents of the discharges are highest at Kawerau and lowest at Wairakei; the gas compositions are not very different between areas.

Ethane is found in the gases, and "n" in the formula $C_nH_{2n+2}$ often ranges between 1.0 and 1.2.

Interpretation of the minor gas constituent results is not simple, especially since methane and hydrogen can result from decomposition of buried organic material. The greatest success with the interpretation of steam analysis has been obtained with the major gas components.

Table 8 shows the contents of carbon dioxide and hydrogen sulphide in some Wairakei discharges during late 1960. The three groups are for major holes in the eastern "Circle" area of the field, for major holes about the Waiora fault line, and for shallow holes discharging a high proportion of steam.

**Table 8**

| Hole No. | Enthalpy (Btu/lb) | Gas content of total discharge (millimoles/100 moles $H_2O$) | | Molecular ratio $CO_2/H_2S$ | Gas output from drillhole (lb/hr) |
|---|---|---|---|---|---|
| | | $CO_2$ | $H_2S$ | | |
| 40 . . . . . | 882 | 137 | 4.5 | 30 | 416 |
| 43 . . . . . | 428 | 3.9 | 0.20 | 20 | 32 |
| 41 . . . . . | 470 | 9.7 | 0.46 | 21 | 59 |
| 39 . . . . . | 455 | 6.1 | 0.30 | 20 | 29 |
| 42 . . . . . | 428 | 24 | 0.67 | 36 | 222 |
| 4/2. . . . . | 462 | 17 | 0.64 | 27 | 105 |
| 46 . . . . . | 495 | 10.8 | 0.49 | 22 | 89 |
| 30 . . . . . | 455 | 7.0 | 0.32 | 22 | 137 |
| 48 . . . . . | 476 | 10.2 | 0.49 | 21 | — |
| 67 . . . . . | 424 | 5.6 | 0.20 | 28 | 148 |
| 27 . . . . . | 483 | 17 | 0.56 | 30 | 177 |
| 20 . . . . . | 475 | 15 | 0.52 | 29 | 205 |
| 8A . . . . . | 740 | 120 | 3.7 | 32 | 59 |
| 14 . . . . . | 1 035 | 229 | 8.3 | 28 | 104 |
| 68 . . . . . | 1 142 | 234 | — | — | — |
| 203. . . . . | 1 200 | 323 | 11.2 | 29 | 79 |

### *Interpretation*

The results in table 8 are explained by assuming that water of enthalpy about 490 Btu/lb (corresponding to the temperatures of about 260°C measured in the holes), and containing in solution about 0.018 moles gas/100 moles water, enters the breccias from channels in the ignimbrite at definite positions in the field (*cf.* water analysis). As the water enters, and is partly tapped by the drillholes, steam separates and gathers at higher levels under the mudstones, carrying away much of the gas from the water. The enthalpy of the water falls.

An illustration follows. If 7 per cent steam separates from a water phase of 490 Btu/lb (about 260°C), containing in solution 0.018 moles $CO_2$/100 moles water, the resultant distribution is at equilibrium about 0.25 moles $CO_2$/100 moles $H_2O$ in the steam phase, and about .0015 moles $CO_2$/100 moles $H_2O$ in the remaining water phase of enthalpy 435 Btu/lb (about 235°C). Ellis (16) gives the solubility of carbon dioxide. The calculated compositions are matched by examples in table 8 although it is unlikely that equilibrium will be quite reached in the natural system.

At Wairakei, for the eastern group of drillholes (all at 1 200-1 600 feet), which are considered to be fed by a separate fissure or set of fissures, the integrated total discharges (water and steam) and gas outputs amount to an over-all ratio of about 0.02 moles gas/100 moles $H_2O$. Bore 40 collects a large proportion of separated steam.

For the middle group in table 8, the evidence shows Hole 27 to be close to a feed point. Just how close may be judged by the different results for Hole 20, only 100 feet away.

Simple gas analysis may therefore be an effective method of locating feed channels accurately once their approximate positions are found by the ion-ratio method. From this knowledge, improved sites for further high-production drillholes may be selected.

The ratio $CO_2/H_2S$ is influenced in two ways. First, hydrogen sulphide is rather more soluble than carbon dioxide at all water temperatures. A small amount of steam separating from the original hot water will be relatively high in carbon dioxide, but for a large steam separation at one place the $CO_2/H_2S$ ratio in the steam will approach that in the parent water. Second, the formation of iron sulphides in the country raises the ratio as steam moves from the point of entry.

The analyses in tables 7 and 8 do not include ammonia, which is more evenly distributed between steam and water phases than the other gases, the proportions depending on the temperature and the extent of steam separation. For accurate results, ammonia should be estimated on samples of water and steam separated at the same pressure.

From a knowledge of the steam/water ratio of the drillhole discharge at a pressure (or the discharge enthalpy), the water analysis and steam analysis can be combined to give concentrations of constituents in the complete discharge. Where the enthalpy corresponds to that for saturated water at the temperatures measured at the base of the drillhole, the composition of the complete discharge is also that of the underground hot water.

Ratios such as $Cl/NH_3$, $Cl/CO_2$, $CO_2/NH_3$ can be calculated for use as further indicators of water and steam movement. The ratio $CO_2/NH_3$ is a sensitive indicator of the degree of steam separation, owing to the differences in solubilities of the two gases. Ammonia becomes less soluble and carbon dioxide more soluble in water with increasing temperature, but at 260°C the distribution coefficients (weight concentration in liquid/weight concentration in steam) are still separated by a factor of about 20 (17).

Table 9 gives examples of the $CO_2/NH_3$ and $Cl/CO_2$ ratios at Wairakei. The concentrations and molar ratios are for complete discharges.

The $CO_2/NH_3$ ratio may show several effects. High $CO_2/NH_3$ ratios (e.g., Hole 203) result when discharges carry an excess of steam which represents the first small steam loss from the underground water supply, or steam that has passed through a cooler water phase.

Low $CO_2/NH_3$ ratios are found for waters that have lost a small amount of steam (Holes 30 and 24), for steam that is lost at a later stage from this water, and for waters that have been heated or reheated by steam. Steam-heated surface waters contain a high ammonia content.

The situation is complicated by waters that lose steam, migrate, and then are heated again by steam of different composition. In the deeper parts of the systems the processes are probably simple losses or gains of steam, but at the surface or on the outskirts of an area, complex cycles of boiling, reboiling, and convection occur.

## Formation of deposits in drillholes

### *Silica*

Silica deposition in bore pipes has not proved troublesome in the hydrothermal areas discussed

**Table 9**

| Bore No. | 20 | 30 | 24 | 28 | 47 | 37 | 58 | 203 |
|---|---|---|---|---|---|---|---|---|
| Enthalpy (Btu/lb) | 475 | 455 | 460 | 505 | 475 | 630 | 460 | 1 200 |
| Cl (ppm) | 1 540 | 1 590 | 1 600 | 1 520 | 1 600 | 1 170 | 1 520 | 0 |
| $NH_3$ (ppm) | 0.60 | 0.55 | 0.80 | 0.95 | 0.85 | 2.5 | 0.70 | 2.0 |
| Molar ratio $CO_2/NH_3$ | 250 | 125 | 130 | 165 | 180 | 140 | 170 | 570 |
| Molar ratio $Cl/CO_2$ | 5.2 | 11.5 | 7.8 | 5.0 | 5.3 | 1.8 | 6.5 | 0 |

above, although considerable deposition takes place in surface flumes carrying waters below 100°C.

It is considered that deposition of silica will occur only when the solubility of amorphous silica (14) is exceeded by the cooling and evaporation caused by flashing of steam. Polymeric forms of silica then become suspended in the solution and coat out on surfaces. Fortunately the growth of quartz crystals appears to be too slow for this stable, less soluble, form of silica to collect as deposits in pipes, although it is forming in the country rocks in the hottest parts of the area.

For Wairakei waters, the saturation point for amorphous silica is reached at about 140°C or saturated steam pressures of about 40 psig. If water is utilized above this temperature little trouble is anticipated.

*Calcite*

The total concentrations of calcium and bicarbonate in thermal waters are usually adequate to give trouble with calcite precipitates if the solubility of this mineral is exceeded. For a typical Wairakei hole discharging 200 tons of water an hour, a loss of 1 ppm calcium from solution could form 0.5 kg of $CaCO_3$ in the period. If this was concentrated over a 3-foot length of 8″ pipe (deposits are usually localised), the diameter could be halved in the order of 50 days.

The solubility of calcite in water and salt solutions at various carbon dioxide pressures has been determined by laboratory studies (see Ellis (18) and later work). The solubility can be expressed by the following equation:

$$(Ca^{++})\ (HCO_3')^2 = Y \cdot P_{CO_2}$$

For 0.05 molar sodium chloride solutions, when partial pressures of carbon dioxide ($P_{CO_2}$) are expressed in atmospheres, and concentrations of ions in parts per million, values of Y are given below.

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| T°C . . . . | 100 | 125 | 150 | 175 | 200 | 225 | 250 | 275 |
| $10^{-4}$ Y . . . | 1 350 | 450 | 120 | 40 | 14 | 4.3 | 1.7 | 0.45 |

From the calcium and bicarbonate concentrations determined by analysis, and the values of Y, it is possible to obtain the minimum partial pressure of carbon dioxide, $P_{CO_2}$ (min), necessary to prevent calcite deposition. The ion concentrations must be adjusted to allow for steam separation, and the bicarbonate concentrations, as analysed, adjusted for the overlapping ionization of boric and silicic acids.

Table 10 presents for three areas the values of $P_{CO_2}$ (min) calculated for the complete discharges (or underground hot water) given by the drillholes. The concentrations are for atmospheric pressure separation, and pressures are in atmospheres.

**Table 10**

| Bore No. | W.28[a] | W.27[a] | W.46[a] | W.67[a] | Wt.6[b] | Wt.7[b] | K.11[c] |
|---|---|---|---|---|---|---|---|
| T°C | 265 | 265 | 255 | 230 | 235 | 240 | 260 |
| $CO_2$ (moles/100 moles $H_2O$) | 0.026 | 0.017 | 0.011 | 0.006 | 0.032 | 0.103 | 0.37 |
| ($HCO_3'$) ppm | 85 | 65 | 65 | 70 | 130 | 160 | 700 |
| ($Ca^{++}$) ppm | 10 | 10 | 9 | 13 | 14 | 4 | 3 |
| $P_{CO_2}$ (min) | 2.9 | 1.7 | 1.0 | 0.75 | 3.2 | 1.5 | 4.8 |

[a] W. = Wairakei. [b] Wt. = Waiotapu. [c] K. = Kawerau.

The high values of $P_{CO_2}$ (min) correlate with examples of troublesome calcite precipitation in the casings of Hole 28 at Wairakei, and the Waiotapu and Kawerau holes. $P_{CO_2}$ (min) could be taken as a measure of the precipitating tendency.

The carbon dioxide partial pressures can be calculated for the underground water before steam separation in the drillhole, from the carbon dioxide content in the complete discharge, and values for the solubility of this gas (16). The pressures are similar in value to $P_{CO_2}$ (min), which shows that the waters are close to saturation with calcite.

Equilibrium gas distribution between steam and water phases is not maintained on steam flashing. For natural steam separation in the country, the carbon dioxide content of the water appears to remain higher than for equilibrium conditions (compare the concentrations for Holes 27 and 67). The solution may become undersaturated, and leaching of calcium from the rock can then occur.

There is evidence, however, from water samples taken under high pressure from drillholes, that waters flashing within the pipe may contain carbon dioxide concentrations several times lower than expected for equilibrium between the phases. Under these conditions the waters with highest $P_{CO_2}$ (min) would have the greatest tendency to precipitate calcite.

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### *Summary*

From experience with the hydrothermal areas of New Zealand, the author makes recommendations for chemical work which would be helpful during the prospection and evaluation of similar areas in other regions.

Examples are given of complete analyses of steam and water from drillholes in three hydrothermal areas (Wairakei, Waiotapu, and Kawerau). For Wairakei and Waiotapu, the chemistry of the discharges from prospecting drillholes is compared with that of the waters from natural springs in the areas.

For Wairakei, the chemical analyses of steam and water from about sixty deep production holes are used to derive patterns of water and steam movement. From this type of information, improved positions for future drillholes can be selected.

Ratios of ions, such as Na/K, Na/Rb, Na/Ca, are useful indicators of water movement, while the composition ($CO_2$, $H_2S$, $NH_3$) and content of gas in the steam give details on conditions of steam separation from hot water.

A measure of the tendency of silica and calcite to precipitate from solution in bore pipes can be obtained from published solubility information, together with the contents of silica, or of calcium and bicarbonate, in the waters, and of carbon dioxide in the complete bore discharge.

## PUITS GÉOTHERMIQUES : ÉTUDES CHIMIQUES

### *Résumé*

Ce mémoire présente des recommandations, fondées sur l'expérience acquise dans les régions hydrothermiques de la Nouvelle-Zélande, en vue de l'exécution de travaux d'ordre chimique susceptibles d'être utiles à la prospection et à l'évaluation de régions analogues dans d'autres pays.

L'auteur donne des exemples d'analyses complètes de vapeur et d'eau en provenance des puits dans trois zones hydrothermiques (Wairakei, Waiotapu et Kawerau). Pour Wairakei et Waiotapu, il compare la composition des produits des puits foncés aux fins de prospection à celle des eaux des sources naturelles de ces mêmes régions.

Pour Wairakei, les analyses chimiques de la

vapeur et de l'eau en provenance d'une soixantaine de puits de production profonds sont utilisées pour établir les régimes des mouvements d'eau et de vapeur. Ces renseignements permettent de mieux choisir à l'avenir l'emplacement des puits.

Les rapports entre les ions, tels que Na/K, Na/Rb, Na/Ca, constituent des indicateurs utiles des mouvements d'eau, tandis que la composition ($CO_2$, $H_2S$, $NH_3$) et la teneur des gaz de la vapeur fournissent des précisions sur les conditions de séparation de la vapeur de l'eau chaude.

On peut évaluer la tendance que présentent la silice et la calcite en solution à précipiter dans les tubages, à l'aide des données publiées sur la solubilité, en liaison avec les teneurs des eaux en silice ou en calcium et en bicarbonate, ainsi que la teneur en anhydride carbonique des produits qui sortent des puits.

# NATURAL STEAM GEOLOGY AND GEOCHEMISTRY

*G. Facca * and F. Tonani †*

## Definitions

All sources of subsurface natural heat that can be utilized for practical purposes produce geothermal energy; it is the possibility of practical use that actually defines this kind of energy. This definition is very wide and covers not only the present, but also the future possibilities of the practical use of natural heat. It is very likely that in the future every kind of geothermal energy will be of practical value. At present, only natural steam is of practical value for industrial development.

A natural steam field man be defined as an area where sufficient natural steam to support an industrial development can be produced by drilling.

This definition implies that our interest is limited to steam fields that can produce large quantities of energy at commercial costs. Owing to the fact that exploration expenses are high and comparable to the cost of petroleum exploration, a lower limit must be established for a commercial interest; a steam field which produces less than a certain quantity of energy is not a commercial natural steam field.

Many factors, both economic and technological, are involved in establishing the lower quantity limit. For the present purpose, however, only an order of greatness is needed. In each venture the risk is high. If the minimum exploration cost is estimated at a million dollars, the production of half a billion kWh per year can justify the risk involved, and can be roughly assumed to be the minimum for a commercial field.

At the present state of technological progress, a rough estimate would be that a steam field which can produce half a billion kWh per year is one which can produce 5 million tons of steam at a pressure of 5 atmospheres or more, with a minimum temperature of 150°C.

From a geological point of view, the geological and geothermal environment which can provide the necessary conditions for such production must be defined. A natural steam field can be defined as one capable of providing a minimum of half a billion kWh per year or an equivalent quantity of energy of a different kind.

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## The source of heat

A natural steam field as defined above may be realized in nature according to the different patterns shown below. In the first place, a source of heat is needed that, in a defined area, can provide natural steam in greater quantity than usual; in other words, a source of heat in the commercial quantity defined above.

Several geological phenomena may be a source of thermal energy; for instance, faulting, some types of geochemical activity, radioactivity, are exothermal processes. The quantity of heat generated in such a manner, however, cannot reach the above-stated requirements for a steam field.

Only one geological process seems to be able to provide sufficient quantities of heat: the mobilisation of subcrustal heat stored in deep-seated magma.

The actual upward movements of the olivin-basatic oceanic magma, the geological processes involved in magmatic evolution, and the genesis of volcanoes, are geological events involving a transfer of heat from the deepest to the superficial layers of the earth's crust.

The natural steam fields now in production may be classified in three main types with regard to the source of heat and the magmatic condition of the heat transfer.

The first type is found in the Larderello steam field, where there is a granitic pluton at an unknown, but not very great, depth. It is a magmatic mass near the surface, but without any direct communication with the surface.

The second type is at the Mount Amiata, Bagnore, steam field; in this case the magmatic mass appears to have reached the upper region of the crust with sufficient energy to give birth to a Pliocenic, or Quaternary, now extinct, volcano.

The third type is the Wairakei, New Zealand, steam field; it is linked to an active volcano.

Therefore, all types of a relatively shallow molten mass can be an effective source of heat for a steam field. The distinction among the three categories of steam field is valuable not only from a theoretical and genetic point of view, but also in exploratory thinking.

Favourable areas for steam exploration may be considered: (*a*) those where relatively shallow intruded molten rock mass can be expected; (*b*) recently extinct volcanoes; (*c*) living volcanoes. Prospecting may be undertaken with a reasonable chance of success in such areas, even if there is little actual thermal activity at the surface.

In oil exploration, the theory of the sedimentary basins is the basic one for an exploratory programme, because it permits a scientific, rational choice of interesting areas, whereas the hydraulic theory helps in locating a single exploratory well. In a similar way, the genetic classification of steam fields provides basic ideas for the choice of areas where it is reasonable to undertake exploratory work and expense. In oil as well as in steam exploration, actual surface manifestations are not a necessary condition for the choice of a drilling site, but they are very useful from a regional point of view.

## Heat accumulation

A source of a large quantity of heat is a necessary condition for a steam field, but this alone is not sufficient. It is easy to imagine a geological pattern that disperses a large portion of the heat from the source or, conversely, prevents its transfer or availability in the shallow drillable depth.

The geological pattern shown in figure 1 represents an ideal steam field, broadly similar to the Larderello steam field. At an unknown depth, a heat source is enclosed by impervious layers; the source's cap rocks may be called the impervious series overlaying the magmatic shallow mass or any other envisaged heat sources.

The magma deposit with its own generally impervious cap rock is a heat source of roughly assigned output. Such an output of heat is not only the most important condition for the existence of a geothermal field, but it also determines, in addition to the surface temperature and the properties of the rocks, the temperature distribution between the bottom of pervious and the top of impervious layers.

In the pervious horizon, the thermal conductivity is raised and the thermal gradient is lowered because of the thermal convection, and vice versa in the impervious horizon. With this condition, the highest possible temperature for the top of a permeable series is assured.

Over the sources cap rock is a very pervious and porous reservoir; it may be called the productive aquifer. It is overlaid by impervious layers, the *aquifer* cap rock. The productive aquifer is sandwiched between two impervious sequences.

The top surface of the source's cap rock permits a steady upward flow of heat. The water of a produc-

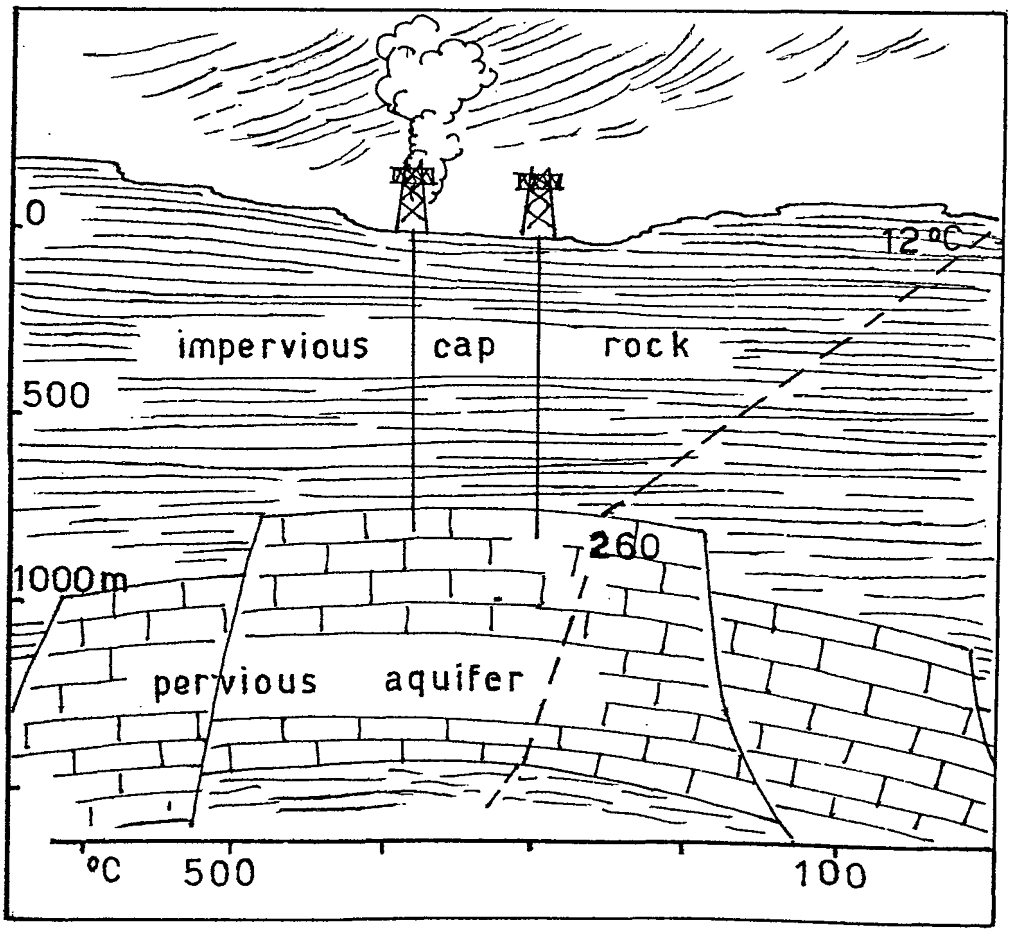


Figure 1

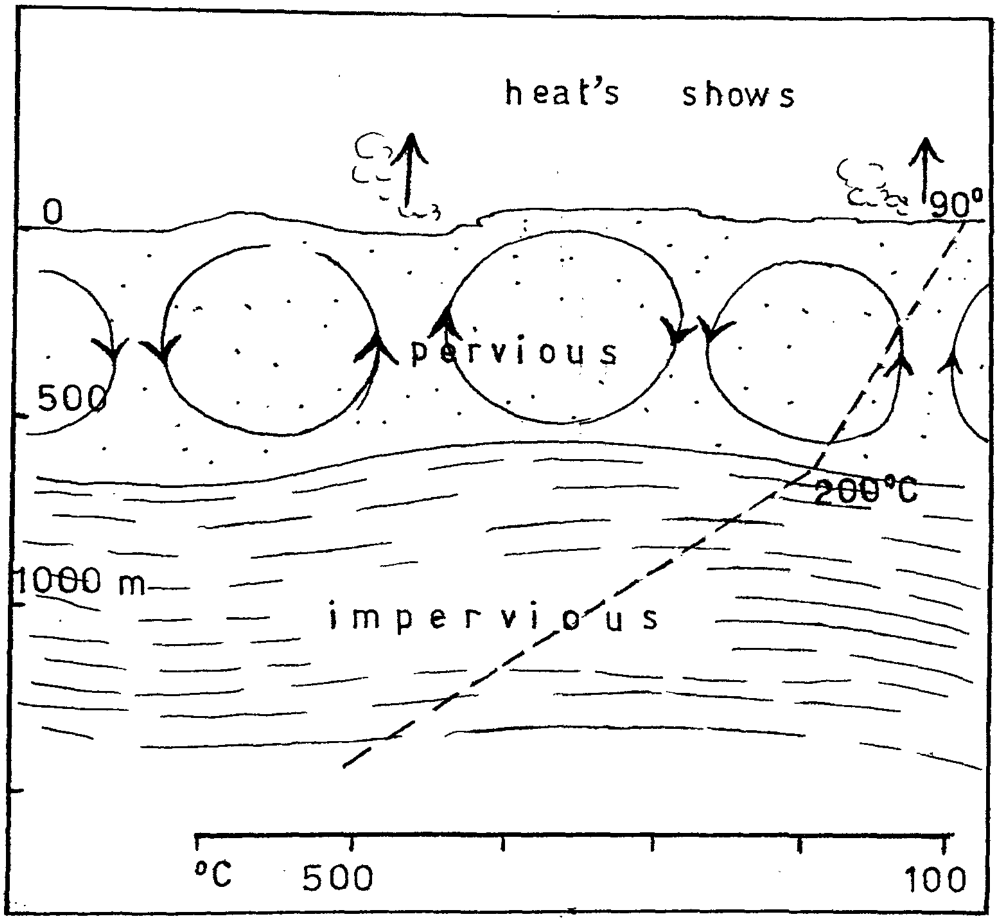


**Figure 2**

tive aquifer is heated at the bottom; if the permeability is high and if the thickness of the productive aquifer is sufficient, convection currents take place and assure an upward transfer of the heat. All the water of the very pervious aquifer is heated, and the temperature at the top of the pervious layer is not very different from the temperature at the bottom. The heat transfer, assured by the convection currents, occurs in an entirely different way from the heat transfer occurring in the impervious beds. Geologically, in pervious beds the strong convection equalizes the top and bottom temperatures of the fluids, whereas in impervious beds where no fluid movement is possible, the temperature increases with depth at the high rate determined by the low conductivity of the rocks and by the total high flow of heat. Therefore the temperature at the pervious bed happens to be high in this case.

In a different geological pattern, the aquifer pervious layers are not covered by a cap rock; they reach the surface. Figure 2 gives a schematic representation of such a geological pattern.

The convection currents take place equally in the aquifer, but the heated water loses part of its heat content at the surface. Hot sources, geysers, chemical activity and superficial waters provide effective dispersal of heat. In any case, the water cannot greatly exceed the boiling point at the atmospheric pressure.

Here there is a temperature-limiting factor in the subsurface; if the permeability is high, and the surface temperature is around the boiling point, the convection currents will tend to equalize the temperatures in depth and, broadly speaking, the water temperature in the subsurface will be under the boiling point because the hydraulic pressure increases in all cases.

These simple observations are a very useful aid in the choice of the best productive interval: the top of the porous under an impervious bed. Since the various methods of porosity logging give fairly adequate information, no difficulties arise in the choice of the interval. A drill stem test can give the other important data: the temperature of the water and the flow rates.

An impervious layer of very limited thickness can stop the upward movement of the convection currents maintaining water temperature around the boiling point corresponding to the hydraulic pressure.

This may be summarized in a single sentence: a steam field is a trap for the convection geothermal currents generated by a sufficient heat flow.

The shape of the reservoir is also an important factor: if the aquifer cap rock is monoclinal to the surface, no effective trap for the convection currents can exist. The trap may be formed by horizontal or sub-horizontal cap rock or by an anticline, an updip pinch-out, any closed positive structure, etc. The trap for convection currents may be similar to, or different from, the oil traps; for instance, a horizontal roof may also be a trap for currents.

## Natural conditions of geothermal fields

Conditions of geothermal fields are determined (*a*) by the mode of occurrence of geothermal energy, i.e., by the sources of heat which have been identified in the first section of this report; (*b*) by the properties of the water which, in different states, is actually the conducive fluid of geothermal energy.

The direction and the orientation of the geothermal gradient, in connection with the vapour tension curve of water, prevent the existence of a permeable vaporiferous horizon at the top. If this exists it will have thermal gradients of such height as to produce imposing manifestations of other kinds (100°C at ground level and molten silicates at 1 000 metres under the extension of the whole area).

Geothermal gradients and the rise of the boiling point in connection with pressure can be compared only starting from a pressure of 10 atmospheres (hydraulic pressure at 100 metres under ground level).

In any case, in a steam horizon there is static instability (*a*) in the water outlying the field and (*b*) in the field itself between vapour and the water on it. The vapour state can subsist statically only in the presence of unusual diaphragms combined with a rather high thermal gradient. Thus even the open structure of a bed of natural gas under hydraulic thrust would be unstable.

As an extreme case of thermal circulation of water, or by induction of magmatic volatile, there would be a stable system of ascending vaporous streams where flowing vapour undergoes a loss of pressure roughly corresponding to the hydrostatic gradient (a further increase of the flow would but enlarge the section of the ascending streams).

With the permeability necessary to ensure satisfactory production per well, the thermal flow required to maintain such a condition is in a higher proportion by two or three orders of magnitude, both to the one adequate to maintain the thermal circulation of water and consequently the production of vapour in a thermal field, and to the thermal flow evaluated for known geothermal fields.

It is thus assumed that the fluid conducive to geothermal energy in the potentially productive layers is water in liquid state.

The recurring presence of carried water, especially during the initial transitory regime of the wells, is already a very important hint. On the other hand, thermodynamics help in the realization that additional explanations for the existence of carried water are unnecessary. Superheated vapour used in known geothermic fields can very well originate from the evaporation of water existing in a liquid state in the productive layer. Exact figures cannot be given because of wide differences in actual geological cases.

Notwithstanding the various causes potentially affecting the thermal content at the top of the well, observed oscillations are not relevant. The highest values are slightly higher than 700 kcal/kg, and often they go as far down as 650 kcal/kg. The most frequent values are between these figures.

Vapour speed can attain several hundred metres a second in the hole, where losses or loads are smaller and the section of flow greater. In such conditions only the fact of doubling the flow section relative to conditions in the layer can account for an increase of the order of ten kcal/kg. A similar effect can be produced by switching from linear motion to eddy motion (the latter is very likely to occur in the passage of the flow through small fissures into the hole).

If this factor is taken into consideration, the thermal content typical of the fluid used in known geothermic fields, like Larderello and Wairakei, can be identified with the one of saturated vapour (at 220-250°C and 20-40 atm., 670 kcal/kg: point M of Mollier's diagram (see figure 3).

This saturated vapour has very important properties from the point of view of geothermal fields. In fact, during the stationary isoenthalpic flow (throttling process), the water begins to evaporate where the pressure attains the pressure of saturated vapour at that given temperature. Two phases at specific different enthalpy take place: saturated vapour with elevated enthalpy and water with low enthalpy. If the thermal equilibrium between the two phases is maintained, the state of the fluid in a given section of the flow channel will be represented by points B′ and B″ of Mollier's diagram.

Until B is to the left of M, the same procedure can be applied to each fraction as to the first saturated vapour E, but the general outcome will be independent of the fractions taken into consideration, depending only on the initial thermal content of water A.

When B″ coincides with M, there is bound to be a change, since it is the highest possible thermal content for a saturated vapour. Further isoenthalpic expansion of the gaseous fraction will produce superheated vapour, corresponding to points like U (see diagram in figure 4).

If, following the different properties of water and vapour, there is a differentiation between the two phases, this will be the case. If the vapour was already accelerated when it was balanced at the thermal equilibrium with water, an increase in the section of the channel, slowing it down or only causing the transition to eddy flow, will bring about

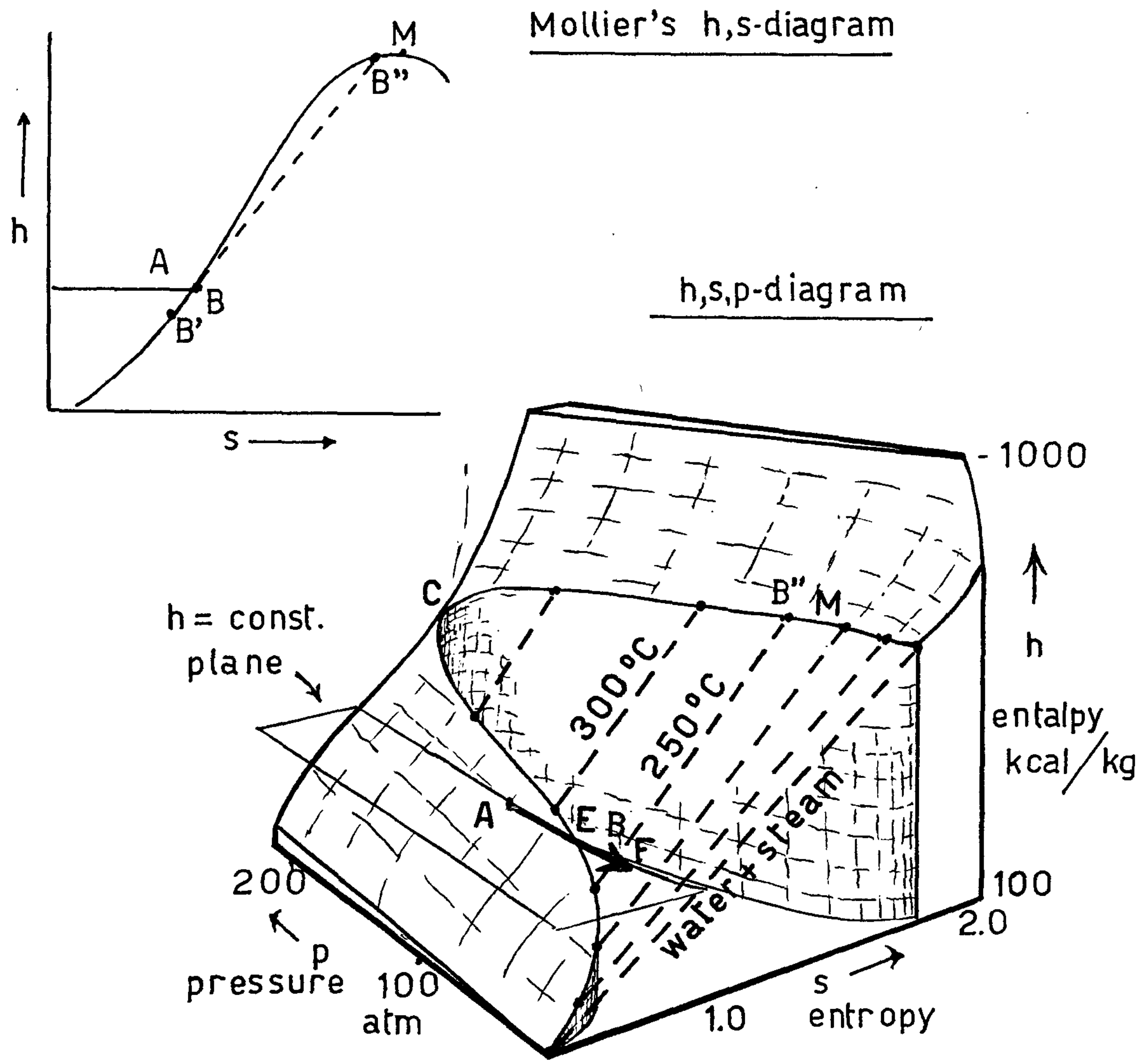


Figure 3

that increase of the thermal content at point M, which has already been mentioned (point U').

If, on the contrary, vapour remains in contact with water, instead of overheating there will be evaporation of the greater part of the water, while the properties of vapour in the various sections of the flowing channel will be given by the curve of saturated vapour.

## Conditions for exploiting geothermal fields with water

The evaporation of water should take place chiefly in the productive layer, and this for various reasons. Besides all considerations regarding the quantitative relationship between the circulation of water and the supply of vapour discussed below, the formation of scales must be taken into consideration. This is absolutely inconsistent with the supply required from industrially productive wells when calcium sulfate waters exist, but in the long run can become damaging in other cases as well, given the limited sections of holes.

The presence of water in the immediate neighbourhood of the well, where the section of the flow is smaller, cuts down by several units the outflow owing to the higher degree of viscosity. The height of the water level on the bottom of the well brings about a proportional loss of outflow.

Obviously the structure of the pervious layer is of the highest importance in the process of differentiating the vapour phase from the liquid phase. It also determines the required permeability, both in its constituents and in checking the scale formation.

### Evaporation space

In gushing holes a flow occurs because of a difference in hydrostatic pressure. Discussion of thermodynamic conditions in a geothermal field in a wider sense must be restricted to a stationary situation.

In this case the flow of water or steam is isoenthalpic. A distribution of pressures around the well or wells takes place at the point or in the area maintained at low pressure by the outflow:

$$P = P(r)$$

(1) $$P(o) = Po,\ P(\infty) = Pi$$

$r$ = distance from the well, variable parameter
$P$ = pressure, variable parameter
$Po$ = pressure at bottom of well
$Pi$ = (hydraulic) layer pressure.

For each section perpendicular to the flow having a total area $f = f(r)$:

$$\frac{dP}{dr} \cdot \frac{\sigma f(r)}{\nu} = Q$$

(2) $$\nu = \frac{\eta}{\rho}$$

$Q$ = mass outflow
$\sigma$ = permeability, possibly $\sigma(r)$
$\nu$ = cinematic viscosity, possibly $\nu(r)$
$\eta$ = viscosity, possibly $\eta(r)$
$\rho$ = density, possibly $\rho(r)$.

Under the condition of constant outflow, the expression for (1) may be obtained from (2), given the condition at the boundary and $f(r)$. This depends on the type of flow, and in homogeneous environment it alone determines the types of distribution of pressures. In the present case, this distribution of pressures can also depend on the distribution of $\sigma$ and $\nu$. Thus it is not necessary to insist on determining the type of flow. The spherical flow is taken into consideration as the ideal case of a stationary flow, with the conditions given to the boundary. Consequently, permeability is assumed to be homogeneous on a somewhat large scale, the casing rather short, and the productive layer powerful enough.

In this way, $f(r)$ is determined and the whole distribution of pressure can be deduced from the determination of $Q$, which can be evaluated at the surface.

$P_s$ indicates the pressure of saturated vapour at the local temperature of the layer. In general this can be defined as isothermal if permeability shows the values required for satisfactory production. The condition $P = P_s$ defines a surface, which can be roughly indicated as a sphere having a radius $r_s$, such as $P_s = P(r_s)$, enclosing the space in which water can evaporate.

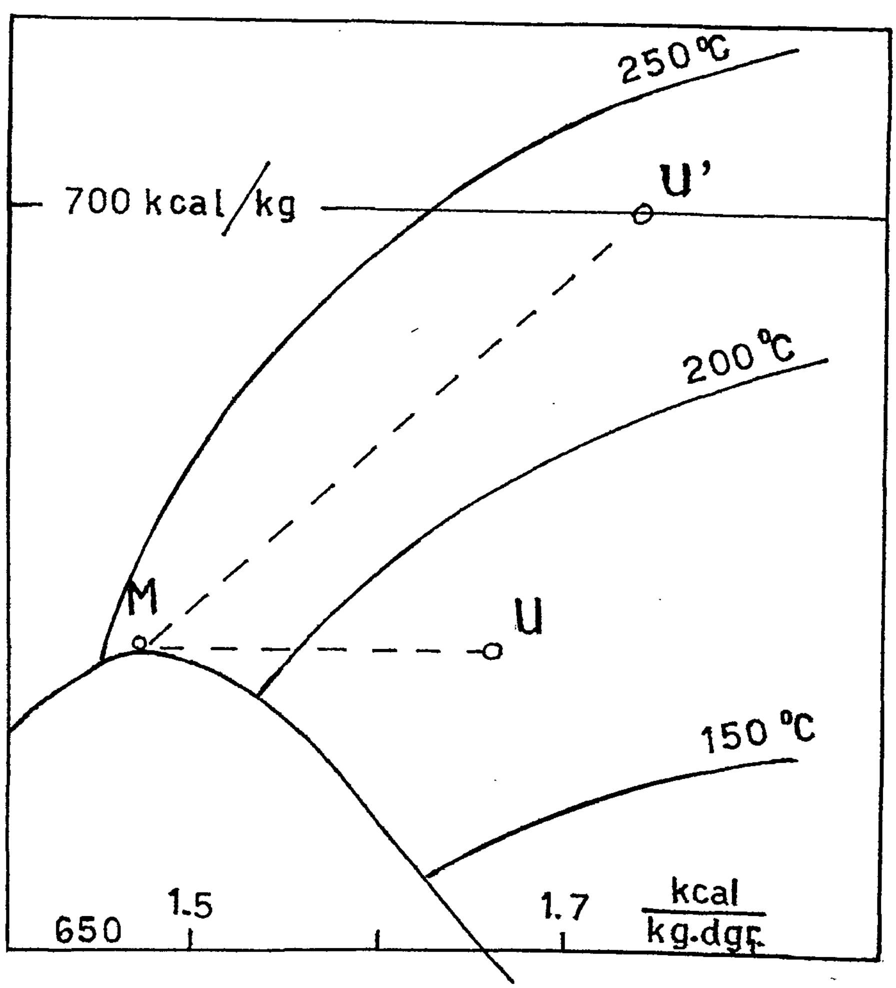


Figure 4

The volume of the space of evaporation is of the highest importance. In fact, the fundamental processes determining the production of geothermic available steam take place inside it : (*a*) formation of a volume of vapour large enough to allow the gravitative differentiation of vapour from water (the volume of steam must exceed the 50 per cent of the total); (*b*) precipitation of salts contained in the fraction of evaporated water, without prejudice to the effect of minor factors like the variation of temperature.

As shown by figure 5, the fraction of precipitated salts tends to become important in a space closer to the well bottom. The space where decantation of water may occur is more extensive.

Calculations involving simple orders of magnitude reveal which parameters are critical in establishing an outflow of steam of industrial significance. The space of evaporation narrows down quickly, causing a substantial formation of scales, or preventing the separation of steam and the supply of water (*a*) with the narrowing of the diameter of the hole, (*b*) with a decrease in rock permeability, (*c*) with overcompression of water in the productive layer, with respect to the tension of saturated vapour at the temperature of the layer itself.

Consideration of the structure of the productive layer must stress the importance of permeability. As to the thermodynamic state of the water in the layer, it is of paramount importance that it should be very close to the boiling point at layer pressure. This again stresses the importance of the cap rock as a thermal insulator. Parenthetically, this proves that ideal conditions for the output of steam exist at the top of the productive layer, and that such conditions deteriorate rapidly with the deepening of the casing in the pervious layer.

Approximate calculations show satisfactory quantitative agreement with the observed facts.

### Relation between steam production and thermal circulation of water

Having established the existence of evaporation space capable of supplying geothermic steam ideally differentiated, it is possible to pin-point some significant orders of magnitude to evaluate geological conditions for the existence of a geothermic field.

Water as commonly found in known geothermic fields can supply about 10 per cent of its own mass in steam at point M, figure 3. This will also be the order of the highest ratio between the mass of produced steam and the output of corresponding underground thermal streams.

From the simultaneous conditions imposed for the general average output of thermal streams $(TS)$ and for the output of geothermic steam $(GS)$, it follows that :

$$\Delta T\ (TS) = \Phi$$
$$600\ (GS) < \Phi$$

when $\Delta T$ is of the order of the thermal difference in the pervious layer, and $\Phi$ is the regional geothermal flow. The required ratio is

$$\frac{(GS)}{(TS)} < \frac{\Delta T}{600}$$

Since an average thermal difference in the pervious state of more than 60° is rather high in relation to the geothermal flow actually observed, the conditions necessary for geothermal steam to be generated from evaporation of layer water are largely satisfied. It would be comparatively easy to establish the relationship between the production by units of area of the field, and the permeability of the productive layer, when the link between the geothermal flow, the permeability, and the average output of thermal streams is known.

### General operative consequences

The mass of steam which can be generated by the mass unit of water increases with the thermal content of water and with the temperature. Consequently it increases, in ideal geological conditions, with the depth of the productive layer.

At deeper levels than the ones mentioned in which water attains its critical point, a similar increase in thermal content cannot be expected.

As all other conditions became still less favourable, a convenient limit for the maximum depth of the top of the pervious productive layer, i.e., of the wells, can easily be foreseen.

## The problem of the origin of geothermal fluid

First, the importance of this problem for prospecting geothermal fields must be emphasized.

Water in magmatic conditions has a thermal content which does not exceed 1 000 kcal/kg; saturated vapour contains less than 700; deep water at the boiling point little less than 300 kcal/kg.

The magmatic volatile cannot bring about evaporation of exogenous water at the boiling point, not even for one-half of its own weight. In other terms, juvenile steam cannot contain more than one-third of evaporated exogenous water. Therefore if it is not proven that the substance constituting known geothermal fluids is a magmatic volatile, it cannot be maintained that in these cases heat might be carried by the magmatic volatile.

Research likewise cannot be restricted to the outlets of the original reservoir (steam-bearing faults).

Even exogenous water brought to the boiling point through direct mixing with magmatic volatile should contain one-quarter of its own mass. If the presence of a fraction of magmatic fluid of such moment cannot be proven, a substantial fraction of geothermal energy must be transferred through thermal water streams. In this case methods of research in agreement with the preceding geological outline should be followed.

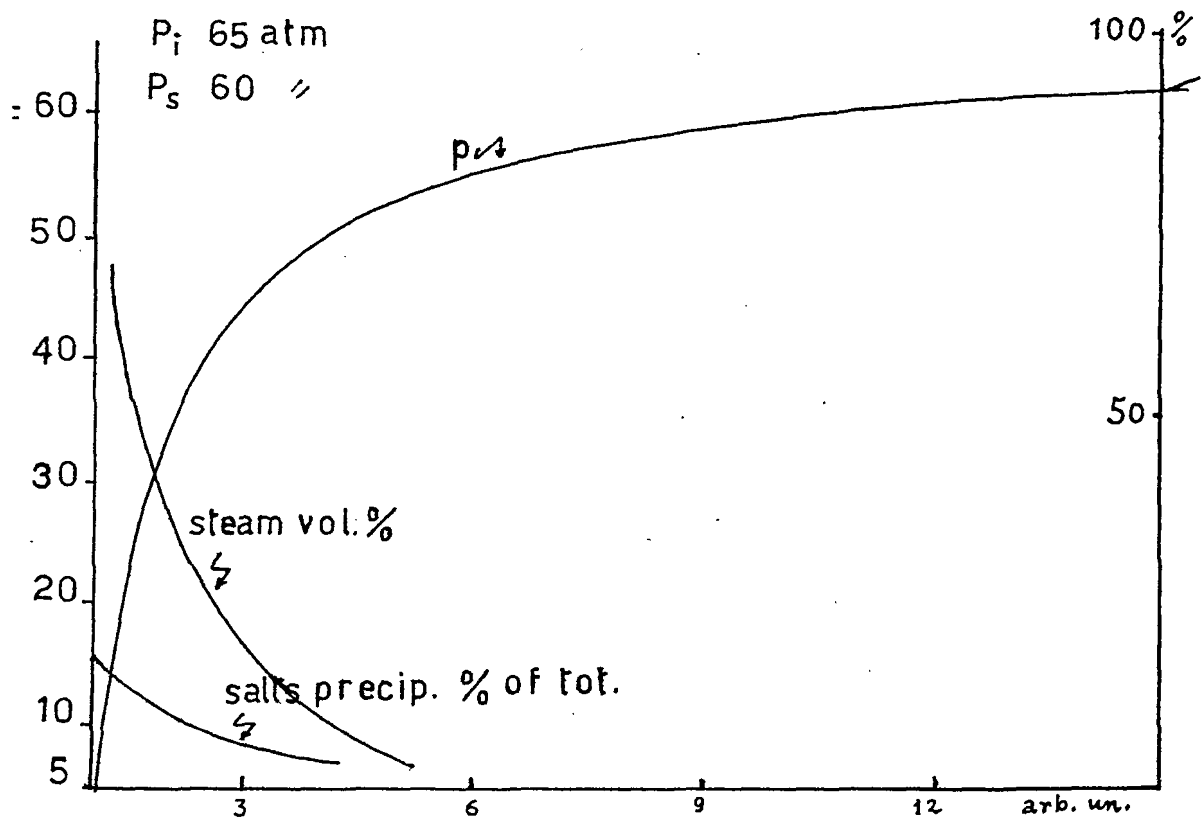


**Figure 5**

Besides difficulties arising from a geochemical probe of the magmatic origin of many volcanic emanations, that referring to known geothermal fields rests on non-existent evidence. The composition of known industrial geothermal fluids is suggestive in various cases of an origin from exogenous waters, waters circulating in sedimentary rocks, brackish waters, and so on. These considerations can be applied to gaseous constituents, such as methane and nitrogen, especially with respect to atmospheric argon, and radiogenic argon, helion, and radon.

Goldschmidt had already questioned the magmatic origin of boric acid; e.g., at Larderello the geothermal fluid originates from marine formations.

According to geochemical data, the fluorine of the emanations must have metamorphic origin; the geochemical distribution of mercury and arsenic also suggests that their presence in volatiles may be a clue to the heating of sediments enriched with these elements.

### Steam exploration

Nearly all steam geologists state that the steam fields are closely associated with a faulting system. This conclusion is derived from the opinion that a part of, or all, the steam is juvenile, i.e., of a direct magmatic origin. The faulting should assure a path for the magmatic steam. Some geologists also think that a close relation links the steam quantity to the size of the magmatic steam conduit.

Since we do not think that the juvenile gas or steam reaches the productive aquifer, we cannot agree with the reported hypothesis. Notwithstanding this, the importance of faulting can not be denied, because (*a*) the faulting generates secondary permeability in rigid rocks, particularly in carbonate rocks, and (*b*) the faulting can provide a suitable trap.

The geological and geothermal knowledge of the steam field furnishes rational help in exploration. The hypothesis may be applied to exploratory surveying.

A satisfactory answer must be provided to three main questions:

(i) In what region can we expect to find a source of heat, i.e., a relatively shallow magmatic mass?

(ii) How can we detect a trap for the convection currents?

(iii) In a given prospect, is the water supply sufficient for industrial production of steam?

#### (*i*) *The first question*

Three types of steam field were classified: the fields linked to a shallow plutonic mass; the fields linked to living volcanoes; the fields linked to recently extinct volcanoes.

No difficulties arise in identifying the areas where active or extinct volcanoes are situated. But it is perhaps useful to add a few words about the age of the extinct volcanoes. All the so-called extinct volcanoes that still present some signs of post-volcanic activity are prospectable; without such signs all Quaternary and Pliocenic volcanoes must be considered prospectable. There is no basis for a rational statement about pre-Pliocenic volcanoes. If there is evidence of actual thermal activity, they deserve further study.

Since plutonism can follow volcanism, especially when severe post-volcanic faulting is known, the age of the extinct volcano is not the only item to be considered : the age of faulting is also important because it is almost certain that post-volcanic plutonism is closely connected with distension faults.

A volcano can provide the source of heat but, as we have already stated, this condition is necessary but not sufficient. We must also detect what we called a trap for the convection currents. A volcanic series can certainly provide such a trap — Wairakei field is an example — but it is more likely that the trap or traps can be detected in a sedimentary series pierced by a volcano. In this case, the sub-surface geological sequence, with its pervious and impervious layers, can be better recognized and forecast. The geological and geophysical data are surer and more valuable; thus the choice of a rational location for the exploratory well is not so difficult. In a series that is entirely volcanic, the pervious and impervious strata can be detected only by drilling, and information will not be available about the lateral extent of the different facies.

To sum up : volcanic areas are favourable for steam exploration; recently extinct volcanoes are also good prospects. A volcano that opened its vent through a sedimentary series (like Vesuvio and Etna) at drillable depth is a better prospect than a volcano entirely made up of volcanic rocks.

*Plutonic masses*

A body of rocks recently intruded at a relatively shallow depth can supply a great quantity of heat during the slow cooling process. If the geological structure and nature of the overlying rocks are favourable, a steam field may actually exist. The Larderello field is of this kind.

Marinelli has presented a paper [1] especially devoted to granitic plutons, and thus long discussion of this topic is unnecessary. Some brief observations related to exploration will suffice.

Any kind of pluton, provided that it is at a relatively shallow depth, can be the heat source for a steam field; the basic plutons also supply heat. For instance, an intrusion similar to the gabbro intrusion of the Skaergaard peninsula in eastern Greenland or the Bushweld complex can be a convenient intrusive body if buried in a suitable country rock and cooling at present, i.e., of recent plutonism.

The intrusive granitic masses of relatively small size (dikes, ring dikes, laccoliths), classified by Rastall in his third group of granitic bodies, and in the process of cooling at shallow depth, are the granitic plutons and are more likely to be the heat source.

The close relationship between granitic plutonism and volcanism induces consideration of the volcanic areas as prospectable also for the Larderello type of steam field. The volcanic trend is also a plutonic trend.

A sedimentary blanket over a hot pluton is favourable, for the reasons mentioned above.

The metallogenic volcanism (hydro-, hypo-, meso-thermal metallogenesis not directly related to the surface volcanism of the volcanic region) is clearly related to the plutons. The areas of metallogenic volcanism are prospectable for steam.

Gravimetric survey is a useful aid in detecting a granitic pluton, but interpretation is difficult. Knowledge of this matter is only elementary.

Surface thermal activity gives a regional indication, not a drilling location.

Geochemistry is a valuable tool for careful study of thermal activity. For example, the high geochemical mobility of mercury and its reactions to abnormal heat apparently can provide very useful information about the geothermal activity.

Radiometric survey, which is so closely related to geochemistry, warrants field tests in steam exploration. Knowledge of steam exploration is inadequate and at present thermal activity must be considered necessary for an exploration prospect.

*(ii) The second question*

Volcanic and thermal activity are regional indications; the first step of an exploration programme ends with the choice of the area. The second step is the choice of a drilling location. We must detect a trap for the convection geothermal current, and drill on the top.

Field practices are very similar to those of oil exploration: systematic geological surveys, including airphoto geology, volcanology and volcanotectonics, morphology, etc. Furthermore, geophysical surveying must be systematic, including gravimetry, airborne and field magnetometry, refraction and reflection seismology. So far as geochemistry is involved, we have already pointed to its usefulness, but it is in an experimental phase.

*(iii) The third question*

A commercial steam field produces water in noticeable quantity. Larderello field produces some 10 million tons per year.

A hydrogeologic survey is needed as part of the exploratory work. In fact, the supply of water can be the limiting factor in production.

[1] Marinelli, G. Thermal anomalies and geothermal fields related to recent plutonism in Tuscany, *Proceedings of the United Nations Conference on New Sources of Energy*, 1961; paper G 58, below, includes a summary in English of the French original.

### *Summary*

A geothermal industrial field is defined as a field capable of producing about 5 million tons of steam per year. It requires (*a*) a source of heat, (*b*) a way of transferring the heat, (*c*) ways of accumulating the heat and the supply of water.

In the earth's crust only magmatic masses can be a source of heat having an adequate output. Three possible cases may be differentiated : (*a*) shallow intrusion (e.g., Larderello, Tuscany), (*b*) volcano-pluton (e.g., Mount Amiata, Tuscany), (*c*) volcanism in the strict sense (e.g., Wairakei, New Zealand). These situations afford regional clues for steam exploration. Active or recent volcanoes (younger than the Pliocene) are conclusive indications for profitable exploration. In other cases, thermal phenomena must be accepted as the most promising clues.

In known geothermal fields, the most probable mechanism of heat transfer is the convection of exogenous hot water rather than the flow of magmatic volatile. The hypothesis of direct heat transfer by means of magmatic volatile is not confirmed from the geochemical point of view. From a thermodynamical point of view, it is unnecessary. Consequently more general cases are to be taken into consideration.

The presence of an impervious cap rock is a necessary condition to the existence of a geothermal field. Only this impervious cap rock is capable of heat accumulation in the lower aquifer layer. The term "impervious" here means "very little pervious in respect of possibilities of thermal convection".

Overheated steam produced in known geothermal fields can very well proceed from the evaporation of water from the productive layer. The water must be at a temperature quite close to the boiling point at the hydraulic pressure of the casing. Such a condition is necessary for evaporation to take place in a large space in the rock around the casing: (*a*) for the separation of steam from water and (*b*) for minimizing scale formation.

It is important to have very pervious rocks in a productive aquifer layer not only because this causes a high flow in each steam well, but also because a very pervious rock (*a*) extends evaporation space, (*b*) makes possible the convection of heat between the top and the bottom of the pervious layer and (*c*) permits the required circulation of water in excess of the mass of generated steam.

Such considerations afford useful guidance for the exploration and exploitation of geothermal fields.


## GÉOLOGIE ET GÉOCHIMIE DES CHAMPS GÉOTHERMIQUES


### *Résumé*

On définit le champ géothermique industriel comme étant un champ capable de fournir annuellement une quantité de l'ordre de 5 millions de tonnes de vapeur. Cela exige : *a*) une source de chaleur; *b*) un moyen pour transmettre cette chaleur; *c*) des moyens de l'accumuler et d'assurer l'alimentation en eau.

Dans la croûte terrestre, les seules sources de chaleur d'une importance suffisante sont constituées par des masses magmatiques. On peut distinguer trois cas :

*a*) Intrusions superficielles (par exemple Larderello, en Italie);

*b*) Volcano-plutonisme (par exemple le mont Amiata, en Italie);

*c*) Volcanisme au sens strict du terme (par exemple Wairakei, en Nouvelle-Zélande).

De telles situations présentent des indications précieuses à la prospection, sur le plan régional. Les volcans actifs ou récemment actifs (postérieurs au pliocène) indiquent par leur existence que l'exploration peut être profitable. Dans les autres cas, il faudra accepter les manifestations thermales comme principaux indices.

Dans les champs géothermiques connus, la convection par des eaux souterraines exogènes semble constituer le mécanisme de transmission de chaleur le plus probable, plutôt que la convection directe par un flux magmatique volatil. En tout état de cause, l'hypothèse de la transmission directe de chaleur par un fluide volatil magmatique n'est pas prouvée, du point de vue géochimique. Elle n'est pas même nécessaire du point de vue thermodynamique. On doit donc prendre en considération des possibilités plus générales.

Il semble indispensable, pour l'existence d'un champ géothermique, d'avoir une couverture imperméable (c'est-à-dire peu perméable à l'échelle des phénomènes de transmission de chaleur par convection qui nous intéressent). Une telle couverture peut seule assurer l'accumulation de la chaleur dans des assises perméables — notamment des masses aquifères situées au-dessous de ladite couche imperméable.

La vapeur surchauffée des champs géothermiques connus peut fort bien prendre naissance en raison de l'évaporation de l'eau contenue dans les horizons productifs. L'eau devra se trouver à une température très voisine de la température d'ébullition à la

pression hydraulique correspondant à la profondeur du tubage. Cette condition est nécessaire pour assurer l'évaporation dans une zone assez large de la roche tout autour du tube : afin d'obtenir la séparation de la vapeur à partir de l'eau; et pour réduire au minimum le processus d'incrustation.

La perméabilité des roches des couches productrices joue un très grand rôle, non seulement parce qu'elle détermine un flux important de vapeur dans chaque forage, mais aussi parce que cette perméabilité :

*a*) Augmente la zone d'évaporation;

*b*) Assure la transmission de la chaleur par convection de la partie inférieure de la couche perméable à sa partie supérieure (qui est l'endroit le plus favorable pour l'exploitation);

*c*) Permet la circulation indispensable d'eau en excès de la masse de vapeur produite.

De telles considérations nous offrent des critères précieux pour la prospection et l'exploitation des champs géothermiques.

# PRELIMINARY INVESTIGATION OF THE RABAUL GEOTHERMAL AREA FOR THE PRODUCTION OF ELECTRIC POWER

*A. C. L. Fooks**

Rabaul, in New Britain, is served by diesel generators for electric power. The Australian Commonwealth Department of Works had investigated the possibilities of a hydroelectric power scheme to satisfy the growing need for additional and cheaper power as the area developed. This was found possible, but comparatively expensive.

Volcanic activity exists near the town, and the Department of Works decided to investigate the possible utilisation of geothermal steam for electric power generation.

The author, accompanied by a geophysicist from the New Zealand Department of Scientific and Industrial Research (DSIR), visited the area with the Chief Investigation Engineer of the Australian Commonwealth Department of Works and made a preliminary investigation of the area.

Since the Commonwealth Department of Works maintains an office at Rabaul and a government volcanologist is stationed there, the following information which was available was used in the survey: (*a*) aerial photographs and topographical maps of the area; (*b*) records of shallow water bores drilled in the township area and near Rapindik (see figure 1); (*c*) temperature measurements made in hot springs near low-tide mark and in the area between Rabalankaia and Matupi Volcano (Tavurvur); (*d*) local knowledge of the geology of the area; (*e*) a survey of the area prepared by G. N. Fisher, Chief Geologist of the Australian Bureau of Mineral Resources, and his report; (*f*) local knowledge of construction facilities and transportation costs.

Matupi volcano erupted in 1937 and was active in 1942. During the earlier eruption a new crater, Baluan, was formed on the western side of Blanche Bay. Figure 1 shows the area of Blanche Bay and Rabaul, and figure 2 is an enlarged scale drawing of the area finally selected for further investigations.

The power requirements were defined as being 5 megawatts within eight years, with an ultimate total of 20 MW, which could be developed in 5 MW steps. Geothermal sources appear well suited to this type of development.

## Description of the area

Rabaul township lies at the northern end of Simpson Harbour and Blanche Bay; the latter has been formed by caldera collapse of an ancient large volcano. The land tongues to the north, east and south-east are comparatively narrow and appear to consist mainly of the volcanic cones, north daughter, mother, and south daughter, all outside the caldera wall, antedating the caldera collapse and not now active. Within the caldera are Rabaul town, the very recent volcanos of Matupi (or Tavurvur) on the east and Vulcan on the west of the harbour. Rabalanakaia, the crater halfway between Rabaul town and Matupi volcano, lies athwart the caldera wall and is also of recent origin. It is thought to have been active later than the caldera collapse, but there is no historical record of its eruption.

Matupi and Vulcan volcanos erupted in 1878 and 1937. There was a further eruption of Matupi volcano in 1941-1942. Distinctive and noticeable inclined lava flows are visible from the rim of Rabalanakaia flowing west and south towards the sea. Basaltic (?) rocks are visible in the caldera wall and on the slopes of Matupi.

If Rabalanakaia was active after the caldera collapse, there is some possibility of lava flow sheets occurring below sea level and forming a layer of cap rock, which could impede the upward flow of hot water and divert it seawards.

## General observations

General observations of the area east and west of Simpson Harbour and Blanche Bay were made, even though the most promising area appeared (as suggested by Fisher) to be that between Rapindik and the slopes of Matupi volcano.

In contra-distinction to the Wairakei area in New Zealand, the heat flows, other than the warm springs at Sulphur Creek, appeared to be intimately associated with the volcanoes Matupi and Vulcan, and from Rabalanakaia crater and the eastern caldera wall. There were no bubbling mud pots in any part of the area, and no activity was seen outside the caldera rim. The only visible steam escape was in the actual crater of Matupi volcano and on a line running almost due south from Rabalanakaia (the crater of Palagiagia). There were obvious seaward flows of fairly hot water into Greet Harbour, apparently originating from Rabalanakaia and particularly Matupi volcano. None of these hot water flows occurred above high-tide level, but by observation of the discolouration of the sea when viewed from the top of Matupi volcano, and as seen on the

* Project Engineer, Ministry of Works, New Zealand.

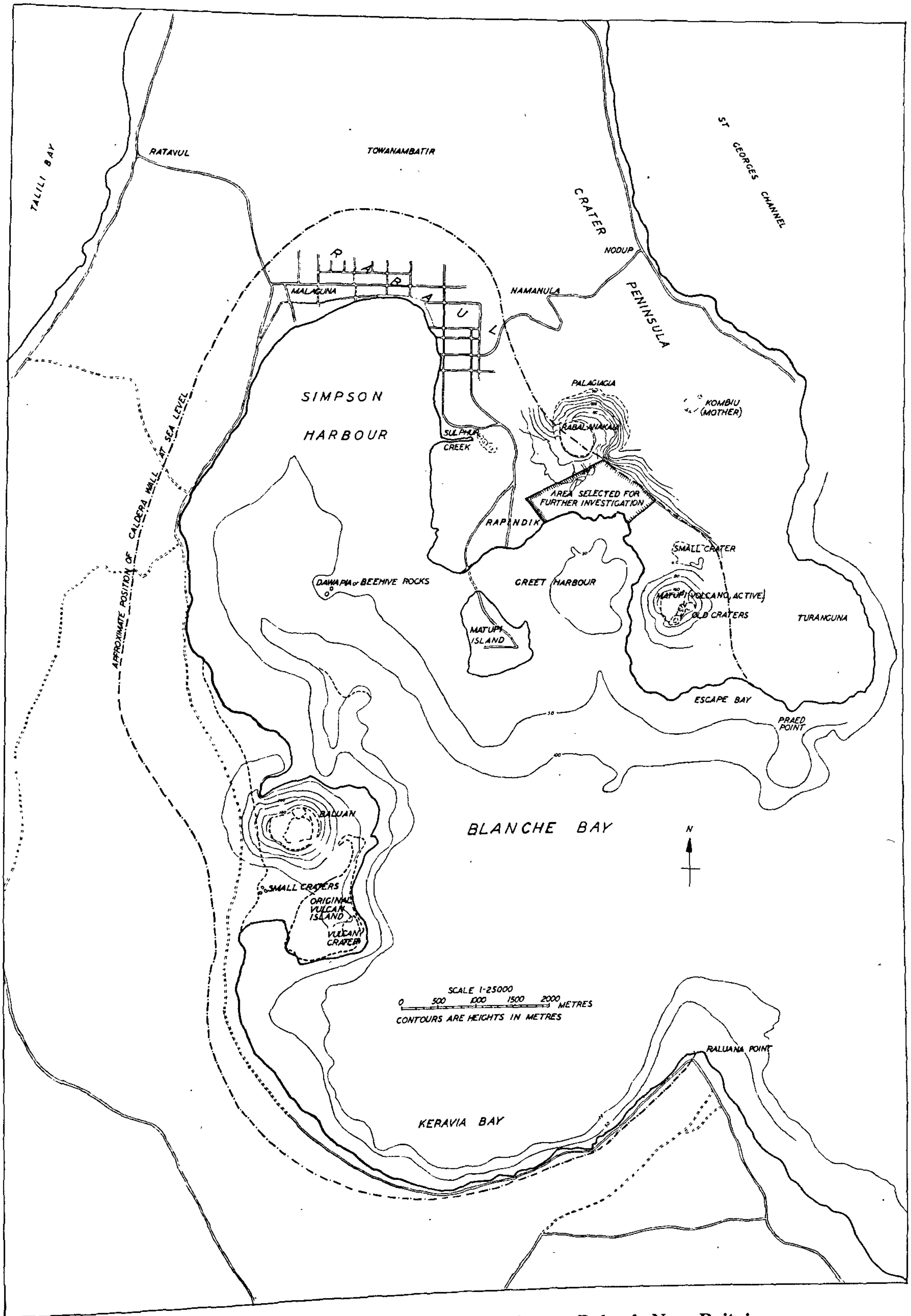


Figure 1. Geothermal steam investigation at Rabaul, New Britain

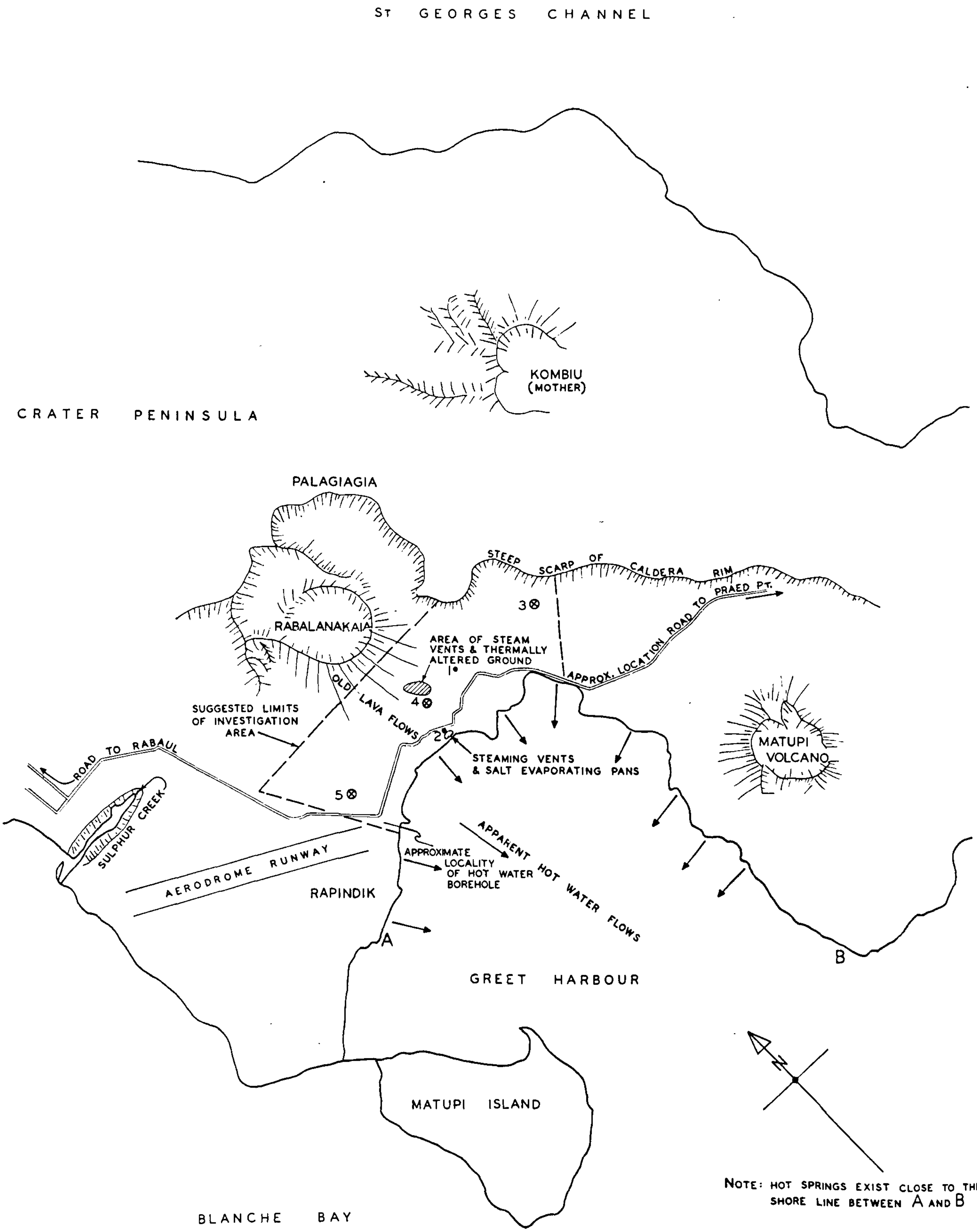


**Figure 2. Geothermal steam investigation at Rabaul, New Britain**

*Map of general area of possible investigations* aerial photographs, the quantity flowing could have been considerable. If this was so, it seemed difficult to account for the origin of the water. The rainfall of the area is of the order of 100 inches per year. Crater Peninsula, south-east of Rabaul township, has an area of only about six square miles, and less than a third of the water is likely to flow westwards into Greet Harbour. This could not account for a flow of more than 5 to 10 cusecs into Greet Harbour.

The bores drilled for water near Rabaul township indicated only normal surface water, with no evidence of the chloride content usually associated with hot spring areas.

The heat associated with Vulcan volcano is small, the area is some six miles from the main township of Rabaul, and Fisher has expressed the opinion that Vulcan is more likely to erupt than Matupi. Further, there is no evidence of lava flows in the vicinity which could form a confining cap rock comparatively near the surface, and the ejecta have been almost exclusively pumice.

Sulphur Creek area shows only minor warm springs, of small flow and no great heat content. No information was obtainable as to whether there was an appreciable seawards flow from this creek, which is thought to be an old explosion chasm of limited activity; nor was any evidence available as to whether there were submarine hot water flows at the bottom of this elongated crater. Even if there is more heat flow than was evident (the only spring seen had a temperature of less than 50°C and a flow of less than 5 gallons per minute) the area must be considered too close to the township for steam production, in an area where the bores may be difficult to control during drilling.

Matupi volcano is steep-sided, and little or no flat or gently sloping land exists between its foot and the sea. It would be very difficult to drill bores in this area; also probably hazardous in the broken basalts and pumice ground.

The only area therefore that appeared to be worth further consideration was the wide fan stretching from Rabalanakaia towards Rapindik in the south-west and to a point approximately half-way between Rabalanakaia and Matupi volcano in the south-east.

This appeared worth further investigation since (*a*) a drill hole near Rapindik had encountered hot water; (*b*) another drill hole farther east formerly discharged hot water, but later the flow ceased after an earth tremor; (*c*) lightly steaming ground areas and some gas vents exist southwards from Rabalanakaia; (*d*) a number of hot water springs exist along the shore edges (but below low-tide level) in this area; (*e*) steam vents some thirty feet above sea level are sufficiently active to have been used for evaporating sea water.

## Additional observations of the selected area

Although no major confining structures are known to exist in the rock formations, it is possible that sufficient steam could be obtained at usable pressures even though high-pressure steam is unlikely at reasonable depths.

As mentioned, lava flows slope downwards south from Rabalanakaia. These appear to be in numerous sheets, and if a fairly continuous sheet occurs below sea level, it could form a confining cap rock. The surface layers are compacted muds and pumice, and these themselves could form a weak confining structure. The area is covered with the heavy kunai grass of the locality, and observation of the extent of the steaming ground is difficult.

Steaming ground is not very noticeable in the climate of New Britain, but in only two places was typically heat-altered ground seen, viz., at the salt processing area beside the coast and at a point near the steaming ground about a quarter of a mile due north (inland and towards Rabalanakaia).

The former consisted of some half-dozen lightly steaming vents over an area approximately 200 feet square. The latter area consisted of two areas of steaming ground each about 20′ × 30′, together with an area of heat-altered ground about three times this size and not visibly steaming.

Stunted scrub, as is usually associated with hot ground in New Zealand, was not seen, but the vegetation of New Britain may be more resistant to hot conditions underfoot.

By New Zealand standards in considering areas that have been surveyed for geothermal steam investigation or exploitation, the natural heat flow in Rabaul was insignificant. Were it not for the hot springs at sea level and the apparent submarine discharge of sediments, the area would not be considered worth further investigation.

The areas of visible heat flow were only 50 to 100 feet above sea level so that, unless the pumice or compacted mud provides more than a cap than is apparent, steam cannot exist near the surface at any great pressure in this area, i.e., it should be reasonably safe for very shallow drilling operations —say to 100 feet or so.

The pumice mud cover is presumed to be the ejecta of the 1937 eruption, and if there was a diminution of the visible steaming ground after this eruption, it could indicate that the compacted mud did form a seal to the flow of very low pressure steam, which now escapes seaward. No firm evidence of this reduction was obtainable.

Areas nearer the caldera wall north and north-east of the steaming ground were not readily accessible, and were not explored. The ground did not appear excessively rough, however, for access roads for drilling equipment.

The analyses of both Bore 9 and the previous hot water bore in the Rapindik area indicate a high content of dissolved solids, and further attention should be given to this (should an investigation prove fruitful) before any decision is made to proceed with power development.

In both cases the sodium chloride content of the waters approached that of sea water. This may indicate that the hot water flows near sea level are merely the result of a convective flow of sea water through a zone of strongly faulted hot rocks. This is more likely since the sea floor dips steeply from the shoreline; the 150′-below-sea-level contour is only 600 feet from the shore at one point; and Blanche Bay is well over 300 feet deep.

The natural springs all appear below high-tide mark and mainly between the eastern end of the aerodrome and the slopes of Matupi volcano (see figure 2). They vary in temperature from 40° to 98°C, but these temperatures were obtained by dipping a thermometer into the sea where the flow appears strongest. It is from these hot spring areas that the discolouration spreads seawards, being traceable on the air photos and from Matupi volcano more than two miles from the shoreline. Whilst no quantitative figures were obtained, this must represent a considerable flow or circulation of hot water.

The area likely to be worth investigation measures about one-half mile north-south by one mile east-west. In summing up the information obtained to this stage, the following conclusions were reached:

(*a*) The area near Baluan-Vulcan was unsuitable.

(*b*) The area near Sulphur Creek was unsuitable.

(*c*) The slopes of Matupi volcano were hazardous and unsuitable.

(*d*) The Rapindik-Rabalanakaia area had a small heat escape, and was unlikely to produce high-pressure steam, but if the lava flows were suitably formed there was a possibility of obtaining low-pressure steam.

Although the natural heat escape was small, experience has not shown that this can be related quantitatively to the heat that can be obtained by drilling. The total power required is small and is equal to the power available from only four bores at Wairakei, New Zealand, even at the 20 MW stage.

## Further investigations

In considering the likely costs of a more detailed investigation, it appeared that if steam were obtained the savings that could be made, compared with the cost of the hydroelectric station, justified further investigation of the Rapindik-Rabalanakaia-Matupi volcano area.

Further investigation was therefore recommended, and was considered capable of division into two phases; the second phase might not be justified unless the first phase showed that reasonable heat flows existed.

The two phases of investigation would consist, first, of measurements of existing physical conditions and of natural heat flows; and, second, of drilling to determine subterranean conditions of geology, temperatures and pressures.

The following measurements were considered desirable during the first phase.

(*a*) A surface temperature survey to define the area of hot ground. This could be either qualitative or quantitative: (i) a qualitative survey would consist of a thorough walk-over survey of the selected area and mapping of ground that was warm to the touch, (ii) a survey, made by taking temperatures at three-foot depth, along not too widely spaced traverse lines, and then more detailed temperatures in the areas found to be above normal temperature, would provide quantitative information for early and for future reference. This survey might reveal lines of heat escape that could be correlated with lava flow directions or faulting parallel or normal to the caldera wall. If the field were later exploited, the survey information would provide a valuable record if natural changes or exploitation caused warm ground to become hotter. A periodic check of hot ground conditions during exploitation of a geothermal field is considered essential, since changes do occur, and preventive work is sometimes required to prevent eruptions.

(*b*) A better defined and more closely controlled temperature survey of the hot springs along the coastline, and more particularly seawards at surface and at several depths to sea bottom, should give an indication of the type of heat flow, i.e., circulating seawater or seawards flow from the land, and the magnitude of the heat flows and quantities involved. If some current flow meter readings were made of the flow from the hot springs, a more quantitative assessment of the quantity of flowing water could be made. Flow rates at high and low tide conditions would be needed.

(*c*) Two bores should be sunk to hot ground water, but not deeper than sea level, in a line from the salt-producing area to the caldera wall. The chemical analyses should give an indication of the flow system. This would not necessarily be the chemistry of deep drill holes, but would serve to determine the heat flow system. The holes could be drilled cheaply and safely without blowout-preventer equipment. Drive casing would be used, and the bores cased to within a few feet of bottom. They should not be continued through an impermeable rock or more than, say, 10 feet into the hot water table. A 4″ or 6″ finished diameter would be satisfactory for chemical sampling and temperature measurement by maximum thermometer. Tentative positions are indicated at 1 and 2 on figure 2.

(*d*) Seismic surveys were not thought likely to be useful in the small area under consideration, particularly in view of the probably heterogeneous nature of the underlying strata.

Six months should be sufficient time for this survey, depending on the staff available. The cost should be less than £10,000. If this survey showed that the heatflow in the system was of the order of 1 000 million Btu per hour (relative to 32°F), it would indicate that the system was worth investigating for a 20 MW power scheme.

Provided the first phase indicated a heat flow of suitable size, it was recommended that the second phase should consist of drilling four bores. These would be programmed for drilling to approximately 2 000 feet depth. Deeper drilling was not thought to be economical for power production in a scheme which proposed to deliver only 5 megawatts in its initial stage and only 20 megawatts in total.

Consideration was given to the type of drilling equipment which should be used for the second phase of the investigations, if this were undertaken.

Small drills of the diamond drill type are light and easily transported. They have the disadvantage that their associated pumping equipment is of small capacity and generally inadequate if hot conditions are met in difficult drilling country. The drill pipe is generally too small to allow adequate flows of drilling fluid for cooling purposes. Core recovery (for geological examination) is frequently poor in broken country. The drills can handle only small diameter casing to the desired depths. Small diameter bores could not later be used for production purposes.

It was concluded that, despite the additional cost, it would be safer to use heavier drilling equipment which would place and adequately cement 7″ or 8″ diameter casings to 1 500 feet or so in depth. These bores, if productive and with properly cemented casings, could later be used to supply a power house. A drilling rig of about 120 hp motor rating with a draw-works capacity of 120 000 pounds, using 12″ × 7 ¼″ pumps, is a desirable size for this work. Lighter drills can be used, but the work is more hazardous and the bores are generally not large enough for production purposes.

It was proposed that four holes should be drilled; three to be approximately in the positions marked 3, 4 and 5, on figure 2, and the fourth to be determined after the first three are drilled. The actual location of the first three bores would be influenced by the position and alignment of zones of hot ground found in the first phase of the detailed investigations.

If a usable steam discharge was obtained from any of these bores, measurements of the possible discharge characteristics and the chemistry of the flow would be necessary; these should include the quantity and type of gases in the steam fraction and dissolved materials in the water fraction.

The possible cost of investigation drilling would be of the order of £200 000.

If the results from the above were satisfactory, the final drilling to prove the capability of the field to produce 20 megawatts of power could proceed. These latter bores should be discharged for at least one year at the pressures and with the necessary draw off envisaged at the final stage of power production.

During this period there should be continuing checks of downhole pressures and temperatures and of any change in the discharge at the well heads. The latter should include the quantities of steam and water and their chemical composition.

## Acknowledgement

The author acknowledges with thanks the permission of the Director-General of the Australian Commonwealth Department of Works to utilise the information obtained during the survey and to publish this paper.

### *Summary*

The Australian Commonwealth Department of Works wished to assess the possibilities of producing electrical power from geothermal steam at Rabaul in New Britain. A hydroelectric scheme was possible but was expensive, particularly in the early stages of power demand. The power requirements were estimated at 5 megawatts within eight years, and the scheme was expected to be capable of ultimate development to 20 megawatts.

The author, assisted by a New Zealand geophysicist and scientists and engineers of the Australian Government, made a preliminary survey of the possibility of obtaining usable steam, and made recommendations along which the lines of more detailed investigations could proceed.

Rabaul stands at the head of a bay formed by the caldera collapse of an ancient volcano. A semi-active volcano lies within four miles of the town. Between the town and the volcano are older craters and vents. Some steaming ground exists, and hot springs occur at sea level.

Areas west of the harbour, close to the town and on the slopes of the volcano, were eliminated as unsuitable. The area selected for more detailed inspection is shown on figures 1 and 2.

The areas of steaming ground were small, and the natural heat escape was much less than that of areas selected as worthy of investigation in New Zealand. The hot springs at sea level are monitored for temperature changes by the resident volcanologist and his staff, and show temperatures up to 98°C. They also appear to discharge seawards appreciable quantities of solid matter into Blanche Bay (figure 1).

No structural cap rocks were known to exist, but it seemed possible that the lava flows from Rabalanakaia could have formed confining beds.

The quantity of natural heat escape is not thought to be a quantitative measure of the amount of heat that can be obtained by deep drilling. It appeared that there was appreciable heat flow (possibly in a seawater convective system) associated with the hot sea springs. Hot water had been found

in two bores sunk near Rapindik; one of three had discharged hot water.

It was concluded that further detailed investigation was justified in the selected area and that this should be divided into two phases.

The first phase would consist of a ground temperature survey (to attempt to locate lines or zones of heat escape at the surface) and also measurements of the flow and contained heat of the discharges from the hot springs; current flow readings in the sea should be made if possible, to define the extent of the seawater circulating system if this did in fact exist.

Provided a heat flow of the order of 1 000 million Btu per hour was disclosed, a second phase of investigation could be instituted. This would consist of three or four drill holes to about 2 000 feet depth, as marked by 3, 4, 5 inside the selected area of figure 2. Temperature and pressure measuring and chemical analyses were recommended; and continuing measurements should be made of the discharges if satisfactory boreholes are obtained.

It was estimated that the cost of the initial stage of investigation would be under £10 000, and that of the second phase would be of the order of £200 000.

## RECHERCHES PRÉLIMINAIRES SUR LE CHAMP GÉOTHERMIQUE DE RABAUL EN VUE DE LA PRODUCTION D'ÉNERGIE ÉLECTRIQUE

### *Résumé*


Le Ministère des travaux publics du Commonwealth australien souhaitait évaluer les possibilités de production d'énergie électrique par vapeur géothermique à Rabaul, en Nouvelle-Bretagne. La réalisation d'un système hydro-électrique était possible mais s'annonçait coûteuse, particulièrement au départ. On prévoyait que les exigences énergétiques atteindraient 5 mégawatts dans les huit ans, et l'on estimait que le système envisagé pourrait éventuellement produire jusqu'à 20 mégawatts.

Avec l'aide d'un géophysicien néo-zélandais, de techniciens et d'ingénieurs du gouvernement australien, l'auteur a procédé à des recherches préliminaires sur la possibilité d'obtenir de la vapeur utilisable et a formulé des recommandations destinées à orienter des recherches plus détaillées.

Rabaul est au fond d'une baie constituée par un effondrement en caldeira d'un ancien volcan. Un volcan en demi-activité se trouve à environ 6 kilomètres de la ville. Entre celle-ci et le volcan, on trouve des cratères plus anciens, ainsi que des évents. Il existe des dégagements de vapeur et, au niveau de la mer, des sources chaudes.

Les régions situées à l'ouest du port, près de la ville et sur les pentes du volcan, n'étant pas appropriées, ont été exclues des travaux envisagés. La région choisie aux fins d'une inspection plus détaillée est indiquée aux figures 1 et 2.

Les régions où le terrain dégage de la vapeur sont restreintes et le débit de chaleur naturelle bien inférieur à celui des régions choisies en Nouvelle-Zélande comme méritant de faire l'objet de recherches. Les variations de température des sources chaudes situées au niveau de la mer sont vérifiées par le volcanologiste résidant sur place et son personnel. Cette température peut atteindre 98 °C. Ces sources semblent également décharger des quantités appréciables de matières solides, dans la Baie Blanche (fig. 1).

On n'a pas connaissance de roches de recouvrement structurel, mais il semble possible que les écoulements de lave de Rabalanakaïa aient pu former des masses encaissantes.

Le débit de chaleur naturelle ne paraît pas constituer une mesure quantitative de la chaleur qu'on pourrait obtenir par des forages profonds. Il semble qu'il y ait un débit appréciable de chaleur (peut-être dans un système de convection intéressant l'eau de mer) en liaison avec les sources chaudes sous-marines. On a trouvé de l'eau chaude dans deux puits foncés près de Rapindik. L'un d'eux a débité de l'eau chaude.

On en a conclu que des recherches détaillées supplémentaires seraient justifiées dans la région choisie et qu'il conviendrait de les diviser en deux phases.

La première phase serait constituée par des recherches sur les températures du terrain (visant à établir les lignes ou zones d'écoulement de chaleur vers la surface), ainsi que des mesures du débit et de la chaleur accumulée par les décharges de sources chaudes. On devra procéder, dans toute la mesure du possible, à des lectures sous-marines du débit du courant, pour définir l'importance du système de circulation d'eau de mer, en admettant qu'il y en ait un.

En supposant que l'on mette ainsi en évidence un débit de chaleur de l'ordre de 1 000 millions de BTU à l'heure, on pourrait passer à la deuxième phase des recherches. Celle-ci serait constituée par le fonçage de trois ou quatre puits jusqu'à 2 000 pieds de profondeur environ (600 m) dans la région choisie, aux emplacements indiqués par les chiffres 3, 4 et 5 (fig. 2). Des mesures de la température et de la pression sont recommandées, ainsi que des analyses chimiques. Si on obtient des puits satisfaisants, on devra continuer lesdites mesures.

Le coût du premier stade de recherches a été évalué à moins de 10 000 livres, et le prix de la seconde phase serait de l'ordre de 200 000 livres.

# GEOLOGY OF NEW ZEALAND GEOTHERMAL STEAM FIELDS

*G. W. Grindley**

## Wairakei steam field

### Stratigraphy

The stratigraphy of the Wairakei Steam Field has been outlined in a marginal text accompanying a geological map of the Taupo Sheet District, within which the steam field is situated (Grindley, 1960). A more detailed description is given in a geological bulletin describing the geology and structure of the Wairakei Steam Field (Grindley, 1961). The Wairakei Steam Field consists essentially of a pumice breccia aquifer (Waiora Formation) varying from 1 500 to over 3 000 feet in thickness, in which hot water at temperatures up to 260°C has accumulated to form a substantial reservoir of heat. This aquifer (Waiora Aquifer) is capped by relatively impermeable lacustrine mudstones (Huka Formation), between 200 and 500 feet thick, at a depth of between 600 and 1 000 feet below surface (See cross section, figure 2). The Huka Formation is overlain by a younger sheet of pumice breccia or lapilli tuff (Wairakei Breccia) which is exposed at the ground surface over the hydrothermal field.

The Waiora Aquifer is underlain by the Wairakei Ignimbrites, a relatively impermeable sequence of dense ignimbrite sheets. The hot water is considered to be fed into the aquifer through the ignimbrites up several steep-dipping fissure zones, which are the downward extension of active faults visible at the ground surface. The ignimbrites are known to be at least 1 700 feet thick from the drilling of one deep exploratory hole, which failed to penetrate them at a depth of 4 020 feet.

The basement rocks underlying the structural depressions in the Central Volcanic District are generally assumed to be Permian-Mesozoic, closely folded and indurated, greywacke and argillite, phyllites and sub-schists, similar to those exposed in the ranges and plateaux bordering the volcanic belt. Gravity surveys show that basement rock is approximately 4 500 feet below sea-level in the central portion of the Wairakei hydrothermal field, i.e., 6 000 feet below the surface and about 2 000 feet below the bottom of the deepest drill-hole. What lies between the ignimbrites and the greywacke basement at Wairakei, i.e., in the undrilled 2 000 feet, is obviously a matter of speculation. A lower aquifer of pumice pyroclastics and sediments has been tentatively postulated on the basis of stratigraphic sequences exposed elsewhere in the Volcanic District, particularly those in the area immediately to the north. Geological mapping in this area (Sheet N85, Waiotapu) has shown that ignimbrites of Wairakei type (Paeroa Ignimbrites) are underlain and interbedded with pumice pyroclastics and sediments that could constitute a lower aquifer if they extended as far south as Wairakei. Only deeper drilling at Wairakei will finally solve this problem.

### Structure

An outline of the structure of the Wairakei field and adjoining regions is given on the Taupo mapsheet and a more detailed account in the Wairakei geological bulletin. The hydrothermal field is situated on the crest of an important structural elevation known as the Wairakei High, originally discovered by gravity surveys (Beck and Robertson, 1955). Basement greywacke is approximately 4 500 feet below sea-level on the crest of the Wairakei High and approximately 8 500 feet below sea-level in the adjoining structural depressions. Drilling of the Wairakei Field has shown that the Wairakei High is a complexly faulted horst or fault-block, and is step-faulted down to the depressions on either side. The Wairakei High, on gravity evidence, continues south for five miles from the central part of the hydrothermal field. Drilling has shown that relatively high gravity values to the south are not due to basement uplift as was originally thought but are due principally to a thick sill of rhyolite up to 1 500 feet thick, intruded into the Waiora aquifer above the Wairakei Ignimbrites. In this area, the Waiora aquifer is divided into two parts separated by the rhyolite. The lower part of the aquifer, the ignimbrites and presumably the greywacke basement, have subsided in this region an amount roughly equivalent to the thickness of rhyolite, i.e., 1 500 feet. The centre of the rhyolite eruptions lies five miles south of the Wairakei field where a large aeromagnetic positive anomaly probably marks the site of a rooted rhyolite intrusion.

It is apparent at Wairakei that the fissures feeding the aquifer through the ignimbrites are located where the ignimbrite is closest to the ground surface, i.e., in the comparatively restricted area of one square mile coincident with the area of basement uplift. From this central feed zone hot water has spread laterally in the Waiora aquifer into the depressions on either side. This spread is made possible by the presence of the Huka lacustrine mudstones which cap the aquifer and act as a confining layer to spread the heat over a wide area.

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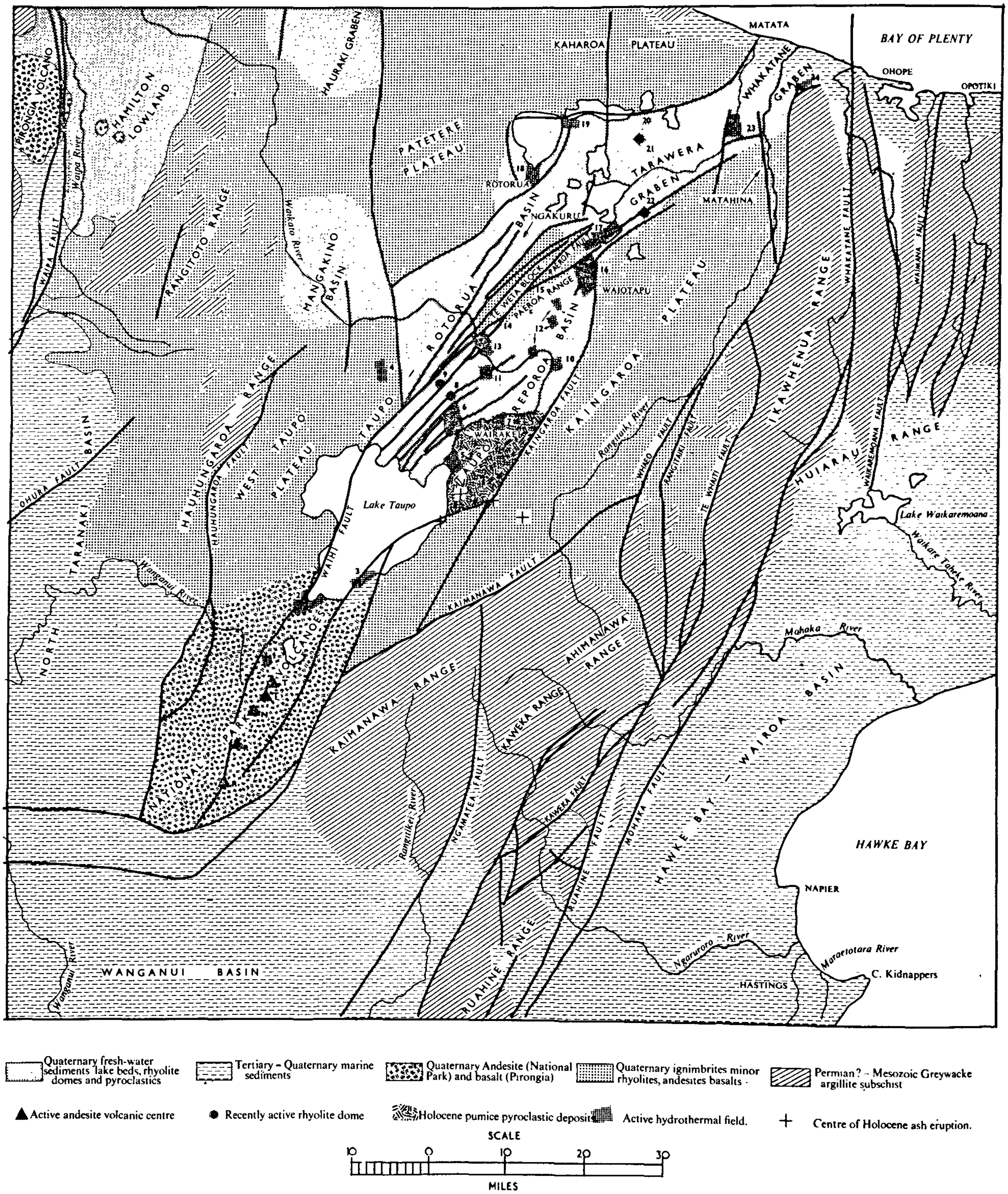


**Figure 1. Generalized geological map of central volcanic district**

The surface thermal activity is largely concentrated in those areas where active faults cut the Huka Formation and allow hot water, trapped in the aquifer, access to the surface along the open fault zones. It is apparent that surface thermal activity is an indicator that heat is present in the Waiora aquifer but is no reliable guide to the location of the fissures feeding the aquifer, due to the wide spread of the heat below the confining layer of mudstone.

## Faults

The major active faults within the Wairakei production area are shown in figure 3. Three north-east-striking faults in the west (Waiora, Wairakei and Kaiapo faults) are the main faults feeding the Waiora aquifer and the bulk of the high pressure steam so far won at Wairakei has come from wells drilled into these faults. These three faults can be traced as active features for several miles to the south-west and north-east of Wairakei, with the exception of the Waiora fault, which cannot be traced north-east of Hole 55. A sub-surface fault, not active at the surface, has been located by drill-holes in the eastern part of the field (Karapiti) and can be traced south-west to the Karapiti thermal area. This fault is probably responsible for feeding a group of high pressure wells in the east.

Investigational drilling to the north-west and south-west of the present production area has shown that other faults contribute hot water to the Waiora aquifer but these faults have not been adequately tested and their productive limits are not known. To the south-west of Wairakei, a major flow of dry steam (over 500 000 klbs/hr) has been found in Hole 204 and investigational holes drilled on the Wairakei fault. Unfortunately, this flow of dry steam was unexpected and the discharge is now uncontrolled. The fissure was tapped in the rhyolite sill within the Waiora Formation at a depth of 1 224 feet. A comparatively low degree of hydrothermal alteration and only moderate temperatures were encountered in Hole 204 to within a few feet of the sub-surface fissure which was presumably capped within the rhyolite. That the fissure was sealed is also shown by the absence of thermal activity, present or past, at the ground surface. After several months of dry steam discharge, Hole 204 was quenched in August 1960 by surface water and is now a boiling lake inside a large crater. Ground vibrations over an elliptical area roughly coincident with the Wairakei fault show that the steam flow is still present and indicate substantial reserves of dry steam in this fissure.

## Siting of drill-holes

Siting of individual drill-holes has mainly been governed by power-house requirements. The Wairakei station, if extended to the full 250 000 kW capacity as originally planned, would require approximately

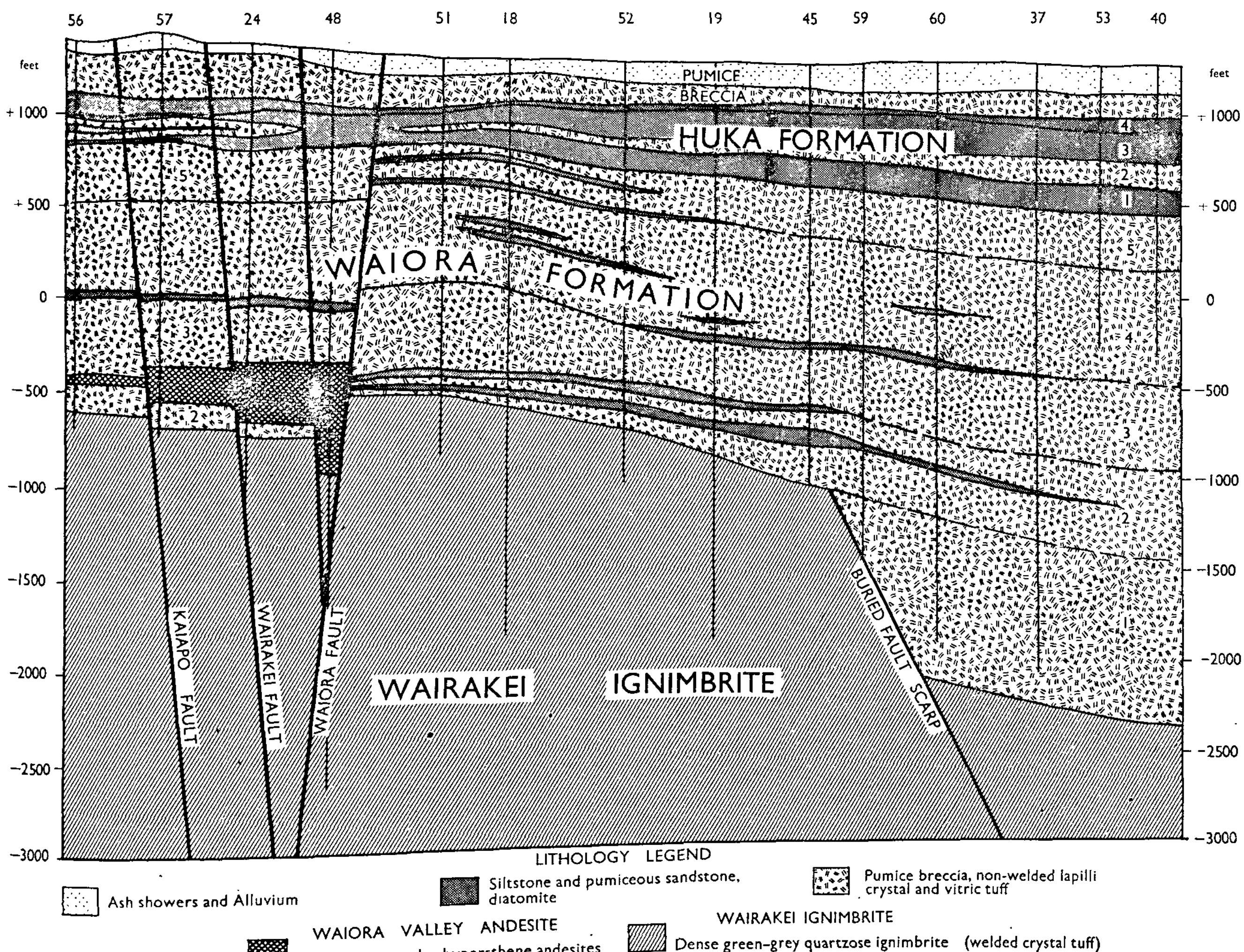


**Figure 2. Cross section from hole 56 to hole 40**

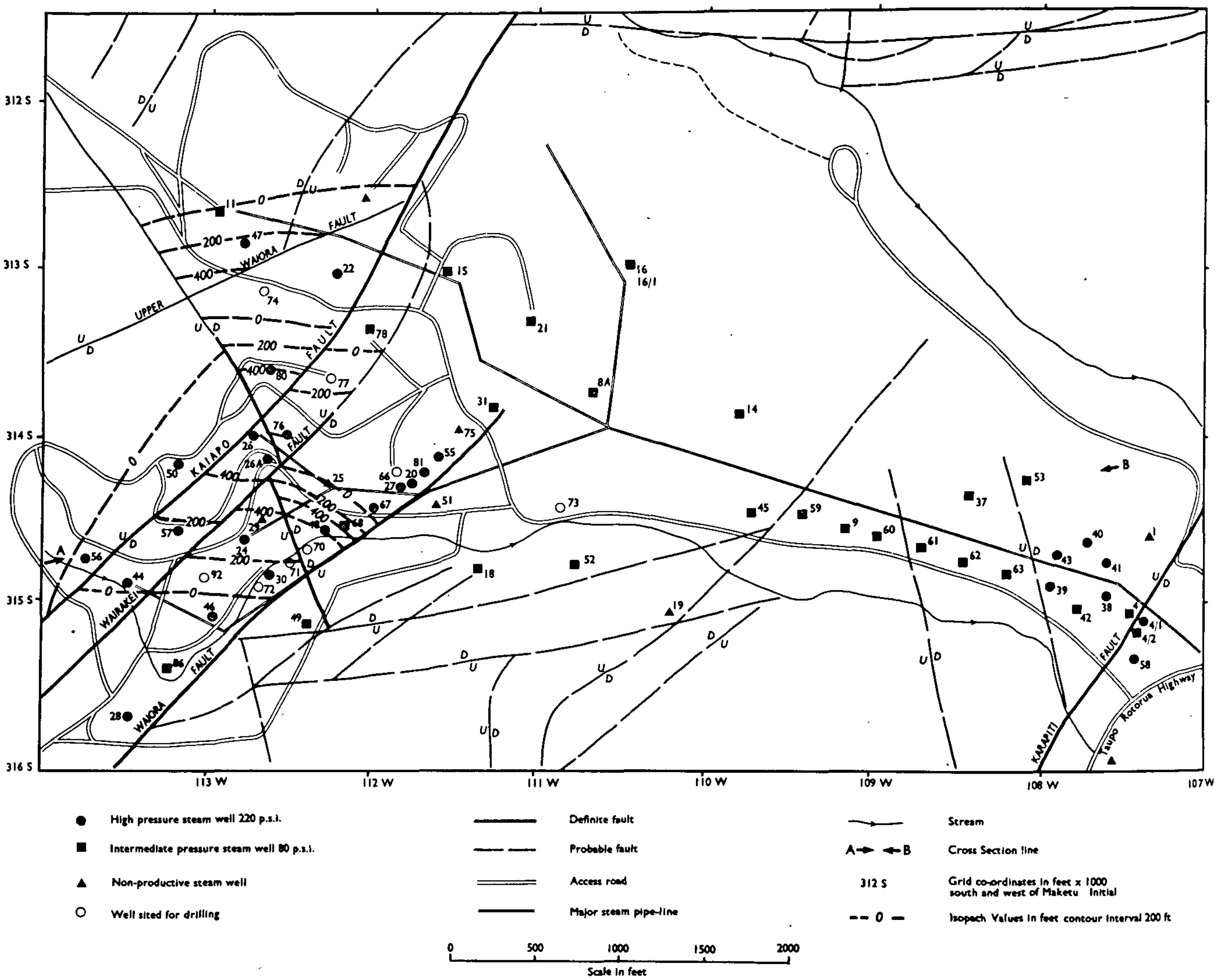


**Figure 3. Isopachs on andesite flows in Wairoa formation**

1 500 klb/hour of direct steam at a turbine admission pressure of 180 psi for high pressure turbines, and 500 klb/hour of direct steam at a turbine admission pressure of 50 psi for intermediate pressure turbines. This HP/IP ratio of 3:1 has governed the steam-winning policy at Wairakei in recent years. In general, it is found that by drilling for HP steam, i.e., in the most favourable known localities, this ratio can only just be maintained. IP steam can be found almost anywhere at Wairakei and it is not necessary to drill wells specially for IP steam. Sufficient IP steam is available from planned HP wells that failed to come up to expectations, from exploratory wells drilled for scientific information, and from borderline wells that have downgraded.

The known high-pressure steam areas in the Wairakei production area are shown on the accompanying map (figure 4). It can be seen that the areas are comparatively restricted and closely associated with the major faulting. The western area is by far the most important and although in an advanced stage of development is by no means thoroughly exploited. Over 20 wells have been drilled on the downthrow side of the Waiora, Wairakei and Kaiapo faults in this region which have a total tested output of over 1 000 klb/hour of direct HP steam. The average spacing of wells along these faults is approximately 500 feet for the Waiora fault and over 1 000 feet for the Wairakei and Kaiapo faults. Smith (1958) has shown that wells 20 and 27, 60 feet apart on the Waiora fault, showed less than 5 psi variation in bottom-hole pressure when running together or separately. Although these two wells are drilled into one of the largest fissures in the field, which is almost certainly a "feed point" into the aquifer, it is apparent from the pressure tests described by Smith that many more wells can be drilled into these faults without affecting those already in production. Other faults, such as the Upper Waiora fault in the extreme west of the production area and others still farther west that have been tapped by investigation holes, show promise comparable to the well-tested Waiora, Wairakei and Kaiapo faults, and are likely to yield similar returns.

Besides these western "fissure" wells, a small number of wells in the eastern part of the field have been producing over 300 klb/hour of direct high pressure steam from an extremely permeable part of the Waiora aquifer. A fault displacement of the Huka mudstones has been found in this area, suggesting a feed zone separate from that in the west. This is also suggested by the chemistry (Na/K ratios). However, the effect of interference between wells spaced at distances below 500 feet and downgrading of some of the wells in this area to IP would suggest that the feed, if it exists, is comparatively small. This area can be considered fully developed.

The methods of hole-siting at Wairakei were described by Grindley (1957). Holes are located about 200 feet distant from the surface trace of the known major faults and on the downthrow (i.e., downdip) side. This is to ensure that the fault or fissure zone is intersected between 1 500 and 2 000 feet where temperatures are reasonably high. In general, the faults are cut as close as possible to the top of the Wairakei Ignimbrites where the fissures appear to be large and open. If the fissures are cut at a higher level (above 1 500 feet), they cannot be relied upon for HP production, and have to be cemented off. Precise hole-siting is therefore essential as cementing of high-level fissures is time-consuming and expensive. Only in a few holes have fissures been drilled in the ignimbrite. Results appear to be no better than immediately above the ignimbrite, and the extra drilling is generally considered not worthwhile.

## Productivity of drill-holes

Wells vary widely in performance and the factors influencing this variation are (*a*) hole diameter, (*b*) depth, (*c*) aquifer pressure, (*d*) temperature, (*e*) length of open hole, (*f*) mass permeability per unit length, (*g*) neighbouring holes if close.

For high-pressure production (200 psi +) it is established by experience that the most critical

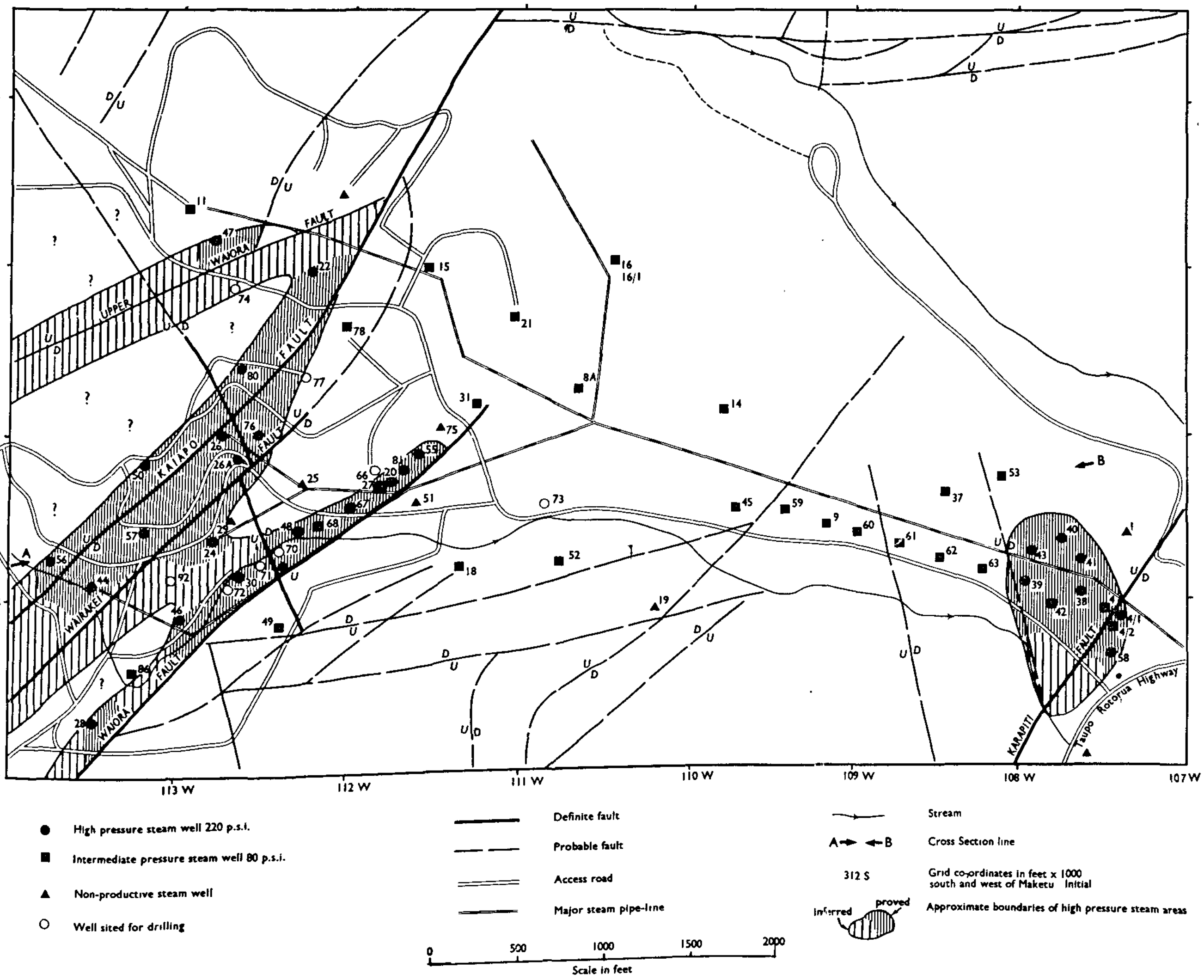


Figure 4. Map showing high pressure 200 psi steam areas at Wairakei and relation to major faults

factors are temperature and permeability. Wells drilled in relatively impermeable but very hot ground and wells drilled in comparatively cool but fissured ground usually end up as IP wells or, in extreme cases, as non-productive wells. Temperatures in the aquifer vary inversely as the distance from the fissures feeding the aquifer and can be predicted fairly precisely from temperature contour maps in the production area. Outside this well-explored area, the temperature pattern is necessarily diffuse and, although generalized contours can be drawn, these will undoubtedly be modified as further wells are drilled. Permeability depends on the mass permeability of the aquifer and on the size of fissure zones. Aquifer permeability is adversely affected by hydrothermal rock alteration, which is most pronounced close to the feeding fissures where the hot water first enters the aquifer. The voids in the Waiora breccias become filled with hydrothermal minerals and so the breccias are rendered impermeable. Holes drilled close to the feeding fissures without actually intersecting them are commonly non-productive and become blocked with large debris when opened for production. In such areas, which include the western part of the production area, drilling for fissures has become accepted practice. Where the aquifer is deep, as in the east, hydrothermal rock alteration is not so far advanced and high pressure production is possible from the aquifer away from fissure zones. The same situation is possible in the extreme west of the Wairakei field, where a deep pumice breccia aquifer has recently been discovered by investigation holes.

An important factor in drill-hole performance is the rapidity of mineral deposition in the casing of discharging drill-holes. Mineral deposits are of calcite and silica and accumulate within the lower part of the cased section (1 000-1 500 feet). Mineral deposition reduces the well diameter and increases friction loss leading to a steady drop in well-head pressure and output, normally accompanied by a slight rise in enthalpy. Tests on mineral lowered into the fissure zone of a discharging well (27) show, however, that no mineral deposition is taking place in the producing fissures (Smith, 1958).

## Relation of heat flow to structure

A considerable body of evidence has now accumulated to show that heat flow into the Waiora aquifer is related to the major active faults extending from the surface down through the aquifer and underlying ignimbrites. This can be shown by (*a*) maximum temperatures in drill-holes, (*b*) rank of hydrothermal alteration with depth, (*c*) sodium-potassium ratios of water discharged by drill-holes, (*d*) silica content of water.

It is not proposed to present this evidence, which is quite detailed, in this paper. A full description is given in the Wairakei geological bulletin (Grindley, in press). It is, however, proposed to illustrate the type of structure controlling the thermal activity by means of isopachs (thickness contours) drawn on buried flows of andesite in the lower part of the Waiora Formation. An association of the andesite with the high-temperature area in the western part of the production area has long been recognised. Only recently, however, have sufficient wells been drilled through the andesite to show the structure of the andesite and its relation to heat flow. Figure 3 shows isopachs drawn on the andesite. It will be noted that the andesite thickens towards the intersections of four north-east faults with a single north-west fault crossing almost at right angles. It will also be noted that thicknesses in the north and south facing quadrants between the intersecting faults are greater than those in the east and west facing quadrants. This can be most simply explained by accepting slight clockwise displacement on the north-east faults which produce small-scale tensional fractures in the north and south facing quadrants, allowing these quadrants to subside most at the time of the andesite volcanism. Interpretation of the north-east faults as normal faults with a slight clockwise transcurrent component is in accord with evidence elsewhere in the volcanic district.

The relation of heat flow to the andesite isopachs is shown by comparison with the high-pressure steam area shown on figure 4. The same relation can be shown by the other methods mentioned earlier. In other words, the present heat flow into the aquifer is apparently controlled by the same intersecting fault pattern that controlled the thickness of the andesite flows. This correlation is so close that it cannot be accidental. A theory has been proposed (Grindley, 1961) that the fault pattern dates from the inception of the horst and graben structure at Wairakei, i.e., from about mid-Pleistocene, and that both the thermal activity and local volcanism (the andesite) have been controlled by this fault pattern. This, together with other evidence, allows the age of the hydrothermal field to be estimated as approximately mid-Pleistocene or 500 000 years old.

The dry steam field recently discovered by Hole 204 on the southern extension of the Wairakei fault poses another problem. Two theories have been proposed. One theory put forward by C. J. Banwell supposes that dry steam produced by fractionation of chloride water in the production area has migrated south to Hole 204 along the fissure zone of the Wairakei fault. The other theory, put forward by the writer, is that Hole 204 has intersected a fissure in direct communication with a reservoir of dry steam at great depth (5 000-6 000 feet) in a structural trap below the Wairakei Ignimbrite. It has also been suggested (Grindley, in press) that the chloride water in the production area has moved into the structural dome at the northern end of the Wairakei High, following up-dip migration from the south in a lower aquifer below the Wairakei Ignimbrites, dry steam separating in structural traps along the path of migration. Both these theories remain to be tested by drilling.

## Other geothermal fields in New Zealand

### Waiotapu

Waiotapu geothermal field, 30 miles north-east of Wairakei (figure 1), has been drilled by seven investigation wells. The regional geology has been described by Grindley (1959). The rock sequence penetrated is similar to that at Wairakei except that the ignimbrites are closer to surface and the overlying aquifer is thin (less than 1 000 feet) and useless for high pressure steam production. A deeper aquifer was drilled within the ignimbrite sequence by three wells and proved initially promising, the three holes giving results comparable with average Wairakei HP wells. However, mineral deposition, principally calcite, rapidly downgrades the wells to IP wells within a few months. The deep aquifer is also thin (200-400 feet) and not greatly permeable due to hydrothermal rock alteration. No fissure zones were drilled, although holes were sited adjacent to fault traces visible on air photographs. A pattern of intersecting faults similar to Wairakei was noted in the undrilled southern part of the field and may yet prove to be the source area for the hydrothermal water. Andesite flows similar to those at Wairakei were encountered within the ignimbrite sequence in the three deep wells and thicken south towards the supposed source area in the southern part of the field. Maximum temperatures increase south also from 270°C to over 290°C. This may mean that volcanism and heat flow are related to the same structural conditions as they are at Wairakei and should prove a useful guide to the search for high-pressure steam when the thermal area is again drilled.

### Kawerau

Kawerau geothermal field, 60 miles north-east of Wairakei (figure 1), has been drilled by twelve investigation wells. A reasonably deep pumice breccia aquifer was drilled (1 500-2 400 feet), capped by thick rhyolite flows. Performance of the wells was initially good, corresponding to average Wairakei production, but most of the wells downgraded after three years' production, owing to recharge by cooler water from the east and south-east. Recently two of the wells were deepened to over 3 000 feet and penetrated andesites (2 400-2 700 feet), similar to those at Wairakei and Waiotapu, underlain by dense ignimbrites. The andesites are extensively fissured; temperatures are high (270°C+) and both wells are now producing at high pressure, giving results equivalent to the best of the Wairakei HP wells. The relation of the andesite aquifer to the overlying pumice breccia aquifer is at present not certain although in one of the wells it appears to be capped by mudstones. The future behaviour of the andesite aquifer is difficult to forecast and largely depends on how effectively it is capped and thus insulated from the overlying aquifer into which cooler water has already penetrated. Comparison with Wairakei would suggest that the thick andesites encountered in these two holes indicate proximity to the heat source and are thus a favourable indication that high pressure production may be maintained over a reasonable period. The Kawerau thermal area is crossed by numerous active faults but these are located a mile to the west of the drilled part of the field. The drilled area is covered by recent alluvium, and faults, if present, are likely to be buried and invisible at the surface.

## Prospecting prior to development of geothermal steam fields

A considerable amount of experience has been won in New Zealand over the past ten years in the selection, initial prospecting, development and exploitation of geothermal fields. Much of this experience is not available in published literature and, indeed, each geothermal field presents unique problems and generalisation is difficult. Before drilling a geothermal field, it is advisable to carry out basic scientific surveys to learn as much as possible of the regional geology and structure. Of these surveys the following are most important.

### Regional geological survey

This should cover a wide area surrounding the geothermal field. This was done at Wairakei in 1950 but the area covered was insufficiently large to assist greatly in the prediction of the geological sequence in the steam field itself. In a recently active volcanic area like the Taupo-Wairakei area, the older formations are concealed by young volcanic material and it is necessary to travel some 30 to 40 miles north of Wairakei to see exposures of the older rocks that are penetrated by drill-holes. This probably applies to some degree to many geothermal fields.

A regional geological survey should allow the forecasting of the thickness and probable depth of potential steam-bearing aquifers, and also of the impermeable formations which separate one aquifer from another. Precise information can then be passed on to engineers and drillers regarding likely depths at which steam will be found.

### Regional Tectonic studies

These also should cover a wide area surrounding the steam field. They were not done at Wairakei till late in the investigation (1956) and almost immediately paid substantial dividends. Siting of drill-holes was placed on a sounder scientific basis and the percentage of successful, high-pressure wells increased from less than 50 per cent to over 70 per cent of the wells drilled. Tectonic studies involve study both on the ground and from air photographs of the active fault pattern and major fault-block structures typical of the region. These fault-blocks are completely buried at Wairakei and can be outlined only by intensive drilling (see figure 2). In the Waiotapu region to the north-east and on the north shore of Lake Taupo to the south-west, the fault-blocks are magnificently exposed. These structures can be projected through the Wairakei area on the evidence of the recent fault pattern. Since the faults are still active, small scarplets produced by recent movements can be traced from areas where the major structure is exposed to areas like Wairakei where it is buried, and predictions made of sub-surface structure before intensive drilling is undertaken.

### Geophysical surveys

The gravity survey of the volcanic district has proved invaluable in the initial interpretation of buried structural relief. The major structure at Wairakei (Wairakei High) was originally discovered by gravity surveys and, although the interpretation of the high as due to basement uplift throughout has been modified following drilling, the essential value of the method remains unimpaired. Gravity work should at all stages be closely integrated with geological and tectonic studies, in the same manner as is customary in the major oil companies. It is an important accessory to the geologist in predicting and interpreting the sub-surface structure.

Magnetic surveys have been carried out over the volcanic district and have also proved of value in showing the presence of hidden bodies of highly magnetic rock, such as the rhyolites at Wairakei. These buried volcanics may have some bearing on the movements of the hydrothermal fluids and commonly constitute relatively impermeable layers separating aquifers. Low magnetic values over hydrothermal fields are usually due to hydrothermal alteration and the spread of low magnetic values may assist in determining the size of the hydrothermal system at depth. It is, however, rarely possible to determine from magnetic surveys alone the location of areas of most intense alteration where the sub-surface aquifers are fed from great depth.

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## *Summary*


In New Zealand the volcanic zone extends for 150 miles between the two active andesite volcanoes of Ruapehu in the centre of the North Island and White Island in the Bay of Plenty. A generalised geological map of the central volcanic district and adjoining regions (figure 1) shows active volcanic centres, thermal areas, major faults and structural depressions. At the two ends the volcanic zone is narrow and dominated by large active andesite volcanoes. The central portion is wider and dominated by acid igneous activity — rhyolite domes, puroclastic pumice deposits and ignimbrites. The major volcano-tectonic depressions are located in this central zone and also most of the active thermal areas. The thermal areas are closely associated with the rhyolite volcanism and with development of the major volcano-tectonic depressions. The boundary of the present active acid volcanic region (shown on figure 1) includes the Taupo-Reporoa, Tarawera and Whakatane depressions. These are strongly faulted, actively subsiding structural depressions filled with considerable thicknesses of pumice pyroclastics that constitute aquifers for the geothermal steam fields. At some of the hydrothermal fields, e.g., Wairakei and Waiotapu, the pumice aquifer is capped by lake beds or ignimbrite sheets; at others, e.g., Rotokawa, Orakei Korako, the pumice aquifer is open.

The hydrothermal fields are closely associated with a north-east belt of active faulting associated with the subsidence of the major structural depressions mentioned above. The major faults up which the hydrothermal fluids ascend from the magma into the pumice aquifers are still active and their continued activity seems essential in maintaining hydrothermal activity. Fissures along these active faults are periodically enlarged and kept open by fault movements. The location of the hydrothermal fields was most probably established in the early stages of subsidence of the structural depressions in which they are found. The present New Zealand hydro-

thermal fields, particularly the major fields like Wairakei, were probably established in the middle Pleistocene period, which is approximately 500 000 years ago. Older hydrothermal fields, now extinct, existed prior to this, but are located in an older and even deeper structural depression, Taupo-Rotorua depression, to the west of the present active belt.

The newer hydrothermal fields in the present active zone of subsidence appear to be located at places where the north-east faults are crossed by important but minor north-west faults. The north-east fault pattern has been tentatively interpreted as a belt of essentially normal faulting with a minor but important component of clockwise transcurrent shear. Tensional faulting at the intersections of the north-east faults with secondary cross faults is induced by the slight component of transcurrent movement. At these fault intersections, hydrothermal activity is principally concentrated in the hydrothermal field so far studied in detail, i.e., Wairakei, and the same relationship is possible in other hydrothermal fields.

# GÉOLOGIE DES GÎTES DE VAPEUR GÉOTHERMIQUE EN NOUVELLE-ZÉLANDE


## *Résumé*

En Nouvelle-Zélande la zone volcanique s'étend sur 150 milles, entre les deux volcans actifs d'andésite de Ruapehu au centre de l'île du nord et de White Island dans la « baie de l'Abondance » (Bay of Plenty). La carte géologique généralisée du district volcanique central et des régions avoisinantes (fig. 1) révèle des centres volcaniques actifs, des champs géothermiques, des failles importantes et des dépressions structurelles. En ses deux extrémités la zone volcanique est étroite et dominée par de grands volcans actifs d'andésite. La partie centrale est plus large et dominée par une activité ignée acide des dômes de rhyolite, des dépôts de pierre ponce pyroplastique et des ignimbrites. C'est dans cette zone centrale que sont situées les dépressions volcano-tectoniques principales ainsi que la majorité des régions thermiques et hydrothermiques. Ces régions sont étroitement associées avec le volcanisme à rhyolite et avec le développement des principales dépressions volcano-tectoniques. Les limites de la région volcanique active acide actuelle (voir fig. 1), comprennent les dépressions de Taupo-Reporoa, Tarawera et Whakatane. Celles-ci ayant une abondance de failles constituent des dépressions structurelles en effondrement actif, remplies d'une épaisseur considérable, de produits pyroplastiques de la pierre ponce, formant les masses aquifères de champs de vapeur géothermique. Dans certains des champs géothermiques par exemple à Wairakei et Waiotapu, la masse aquifère de pierre ponce est recouverte par des lits de lacs ou des masses d'ignimbrite; en d'autres lieux, par exemple à Rotokawa, Orakei Korako, l'aquifère en pierre ponce est ouvert.

Les champs hydrothermiques sont étroitement associés avec un bassin orienté vers le nord-est de failles actives qui s'accompagnent de l'effondrement des dépressions structurelles principales mentionnées ci-dessus. Les failles principales, le long desquelles les liquides hydrothermiques montent du magma dans les aquifères en pierre ponce, sont encore actives et le maintien de cette activité semble essentiel à celui des manifestations hydrothermiques. Des fissures le long de ces failles en activité sont périodiquement agrandies et tenues ouvertes par des mouvements formateurs de failles. La situation des champs hydrothermiques a probablement été établie lors des premiers stades d'effondrement des dépressions structurelles dans lesquelles on les trouve. Les champs hydrothermiques néo-zélandais actuels, particulièrement ceux qui sont importants tels que ceux de Wairakei, ont probablement été établis au milieu de la période du pléistocène, c'est-à-dire, il y a environ 500 000 ans.

Les champs hydrothermiques plus anciens maintenant éteints existaient avant cela mais ils sont situés dans une dépression structurelle plus ancienne et plus profonde, telle que celle de Taupo-Rotorua, à l'ouest de la région actuellement active.

Les nouveaux champs hydrothermiques dans la zone actuellement active où l'on trouve des effondrements semblent être situés en des lieux où les failles, situées nord-est, sont traversées par d'autres d'importance secondaire, orientées nord-ouest. La disposition des failles nord-est a été interprétée provisoirement comme étant un bassin de failles essentiellement normales, avec une composante mineure, mais importante due à un cisaillement transcurrent dans le sens des aiguilles d'une montre. Aux intersections des failles nord-est avec les failles transversales secondaires, les failles tensionnelles sont provoquées par la composante légère des mouvements transcurrents. A ces intersections de failles, l'activité hydrothermique est principalement concentrée dans le champ jusqu'à présent étudié en détail, par exemple, Wairakei; on peut donc espérer les mêmes rapports quant aux autres champs hydrothermiques.

# THE PRESENT POSITION REGARDING THE UTILIZATION OF GEOTHERMAL ENERGY AND THE ROLE OF GEOTHERMAL ENERGY FROM THE VIEWPOINT OF ENERGY ECONOMY IN JAPAN

*Hisachi Harada* and Tsunetada Mori†*

## A survey of past researches and explorations into the utilization of geothermal energy in Japan and evaluation of the results

The utilization of geothermal energy for the purposes of electric power generation has been under consideration in Japan since around 1920, and in this respect various kinds of investigations and exploratory drillings have been carried out in many geothermal fields.

### Organizations concerned in the research and exploration into geothermal energy

There are a number of research organizations and companies in Japan which are performing research and exploration on geothermal energy development. However, there has not been any organization which centralizes and co-ordinates these researches. For instance, the Geological Survey Institute as one of the governmental organizations is mainly conducting exploration into geothermal fields from the standpoint of research into geological structures. Academic research in relation to the utilization of geothermal energy, as part of general research into volcanos and hot-springs, is being carried out by the Volcano and Hot-spring Research Institute of Kyoto University among the national universities. Research and development for the purpose of producing electric power at a low cost by utilizing geothermal energy were and/or have been conducted by private companies, especially by electric power companies (such as the Kyushu Electric Power Co., the Tokyo Electric Power Co. and the Chubu Electric Power Co.) and metal refinery companies (the Azuma Kako Co.). This company has been interested in geothermal power generation for a long time and conducted some preliminary exploration. Recently, the company has appealed to the other companies concerned and established the New Japan Geothermal Development Co. which is undertaking exploratory drillings in the Matsukawa district in the Tohoku area of Japan. In addition, boring companies (the Shonan Drilling Co. and the Tone Boring Co.) have been studying the technique of bore drilling for deriving geothermal energy from underground.

Besides the above, the Central Laboratory of the Japan Monopoly Corporation is conducting research into salt manufacture by means of geothermal heat and, further, some private salt manufacturing companies are producing salt by heating and enriching sea water with the aid of geothermal heat.

In addition to the various organizations and companies which are undertaking research and exploration in connection with the utilization of geothermal energy as mentioned above, the Japan Geothermal Research Association has recently been established, composed of members who are interested in this matter, in answer to their request for the establishment of an organization which would facilitate mutual communication and exchange of information between those concerned in the research and exploration programmes.

### A survey of programmes of research and exploration into geothermal energy and their expenses

For the first time, the then Tokyo Electric Lighting Co. installed a geothermal power station with a rating of 1 kw at Beppu Hot-spring in Kyushu in 1925 and conducted various explorations there. Thereafter, many research and exploratory programmes were and have been undertaken in various places as shown below, but no satisfactory results have been available to date:

1947. Tone Boring Co. Exploration was started in the Naruko district in the Tohoku area and more than 250 borings have been performed over several years.

1948. Tone Boring Co. Geothermal power generation at 8 kw has been performed at Yunosawa, Izu, in the Kanto area.

1951. Agency of Industrial Science and Technology. Geothermal power generation at 30 kw has been performed at Beppu in the Kyushu area.

1952 and after. Geological Survey Institute. They have engaged in geological surveys in the Hokkaido, Tohoku, Kanto and Kyushu areas, respectively.

1953-1956. Kyushu Electric Power Co. Several exploratory borings were made in the Otake district in Kyushu.

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1955. Tokyo Electric Power Co. and Chubu Electric Power Co. Exploratory borings were made in the Kusatsu district in the Kanto area.

1958 and after. Tone Boring Co. Exploratory borings were made at Mt. Bandai in the Tohoku area.

1959 and after. Volcano and Hot-spring Research Institute of Kyoto University. Geothermal exploration is under way in the Otake district in the Kyushu area.

1960. New Japan Geothermal Development Co. Exploratory borings are under way in the Matsukawa district in the Tohoku area.

1960. Hotel Kowakuen. They are performing 30 kw geothermal power generation at Hakone in the Kanto area.

Details of the funds invested for the aforementioned research and exploratory developments are not yet available. The major ones which are available are as follows :

Kyushu Electric Power Co., 70 million yen (including 26 million yen of government subsidy).

Tokyo Electric Power Co. and Chubu Electric Power Co., 24 million yen (including 4 million yen of government subsidy).

Volcano and Hot-spring Research Institute of Kyoto University, 1 million yen.

Geological Survey Institute, 24 million yen.

## Major aspects of past exploration of geothermal energy and the results

1. The exploration of geothermal energy has been carried out in areas where natural fumaroles and hot-springs exist around volcanos formed in the era between the Pliocene and Quaternary. The geological structure of those areas comprises volcanic rocks consisting mainly of andesite partially mixed with tuff. Comparatively little sedimentary rock is found in these areas.

2. As regards the methods of exploration, at first, the condition of underground strata was assumed, based on preliminary explorations such as geological and/or physical surveys, and then some comparatively shallow test drillings were carried out.

3. Most of the exploratory wells were drilled on a small scale, having a diameter from 2 to 4 inches and a depth of from 100 to 400 metres. There are several wells with diameters from 6 to 8 inches and reaching a maximum depth of 900 metres.

4. Usually, saturated steam and sometimes a small amount of superheated steam came out from shallow wells drilled in the geothermal field around volcanos. However, considerable quantities of water at high temperature (saturated water) spouted out from deeper exploratory wells (say 300 metres or more).

5. Although the conditions of the test wells varied according to location, depth and some other factors, in general, the data obtained are as follows : closed well pressure, 3-7 kg/cm$^2$; highest temperature at the bottom of the well during drilling, 150-190°C; flow rate per well (in case of steam) : 100-5 000 kg/hr.; (in case of water at high temperature) 30 000-100 000 kg/hr. In the case of steam spouted out, it is composed mainly (more than 99 per cent) of $H_2O$ and the remainder consists mostly of $CO_2$.

6. There were considerable discrepancies between the assumptions based on the preliminary explorations and actual results of boring, and they indicate how complex the underground features are.

## Review of results obtained

Reviewing the results of past exploratory surveys, the volcanic geothermal fields are considered.

1. Within the scope of the depth explored, it was observed that underground strata consist mainly of volcanic rocks and comparatively little sedimentary rock and no impermeable layers on a large scale as observed in Larderello, Italy. It is estimated that there are hardly likely to be impermeable layers of sedimentary rocks at greater depth (say 1 000 to 2 000 metres).

2. It is assumed that natural steam vents result from evaporation at the surface of high temperature water situated normally at a shallow depth. Therefore, the steam spouted out when drilling took place in the localities which have suitable geological conditions from above the layer containing the high temperature water. Steam vents coming from shallow wells is of such a kind. When a well is drilled deep enough to reach the high temperature water zone or deeper, naturally, the high temperature water spouts out and its flow rate is comparatively high.

3. Steam vents from shallow drillings contain mainly $CO_2$ as impurities. The composition of the steam in general is similar to that of natural steam vents from fumaroles in that area. On the other hand, the composition of high temperature water spouting from deep wells varies very much according to the wells. There is less possibility of the existence of impermeable layers underground to such a large extent as is found in the continents because the crust is of much more complicated structure and the scale is smaller. Further there is much rainfall all over the country (annual mean rainfall is 1 500 mm or more). Consequently, surface water readily penetrates deep into underground layers and it is considered that this makes it difficult to obtain a large amount of primary steam originated by magma as seen in Larderello.

## Methods of geothermal power generation development suitable to the Japanese situation

Methods of geothermo-electric generation can be divided into these two major classifications : utilizing primary steam originated by magma — steam system; utilizing secondary steam produced by means of pressure reduction of high temperature water — high temperature water system.

The geological conditions of the field will determine which system should be adopted.

It is not positively "impossible" but very difficult in Japan to find, with the current exploratory techniques, areas where a great amount of primary steam originated by magma is available. On the contrary, high temperature water is available in various districts throughout the country. Therefore, it is recommendable to concentrate on development of geothermo-electric generation depending upon utilization of the high temperature water system which is more feasible, and to establish an exploratory technique in connection with primary steam suitable for the geological conditions in Japan before proceeding with further gradual exploration.

## The role of geothermal energy in electric power generation from the viewpoint of energy economy in Japan

Japanese state economy has entered a stage of expansion after the post-war period of reconstruction. It is anticipated that it will rapidly grow from now on. The role of geothermal energy within the scope of geothermal power generation is taken into consideration.

### The electric power situation in Japan

The demand for electric power in Japan has been growing considerably in line with the development of various industries and improvements in the national living standard in these days, and it is anticipated that such a trend will continue in the future, as shown in table 1.

It is evident from tis table that the percentage of hydroelectric power generation decreases as the future power demand increases. This means that the hydro-electric power sources available for development are becoming exhausted, and it becomes necessary to rely mainly on the development of thermal power in order to meet the future growth on the power demand.

On the other hand, judging from present coal reserves and the location of mine shafts, it is estimated that economical coal production will total about 55 000 000 tons per year, and that the maximum amount of coal available for the generation of electric power will be limited to about 45 per cent of the total output. Consequently, to meet the growing power demand, it will be necessary to depend on imported resources of heavy oil.

### The role of geothermal power generation in the energy situation in Japan

As mentioned above, it appears to be natural that thermal power generation firing imported heavy oil will meet the future growth of the power demand. In addition, nuclear power and geothermal power generation and some sources other than the conventional must be taken into consideration.

Even though there are great expectations that nuclear power generation will contribute to need for electric power generation as a new source of energy in the future, it is economically inferior to conventional thermal power generation and still involves large problems regarding safety and site location in Japan. Therefore, it will require an interval of several years before it becomes available for practical application.

Although it is hardly to be expected that geothermal power generating facilities will develop a large capacity in competition with conventional hydro or thermal power generating facilities, it has some significance as a new source of energy in Japan, in view of the following considerations:

1. Volcanic geothermal fields are found in many places all over the country. It is not so difficult to find sites suitable for the high temperature water generating system in such geothermal fields. Therefore, it is feasible to construct a number of power plants with a small individual output but capable of a large total production.

2. Since a wide transmission line network covering all the country already exists, these power plants can easily provide the power output of the network.

3. Geothermal power generation will enable a saving, to some extent, in the amount of imported heavy oil which is expected to increase in the future.

**Table 1. An estimate of the power demand, required power generation and required fuel in Japan**

| | | *1956-58 (Average)* | *1963* | *1970* | *1980* |
|---|---|---|---|---|---|
| Power demand . . . . | $10^6$ MWH | 67.2 | 110.9 | 193.5 | 332.2 |
| Required power generation . . . . . . | $10^6$ MWH | 77.9 | 124.9 | 216.7 | 369.3 |
| Hydro . . . . . . | | 56.5 | 69.4 | 87.5 | 105.0 |
| Thermal. . . . . . | | 21.4 | 55.5 | 129.2 | 264.3 |
| Required fuel : | | | | | |
| Coal . . . . . . . | $10^3$ ton | 9 300 | 20 000 | 25 000 | 25 000 |
| Heavy oil . . . . . | $10^3$ kl | 1 000 | 2 600 | 17 600 | 48 300 |

Note: Heat value of coal = 5 200 kcal/kg; heavy oil = 10 000 kcal/kg.
(Ref.: *Long Term Economic Out-look* by Economic Planning Agency, May 1960.)

4. It is estimated that the generating cost of geothermal power generation is low compared with conventional thermal power generation in Japan where the cost of fuel is high.

Reviewing the results of past research and exploration carried out in the geothermal field in Japan, it is concluded that the geothermal power generation by means of the high temperature water system is the most suitable means of development and that the further development of geothermal power generation by the said system will play an important role in the new phase of energy economy.


### *Summary*

A number of research projects and explorations into the utilization of geothermal energy have been carried on for a long time in Japan; however, no satisfactory results are yet available. In view of the number of organizations which have participated in past research and exploration and of the scope of their research, this paper is concerned mainly with problems of geothermal power generation.

Past explorations indicate that geothermal fields in Japan exist in areas around volcanoes where natural fumaroles and hot springs are found. The fluids available in those areas are water at a high temperature or secondary steam generated by the evaporation of the high temperature water. No primary steam originated by magma has been available in large quantity, as is the case at Larderello, Italy. Since there exist numerous volcanic geothermal fields all over the country, high temperature water is readily available. It would not involve too great difficulties to find localities suitable for geothermal power generation in those areas. Consequently, it is considered that generating systems utilizing high temperature water constitute the most attractive means of developing geothermal power generation for the time being.

The Japanese state economy has entered a stage of expansion after passing the postwar period of reconstruction. Accordingly, it is anticipated that the energy demand will grow considerably from now on. Against the growth in demand, there are certain restrictions on coal production owing to various adverse conditions. Further, the greater part of the heavy oil supply depends upon overseas imports. Under these conditions, geothermal energy is likely to play an increasingly important part.


## STATUT ACTUEL DE L'UTILISATION DE L'ÉNERGIE GÉOTHERMIQUE ET ROLE DE L'ÉNERGIE GÉOTHERMIQUE DANS L'ÉCONOMIE ÉNERGÉTIQUE DU JAPON


### *Résumé*

Il y a longtemps que l'on mène au Japon nombre de projets de recherches et d'exploration en vue de la mise en œuvre de l'énergie géothermique, mais les résultats obtenus n'ont pas été satisfaisants jusqu'à présent. Compte tenu du nombre des organismes qui ont participé aux recherches et à l'exploration dans le passé, ainsi que de l'étendue de leurs travaux, on ne s'intéresse, dans le présent mémoire, qu'aux problèmes soulevés par la production d'énergie géothermique.

Les explorations faites il y a quelque temps indiquent que les champs géothermiques du Japon se trouvent dans des régions qui entourent des volcans, où l'on trouve des fumerolles et des sources chaudes naturelles. Les fluides que l'on trouve dans ces régions sont l'eau à haute température ou la vapeur secondaire produite par l'évaporation de cette eau. On n'a pas trouvé de quantités appréciables de vapeur primaires en provenance d'un magma, telle que celle de Larderello, en Italie. Étant donné que l'on trouve nombre de champs géothermiques volcaniques de par tout le pays, on se procure facilement de l'eau à haute température. Il ne serait pas particulièrement difficile de trouver des emplacements se prêtant à la production d'énergie géothermique dans ces régions. En conséquence, on estime que les systèmes de production d'électricité faisant usage d'eau à haute température constituent la méthode la plus attrayante pour l'énergie géothermique en œuvre dès aujourd'hui.

L'économie du Japon étant entrée dans un stade d'expansion après la période de reconstruction de l'après-guerre, on s'attend à ce que les exigences d'énergie augmentent à partir de maintenant d'une manière frappante. Compte tenu de cette évolution, il faut se rappeler qu'on se heurte à quelques difficultés quant à la production de charbon, eu égard à certaines conditions négatives et, en outre, que la majeure partie des grosses fournitures de pétrole dont le Japon a besoin sont tributaires de l'importation. Dans ces conditions, il semblerait que les sources actuelles d'énergie géothermique doivent jouer à l'avenir un rôle plus important qu'aujourd'hui dans l'économie de ce pays.

# GEOLOGY AND GEOTHERMAL ENERGY IN THE TAUPO VOLCANIC ZONE, NEW ZEALAND

*J. Healy**

Although hot springs occur at widely scattered localities in New Zealand (figure 1), the most extensive hydrothermal areas and all the boiling springs and fumaroles are confined to the Taupo Volcanic Zone. During late Pliocene and Quaternary time, nearly 4 000 cubic miles of lava and pyroclastics, ranging from basalt to rhyolite but predominantly of acid composition, have been erupted from within and adjacent to the zone, so there is strong evidence for associating the hydrothermal activity with acid volcanism. Large-scale fusion of the crust has undoubtedly produced granitic magma comparatively close to the surface, and shallow reservoirs are suggested as the sources of the heat dissipated from the larger thermal areas at least.

Use of the heat dates back to pre-European times, when the Maori inhabitants made free use of the hot springs for cooking, washing and medicinal purposes. By 1940, a few wells had been drilled to tap hot water in Rotorua, but the discovery about then that gushers of boiling water and steam could be drilled over a large area of the town ushered in a wave of drilling and there are now over 300 wells in use for domestic and industrial purposes.

At Tokaanu two wells were drilled in 1940, and others subsequently. In 1949, a well drilled near the lower end of Waiora Valley at Wairakei to tap hot water for the Wairakei Hotel encountered high pressure steam. Shortly after this the area was selected for prospection of steam for geothermal power which is now being generated there.

In other parts of New Zealand, wells for hot water have been drilled at Ngawha, Helensville, Waiwera, Hamilton, The Aroha, Tauranga, Mt. Maunganui, Okauia, Lyttelton and Hanmer, but the temperatures are below boiling point and waters are used mainly for mineral baths.

## Geological setting of the chief thermal areas

The Taupo Volcanic Zone (figure 2) is a 10 to 15 mile wide belt extending across the centre of the North Island in a north-east direction for 190 miles. It is flanked in the central part by plateaux of flat-lying sheets of ignimbrite, erupted from vents within the zone in which pronounced subsidence accompanied the outpourings. Late intrusion has folded the sediments and pyroclastics laid down in the subsided basins, and has produced numerous rhyolite extrusive volcanoes, especially in two eruptive centres. The hot springs are not located on the ignimbrite plateaux or within the eruptive centres, but rather on the margins of the latter.

At the south-west end of the Taupo Volcanic Zone is the Tongariro group of volcanoes, with its vast andesitic cones of Ruapehu, Ngauruhoe and Tongariro. Apart from crateral activity, hydrothermal action is limited to fumarolic activity at Ketetahi on the northern slopes of Tongariro.

Between Tongariro and Lake Taupo is another volcanic pile, consisting of the extinct and successively younger andesitic cones of Kakaramea and Tihia and basaltic cone of Pihanga. From the first two radiate extensive andesitic flows through which the fumaroles of Waihi and the boiling springs of Tokaanu emerge along north-east fractures. The fumaroles are located at high altitude, but the boiling springs rise near lake level in alluvium beneath which andesite was proved by drilling. Three-quarters of a mile south-east from Tokaanu is the youthful dacitic cone of Maunganamu, flanked on the north-west and west by warm ground and hot springs.

Western Bay, which forms part of Lake Taupo, is a caldera that presumably marks an eruptive centre, though no thermal activity is known from that locality. The north-eastern side of the lake and its environs include the foci for recent explosive pumice eruptions, but there are no hot springs except near Taupo itself. The Rotokawa hot springs, 7 miles north-east from Taupo, occupy in part craters formed by hydrothermal explosions about 4 000 years ago.

Maroa Volcanic Centre consists of a rhyolite extrusive complex 8 to 10 miles in diameter. No hot springs occur within it, but there is an outer ring structure marked by a curving line of rhyolite extrusions, and on it lie the thermal areas of Mokai and Orakeikorako, while Wairakei is on the southern flank.

Okataina Volcanic Centre, which includes the volcanic complexes of Haroharo and Tarawera, has the Rotomahana hot springs on the margin and those of Waiotapu on its southern flank. The hot springs of Whakarewarewa and Tikitere are located on marginal fractures of Rotorua Caldera, a subsidiary structure on the west of the volcanic centre.

* New Zealand Geological Survey Department of Scientific and Industrial Research.

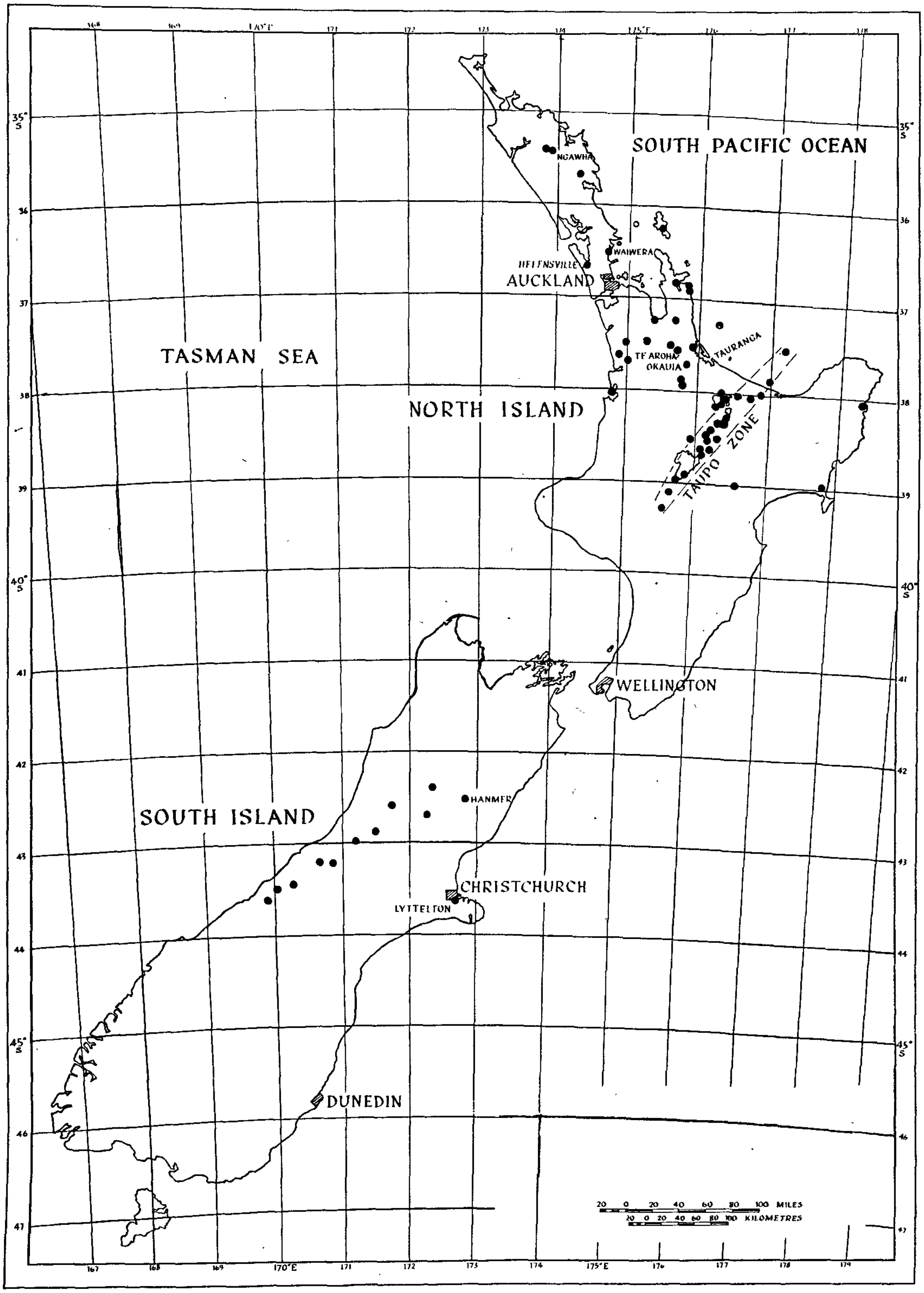


**Figure 1. Locations of New Zealand hot springs**

Between Maroa and Okataina extend a series of north-east trending blocks in the form of an anticline faulted along the crest to form Ngakuru Graben. This structure and the Maroa and Okataina volcanic centres appear to be associated with an intrusive belt along which hot springs are located on the south-eastern flank, notably on the Paeroa Fault.

North-east of the Okataina Volcanic Centre the only hot springs of importance are those of Onepu, at Kawerau. They are located within the Wakatane Graben where rhyolite extrusions appear to be associated with north-east faulting. At sea are Whale Island, which is the remains of a small andesite volcano with a few hot springs, and White Island, an active fumarolic volcano also of andesitic composition.

In general the locations of the hot springs are determined by faults. In some cases these are clearly of major significance; for example, along the important Paeroa Fault lie the thermal areas of Waikite, Te Kopia and Orakeikorako.

At Wairakei, on the other hand, the field is traversed by numerous fault traces along which some

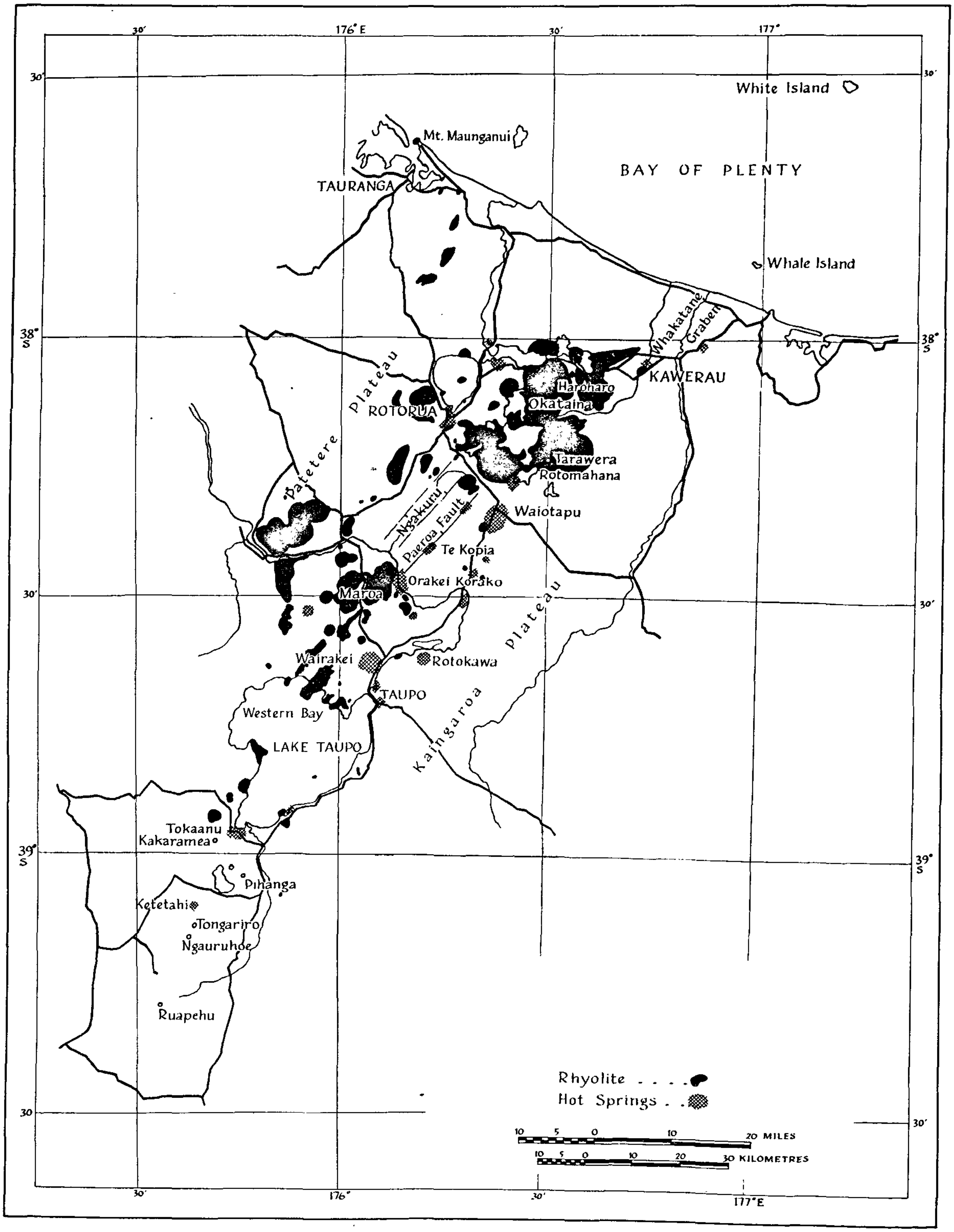


**Figure 2. Map showing hot springs and rhyolite extrusives of the Taupo Volcanic Zone**

of the hydrothermal activity is located. In particular the Wairakei and Waiora faults are believed to channel hot water to the surface from a depth of at least 2 000 ft, but these faults produce little dislocation in the top few hundred feet of strata and their significance at depth is not fully known. Possibly the channels that feed the Wairakei system occupy a fissured zone of which the two faults above are relatively superficial members. (For details of geological structure of the Wairakei field, see the paper by G. W. Grindley.)

The ignimbrite and other eruptions of the Taupo Volcanic Zone were accompanied by large-scale subsidence and the formation of extensive lakes in which were laid down siltstones and sandstones interbedded with pumiceous pyroclastics and ignimbrites. These stratified deposits are of importance in geothermal problems, as the pyroclastics constitute aquifers and the fine-grained sediments impermeable strata and cap rocks.

## Hydrothermal activity

The natural heat flow at Wairakei was originally estimated to be 130 000 kg-cal/sec (Healy, 1956), but refinements in the method of measuring heat loss from steaming ground by Bensemann (1959 a, b) have shown that this was probably too low. If it be taken as 160 000 kg-cal/sec (see paper by Thompson and others) and Wairakei is regarded as discharging one-sixth of the regional heat loss from hot springs, then this amounts to 960 000 kg-cal/sec. The eruption of 4 000 cubic miles of lava over a period extending from the Pliocene to the present dissipated approximately $16 \times 10^{18}$ kg-cals of heat, which is equivalent to the hot springs' discharges for a period of 530 000 years.

The present heat discharge of hot springs could thus appear to be important in relation to volcanism, but its true significance cannot be estimated because nothing is known of the extent of hydrothermal activity throughout the Pleistocene. A cooling magma losing 5 per cent of its weight as steam would discharge one-sixth only of its heat in that form (Healy, 1956). The remainder of the heat loss would be by conduction, which could only maintain extensive and vigorous hydrothermal activity if the magma lay at shallow depth to permit easy circulation of ground water to carry away the heat. If the activity was to be maintained for a long time, convection within the magma might be necessary.

White (1957) favours magmatic steam contributions from shallow convecting magma reservoirs as the heat sources for the American hot springs of volcanic association. The present writer (loc. cit) favoured magmatic steam as the heat source at Wairakei, for which the evidence is strengthened if the heat flow is greater than previously thought. More recently Ellis and Wilson (1960) quote chemical evidence in favour of a magmatic steam contribution. In any case conductive heat loss would be an important factor in the early stages of magmatic intrusion.

The role of hydrothermal activity in volcanism is of fundamental importance to geothermal problems, because if there is evidence for the presence of convecting magma reservoirs at shallow depth the potential heat supply can be large. At Wairakei, the presence of hydrothermal breccias beneath volcanic ash erupted 10 000 or more years ago shows that the area was hot then. Similar breccias, interbedded with the sediments underlying the area, indicate much older activity, so there is evidence of activity at various times over a long period but none to show whether it has been continuous. At Waiotapu, hydrothermal eruptions are known to have occurred about 900 years ago (Lloyd, 1959).

The hot springs discharge mostly ground water, and its occurrence and circulation are related to the geology. The basement rocks of the region are Paleozoic and Mesozoic greywackes and argillites, which form the ranges east and west of the volcanic region and underlie it except where replaced by intrusive granite or magma. These rocks have low permeability except possibly in fissure zones, from which good steam yields have been obtained at the Geysers in California. In New Zealand and Fiji, however, discharges from hot springs in greywackes are small.

Thick accumulations of ignimbrites, pumice breccias and tuffs, rhyolites and associated detrital sediments fill the depressions of the Taupo Volcanic Zone and adjoining areas. Permeability in these beds varies but is generally appreciable, and the supply of groundwater is comparatively plentiful.

Most discharging hot springs and drilled wells produce chloride water. Sulphate springs are formed superficially only by oxidation of $H_2S$, and bicarbonate springs where underground structure causes steam to separate and be channelled directly to the surface into non-saline groundwater. Steam boiled off from the hot water escapes from numerous vents and fumaroles.

The character of hot springs is an indication of conditions underground. Copious springs with temperatures below boiling point, such as those at Okauia and elsewhere on the Hauraki Plains, indicate low thermal gradient immediately underground, and little increase in temperature can be expected by drilling. If on the other hand the discharge is small, as at Ngawha, this may indicate poor permeability and steeper thermal gradient, in which case higher temperatures would be encountered by drilling.

The association of boiling springs and steaming ground, with or without geysers, indicates the presence of boiling point temperatures underground. At Wairakei, where the highest temperature measured in the wells was 266°C, the area might be regarded as fed by water at this temperature, boiling as it approaches the surface and thus producing both hot springs and steam jets. The ratio of heat discharged in steam to that in water at Waiotapu was appreciably higher than at Wairakei, and temperatures up to 295°C were measured in the wells.

Where hot springs and steaming ground are scattered over a large area, the presence of a shallow caprock and aquifer may be inferred. Hydrothermal activity occurs sporadically at Wairakei over an area of 7 square miles, within which hot water and steam are obtained in pumice breccias underlying mudstone and sandstone at a depth of 500 ft and more. At Waiotapu, most of the hydrothermal activity is scattered over an area covered at shallow depth by a thin mudstone. At Orakeikorako, where there is a large area of boiling springs and steaming ground, one could infer the presence of a caprock and temperatures at depths similar to those at Wairakei. In all cases the shallow confining strata are cut by numerous faults through which the steam and hot water escape.

At Larderello, the covering strata appear to be tight and underbroken because, although steam is found in permeable zones over a large area, the original hot springs were few, though vigorous. These conditions do not apply in the Taupo Zone, but at Ngawha in Northland small patches of hydrothermal activity occur in an area of thick, impermeable Cretaceous shales. Deep drilling here might produce steam.

### Geology and geothermal prospection

Although the quantity and chemical character of the available hot water determine the ultimate geothermal resources of a field, the primary requirements for a producing well are heat, as indicated by temperature, and permeability in a suitable aquifer.

In the Taupo Zone, the strata essentially form layered sequences, so a knowledge of stratigraphy is important in siting wells. However, as the relief and dip of the beds are low and there is a widespread mantle of volcanic ash, most of the details must be obtained by drilling. The first aim of the geologist is to relate the hydrothermal activity to geological structure and indicate the likely stratigraphic succession, and on this basis to select early drilling sites to yield the maximum geological and other information so that future production drilling can be planned. Geophysical data may be of use at this stage, but are more useful once drilling has produced definite information from depth.

The first investigational hole in any area should if possible be sited to give the stratigraphic succession, temperature at depth and its relationship to stratigraphy and inferred structure, the nature and extent of hydrothermal alteration, formation characteristics for drilling purposes and, if the well produces steam, discharge characteristics and samples for chemical analysis.

Some time is necessary for the preparation of sites for drilling, so it is necessary to plan these in advance. As it is desirable to make use of the information gained by drilling, however, site preparation should not be kept unduly far ahead. During recent investigational drilling at Wairakei it has been found profitable to change both the sites and order of drilling of some holes in the light of fresh discovery.

At Wairakei, a line of holes was first drilled in 1950 and 1951 across the suspected hot area at right angles to the known structural features. The holes were drilled to an arbitrary depth of 600 ft though two went to 1 000 ft, the limit of the machines available. It was proved that beneath a widespread mudstone (Huka) at depths of about 500 ft, production could be obtained from permeable pumice breccias. The drilling of production wells to depths ranging from 500 ft to 1 500 ft to provide steam for a 20 MW power station was commenced.

At Waiotapu, the drilling of 600-ft holes would have proved abortive, because there the superficial mudstone is too thin and broken to retain pressure beneath it.

However, with the arrival of larger drilling machines in 1953, investigation to greater depth changed ideas on the scheme of drilling. Hole 20, the first of the deep wells, struck at 2 025 ft a fissure in the top of hard ignimbrite underlying the pumice breccias and set the pattern for future drilling in the western half of the production area. Farther east Hole 37, drilled to 3 700 ft, failed to encounter the ignimbrite, proving that it dips sharply in that direction beneath a much greater thickness of the pumice breccias.

Within the present production area, therefore, two programmes of drilling have emerged. In the western half, wells are drilled to depths over 2 000 ft to intersect fissured zones in the top of the ignimbrite or in andesite, which in places overlies it.

In the eastern half, wells are drilled more or less on a grid pattern to intersect suitable producing horizons in the pumice breccias. The depths vary from about 1 100 ft in "the circle" area, where there is believed to be a direct hot water feed from depth, to over 2 000 ft west of it.

Although production can be obtained at about 600 ft immediately beneath the Huka mudstones, the higher temperatures and pressures encountered at greater depths have been found preferable, and this principle has guided later investigations. At Wairakei recent exploratory wells have been drilled to 3 000 ft, though one in the production area went to 4 026 ft, and at Waiotapu the deepest exploratory well reached 3 643 ft. Production wells at Kawerau reach a maximum depth of 3 250 ft.

Exploration of the remaining part of the Wairakei field west and south of the production area is now far advanced, and it has been found that geological conditions divide it into two parts. In the southern half, up to 1 500 ft of buried rhyolite lavas lie beneath 600 ft to 1 200 ft of pumice breccias and sandstones and are underlain by breccias and ignimbrites. Temperatures are higher in the upper part of the rhyolite than in the lower half.

In the northern area, impermeable sandstone breccias and interbedded tuffs extend down to 2 000 ft and are underlain by pumice and rhyolite breccias with interbedded sandstones. The highest temperatures are found in the breccias below 2 500 ft.

At Waiotapu, holes drilled in an area two miles long penetrated a stratigraphic succession of ignimbrites and interbedded pumice breccias which is the same throughout the field, except for andesite present at the lowest levels at the south end.

Exploratory holes drilled at Kawerau revealed the presence of rhyolite between 200 ft and 300 ft from the surface, extending down to 1 258 ft in Hole 1, which produced a fair discharge from the lower part of the rhyolite and from pumice breccia beneath it. The thermal gradient showed temperature to increase through sandstones extending to the bottom at 1 475 ft, so six production wells were later drilled to about 2 000 ft and they produced successfully from pumice breccias interbedded with sandstones. The later deepening of four of these showed 500 ft of andesite to be present, and further production has been obtained from this.

East geothermal field has proved to possess its own geological and other problems which require to be solved by drilling before production drilling can be planned. However, all the areas drilled have one feature in common — good production has not yet been obtained in any well drilled more than half a mile from the limits of visible hydrothermal activity.

The relative abundance of ground water promotes the dissipation of heat by convective circulation, especially where superficial impermeable strata are punctured by fissures or explosion vents. Such conditions do not favour the development of extensive hot water or steam reservoirs of which there are no signs at the surface. Certainly the upper Wairakei aquifers are spread by the overlying mudstones to cover an area of 7 square miles, but the presence of hot water is indicated by scattered thermal activity.

To depths of 4 000 ft it has not proved possible so far to drill successful wells more than half a mile from visible activity, and possibly this is a general rule in areas of young, permeable volcanics. At greater depths conditions may be different.

## Problems of production

The two chief problems of production are firstly size and continuity of the supply of hot water and steam, and secondly effects of mineral deposition. In the original report on the proposed 20-megawatt power scheme for Wairakei the writer stated in 1952 that, although the natural heat flow could be drawn continuously from wells in a hydrothermal area, heat already stored in the country could also be drawn at a rate not then known. The same view was later conservatively stated by Grange (1955, p. 14), and discussion on this topic is elaborated in the paper by C. J. Banwell.[1]

[1] The rating of the power station was subsequently increased as a result of the success of deeper wells.

It was considered at the time that the factors controlling heat flow into the Wairakei system were conditions at depth, which would be little affected by shallow wells. After some years of continued production, water level has fallen in the aquifer and there has been some reduction of pressure in the fissures feeding the main wells, as explained by Mr. C. J. Banwell, who considers that the flow of hot water upwards through the ignimbrite has increased. Ellis and Wilson (1960) consider the entire area to be fed by a uniform body of hot water, so the presence of a large reservoir of hot water, probably beneath the ignimbrite, is inferred. Presumably this reservoir is being drawn upon. As its extent is not known, the ultimate resources of the Wairakei geothermal field cannot as yet be estimated.

After three years of production from the six 2 000-ft wells in the Kawerau field, it was found necessary to drill out deposits of mineral, but after this was done discharges and temperatures remained lower than they originally were. Colder water appeared to have encroached from the south-east into the stratified rocks so, as thermal gradients in the wells indicated higher temperatures to exist at lower levels, four were taken to depths ranging from 2 750 ft to 3 250 ft. Temperatures up to 277°C have been measured, and wells penetrated andesite which in the upper part is fissured and hydrothermally altered like andesite, rhyolite and ignimbrite at Wairakei. Increased production has been obtained, and it now remains to be seen whether further production will cause colder water to encroach again or hotter water to flow from deeper down.

Deposition of silica or calcite, or both, which has occurred in all the areas, is the second important problem. Experiments at Wairakei have shown that deposition occurs at and above the levels at which flashing or boiling commences. At Rotorua, where well temperatures rarely exceed 160°C, and at Wairakei, where they are often less than 250°C, boiling and consequently mineral deposition tend to occur in the cased portions of the wells, where the encrusting material may be drilled out when blockage becomes effective.

At Kawerau, where temperatures up to 277°C have been measured, boiling could be expected to occur at a depth of about 2 400 ft, which is below the level to which casing extends. Whereas Hole 8 produced a large discharge and Hole 12 considerably less, cores of andesite from the latter well at a depth of 2 450 ft contain numerous calcite veins, the deposition of which may account for a reduction in permeability and the lower discharge.

In this field, the boiling induced by lowering of pressure in the country when the wells are discharged could induce deposition of calcite in fissures and pores until permeability is permanently reduced. Possibly reduction of permeability in the hottest zone by this process may have been a factor in inducing the encroachment of colder water into the 2 000-ft wells.

At Waiotapu, where temperatures up to 295°C were measured and calcite deposition has occurred in wells, this problem could also prove to be important.

Geothermal fields in which wells tap hot water are therefore of two types so far as mineral deposition is concerned — those in which boiling occurs within the cased parts of the wells, and those in which it occurs at lower levels and in the country itself. It is perhaps fortuitous that Rotorua and Wairakei, the first areas to be drilled to any extent, seem to have fallen within the first category, but over-production from such an area can lower water levels to such an extent that it becomes one of the second type.

Although the problems of supply and mineral deposition have been described separately, they are possibly connected. In eminently permeable country, where the dissipation of heat by convection is promoted, temperatures in the water phase will be lower, resources greater and mineral deposition will tend to be shallow. Where the rocks have less permeability and convective circulation is restricted temperatures will be higher, groundwater resources lower, and mineral deposition deeper.

However, where there are extensive and thick impermeable beds capping permeable beds, these may be filled with steam rather than hot water, and in that case mineral deposition would not be a problem unless the steam temperature was high. These last conditions have not been found in New Zealand so far.

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## *Summary*


Hot springs are scattered widely throughout New Zealand, but the hottest and most extensive are confined to the Taupo Volcanic Zone, from which nearly 4 000 cubic miles of lava and pyroclastics were erupted during late Pliocene and Quaternary time. The hot springs of the zone are of volcanic association and are believed to derive their heat from shallow magma.

The Taupo Volcanic Zone extends across the North Island for 190 miles in a north-east direction, forming a narrow belt of complicated topographic relief of structural and volcanic origin, flanked by flat-lying ignimbrite plateaux. Crustal fusion has produced dominantly rhyolitic lavas, the youngest of which are notably concentrated in the Maroa and Okataina volcanic centres, lying athwart the Taupo Zone.

The hot springs generally are located on faults that lie along the south-east flank of the intrusive belt and the volcanic centres, though the Rotorua springs lie west of it in the Rotorua caldera. The zone is marked by subsidence which accompanied the volcanism, and the permeable volcanics which fill the basins provide a relatively abundant supply of ground water for the springs.

On account of the permeability of the strata generally, no widespread reservoirs of hot water or steam are believed to exist unsuspected within 4 000 ft of the surface. Extensive areas of scattered hot springs, such as that at Wairakei which spreads over 7 square miles, indicate the presence of an aquifer beneath a shallow caprock, but so far no wells drilled more than half a mile from the limits of visible hydrothermal activity have produced steam. Conditions below 4 000 ft are not yet known.

The rocks generally form layered sequences, in which pumice breccias, tuffs, jointed andesite, rhyolite and ignimbrite form permeable aquifers, and sandstones and mudstones impermeable strata. Surface geological information is in most cases sparse, so the drilling of exploratory holes, sited to give maximum information on stratigraphy and structure and the relationship of temperature to them, is essential in each field before production drilling can be planned.

The wells tap chloride waters at depths ranging from 500 ft to over 3 000 ft and at temperatures which reach 266°C at Wairakei, 277°C at Kawerau and 295°C at Waiotapu. In Rotorua, temperatures are rarely above 160°C, but there no deep wells have been sunk in the hottest areas.

At Wairakei only is steam used for the generation of electric power. At Kawerau high pressure steam is used at the Tasman pulp mill for process purposes,

and at Waiotapu the exploratory stage has not been passed.

Although it was found that production could be obtained from an aquifer beneath 500 ft from the surface at Wairakei, later deep drilling showed that the higher temperatures, pressures and discharges from 2 000 ft are preferable, and this has governed later investigations. Most production wells at Wairakei are deeper than 2 000 ft, though one large one is 1 140 ft. Production wells at Kawerau range from 2 000 ft to 3 250 ft, and at Waiotapu the deepest exploration hole is 3 643 ft deep.

In the western half of the Wairakei production area, wells are drilled to more than 2 000 ft to intersect fissures in the upper part of hard ignimbrite or, in a few places, andesite. Farther east the wells are generally shallower, and tap the pumice breccia aquifer which overlies the ignimbrite to greater depth there.

At Kawerau, six wells drilled to 2 000 ft tapped hot water in stratified pumice breccias and sandstones, but following the encroachment of colder water after three years of production, four of them have been deepened to an average of 3 000 ft. They cut 500 ft of andesite and now produce greater discharges from fissures within it.

At Waiotapu, there is a thick sequence of ignimbrites, pumice breccias and occasional interbedded sandstones.

The chief problems are continuity of supply and chemical deposition. Stored heat can be estimated to depths for which there is information, but at Wairakei, for example, there appears to be evidence that many wells are now drawing on a reservoir somewhere below 4 000 ft, and its character and extent are not known.

The first production wells at Kawerau appeared to draw heavily on aquifers which they intersected, but it is not yet known whether the deepened wells will do likewise or draw on deeper resources.

Deposition of calcite or silica, or both, occurs in many wells, above the point at which boiling occurs. The problem is a minimum where the temperatures are such that this occurs within the cased portions of the wells, but in hotter areas the boiling can occur at lower levels in the country and so cause deposition of mineral in pores and fissures with loss of permeability.

The problems of hot water resources and loss of permeability by mineral deposition may be connected, because high permeability induces more rapid circulation and lower temperatures.

## CONSIDÉRATIONS GÉOLOGIQUES ET ÉNERGIE GÉOTHERMIQUE DANS LA RÉGION VOLCANIQUE DE TAUPO (NOUVELLE-ZÉLANDE)

### *Résumé*


On trouve des sources chaudes un peu partout en Nouvelle-Zélande, mais les plus chaudes et les plus importantes d'entre elles sont limitées à la zone volcanique de Taupo dont près de 4 000 miles cubes (16 700 km$^3$) de laves et de produits pyroclastiques firent éruption vers la fin du pliocène et pendant le quaternaire. Les sources chaudes de la région ont un caractère volcanique et l'on croit que la chaleur leur est fournie par une masse de magma peu profondément située.

La région volcanique de Taupo coupe l'île du Nord sur 190 miles (300 km environ) dans une direction nord-est, formant une zone étroite au relief topographique compliqué, d'origine structurelle et volcanique, flanquée de plateaux d'ignimbrite horizontaux. La fusion de la croûte a produit des laves qui, dans l'ensemble, sont rhyolitiques et dont les plus jeunes sont visiblement concentrées dans les centres volcaniques de Maroa et Okataina, lesquels, à leur tour, coupent la zone de Taupo.

Les sources chaudes sont généralement trouvées sur des failles disposées le long du flanc sud-est de la zone d'intrusion et des centres volcaniques, bien que les sources de Rotorua soient à l'ouest de ce système, dans la caldera du même nom. La zone est marquée par un affaissement qui a accompagné le volcanisme, et les produits volcaniques perméables qui remplissent les bassins fournissent des réserves relativement abondantes d'eaux souterraines qui alimentent les sources.

Compte tenu de la perméabilité générale des couches rencontrées, on ne pense pas qu'il existe de réservoirs importants d'eau chaude ou de vapeur sans qu'on le sache à moins de 4 000 pieds (1 200 mètres à peu près) de la surface. Des régions importantes de sources chaudes diffuses, telles que celle de Wairakei, qui s'étend sur 7 miles carrés (18 km$^2$), indiquent la présence d'une masse aquifère sous un terrain de recouvrement peu épais, mais, jusqu'à présent, aucun des puits qui ont été foncés à plus de 1/2 mile (0,8 km) des limites de l'activité hydrothermique visible n'a donné de vapeur. On ne connaît pas encore les conditions au-dessous de 4 000 pieds (1 200 m).

Les roches constituent généralement des structures litées, dans lesquelles des brèches de pierre ponce et des tufs, avec l'andésite, la rhyolite et l'ignimbrite fissurées forment des masses aquifères perméables, les grès et les schistes argileux des couches imperméables. Les renseignements géologiques en surface sont peu abondants dans la majeure partie des cas, si bien que le fonçage de puits d'exploration en des

points choisis pour renseigner le plus possible sur la stratigraphie, la structure et les rapports que présente la température avec eux, est indispensable pour chaque champ avant que l'on puisse organiser le forage de production.

Les puits dégagent des eaux chlorurées à des profondeurs qui s'échelonnent entre 500 pieds (150 m) et plus de 3 000 pieds (900 m) et à des températures qui atteignent 266 °C à Wairakei, 277 °C à Kawerau et 295 °C à Waiotapu. A Rotorua, les températures dépassent rarement 160 °C mais, dans cette région, on n'a pas foncé de puits profonds dans les régions les plus chaudes.

Ce n'est qu'à Wairakei que l'on se sert de la vapeur à la production d'énergie électrique. A Kawerau, on fait usage de vapeur sous haute pression à l'usine à pulpe de Tasman dans divers procédés de préparation et Waiotapu n'a pas encore dépassé le stade exploratoire.

Bien que l'on ait découvert qu'il est possible d'obtenir une production d'une masse aquifère trouvée à moins de 500 pieds (150 m) de la surface à Wairakei, les puits profonds qui ont été foncés par la suite ont démontré que les températures, les pressions et les débits plus élevés qui sont rencontrés à 2 000 pieds (600 m) sont préférables et cette constatation a donné le ton aux recherches ultérieures. La plupart des puits en production à Wairakei sont à une profondeur qui dépasse 2 000 pieds (600 m) bien qu'il en existe un gros de 1 140 pieds (347 m). Les puits en production à Kawerau s'échelonnent entre 2 000 et 3 250 pieds (600 et 991 m) et à Waiotapu, le puits d'exploration le plus profond va jusqu'à 3 643 pieds (1 110 m).

Dans la moitié occidentale de la zone en production à Wairakei, les puits sont foncés à plus de 2 000 pieds (600 m) pour réaliser l'intersection avec des fissures qui se trouvent dans la partie supérieure de l'ignimbrite dure ou, en quelques lieux, de l'andésite. Plus à l'est, les puits sont généralement moins profonds et tributaires de la masse aquifère en brèche de pierre ponce qui recouvre l'ignimbrite en ce lieu sur une plus grande épaisseur.

A Kawerau, six puits foncés à 2 000 pieds (600 m) ont rencontré de l'eau chaude dans des brèches stratifiées en pierre ponce et des grès mais, étant donné des pénétrations d'eau plus froide après trois ans de production, quatre d'entre eux ont été approfondis jusqu'à une moyenne de 3 000 pieds (900 m). Ils traversent 500 pieds d'andésite et débitent maintenant davantage de fissures trouvées au sein de cette andésite.

A Waiotapu, on trouve une série épaisse d'ignimbrites, de brèches de pierre ponce avec, à l'occasion, des grès interstratifiés.

Les principaux problèmes sont la continuité de la fourniture et les dépôts chimiques. La chaleur en réserve peut être évaluée jusqu'aux profondeurs pour lesquelles on dispose de données mais, à Wairakei par exemple, on semble disposer d'indications suivant lesquelles nombre de puits seraient alimentés par un réservoir situé quelque part au-dessous du niveau de 4 000 pieds (1 200 m) et on ne connaît ni son caractère, ni son étendue.

Les premiers puits en production à Kawerau semblaient s'alimenter largement des masses aquifères qu'ils rencontraient, mais on ne sait pas encore si les puits approfondis feront de même ou seront alimentés par des ressources plus profondément situées.

Des dépôts de calcite ou de silice, voire des deux, se produisent dans nombre de puits, au-dessus du point duquel l'ébullition intervient. Le problème n'est pas trop grave lorsque les températures sont telles que cela se produit dans les parties tubées des puits, mais, dans les régions plus chaudes, l'ébullition peut se produire plus bas dans la roche encaissante et provoquer de la sorte des dépôts de minéraux dans les pores et les fissures, réduisant ainsi la perméabilité du milieu.

Les problèmes relatifs aux ressources en eau chaude et aux pertes de perméabilité à la suite du dépôt de minéraux sont peut-être apparentés, car une perméabilité marquée cause une circulation plus rapide et des températures plus basses.

# ISOTOPE GEOLOGY IN THE HYDROTHERMAL AREAS OF NEW ZEALAND

*J. R. Hulston**

Hydrothermal isotope work at the New Zealand Institute of Nuclear Sciences has concentrated on two main lines of work: the studies of natural variations of the stable isotopes of carbon and sulphur, which have led to the investigation of the use of isotopic equilibria established underground to determine temperatures at depth, and the use of the natural radioactive isotopes carbon-14 and more recently tritium as tracers for the estimation of ground-water turnover times. Both these lines of work have led to the use of the mass spectrometer to analyse the residual gases (i.e., those not absorbed by sodium hydroxide) for nitrogen, argon, methane and hydrogen in order to obtain information on the state of equilibrium of the carbon dioxide-methane reaction, as well as on the $C^{14}$/Argon ratios.

The study of the natural hydrogen/deuterium ratios together with the oxygen 18/oxygen 16 ratio appears useful (1) as an indication of the source of the recirculated water and of the magmatic/recirculated water ratio. As a first step in this, a deuterium mass spectrometer has been built and a number of preliminary samples analysed.

## Measurement of underground temperatures by isotopic equilibria

Craig (2) has suggested the possibility of using the temperature dependence of the isotopic equilibrium constants for an underground exchange between methane and carbon dioxide as a means of estimating underground temperatures. The necessary condition for this to be useful is that the rate of exchange must be sufficiently fast for a state of isotopic equilibrium to be attained during the time the two components exist underground at a reasonably constant temperature but not so fast that the state of isotopic equilibrium can be disturbed in the time taken for these two components to reach the surface. Craig made some measurements on methane and carbon dioxide samples from Yellowstone Park, but did not have a means of checking the temperatures obtained.

While a survey of $C^{13}/C^{12}$ ratios in some of the hydrothermal areas of New Zealand was being undertaken (3), it was felt that further investigation of this method would be useful particularly on samples from the Wairakei drillholes for which temperature and depth charts are available from geothermograph records. With this in view, samples from five drill holes in the Wairakei area were collected together with a number of other samples from fumaroles and hot springs in several N.Z. hydrothermal areas and a few methane samples from other colder areas.

The sampling procedures used depended largely on the methane concentration in the discharge. In the majority of cases the samples were condensed into evacuated flasks about $\frac{1}{10}$ filled with concentrated sodium hydroxide solution. The carbon dioxide and hydrogen sulphide were absorbed in the solution which became diluted by the condensed steam while the gases not absorbed (here called residual gases and including the methane) collected in the evacuated space above. In some cases, namely, the Wairakei drill holes and Karapiti fumarole, it was necessary to condense and separate off most of the water phase prior to the collection flask (see reference (3) for further details).

Back in the laboratory, a portion of the residual gases was removed and analysed. The mass spectrometer was used for this as it has the advantage of being able to measure argon-to-nitrogen ratios easily. Using this analysis, sufficient of the remaining residual gases containing about 10 cc. at NTP of methane was introduced into a Cu-CuO furnace and converted to carbon dioxide which was frozen in a trap cooled by liquid air. (Water was removed in a dry-ice trap.) A considerable number of passes through the furnace were required to obtain satisfactory conversion for the samples which had a high nitrogen concentration.

The $C^{13}/C^{12}$ ratios were measured on a 60° Nier type mass spectrometer (4) and are recorded as $\delta\ C^{13}$ values in parts per mil (°/₀₀) where

$$\delta\ C^{13}\ (^{\circ}/_{\circ\circ}) = \frac{(C^{13}/C^{12})\ \text{sample} - (C^{13}/C^{12})\ \text{standard}}{(C^{13}/C^{12})\ \text{standard}} \times 1000$$

The results given in the tables have been referred to the PDB standard used by Craig (5).

The $C^{13}/C^{12}$ ratios of a few samples (3) are shown in table 1, columns 3 and 4. The equilibrium temperatures calculated from the Table of Isotope Exchange equilibria given by Craig (2) and abridged here in table 2, are listed in column 5, while the maximum drill hole temperature (or surface temperature where indicated) is recorded in column 6.

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Table 1

| *Location* | *Sample No.* | *Total $CO_2$-$\delta C^{13}$ (‰) wrt. PDB* | *Methane -$\delta C^{13}$ (‰) wrt. PDB* | *Isotopic temp. (°C)* | *Measured temp. (°C)* | *Kx* | *Chemical equilibrium temp. (°C)* |
|---|---|---|---|---|---|---|---|
| *Wairakei drillholes* | | | | | | | |
| Bore 11 . . . . . . . . | R 400 | — 3.5 | — 26.0 | 260 | 203 | $3 \times 10^{21}$ | 240 |
| 18 . . . . . . . . | R 402 | — 3.7 | — 27.0 | 250 | 235 | $3 \times 10^{20}$ | 260 |
| 30 . . . . . . . . | R 403 | — 3.5 | — 27.3 | 245 | 260 | $5 \times 10^{24}$ | 200 |
| *White Island fumaroles* | | | | | | | |
| Big Donald . . . . . | R 507/2 | — 3.1 | — 16.1 | 440 | 453 * | $1 \times 10^{12}$ | 365 |
| Seven Dwarfs . . . . | R 507/6 | — 4.5 | — 23.3 | 250 | — | $1 \times 10^{22}$ | 235 |
| *Karapiti Fumarole, Wairakei* | | | | | | | |
| 712 . . . . . . . . . . | R 433/1 | — 3.9 | — 28.5 | 235 | — | $1 \times 10^{21}$ | 250 |
| *North Island hot springs* | | | | | | | |
| Awakeri Springs (54°C) | R 470/6 | — 9.0 | — 39.0 | 130 | — | $4 \times 10^{28}$ | 140 |
| Champagne Pool (99°) Waiotapu . . . . . . | R 407/2 | — 6.5 | — 27.9 | 280 | 280 † | $\sim 2 \times 10^{22}$ | ~ 230 |
| *Warm and cold springs* | | | | | | | |
| Helensville, North Is. . | R 464/4 | | — 58.0 | | | | |
| Beauley Tinui, Wairapara (15°C) . . . . | R 608/2 | + 17.0 | — 38.4 | | | | |

* Surface temperature.
† Temperature of nearby drillhole.

It will be seen from table 1 (columns 5 and 6) that there is a reasonable correlation between calculated and measured temperatures.

The samples of methane and carbon dioxide from the cooler pools were collected in order to check the possibility that the methane $\delta$ $C^{13}$ values from all regions were in the —25 to —30 ‰ ranges and that the satisfactory temperatures obtained were only coincidental. The values of —58 ‰, —38.4 ‰ obtained from Helensville and Beauley are an excellent rebuff to this suggestion.

In order to give further weight to the use of methane isotopic temperatures it was decided to look for a further means of checking that isotopic equilibrium existed. The mechanism by which the isotopic exchange takes place was suggested by Craig (2) to be the reaction

$$CH_4 + 2\,H_2O \rightleftharpoons CO_2 + 4\,H_2$$

If this reaction is responsible for the isotopic equilibrium and if isotopic equilibrium exists, then chemical equilibrium should also exist. The residual gas analyses were therefore converted to concentrations relative to the original discharge.

Ellis (6) has given values of the equilibrium constant ($K_p$) at various temperatures for this reaction, and these are given in table 3.

$K_p$ is defined by the equation

$$K_p = \frac{P_{CH_4} \cdot P_{H_2O}^2}{P_{H_2}^4 \cdot P_{CO_2}} \tag{1}$$

where $P_z$ is the partial gas pressure of $z$. The figures which are available directly are not the maximum gas pressure at depth, when the gases are dissolved in a single phase, but the molar concentrations ($x_z$) in the whole discharge at the surface.

The partial pressures, for a system in the liquid phase, are obtained by the relationship

$$P_z = P \cdot x_z / D^\circ_z \tag{2}$$

where $x_z$ is the molar concentration of $z$.

$D^\circ_z$ is the distribution coefficient (7)

$$D^\circ_z = \frac{\text{mole fraction in the liquid phase}}{\text{mole fraction in the gas phase}}$$

and P is the total pressure.

Insertion of equation (2) into equation (1) yields the relationship

$$K_p = \frac{(D^\circ_{H_2})^4 \cdot D^\circ_{CO_2}}{D^\circ_{CH_4} \cdot (D^\circ_{H_2O})^2} \cdot \frac{1}{P^2} \cdot \frac{[CH^4]}{[H_2]^4} \cdot \frac{[H_2O]^2}{[CO_2]} \tag{3}$$

By assuming that the total pressure P is equal to the saturated water vapour pressure at that temperature (this has been found to be a reasonable approximation) and that $D^\circ_{H_2O} = 1$, it is possible to split equation (3) so that all the temperature dependent terms are on one side of the equation, viz.

$$K_p = \frac{D^\circ_{CH_4}}{(D^\circ_{H_2})^4\, D^\circ_{CO_2}} \cdot P^2 = \frac{[CH_4]}{[H_2]^4} \cdot \frac{[H_2O]^2}{[CO_2]} = K_x \tag{4}$$

Table 2. Isotopic exchange equilibrium between $CO_2$ and CH (after Craig (2))

| | | | | | | |
|---|---|---|---|---|---|---|
| T °K | 0 | 273.1 | 298.1 | 400 | 500 | 600 |
| $\frac{C^{13}H_4}{C^{12}H_4} \Big/ \frac{C^{13}O_2}{C^{12}O_2}$ | 0 | 0.935 | 0.943 | 0.963 | 0.975 | 0.981 |

Values of $K_x$ have been evaluated for the range 100-374°C (table 3) from the extrapolated $K_p$ values of Ellis (6) and the solubility figures of Ellis and Fyfe (7). As methane solubility figures above 100°C were not available, the figures for oxygen, which are very similar to methane below 100°C, were used.

The temperature values corresponding to values of $K_x$ derived by solving equations of type (4) are listed in table 1 and indicate very strongly the existence of chemical equilibrium. This supports the existence of isotopic equilibrium through this reaction. From this it was thus concluded that the estimation of underground temperature from the isotopic equilibrium between carbon dioxide and methane is feasible at least under the conditions existing in the hotter hydrothermal areas of New Zealand.

## Sulphur isotopes

Work on sulphur isotopic measurements in N.Z. hydrothermal areas has been reported by Rafter, Wilson and Shilton (8), (9) and by Rafter, Kaplan and Hulston (10).

The isotopic ratios of the sulphate in solution and the $H_2S$ in the gas phase have been found to differ by $17 \pm 4$ ‰ in the Wairakei drill holes. Assuming the existence of an isotopic equilibrium between $H_2S$ and $SO_4^=$, calculations were made of the isotopic equilibrium constant for this exchange at a number of temperatures in the range 0-500°C and an equilibrium temperature of $370 \pm 70$°C was calculated for the Wairakei drill holes. It is necessary to consider the evidence for the existence of isotopic equilibrium in any measurement of this type and particularly in this case where the temperature obtained does not agree with either the measured temperatures in the drillholes or the isotopic temperatures obtained from the methane-carbon dioxide exchange.

Several possibilities exist which warrant brief consideration. First, isotopic equilibrium may not exist and either the $H_2S$ and $SO_4^=$ have different origins or the $SO_4^=$ has been formed from $H_2S$ in an unidirectional reaction and a state of isotopic equilibrium is being approached. Secondly, isotopic equilibrium may exist and either the information from which the isotopic equilibrium constant was calculated is in error or else the temperature derived refers to a part of the hydrothermal system prior to the bulk of water at 240-260°C which feeds the drillholes. If this is so, it would imply that the isotopic exchange rate between $H_2S$ and $SO_4^=$ is very much slower than that between $CH_4$ and $CO_2$. A calculation of the state of chemical equilibrium of a reaction likely to represent the over-all exchange between $H_2S$ and $SO_4^=$ would probably assist the elucidation of this problem, although the apparent variable loss of gas suggested by Rafter, Wilson and Shilton (8) would have to be taken into account.

## Groundwater circulation times

Recirculated groundwater is considered to be a major contributor to the hydrothermal discharge in most New Zealand areas and information on the circulation time is desirable for the estimation of the heat stored in the water. The evidence for this large groundwater contribution compared with the magmatic water contribution is largely that of the chloride content of the water, together with oxygen and hydrogen isotopic data. On the basis that the water in the oceans was originally derived from

Table 3. Variation with temperature of $K_p$ and $K_x$ for equation (4)

| *Temperature* °C | $K_p$ (after Ellis (6)) | $K_x$ |
|---|---|---|
| 100 | | $8 \times 10^{31}$ |
| 127 | $2.75 \times 10^{12}$ | |
| 160 | | $2 \times 10^{27}$ |
| 200 | | $2 \times 10^{24}$ |
| 220 | | $9.5 \times 10^{22}$ |
| 227 | $8.73 \times 10^{7}$ | |
| 240 | | $5.0 \times 10^{21}$ |
| 260 | | $2.4 \times 10^{20}$ |
| 280 | | $1.6 \times 10^{19}$ |
| 300 | | $1.6 \times 10^{18}$ |
| 327 | $7.4 \times 10^{4}$ | |
| 360 | | $9.0 \times 10^{12}$ |
| 374 | | $3.0 \times 10^{8}$ |
| 427 | $4.21 \times 10^{2}$ | |

magmatic water, it is usually considered that magmatic water has a chloride content similar to that of seawater, i.e., approximately 2 per cent. The water in the Wairakei area has a chloride content of 0.15 per cent (11), indicating the magmatic contribution in the order of 8 per cent.

The isotopic evidence is based on the work of Craig, Boato and White (1), who found that the $O^{16}/O^{18}$ and H/D ratios of hydrothermal samples in a number of areas of the world including New Zealand fell, when plotted on a graph of $D/H$ v. $O^{18}/O^{16}$, in lines of slope about 3, originating at a point close to the value of the $D/H$ and $O^{18}/O^{16}$ ratios of the local groundwater. If there had been a significant contribution of juvenile or magmatic water, then the $D/H$ and $O^{18}/O^{16}$ ratios would have tended towards a point corresponding to the value for juvenile or magmatic water. As this did not occur it was concluded that the magmatic contribution is of the order of 10 per cent or less. Preliminary D/H measurements made by the present author on N.Z. hydrothermal samples tend to confirm this conclusion, although the D/H values extend only over a range of 5 per cent.[1]

One of the most useful isotopes for the study of the underground circulation time is tritium (12.5 years half-life) as this is an isotope existing in the water itself rather than something which is only associated with the water. The estimation of the circulation time requires a knowledge of the tritium content of the feedwater to the circulation system as well as that of the discharge output. It is thus necessary to make measurements on surface waters in the surrounding area. In interpreting the results obtained, the possibility of leakage of young groundwater into the circulation system in a region close to the discharge point must be considered. This would have the effect of decreasing the apparent age of the discharge to an extent which depended on both the dilution factor and the circulation time of the bulk of the discharge.

Natural tritium determinations in the Wairakei area, reported by O'Brien and Bainbridge (12), show recent drillhole tritium activities of the order of 0.5 TU compared with between 2 and 3 TU for the average of a number of samples from Lake Taupo and Lake Wairakei, thus indicating an age considerably greater than one half-life of tritium.

The use of the carbon-14 isotope (5 760 years half-life) has been studied by Fergusson and Knox (13), who obtain $C^{14}$ activities in the range 0.4 to 1.8 per cent of normal groundwater. The low activities obtained for this carbon dioxide gas are due to the addition of old carbon dioxide to the system from either the magmatic gases or from the decomposition of carbonate layers at depth. The problem thus becomes one of finding a method of estimating this dilution. Fergusson (14) has made some initial investigations into the use of the atmospheric argon to carbon-14 ratio as a means of estimating this dilution and found reasonable agreement in this ratio between groundwater and hydrothermal samples. This method is based on the assumption that the carbon-14/dissolved atmospheric argon ratio of groundwater is reasonably constant and that any processes operating underground do not alter this ratio.

Because of the large $CO_2$ dilution at Wairakei, this method may only be useful if the turnover time is of the order of half the half-life, i.e., 3 000 years, but would be of considerably greater use in an area in which the dilution by old $CO_2$ was much lower and hence the carbon-14 activity considerably greater than that found in the New Zealand areas.

[1] One interesting sidelight of these $D/H$ measurements is that the hydrothermal water samples are not enriched in deuterium to any extent of economic importance for heavy water production.

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## *Summary*

Isotope work in New Zealand has concentrated largely on the radioactive carbon-14 isotope and on the stable isotopes of carbon and sulphur. More recently, measurements of natural tritium and deuterium have been made.

The most promising application of the stable carbon-13 isotope has been in the estimation of underground temperatures from the isotopic equilibrium between the carbon atoms of carbon dioxide and methane. Temperatures calculated by this method have been found in good agreement with the bottom of the bore temperatures ($\sim 250°$) at Wairakei and with the vent temperature (450°C) of a fumarole measured on White Island. The isotopic exchange is thought to proceed via the reaction with hydrogen and water, i.e.,

$$CO_2 + 4\,H_2 \rightleftharpoons CH^4 + 2\,H_2O$$

Analyses of bore gases indicate that this reaction is close to chemical equilibrium.

Measurements of $S^{32}/S^{34}$ sulphur isotopic ratios were made for steam and water phases of bore discharges.

Studies of water circulation times, which are important as an indication of the water storage, have been undertaken using natural tritium and carbon-14. The tritium activity obtained indicates an age of less than fifty years if there is a single circulation path. It is possible, however, that there are several circulation paths and the tritium activity may be due to dilution by shallower groundwater of much younger age.

The carbon-14 isotope (5 760 years half life) is useful for much longer circulation times, but the results are complicated by the addition of old carbon dioxide to the system underground. Production bores sampled at Wairakei had $C^{14}$ activities of $\frac{1}{2}$ to 1 per cent of atmospheric. Measurements of argon concentration have been made as a possible means of estimating this dilution.

Natural deuterium measurements have been made as the first step in obtaining H/D v $O^{16}/O^{18}$ graphs. The variation of H/D has been found to be rather small ($\sim$ 5 per cent).

# GÉOLOGIE ISOTOPIQUE DANS LES RÉGIONS HYDROTHERMIQUES DE LA NOUVELLE-ZÉLANDE

## *Résumé*

Les travaux effectués avec les isotopes en Nouvelle-Zélande se sont concentrés principalement sur le carbone 14, lequel est radioactif, ainsi que sur les isotopes stables du carbone et du soufre. Plus récemment, on a procédé à des mesures sur le tritium et le deutérium naturels.

Le carbone 13, isotope stable, a trouvé son application la plus fructueuse dans l'évaluation des températures souterraines d'après l'équilibre isotopique entre les atomes de carbone de l'anhydride carbonique et ceux du méthane. Les températures calculées par cette méthode ont été en bon accord avec les lectures faites en fond de puits (environ 250°) à Wairakei et avec les températures lues dans l'évent d'une fumerolle (450 °C) à White Island. L'échange isotopique, à ce que l'on pense, intervient sous forme d'une réaction avec l'hydrogène et l'eau de la forme suivante: $CO_2 + 4\,H_2 \rightleftharpoons CH_4 \pm 2\,H_2O$.

Les analyses faites sur les gaz que l'on trouve dans les puits indiquent que cette réaction est très voisine de l'équilibre chimique.

Des mesures ont été faites sur les rapports isotopiques entre les soufres $S^{34}$ et $S^{32}$ pour les phases vapeur et eau des produits s'échappant des puits.

Des déterminations des temps de circulation de l'eau, qui sont importantes en tant qu'indications de l'emmagasinage de ce fluide, ont été entreprises en se servant de tritium naturel et de carbone 14. L'activité obtenue pour le tritium indique un âge de moins de 50 ans s'il y a une seule voie de circulation. Il est possible, toutefois, qu'il y ait plusieurs passages qui se prêtent à la circulation et que l'activité du tritium soit due à la dilution de l'eau par une nappe souterraine moins profondément située et de formation beaucoup plus récente.

L'isotope carbone 14 (période 5 760 ans) rend des services quand il s'agit de durées de circulation beaucoup plus longues, mais les résultats sont compliqués par l'addition d'anhydride carbonique ancien au système souterrain. Les puits de production qui ont donné lieu à des échantillonnages à Wairakei avaient des activités, en $C^{14}$, qui s'élevaient de 1/2 à 1 p. 100 de l'activité atmosphérique. On a fait des mesures de la concentration en argon en tant que moyen possible d'évaluer cette dilution.

On a fait des mesures sur le deutérium naturel comme première étape dans l'établissement de graphiques H/D $O^{16}/O^{18}$. Les variations du rapport H/D ont été assez faibles (environ 5 p. 100).

# ALTERNATIVE METHODS OF DETERMINING ENTHALPY AND MASS FLOW

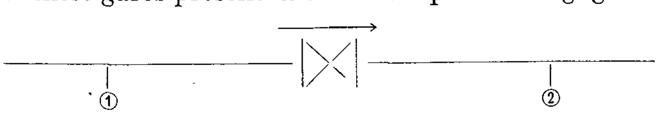
*Russell James**

## (1) *Beta-ray method*

A nozzle was attached at the end of a pipe through which varying quantities of steam/water mixtures were passed at constant values of enthalpy (total heat). A beta-ray source was positioned on the throat of the nozzle and diametrically opposite was a Geiger tube probe. The density of the steam/water mixture could be measured in a small column, with the throat diameter as axis, by estimating the absorption of the beta-rays. A single density determination was shown to be sufficient to estimate the dryness fraction. Using the upstream pressure it was also shown that the mass flow could be determined using an empirical equation similar in form to that derived from Bernoulli's principle. Estimations made of the limits of accuracy inherent to the system were ± 10 per cent for both mass flow and dryness fraction.

## (2) *Gas method*

Wairakei steam/water mixtures contain a number of non-condensable gases in the steam phase, the major constituent being carbon dioxide. The amount of these gases present in the water phase is negligible.




To determine the enthalpy in the line drawn above, the throttle valve is closed down until a pressure difference of at least 50 psi, and preferably over 100 psig, is obtained between points (1) and (2). A small cyclone is attached at each point and a sample of steam/water is extracted and then separated. The water is rejected and the dry steam is condensed in a flask which also collects the non-condensable gases, mainly carbon dioxide. By introducing sodium hydroxide into the flask and agitating, the carbon dioxide is taken into solution and the percentage mole fraction of the gas in the steam can be determined. Let suffixes 1 and 2 denote the sampling points.

$h$ = sensible heat of water. Btu/lb
$L$ = latent heat of steam. Btu/lb
$q$ = dryness fraction
$m$ = per cent mole fraction of carbon dioxide in steam.

As the enthalpy at points (1) and (2) is approximately equal, then

$$h_1 + q_1 L_1 = h_2 + q_2 L_2.$$

It can be shown that

$$\frac{q_2}{q_1} = \frac{m_1}{m_2}$$

is nearly correct.

The values of $h$ and $L$ are obtained from the steam tables for the pressures at (1) and (2) and the values of $m$ are obtained as above. The remaining unknowns $q_1$ and $q_2$ are solved using the two equations, and by this means the common value of enthalpy is obtained.

Although this method alone gives no information on mass flows, it can be used in conjunction with method 4 to obtain these values.

## (3) *Magnesium sulphate injection*

In an attempt to measure the flow of the liquid phase in a pipe carrying a water/steam mixture under pressure, a near-saturated solution of magnesium sulphate was injected at a steady rate into an upstream location and then sampled at a position downstream. It was considered that the amount of dilution of the solution would enable the water flow to be determined. The injection apparatus consisted of a 6 cu ft, 2 000 lb/sq inch nitrogen cylinder with a pressure reduction valve and gauges as used on cylinders of oxygen for welding purposes, a 1 cu ft steel pressure vessel to contain the injection solution (this vessel had a sight glass so that the liquid level could be observed) and two lengths of flexible high pressure hose: one to connect the two containers and the other to connect the bottom of the liquid container to an inlet valve on the pipeline.

It was possible to inject the solution at a steady rate into the pipeline for about 20 minutes, and this was ample time to take 12 to 15 samples at the downstream position. The concentration of samples at the downstream position was of the order of 10 parts per million of magnesium ions.

Calculations of the water flow-rates were found to be surprisingly poor and gave answers which were an average of 50 per cent too high. Numerous tests showed that good mixing was occurring due to the high turbulence in the line, which left the possibility of chemical adsorption of some of the magnesium ions within the pipeline, due to the presence of other

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chemicals (such as silica) in the liquid phase. Simultaneous with these tests, a series had been conducted in which larger quantities of the solution had been added to open flumes carrying near-boiling water. The downstream sample concentrations were of the order of 100 parts per million. The water flow results in this case were high by about 10 per cent. It would appear, therefore, that the higher the concentration at the downstream sampling point the greater the accuracy. Before a new series of tests was initiated using a variety of chemicals other than magnesium sulphate, a more direct physical method (4) was discovered which could be used to measure the flow of steam/water mixtures passing into the atmosphere if the enthalpy is known.

(4) *Critical lip pressure*

It has been found that if a fairly large flow of steam or steam/water mixture is expanded along a pipe to the atmosphere, then there is at the extreme end of the pipe a positive pressure above atmospheric which is proportional to the mass flowing and enthalpy, as in the following formula:

$$\frac{G\,E^{1.102}}{P_L{}^{\cdot 96}} = 11\,400$$

where $G$ = mass-velocity lb/sq ft (sec)
$E$ = enthalpy Btu/lb
$P_L$ = critical lip pressure lb/sq in absolute.

The results of work completed so far show this formula to be accurate to $\pm 3$ per cent in estimating flow-rates.

To obtain the lip pressure tapping, the following must be accomplished. A small hole, equal to, or smaller than, 1/25 of the pipe diameter, is drilled as near to the pipe outlet (the "lip") as is possible; a steel socket is now welded externally to the pipe at this position to take a pressure gauge. It is preferable to use a glycerine-damped gauge with a needle valve to eliminate the pulsations which are natural to two-phased flashing flow.

Using this system it is now possible to measure the flow of cyclone separated water flashing to the atmosphere along pipes. Also, the measurement of dry steam bores is easily accomplished using only a pressure gauge (the enthalpy of dry steam is approximately 1 200 Btu/lb).

### Example 1

The flow from a geothermal borehole is passed into a cyclone at 220 lb/sq in gauge where the steam is separated from the water and passed along an 8-inch pipe to be measured by means of an orifice before entering a power house. The high temperature water is allowed to flash from a throttle valve along an 8-inch pipe to the atmosphere. The lip pressure reads 25 lb/sq in gauge. What is the water flow and the enthalpy of the bore, if the steam flow was 60 000 lb/hour?

If the atmospheric pressure is 14.7 lb/sq in, then the lip pressure is $25 + 14.7 = 39.7$ lb/sq in absolute. At a cyclone pressure of 220 lb/sq in gauge, the enthalpy of water from the steam tables is 370.3 Btu/lb.

From the formula,

$$\frac{G\,370.3^{1.102}}{39.7^{0.96}} = 11\,400$$

Therefore $G = 572$.

Flow through 8-inch diameter pipe is $G\,\frac{\pi}{4}\left(\frac{d}{12}\right)^2$

$3\,600$ lb/hr $= 572\,\frac{\pi}{4}\left(\frac{8}{12}\right)^2 3\,600 = 720\,000$ lb/hr at 370.3 Btu/lb. At 220 lb/sq in gauge, the enthalpy of steam is 1 201.5 Btu/lb. Borehole enthalpy $=$

$$\frac{(60\,000 \times 1\,201.5) + (720\,000 \times 370.3)}{60\,000 + 720\,000} = 434 \text{ Btu/lb.}$$

### Example 2

A dry steam geothermal borehole blows vertically through a 6-inch internal diameter pipe. A pressure gauge at the extreme end of the pipe indicates 13.5 lb/sq in gauge. What is the flow?

Lip pressure $= 13.5 + 14.7 = 28.2$ lb/sq in absolute.

Enthalpy $= 1\,200$ Btu/lb.

$$\frac{G\,1\,200^{1.102}}{28.2^{0.96}} = 11\,400$$

Therefore $G = 112.6$.

Flow through a 6-inch diameter pipe is

$$112.6\,\frac{\pi}{4}\left(\frac{6}{12}\right)^2 3\,600 = 79\,500 \text{ lb/hour.}$$

### Measurement of heat flow from a borehole

The product of the factors G and E gives units of Btu/(sq ft) (sec) which are units of the rate of heat flow, or heat flux.

To see the effect of the factors involved, the original formula can be adjusted as follows, where $H$ = heat flux Btu/(sq ft) (sec) $= G \times E$

$$\frac{G\,E^{1.102}}{P^{0.96}} = 11\,400 = \frac{H\,E^{0.102}}{P_L{}^{0.96}}$$

Therefore

$$H = \frac{11\,400\,P_L{}^{0.96}}{E^{0.102}}$$

If the enthalpy of a borehole is not known but is between, say, 300 and 1 200 Btu/lb, then the value of H will be obtained accurate to $\pm 10$ per cent. At Wairakei, most of the boreholes have an enthalpy between 350 and 600, and in this case the heat flux can be obtained accurate to $\pm 3$ per cent.

EXAMPLE 3

A borehole whose enthalpy is unknown blows a steam/water mixture to the atmosphere through an 8-inch internal diameter pipe. A pressure gauge situated at the extreme end of this pipe reads 23 lb/sq in gauge. Find the heat flow in lb/hour.

Take the possible enthalpy range as 300 to 1 200. The average enthalpy value to take will be $\sqrt{300 \times 1\,200} = 600$.

Lip pressure = 23 + 14.7 = 37.7 lb/sq inch absolute

$$\text{Heat flux, } H = \frac{11\,400\, P_L^{0.96}}{E^{0.102}} = \frac{11\,400 \times 37.7^{0.96}}{600^{0.102}}$$

$$H = 1.92 \times 10^5 \text{ Btu/(sq ft) (sec)}$$

Heat flow through pipe per hour

$$= 1.92 \times 10^5 \frac{\pi}{4}\left(\frac{8}{12}\right)^2 3\,600$$

$$= 2.42 \times 10^8 \text{ Btu/hr} \pm 10 \text{ per cent}$$

EXAMPLE 4

If the enthalpy for example 3 is known to be within the range 350 to 600, find the heat flow in lb/hour.

Average value of enthalpy to be used will be $\sqrt{350 \times 600} = 458$

Heat flux,

$$H = \frac{11\,400 \times 37.7^{0.96}}{458^{0.102}} = 1.98 \times 10^5 \text{ Btu/(sq ft) (sec)}$$

Heat flow through pipe per hour

$$= 1.98 \times 10^5 \frac{\pi}{4}\left(\frac{8}{12}\right)^2 3\,600$$

$$= 2.48 \times 10^8 \text{ Btu/hr} \pm 3 \text{ per cent}$$

## References


1. Belin, R. E. and Bainbridge, A. E., Estimation of Dryness Fraction and Discharge of Geothermal Bores. *Proc. I. Mech. E. 171*: 36. 967-82, 1957.
2. Mahon, W. A. J., this series of papers (G/46).


## *Summary*


Many methods have been suggested for measuring the quantities of steam and water issuing from geothermal boreholes and the more obvious ones have been used. These, however, usually suffered from a requirement of heavy and bulky equipment. The measurement of the fluid quantities over a range of well-head pressures form the characteristic output curves of a borehole which may vary with time for a given hole. It is of importance, therefore, to have available some easily transportable apparatus which can be used to determine these mass flows at a given well-head pressure. It is preferable to have the equipment manoeuvrable by, at the most, two men, and the method simple enough for a technician to be able to make the determinations. Because of the high erosive action of water-steam mixtures, it is best to avoid inserting anything mechanical into the pipe cross-section for any length of time, particularly near the pipe outlet where the velocity of flow is greatest.

Four methods have been employed in New Zealand and these are described:

*Beta Ray Method*, where a beta ray source is mounted on one side of a nozzle and a Geiger counter diametrically opposite.

*Gas Method*, where samples of two phase mixtures are taken either side of a throttling valve and the gas content of the steam phase is analysed in each sample and the enthalpy calculated.

*Magnesium Sulphate Injection*, where a known concentration is injected at a steady rate into two-phase mixture and sampled after adequate mixing, and the magnesium content of the water phase analysed and the flow calculated.

*Critical Lip Pressure*, which measures the pressure at a predetermined point near the discharge of a bore under pressure to atmosphere. An empirical relationship has been found of mass flow, enthalpy and critical lip pressure.


# VARIANTES DES TECHNIQUES DE DÉTERMINATION DE L'ENTHALPIE ET DU DÉBIT EN POIDS

## *Résumé*


On a mis en avant nombre de méthodes pour mesurer les quantités de vapeur et d'eau qui jaillissent des puits géothermiques et on a fait appel à celles qui étaient les plus évidentes. Néanmoins, elles présentaient l'inconvénient d'exiger un matériel lourd et encombrant. La mesure de quantités de fluide sur une ample gamme de pressions en bouche de puits donne des courbes caractéristiques de débit qui peuvent varier en fonction du temps pour chaque puits. Il est donc important de disposer d'un matériel facile à transporter, dont on peut se servir pour déterminer simplement ces débits en poids à une

pression donnée de bouche de puits. Il est préférable que le matériel puisse être manœuvré par deux hommes au plus et que la méthode soit d'une simplicité telle qu'un technicien puisse procéder aux déterminations voulues. Compte tenu de la puissante action érosive des mélanges vapeur-eau, il est indiqué d'éviter d'introduire une pièce mécanique quelconque dans le tube pendant un temps appréciable, particulièrement près de son orifice où la vitesse de l'écoulement est la plus élevée. On a fait usage, en Nouvelle-Zélande, de quatre méthodes dont la description est donnée ci-dessous :

*Méthode des rayons bêta*, par laquelle une source de rayons bêta est montée d'un côté d'une buse et un compteur de Geiger-Müller en une position diamétralement opposée.

*Méthode du gaz*, par laquelle des échantillons des mélanges biphasiques sont prélevés de chaque côté d'une vanne d'étranglement, après quoi on analyse la teneur en gaz de la phase vapeur pour chaque échantillon et on calcule l'enthalpie.

*Méthode de l'injection du sulfate de magnésium*, avec laquelle on injecte, à un régime continu, une concentration connue du composé dans le mélange biphasique et on prend des échantillons après un brassage suffisant, à la suite de quoi la teneur de la phase eau en magnésium est déterminée et le débit calculé.

*La pression en un point critique*, qui mesure la pression en un point prédéterminé situé près de la sortie à l'air d'un puits sous pression. Un rapport empirique a été établi entre le débit en poids, l'enthalpie et la pression critique en bord de tube.

# SAMPLING OF GEOTHERMAL DRILLHOLE DISCHARGES

*W. A. J. Mahon**

At Wairakei, most of the deep drillholes discharge a mixture of steam and water of enthalpy between 400-500 Btu/lb. This means that at atmospheric pressure the steam makes up about 30 per cent by weight of the total discharge. The mass outputs of most of these drillholes lie within the range 200-1 000 klb/hr.

Before the production stage is reached, a typical well-head set-up consists of a horizontal by-pass pipe making a T-join with the vertical pipe. There are gate valves above and below the T-join, and on the by-pass close to the join. The discharge is either passed directly into the atmosphere from the end of the steel by-pass pipe or through a concrete silencer, which consists of a series of expanding concrete pipes (Smith, 1958).

Later, the drillholes are fitted with vertical twin-tower cyclone silencers at the end of an approximately 50-foot by-pass as described by Smith. In these silencers the separated steam emerges from the top of the towers, while water passes through a weir box into drainage channels. In most cases a throttle valve or back-pressure plate is inserted in the by-pass so as to maintain the well-head pressure at the production value. At Wairakei, "high-pressure" holes run at about 200 psig, and "intermediate" pressure holes at 80-100 psig.

When the drillholes are supplying steam to the power station, steam and water are separated at the well-head by inverted U-bend and cyclone separators, operating at either 210-220 or 75-85 psig.

From the time the drillhole is opened until the time its discharge is usefully employed, various sampling methods will be necessary. Examples of the methods used at Wairakei are given, together with information on the general flow patterns which may exist in horizontal by-pass pipes.

## Low-pressure sampling

### Water alone

To obtain the approximate chemical composition of the thermal water, an insulated double-walled bucket can be used to collect water from the end of the pipe, or from the side of the silencer. This water, which separates from the mixed steam/water discharge at about 99°C, is found in many cases when collected to be as cool as 70°C, and it is necessary to apply a correction assuming that the cooling is due to evaporation in the air. The concentrations of constituents determined this way can be in error by several per cent due to steam condensation within the bucket and the silencer, and imperfect evaporation corrections, but ratios between ions are satisfactory.

When twin-tower cyclone silencers are fitted to the by-pass pipes, excellent water samples can be collected at 98-99°C (local atmospheric boiling point) from the weir boxes. The samples are representative of the water in the discharges for the separation of steam at atmospheric pressure. Corrections for cooling by evaporation are almost negligible, as the water can be bottled near to 98°.

### Complete discharge

If the steam-to-water ratio, or the enthalpy, of the discharge from the drillhole is known, the chemical results obtained from separate steam and water phases can be combined to give concentrations in terms of the total discharge.

At Wairakei, the pressures at the end of a by-pass are usually not greater than 30-40 psig, and are sometimes as low as 10 psig. At these low pressures, samples may be taken from a point near the end of the by-pass through a small sampling valve, and separate steam and water phases obtained by use of a simple separator operating at atmospheric pressure (figure 1).

The separator, calorimeter, and piping must be heavily lagged to prevent heat losses, otherwise diluted water samples and concentrated steam samples will result. Before taking samples, the separator is allowed to warm up for 15 minutes.

The samples of steam and water obtained by this method are of correct composition only if the enthalpy of the sample entering the separator is the same as that of the discharge in the by-pass.

At sampling pressures of a few tens of pounds, the errors due to steam and water being sampled in incorrect proportions are often small, but the proportions of steam and water entering the separator should be checked by a simple water calorimeter (figure 1) and corrections to concentrations made (Ellis and Wilson, 1960). A discharge of almost pure steam or water is sometimes obtained from low-pressure sample points (see later) in which case extreme dilution of the small quantity of water by condensed steam will occur, or of the steam by flashing of the excess water.

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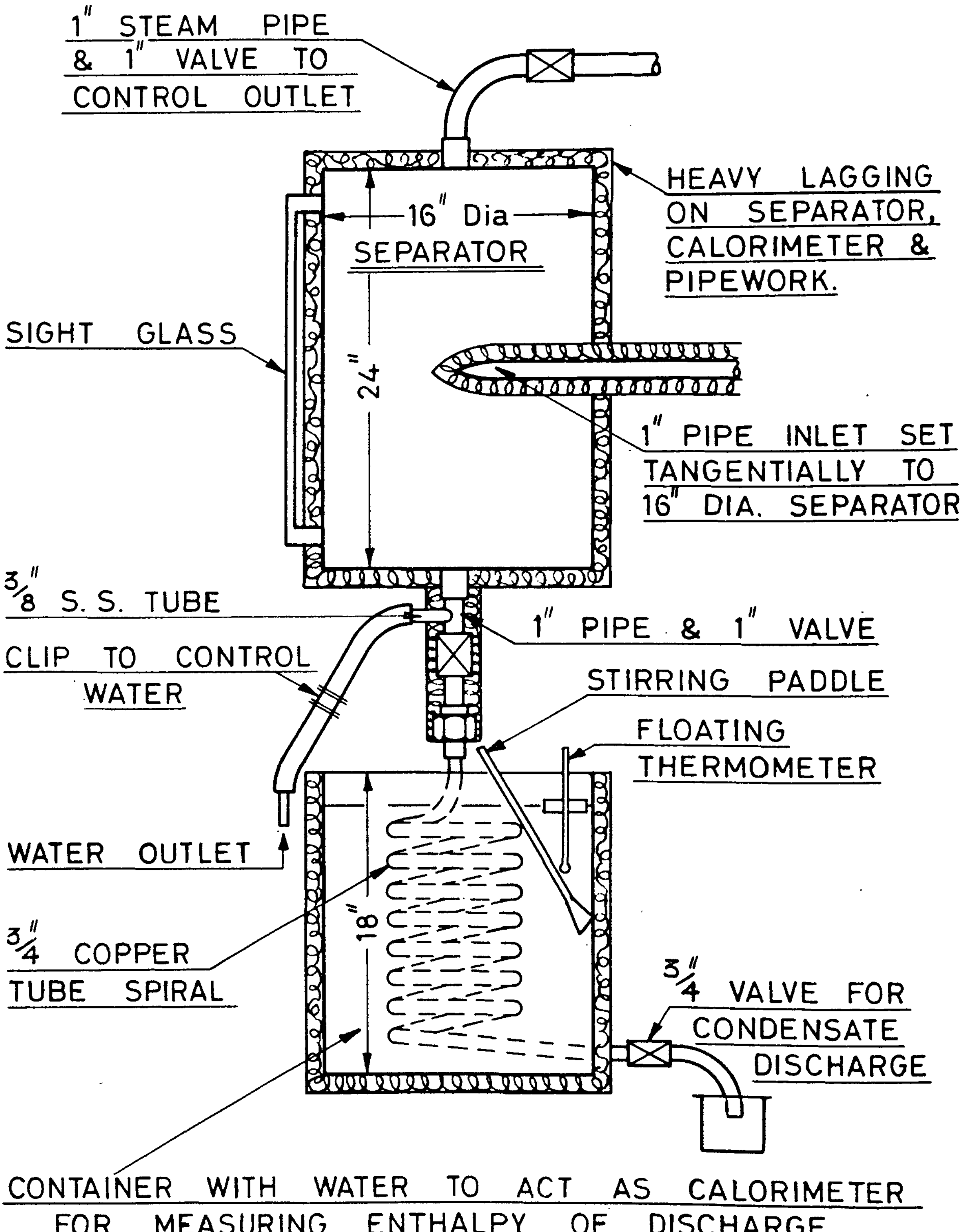
1" STEAM PIPE & 1" VALVE TO CONTROL OUTLET
HEAVY LAGGING ON SEPARATOR, CALORIMETER & PIPEWORK.
16" Dia
SEPARATOR
SIGHT GLASS
24"
1" PIPE INLET SET TANGENTIALLY TO 16" DIA. SEPARATOR.
3/8" S. S. TUBE
1" PIPE & 1" VALVE
CLIP TO CONTROL WATER
STIRRING PADDLE
FLOATING THERMOMETER
WATER OUTLET
18"
3/4" COPPER TUBE SPIRAL
3/4" VALVE FOR CONDENSATE DISCHARGE
CONTAINER WITH WATER TO ACT AS CALORIMETER FOR MEASURING ENTHALPY OF DISCHARGE.

Figure 1

The errors caused by sampling even slightly incorrect proportions of steam and water through an atmospheric pressure separator become large at high pressures. A separator working at the high sampling pressures is necessary.

## Sampling at higher pressures

### Flow pattern in pipes

From experiments on sampling steam and water at various positions on the discharge pipes of drill-holes, it is possible to find the best conditions for taking representative samples with the correct concentrations.

In taking high-pressure samples at Wairakei, small 2-in ID stainless steel Webre separators (Pollak and Work, 1942) are used, capable of operating at several hundred pounds steam pressure. The pressure drop through these separators is very small and samples are obtained of high-pressure steam, and of water cooled under pressure by passing through a cold-water jacketed pipe. Again, the separators are well lagged.

Although small variations in the steam/water ratio of samples entering the high-pressure separators do not affect the results, an inflow containing a large excess of steam results in the water samples being diluted through the condensation caused by slight heat losses. Entry of a large excess of water causes the steam samples to be diluted.

The results from two sets of experiments using different arrangements on by-pass pipes are given below. The pipes were of 8″ diameter, and the enthalpy of the discharges varied between 400-500 Btu/lb.

### Results from collection with open by-pass

The arrangement of sample points for this experiment was as shown in figure 2, but without the constriction (S) in the by-pass pipe. The sampling points 1, 2, 3, 4, 5, 6, 7, 8, 9, 10 consisted of 1-in sockets welded to the by-pass. The discharge through holes drilled in the pipe at these points was controlled by 1-in gate valves fitted to the sockets. With an open by-pass, the well-head pressure was over 50 psig.

Steam and water samples were taken at sampling points 1, 2, 3, 4, 8, 9 and 10 through high-pressure Webre cyclones, and water samples were taken from the weir box marked 11. The chloride content of the water samples and the carbon dioxide content of the steam samples were determined. Calorimeter measurements were made on the discharge emerging from each sample point.

From a knowledge of the enthalpy of the discharge from the hole, the chloride concentrations, as determined on the waters collected at high pressures, were corrected to the concentrations that would exist in water separated from the discharge at atmospheric pressure. This is the simplest basis for comparison purposes (Ellis and Wilson, 1960). The carbon dioxide results were recalculated to express the concentrations of this gas in the complete discharge.

The enthalpies of the steam/water mixtures from points 1, 2, 3 and 4 were of similar order to the known enthalpy of the discharge in the 8-inch by-pass (see table 1). Water samples representative of the water in the by-pass were separated from discharges by these points. The enthalpies of the discharges issuing from points 8, 9 and 10 were found to be very much higher than the true enthalpy of the discharge in the by-pass, with point 8 giving the least excess steam and the best chloride results. The low chloride results from the other two points reflect the high steam content of the mixtures. Consistent chloride results were obtained for the water samples from the weir box. These were in approximate agreement with chloride values from the high pressure sample points. The carbon dioxide results for the total discharge were similar for steam samples taken at all points along the by-pass.

### Results with constriction in by-pass

The arrangement used for this set of experiments was as in figure 2, with a constriction (S) in the

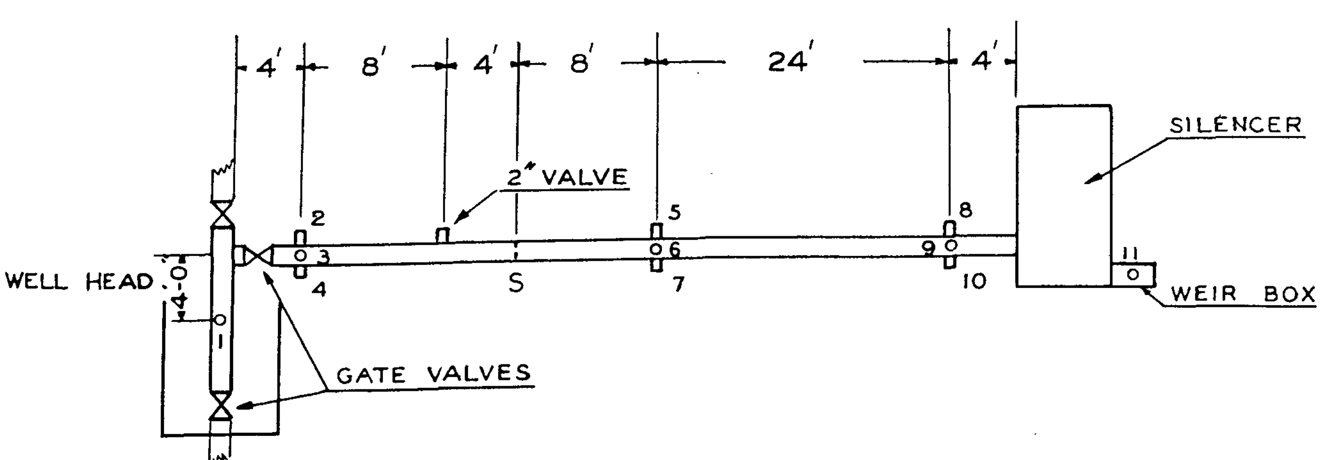


Figure 2

**Table 1. A selection of results obtained from drillhole 48 under open by-pass conditions**

| *Sampling point No.* | *S P (psig.)* | *Cl in water at 0 psig (ppm)* | *$CO_2$ in steam at SP (millimoles/100 moles $H_2O$)* | *$CO_2$ in total discharge (millimoles/100 moles $H_2O$)* | *Measured E of discharge from point using calorimeter (Btu/lb)* |
|---|---|---|---|---|---|
| 1 . . . . . . . | 90 | 2 234 | 65.1 | 7.2 | 460 |
| 1 . . . . . . . | 90 | 2 234 | 65.0 | 7.2 | 445 |
| 2 . . . . . . . | 60 | 2 250 | 55.2 | 7.5 | 520 |
| 2 . . . . . . . | 60 | 2 219 | 55.0 | 7.5 | 540 |
| 2 . . . . . . . | 60 | 2 226 | 55.4 | 7.5 | — |
| 3 . . . . . . . | 60 | 2 250 | 55.4 | 7.5 | 465 |
| 3 . . . . . . . | 60 | 2 250 | 55.6 | 7.6 | 520 |
| 4 . . . . . . . | 60 | 2 250 | 55.4 | 7.5 | 440 |
| 4 . . . . . . . | 60 | 2 250 | 56.7 | 7.7 | 480 |
| 8 . . . . . . . | 33 | 2 177 | 48.0 | 7.9 | 780 |
| 8 . . . . . . . | 33 | 2 221 | 48.2 | 7.9 | 670 |
| 9 . . . . . . . | 33 | 1 959 | 44.8 | 7.4 | 990 |
| 9 . . . . . . . | 33 | 1 968 | 46.2 | 7.6 | 890 |
| 10 . . . . . . . | 33 | 2 134 | 45.2 | 7.5 | 955 |
| 10 . . . . . . . | 33 | 2 150 | 46.8 | 7.5 | 790 |
| 11 . . . . . . . | weir box | 2 269 | — | — | — |
| 11 . . . . . . . | weir box | 2 269 | — | — | — |

WHP of drillhole was 108-110 psig.
Enthalpy of drillhole discharge was 400 Btu/lb.
SP = sampling pressure.
E = enthalpy.

form of a back-pressure plate placed in the by-pass 12 feet downstream from points 2, 3 and 4.

The pressures obtained in the by-pass of any drillhole with the above set-up depend on the mass output from the hole, the diameter of the by-pass, and the size of the throttling orifice. In the experiments the pressure upstream of the constriction was 200 psig, whilst at points 8, 9 and 10 the pressure was 25-30 psig.

The enthalpies of discharges from points 1, 2, 3 and 4 were again similar to the true enthalpy of the drillhole discharge (table 2). Reasonably consistent chloride results, agreeing with those from the weir box, were obtained for water samples taken at these four points.

At point 5, after the orifice constriction, a very low enthalpy discharge was obtained. It was impossible to take a steam sample as the separator became flooded. The chloride result tended to be low. Point 6 gave a reasonable steam sample, but again a rather low chloride and enthalpy result was obtained. The bottom point, 7, in contrast, gave almost all steam which resulted in a very low chloride concentration in the water sample. The gas concentration in the steam was not correct.

The lowest pressure points, 8, 9 and 10, gave discharges with enthalpies very much higher than the true enthalpy in the 8-in pipe, with almost dry steam being given from points 8 and 9. In agreement with this, the chloride content of the water samples taken from these two points was found to be diluted with steam condensate. The chloride content of water separated from point 10 was still low, but of the right order.

With the exception of samples from points 5 and 7, the carbon dioxide results were consistent.

### INTERPRETATION OF SAMPLING EXPERIMENTS

The general flow pattern of the discharges in 8-in by-pass pipes for the above conditions can be discussed in the light of the experimental results. Other similar experiments with the back-pressure plate and sampling points at different positions along the by-pass are taken into account.

The results with an open by-pass (table 1) are examined first. The hot water (250-260°C) from depth, as it rises up the vertical drillpipe, begins to boil when the pressure is sufficiently low. At the well-head a considerable amount of steam is present, the exact amount depending on the initial temperature of the water and the well-head pressure. The wellhead T causes a slight throttling effect on the discharge.

At 4 to 6 ft downstream from the bend, the steam and water were in an agitated condition which allowed representative samples of both phases to be collected at all positions around the pipe. The enthalpy of the discharge from a point located 12 ft downstream of the well-head T on the top of the by-pass was higher than for point 2, showing that at the 12-ft distance water had a tendency to flow at the bottom of the pipe.

The velocity of the discharge increases considerably as it passes down the by-pass to atmosphere. From the evidence available the greater portion of the water flows along the bottom of the by-pass pipe, with the steam above. However, water was still available for sampling at point 8 as water samples with reasonable chloride concentrations were obtained here. The discharge from point 8 had a relatively low enthalpy compared with that for points 9 and 10.

The dryness and poor water samples obtained from point 10 are rather surprising when other evidence suggests that water was flowing over this point. One possible explanation is that the water trying to enter the sampling socket was drawn back into the by-pass in a vortex due to the momentum of the discharge above.

At any point on the pipe under open by-pass conditions, equilibrium appeared to have been attained in the steam phases, i.e., there was good mixing between old steam and new flashed steam. Inside the twin-tower silencer there is little steam condensation and the water passing into the weir-box is not appreciably diluted.

With a constriction in the by-pass, for a distance of at least 12 ft upstream from the plate an agitated condition existed in the steam and water phases. Representative samples were obtained from points at positions around the by-pass 4 to 6 ft downstream of the well-head T.

The velocity of the discharge in the by-pass was considerably smaller upstream and considerably greater downstream of the constriction, compared with the velocities that existed under open by-pass conditions. After passing through the constriction, a proportion of the water in the discharge was thrown to the top of the by-pass and impinged of the pipe 8 to 10 ft from the orifice. Point 5 gave an enthalpy value which corresponded approximately with that of the water in the pipe at 180 psig before it passed through the constriction. When the constriction was a partly closed gate valve, similar results were obtained. The phases are not at equilibrium at this short distance after a constriction and poor sampling conditions exist.

The distance that water travels along the top of the pipe is not known, but 30 ft downstream of the constriction there was little water left on the top of the pipe (see high enthalpy and low chloride results for point 8, table 2). Thirty feet downstream the phases were in equilibrium again and representative steam samples were collected from points 8, 9 and 10.

The minimum distance downstream of the constriction at which the steam phase is at equilibrium is not known, but at Wairakei it is greater than 12 ft.

## Recommended sampling positions

Summarising the results from Wairakei, the following positions are recommended for representative steam and water sampling.

Water and steam samples can be collected under pressure (60-200 psig) from sampling points 4 to 6 ft downstream of the well-head T. The points can be located on the top, bottom or side of the by-pass and the sampling is not greatly influenced by a constriction in the pipe 12 to 20 ft downstream from the points.

Water and steam samples can be collected under pressure (60-200 psig) from a sampling point 4 ft upstream of the well-head T on the vertical well-head pipe.

Steam samples can be collected under pressure (10-50 psig) at a distance 30 ft downstream of a constriction, or at any position on the by-pass under

**Table 2. A selection of results obtained from drillhole 48 under constricted by-pass conditions**

| *Sampling point No.* | *SP (psig)* | *Cl in water at 0 psig (ppm)* | *$CO_2$ in steam at SP (millimoles/100 moles $H_2O$)* | *$CO_2$ in total discharge (millimoles/100 moles $H_2O$)* | *Measured E of discharge from point using calorimeter (Btu/lb)* |
|---|---|---|---|---|---|
| 1 . . . . . . . | 198 | 2 287 | 65.2 | 6.1 | 460 |
| 1 . . . . . . . | 198 | 2 287 | 65.4 | 6.1 | 490 |
| 2 . . . . . . . | 180 | 2 249 | 62.9 | 6.5 | 490 |
| 2 . . . . . . . | 180 | 2 249 | 61.9 | 6.4 | 470 |
| 3 . . . . . . . | 180 | 2 289 | 62.0 | 6.4 | 460 |
| 3 . . . . . . . | 180 | 2 289 | 62.8 | 6.5 | 460 |
| 4 . . . . . . . | 180 | 2 266 | 62.9 | 6.5 | 465 |
| 4 . . . . . . . | 180 | 2 266 | 62.9 | 6.5 | 480 |
| 5 . . . . . . . | 40 | 2 231 | Separator flooded | | 360 |
| 6 . . . . . . . | 40 | 2 228 | 30.4 | 6.8 | 420 |
| 7 . . . . . . . | 40 | 1 639 | 16.0 | 3.2 | 925 |
| 8 . . . . . . . | 28 | 1 008 | 29.2 | 6.3 | 1 045 |
| 8 . . . . . . . | 28 | 549 | 28.6 | 6.2 | 1 020 |
| 9 . . . . . . . | 28 | 1 052 | 29.2 | 6.3 | 1 020 |
| 9 . . . . . . . | 28 | 1 067 | 29.0 | 6.3 | 1 040 |
| 10 . . . . . . . | 28 | 2 010 | 28.7 | 6.2 | 925 |
| 10 . . . . . . . | 28 | 2 056 | 29.4 | 6.4 | 945 |
| 11 . . . . . . . | weir box | 2 284 | — | — | — |
| 11 . . . . . . . | weir box | 2 284 | — | — | — |

WHP of drillhole was 190-205 psig.
Enthalpy of drillhole discharge was 440 Btu/lb.

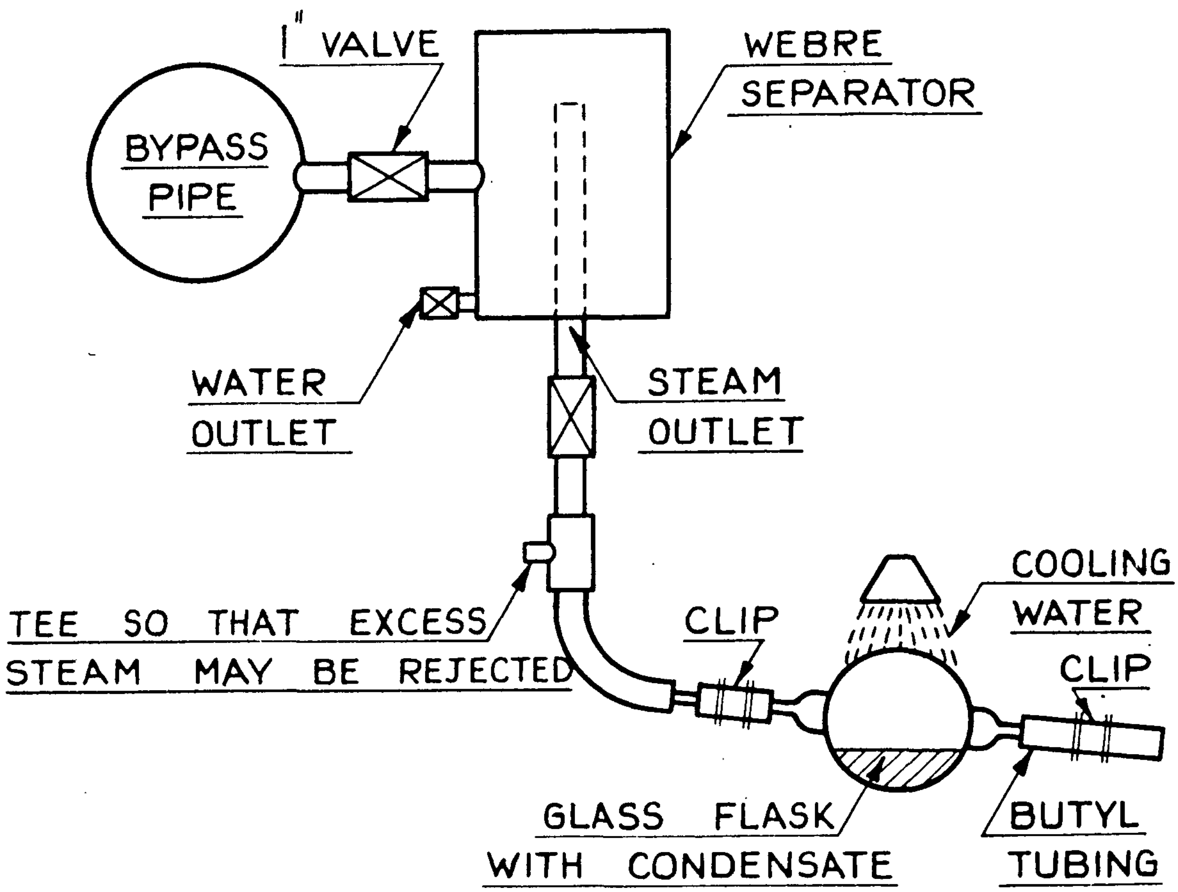


*Figure 3*

open by-pass conditions. In both cases the sampling point can be on the top, bottom or side of the by-pass.

When the complete discharge of a drillhole is being separated for utilization purposes, good water samples can be taken under pressure from the hot water main through the cold-water jacketed cooling assembly attached to the Webre sampling separators. Steam samples may be taken from the high-pressure steam main as shown in figure 3, with the omission of the Webre separator.

Water samples can be collected at atmospheric boiling point from the weir box of twin-tower silencers.

In all methods of sampling under pressure it is essential that there be only a very small pressure drop through the separators and that heat losses be negligible. A concentrated steam sample or diluted water sample will otherwise be obtained.

It should be noted that although representative steam samples can be taken at high pressures, it is not possible to calculate the gas content of the total discharge with any precision unless the enthalpy of the drillhole discharge is known accurately. For example, the percentage of steam at 200 psig is 16.5 per cent if the enthalpy is 500 Btu/lb, but only 10.6 per cent for an enthalpy of 450. Single steam samples will give a more accurate measure of the gas content of the discharge if they are taken at low pressures.

### Technique of collection

At Wairakei, steam samples are collected and condensed in thin-walled pyrex flasks of $2\frac{1}{2}$, 5 or 12 litres capacity held for protection in padded wooden stands. (Figure 3, also Wilson, 1955.) Lengths of high-pressure butyl rubber tubing are attached to each end of the flask, together with a clip to close the flask to atmosphere. Before starting a collection, the flask is evacuated with a vacuum pump and purged by allowing a jet of steam from the separators to pass through the flasks for five to ten minutes. Alternatively, the flasks may be filled with water which is then blown out by steam, and purged as before. With the steam still passing through the flask, any condensate which has been collected in the purging operation is removed. The flask is then closed to the atmosphere by screwing down the clip on the butyl rubber, and the steam which enters from the separators is condensed by playing water on to the surface of the flask. The non-condensable gases associated with the steam are collected in the flask above the condensate. After collecting the required amount of condensate the flask is closed to the separator. A pressure of non-condensable gases of about one atmosphere should be aimed at in the collection. For a gas content of 0.02 moles/100 moles of water, this requires the flask to be about quarter filled with condensate.

The flask is taken to the laboratory where hydrogen sulphide and carbon dioxide are absorbed into the condensate by the addition of alkali, and the residual gases are pumped off for conventional gas analysis, or gas chromatography.

The following procedure was worked out by S. H. Wilson, then at the Dominion Laboratory (unpublished work). Insert the narrow end of the glass tube (figure 4) into one of the butyl rubber tubes on the flask, and provide the wide end with a short length of wide-diameter tubing and a screw clip. Add 8-10 ml of 50 per cent sodium hydroxide solution for each litre capacity of the flask, fill with water to displace air and close off from the atmosphere. Open the lower clip and shake the alkali down into the flask, then shake again to extract the acid gases into solution. Invert the flask to refill the tube, close off, and remove the tube. Weigh the flask to obtain the quantity of condensate.

The flask is placed in a felt-lined box and one tube is connected to a vacuum system with manometer, McLeod gauge, and rotary oil pump. After half an hour, the temperature in the box is read, and the flask connection is opened to allow the gas pressure to be read on the mercury manometer. The residual gas is pumped over into a sample tube (figure 5), using water from the same drillhole, with salt added,

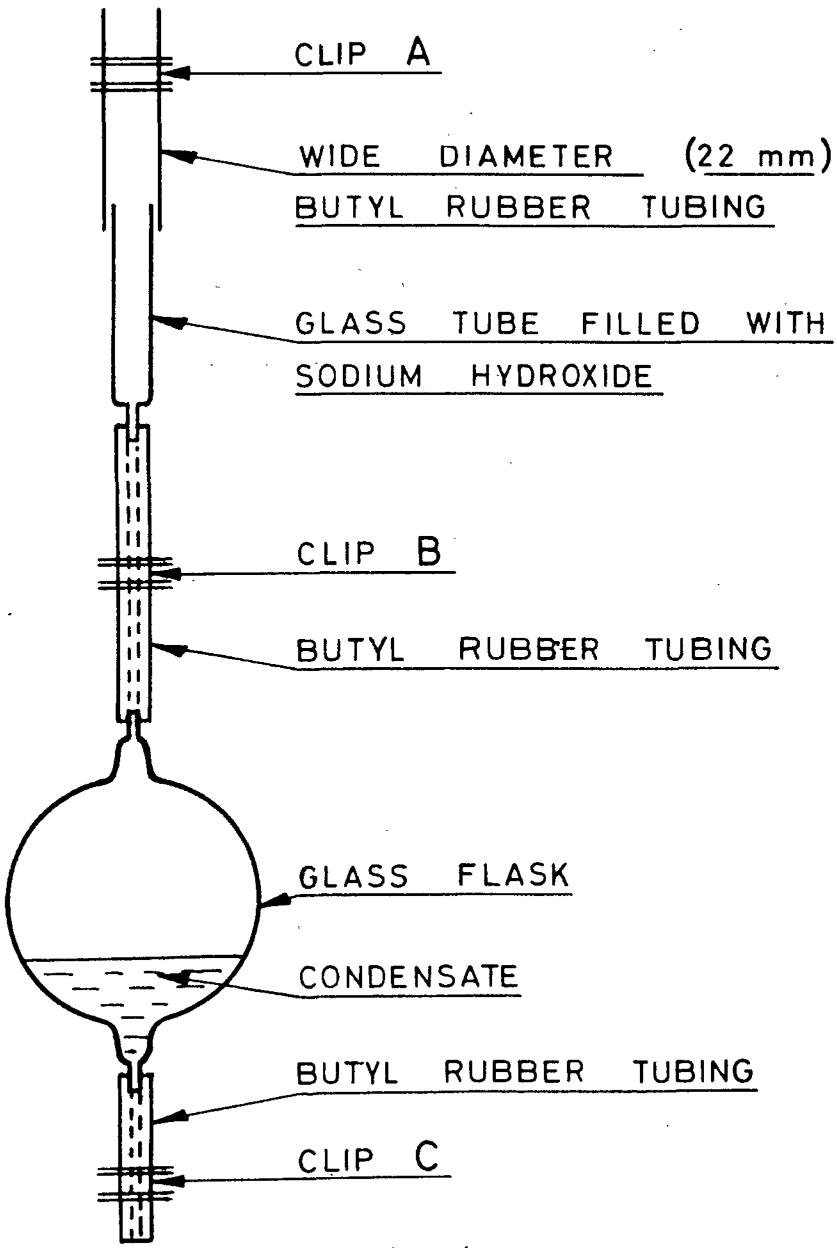


Figure 4

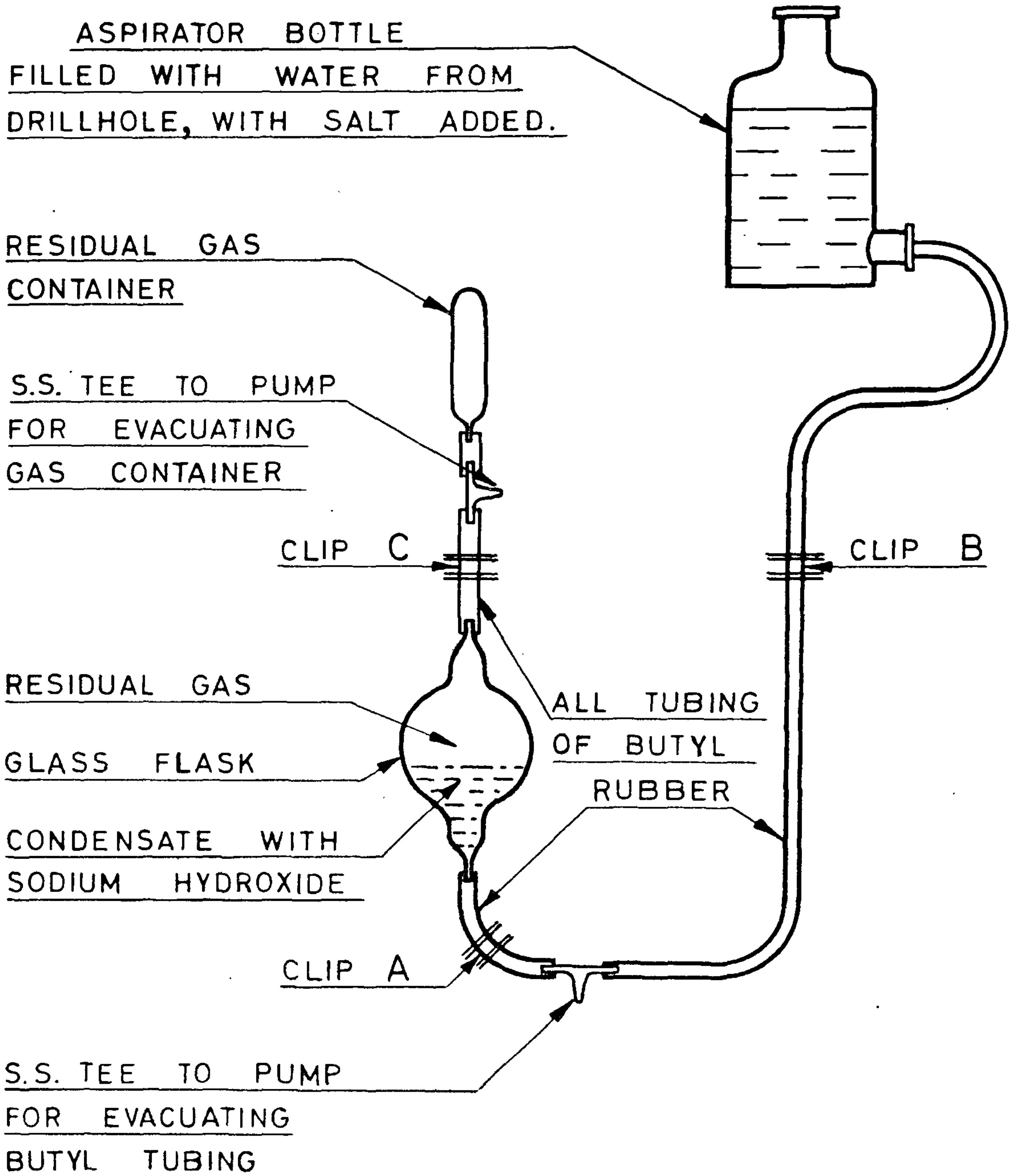


**Figure 5**

to fill the collection flask and compress the gas into the sample tube. A 10 per cent solution is convenient, with a dye added so that any mixing of the condensate and salt solution can be seen. The water from the drillhole has the advantage of containing no oxygen and little other dissolved gas.

After the gas transfer the salt solution is taken back into the bottle, the mixed layer and the bottom two-thirds of the condensate are rejected. Aliquots of the remaining condensate are taken immediately for sulphide and carbon dioxide analysis. If the samples are to be kept for a few days before analysis, the condensate is put in bottles capped with wide-diameter butyl rubber tubing. The bottles are filled to overflowing and the rubber clamped to exclude air.

Carbon dioxide and hydrogen sulphide, which make up approximately 97 per cent of the gases present in the drillhole discharges at Wairakei, are analysed in the alkaline condensate by acid and iodine titration. (Ritchie, this series of papers, G/29.)

Separate steam condensate samples are collected from the drillhole discharge for ammonia, boric acid, fluoride, and chloride determinations. As chloride and sodium ions exist only in the water phase, a determination of either ion in the condensate samples allows the amount of water associated with the steam to be estimated.

Water samples on which gas analyses or pH determinations are to be carried out are collected in glass bottles of 500 cc capacity with a piece of butyl tubing fitted to the top as for alkaline condensate storage. The outlet of the separator is lowered to the bottom of the collection bottle and at least 1 000 cc passed through the bottle to ensure that the 500 cc collected is not contaminated by air. The bottle is sealed, air-free, by means of a clip on the butyl rubber lead.

Water samples which are to be used for the determination of major constituents are collected in 500 cc glass medicine bottles. One 500 ml sample for determination of arsenic and antimony is filtered through a fine sintered glass frit. This prevents the adsorption of these metals on suspended rock particles. For other trace metals, 10-litre water samples are collected in acid-cleaned pyrex glass bottles.

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## *Summary*

Representative sampling of steam and water discharging from a drillhole is not simple, as the pipe contains a rapidly flowing mixture in which the volume ratio, steam/water, may be several hundred to one. Separate steam and water samples are necessary, and analyses are combined to give results for the complete discharge from a knowledge of its dryness fraction.

Sampling methods depend on the arrangement of the wellhead and by-pass of a drillhole, as changes occur between the time the hole is first opened to the time it reaches the production stage. Various sampling methods are described, with comments on the possible errors which may arise out of their use.

The requirements of adequate sampling are examined in the light of the flow patterns which have been found to exist in the horizontal discharge pipes at Wairakei. Errors may occur when steam and water are not sampled in the same proportion that exists in the pipe at the sampling pressure.

Steam samples are condensed in water-cooled glass flasks of several litres capacity, and are analysed for their gas contents, as well as for the dissolved constituents, ammonia, boric acid, fluoride and chloride. Several water samples are collected for specific estimations such as major ionic constituents, trace metals, isotope ratios, and pH and dissolved gas determinations.


# ÉCHANTILLONNAGE DES PRODUITS DES PUITS GÉOTHERMIQUES


## *Résumé*

On se heurte à des difficultés quand on cherche à se procurer des échantillons types de la vapeur et de l'eau qui sortent d'un puits, car le tube utilisé contient un mélange en écoulement rapide, dans lequel la proportion vapeur/eau peut atteindre des centaines contre l'unité. On doit avoir recours à des échantillons séparés de vapeur et d'eau et combiner les analyses pour obtenir des résultats valables pour la totalité des produits quand on en connaît le degré de sécheresse.

Les techniques d'échantillonnage sont conditionnées par la disposition de la bouche du puits et la dérivation, car il y a des changements entre son ouverture initiale et le moment de son entrée en production. On décrit diverses méthodes d'échantillonnage et on formule quelques commentaires sur les erreurs auxquelles peut mener leur emploi.

On examine les exigences applicables à l'échantillonnage satisfaisant à la lueur des régimes d'écoulement établis pour les tuyaux de sortie horizontaux

en service à Wairakei. On peut aboutir à des erreurs quand on n'échantillonne pas la vapeur et l'eau dans les mêmes proportions que celles qui règnent dans le tuyau à la pression d'échantillonnage.

On condense les échantillons de vapeur dans des flacons en verre à refroidissement par l'eau et on procède à l'analyse de leur teneur en gaz et en éléments constitutifs dissous tels que l'ammoniac, l'acide borique, les fluorures et les chlorures. On recueille plusieurs échantillons d'eau en vue de procéder, sur eux, à des évaluations spécifiques portant, notamment, sur les principaux ions qu'elle contient, les métaux rares, les proportions d'isotopes, le pH et la teneur en gaz dissous.

# PHOTOGEOLOGY APPLIED TO NATURAL STEAM EXPLORATION

*Professor Enrico Marchesini* *

The photogeological phase of a survey carried out in the Tolfa area for natural steam exploration is discussed here as an example of the possibilities offered by photogeological techniques in this particular field.

The area of the survey covers approximately 900 Km² in the neighbourhood of Civitavecchia, 80 km NW of Rome.

Two major features of the area have attracted the attention of the explorers for steam:

The occurrence of neogenic vulcanites connected with surface indications of high thermality, such as mineralized hot springs, sulphides, and travertine deposits.

Stratigraphic conditions rather similar to those of the two producing areas of Larderello and Mt. Amiata.

The following specialists have contributed to the survey and related studies: F. Battini, R. Burgassi (steam-technicians for the Larderello Co.), A. Celandroni, G. C. Facca, E. Marchesini, A. Pistolesi (GEOMAP's geologists), K. Hormann and G. Tacchi (paleontologists), A. Rittmann (volcanologist).

The related gravity-meter and magnetometer surveys have been carried out by the Compagnie générale de Géophysique.

* GEOMAP, Florence, Italy.


**Fig. 1. Location map: O = area of survey**

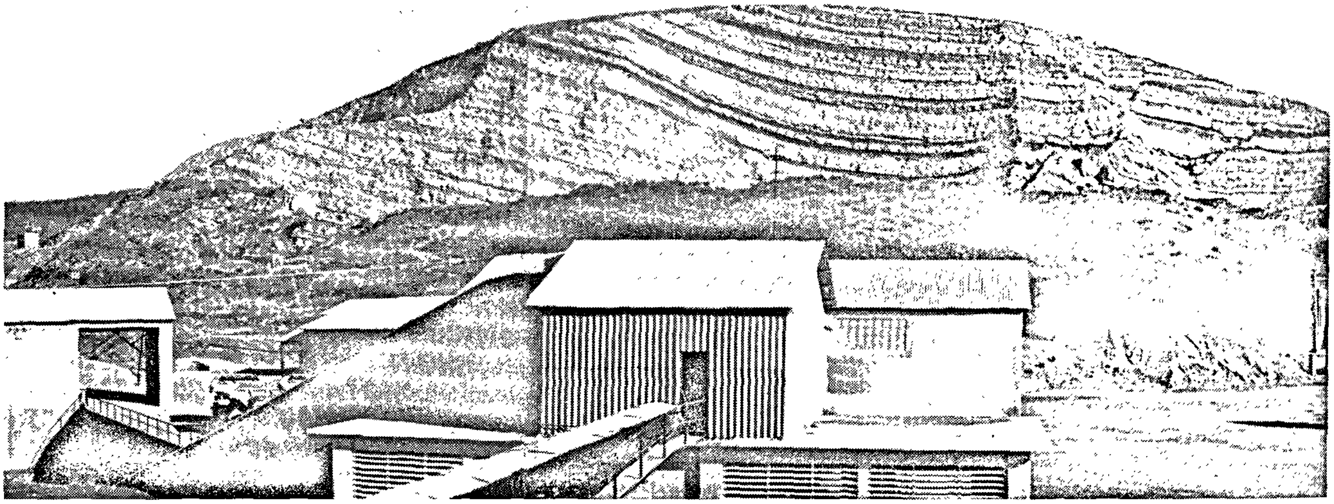

Figure 2. Exposure of Cretaceus Flysch at Mt. Ferrara (Tolfa)

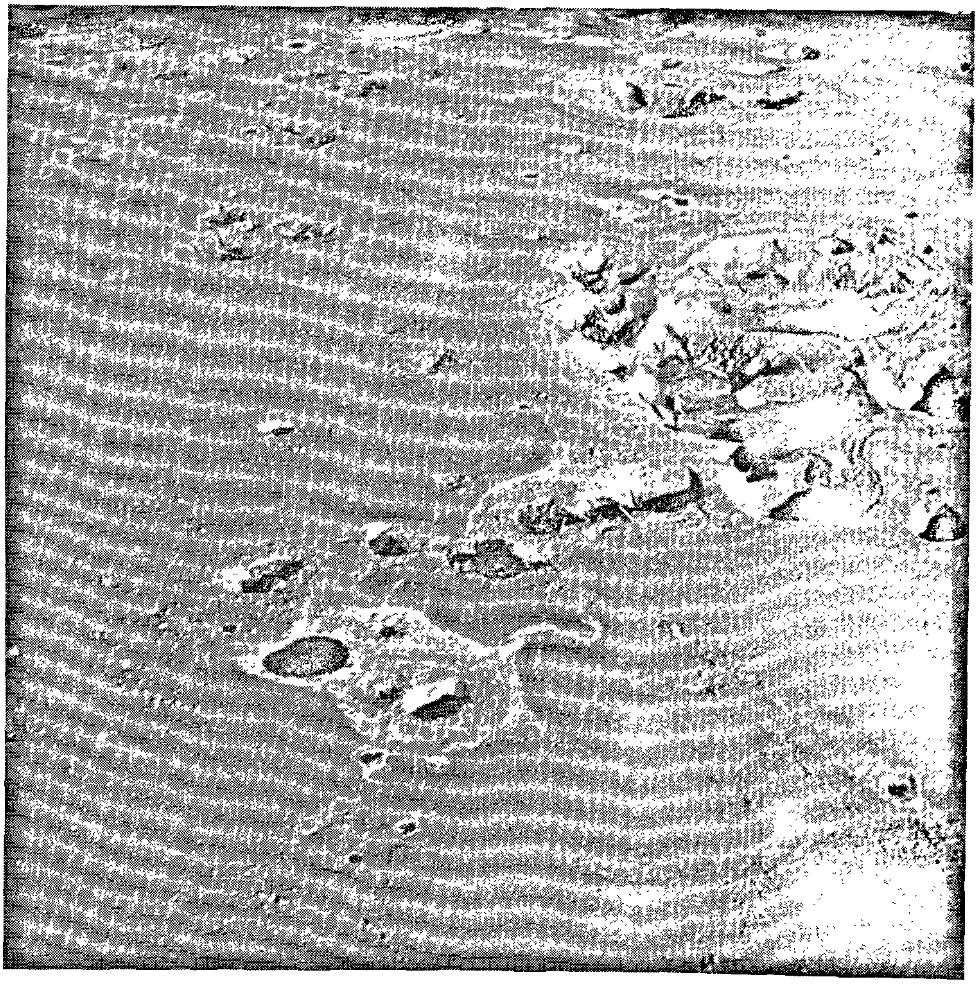

Figure 3. The occurrence of $H_2S$ at La Caldara, 15 km east of Tolfa

The Larderello Co. is now drilling a few km WSW of Tolfa.

## Stratigraphic outline

The stratigraphic sequence exposed in the Tolfa area is as follows (from top to bottom):

### Quaternary

Alluvial and litoral deposits; river and beach conglomerates with volcanic elements from the Tolfa ignimbrites; volcanic tufas, as thick as 70 m, originated by the Bracciano explosive crater.

### Lower Quaternary to Upper Pliocene

Ignimbrites and lavas from the Tolfa volcano, reaching a maximum observed thickness near to 300 m.

### Pliocene

Marine shales and gypsiferous shales; conglomerates with elements from the local Mesozoic to lower Tertiary formations and without volcanic elements. The maximum thickness observed reaches 200 m.

### Miocene

No definite beds have been referred to the Miocene for lack of typical fauna. However, it is admitted that some beds near the bottom of the preceding group could pertain to the Miocene.

### Oligocene-Eocene

Grey shale, thinly bedded argillaceous limestone, marls and variegated shales containing Oligocene to Eocene fauna, reach a thickness of 400 m. The lithological similarity of this group with the cretaceous sediments makes separation in the field sometimes difficult.

### Paleocene-Cretaceous

To this age group is referred the major bulk of the sediments outcropping in the area. These sediments consist of fine and medium clastics (shale to sandstone) including less than 20 per cent intercalations of marly limestones and calcarenites. The total thickness is not less than 1 500 m.

These sediments, together with those of the lower tertiary, represent the filling of a large basin

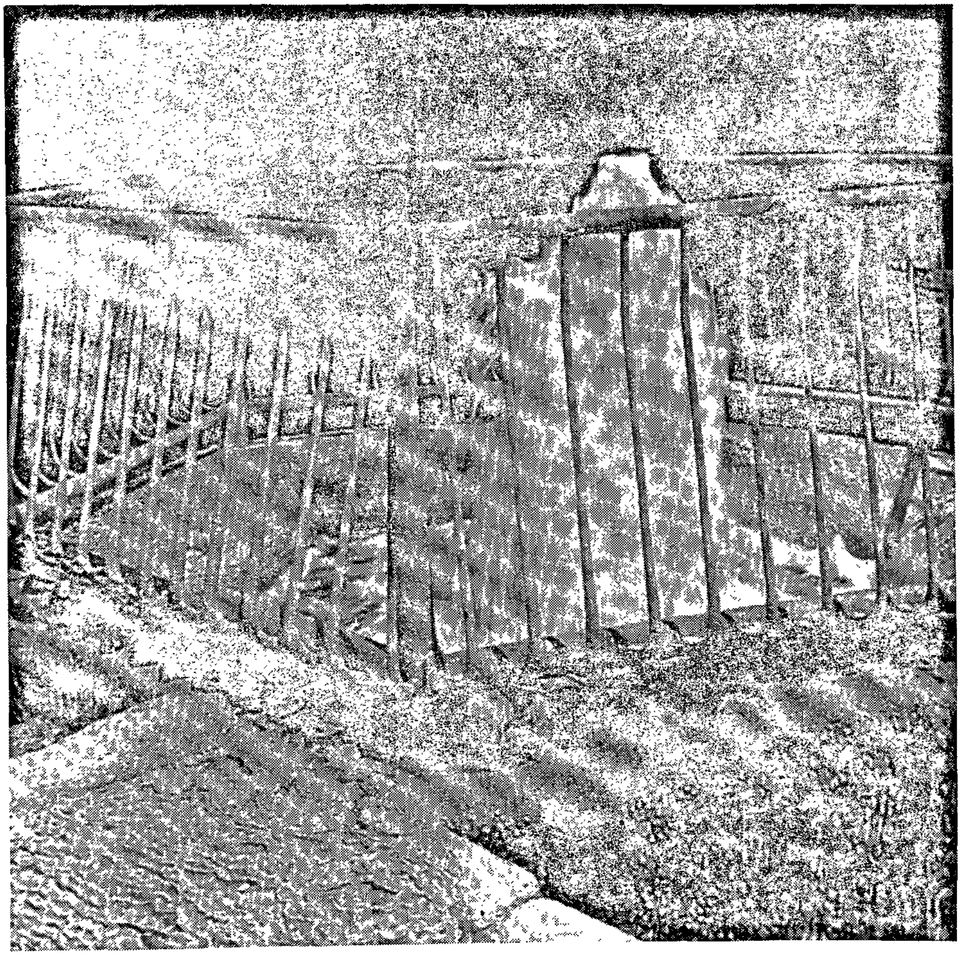

**Figure 4. Hot spring with $CO_2$ at Bagni di Stigliano, 10 km east of Tolfa**

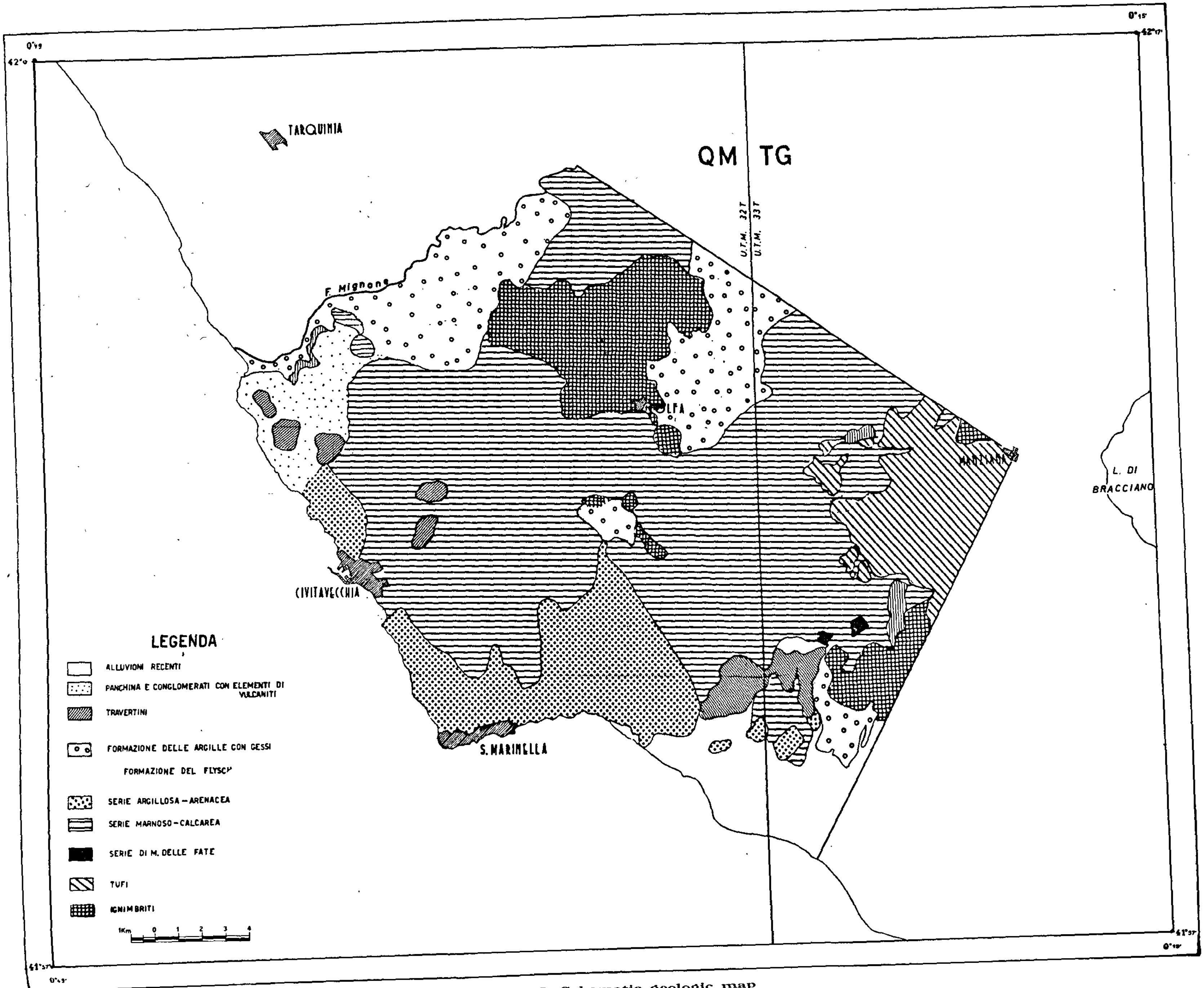


Figure 5. Schematic geologic map

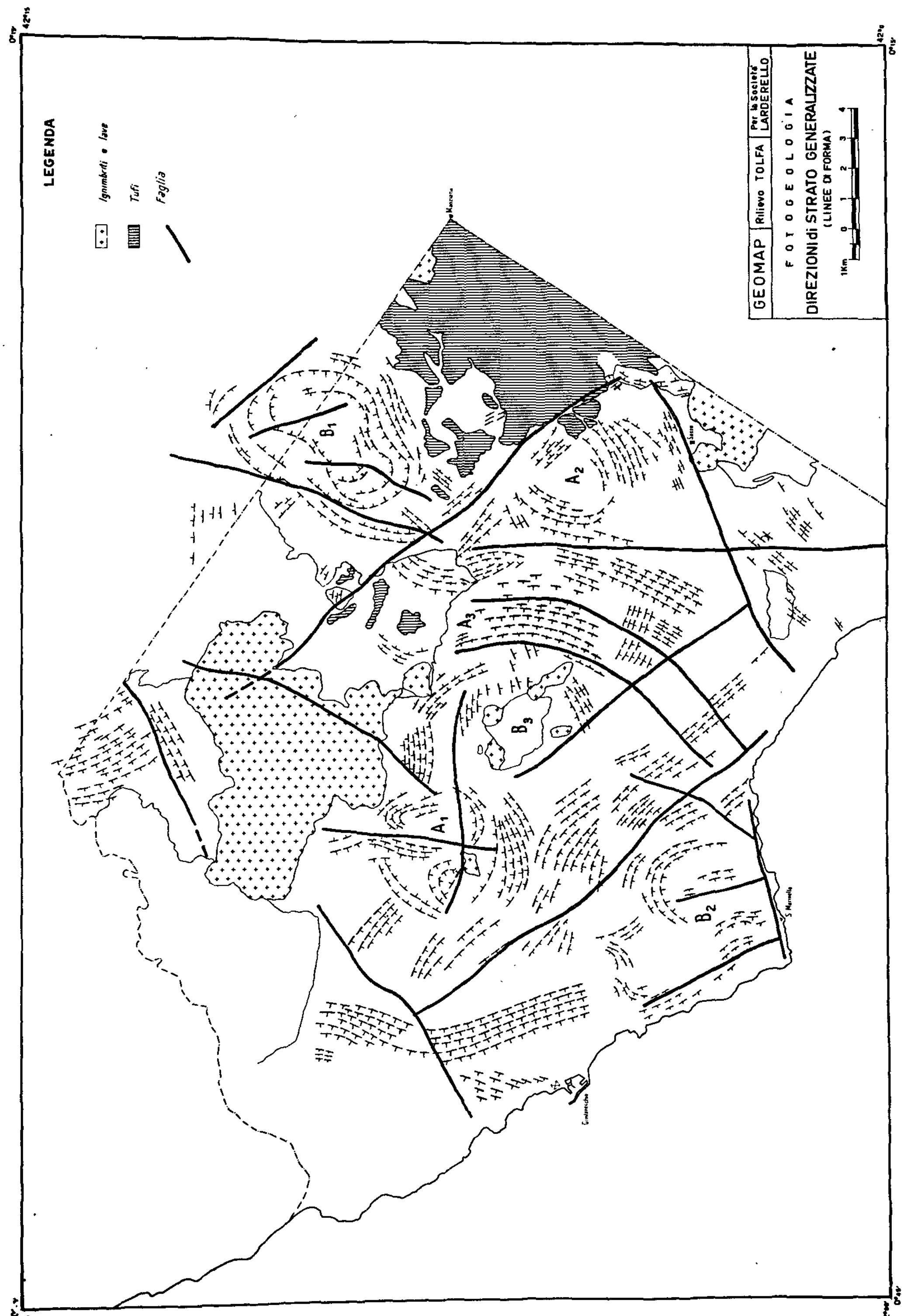


Figure 6. Structural form lines from photo-interpretation

extending from northern Tuscany to the south of Rome. They are often grouped under the general term of Flysch.

### Lias-Trias

Three small outcrops near the "Monte delle Fate" show the calcareous bottom of the Flysch basin. They consist of a hard limestone, light grey to dark grey, with nodules and veins of chert. Although organic fragments are abundant, only a few fossils are recognizable and referred to the Upper Triassic or the Liassic.

A stratigraphic gap occurs between these limestones and the overlying Flysch clastics. The lower part of the limestone series is not exposed. However, regional analogies suggest that it could well consist of a cavernous or vuggy dolomitic limestone with anhydrite having favourable reservoir characteristics.

## Structural outline

There is a sharp contrast between the relatively simple pattern of the basement to the top of the limestone series, and the essentially disharmonic

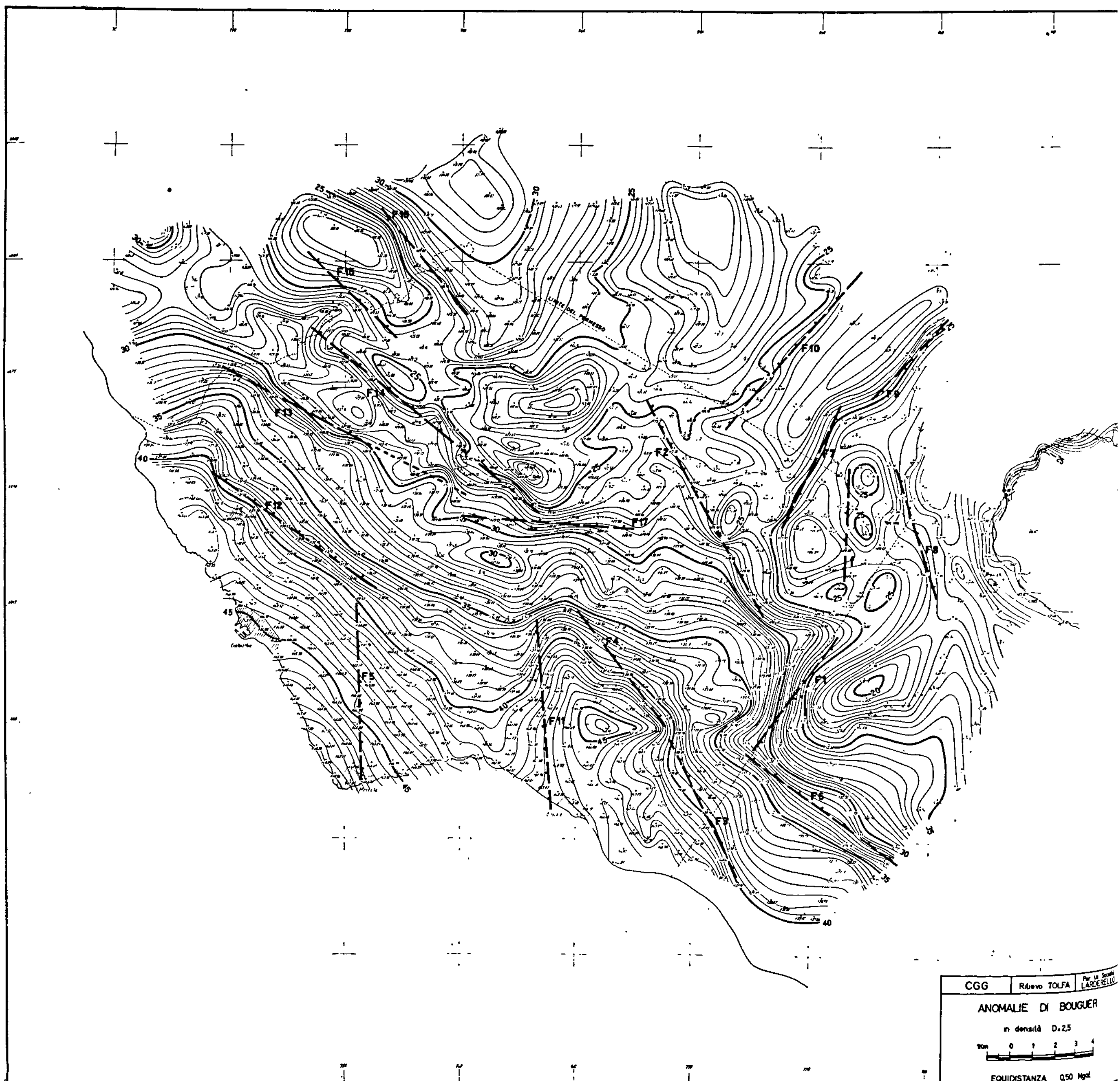


**Figure 7. Gravity: Bouguer anomaly D = 2.5**

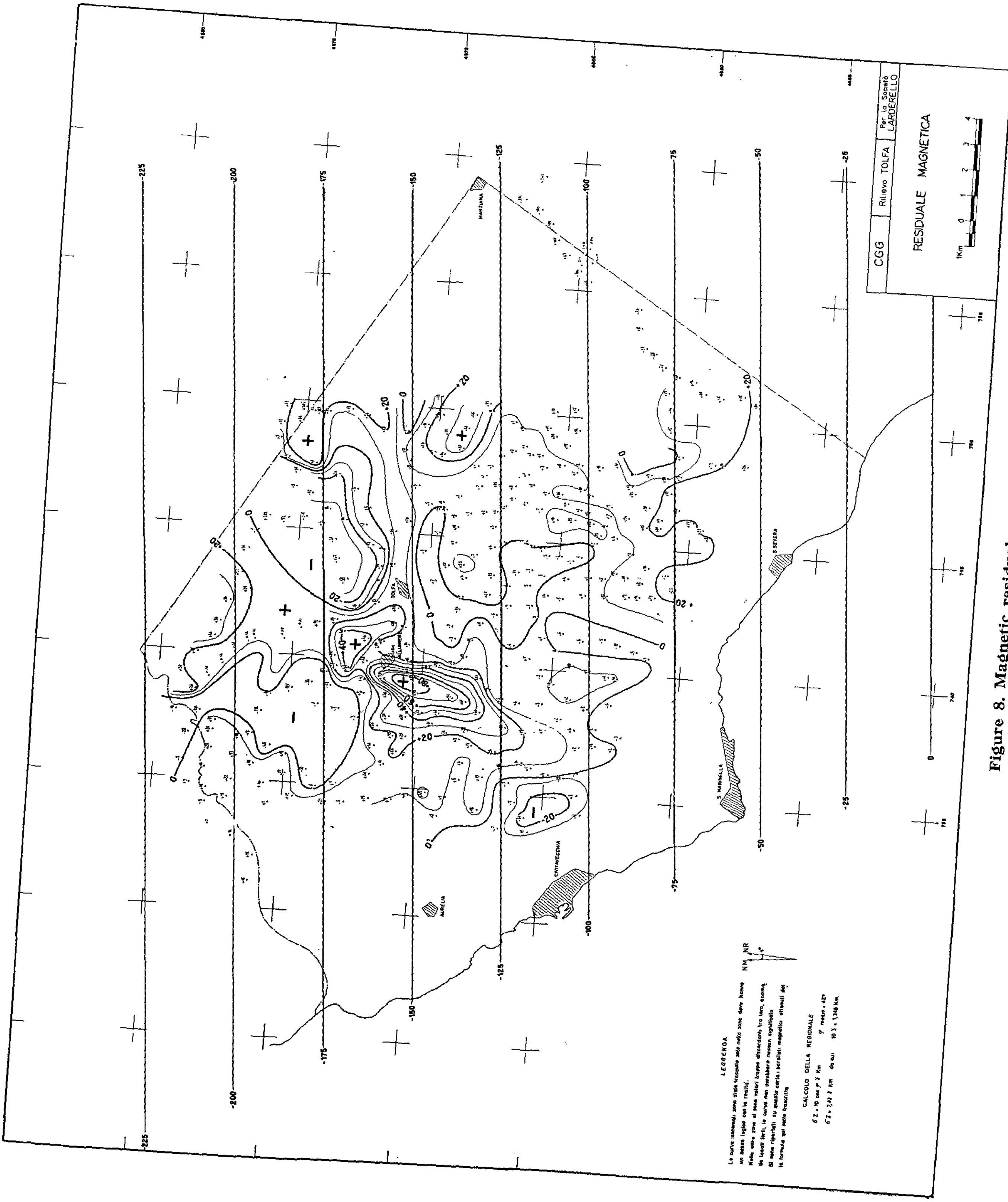


Figure 8. Magnetic residual map

folding which dominates the plastic filling. Two major tectonic trends are observed which affect both the distribution of the major outcrops and the general morphology of the area: one principal trend (Appenninic), oriented to the NW, and one cross-trend oriented to the NE.

The photogeological interpretation has proved a valuable tool both in helping detect major fracture lines and in mapping the highly complex forms of the plastic cover. As it usually occurs in the vicinity of volcanic areas, the fracture net appears rather dense and complex. A remarkable help for its analysis has also been offered by the photo interpretations. The photogeological phase has been solidly attached to the surface work, both phases having been carried out by the same geologists. The photographs, which have been obtained from the Italian Air Force, are of good quality at the approx. scale of 1/35 000. The surface data have been accurately annotated on the photos as guidance and check for further interpretation work.

The great amount of information covering strike and dip of beds, faults and joints obtained from the photos allows the use of interpolation techniques similar to those applied to the interpretation of scismic profiles by "phantoms". Where definite key-beds are lacking, such a procedure can lead at least to a qualitative delineation of important structures by form-lines.

Figure 6, condensing the major faults and structural features, shows several individual disharmonic structures affecting the Flysch beds, cut through by faults and slip-lines. The positive structures are indicated with letter A, and the negative structures are indicated with letter B. Structures A 1 and A 2 appear similar to faulted brachianticlines, while A 3 approaches the type of a faulted monoclyne. In the vicinity of these positive structures are observed hot springs and mineralizations.

The gravity survey also indicates positive anomalies in coincidence particularly strict with A 1 and A 2 (figure 7). Also, on a regional basis, the gravity picture appears to fit the general structural pattern.

The observed consistency between positive structures of the plastic cover and positive gravity anomalies justifies the hypothesis that in such areas the calcareous bottom is also raised. This condition is of obvious interest for exploration because it affords better chances to reach the reservoir at shallower depths, although is not necessarily related to better productivity. The first exploration well of the area has been located on A 1.

*Summary*

Photogeology is proving an effective tool in natural steam exploration.

The present paper is a short account of a geological survey carried out by GEOMAP for natural steam exploration in Italy, sponsored by the Larderello Company.

The surface survey met with remarkable difficulties in mapping the highly complex structure of the plastic cover which overlies the calcareous possible reservoir.

Form lines and faults, obtained by photointerpretation, led to a picture that coincides fairly well with gravimetric and magnetometric evidence. The picture compares favourably with two producing areas at Larderello and Mt. Amiata in Tuscany.

The Larderello Company is now drilling on the project.

## APPLICATION DE LA PHOTOGÉOLOGIE A LA PROSPECTION DES GÎTES DE VAPEUR NATURELLE

*Résumé*

La photogéologie s'est avérée efficace, entre autres, dans les travaux de prospection à la recherche de gîtes de vapeur naturelle.

On trouvera, dans le mémoire, une brève description des travaux d'exploration géologique exécutés par la GEOMAP à la recherche de vapeur naturelle en Italie, sous les auspices de la compagnie Larderello.

Les examens pratiqués en surface se sont heurtés à des difficultés notables quand il s'est agi de faire des relevés cartographiques de la structure éminem-

ment complexe de la roche de couverture sous laquelle se trouve un réservoir possible constitué par des formations calcaires.

Les contours et les failles révélées par l'interprétation des photographies ont permis d'aboutir à une image qui correspondait raisonnablement bien aux données gravimétriques et magnétométriques. Cela peut être comparé favorablement avec les constatations faites sur les sites des deux champs en production à Larderello et Monte Amiata, en Toscane.

La compagnie Larderello fonce actuellement des puits dans ces régions.

# LES ANOMALIES THERMIQUES ET LES CHAMPS GÉOTHERMIQUES DANS LE CADRE DES INTRUSIONS RÉCENTES EN TOSCANE

*G. Marinelli**

Parmi les champs géothermiques connus dans le monde entier, les champs de la Toscane sont actuellement ceux qui fournissent la plus grande production d'énergie géothermique et même depuis longtemps les plus exploités. Un bref exposé de toutes les données qui permettent d'établir assez vraisemblablement les modes de gisement des champs géothermiques de la Toscane peut fournir, outre qu'un indice de recherche pour les zones limitrophes de la Toscane elle-même et du Latium septentrional, un exemple pour commencer des recherches dans d'autres zones de la surface terrestre qui présenteraient des conditions géologiques analogues à celles décrites dans ce rapport.

Dans l'évolution géologique de l'orogenèse des Apennins, les phénomènes magmatiques sont liés à la phase finale du cycle, c'est-à-dire à la subsidence de tout le versant occidental de cette chaîne montagneuse. De tels phénomènes magmatiques sont représentés par un volcanisme qui a eu ses débuts à la fin du pliocène et qui est encore actif en partie, et par un ensemble de phénomènes intrusifs qui ont porté à la mise en place et ensuite dénudé un certain nombre de petites coupoles acides. De telles intrusions affleurent en partie dans les îles de l'Archipel toscan et en partie sur la côte toscane.

D'après l'observation des récents levés de la morphologie sous-marine, il est très probable qu'il existe sur la plate-forme côtière de la mer Tyrrhénienne, en face de la côte toscane et du Latium, d'autres petits stocks engloutis par le phénomène accentué de subsidence de ladite zone. Si l'on ajoute ces coupoles sous-marines aux six autres qui se montrent à la surface en Toscane et dans les îles de l'Archipel toscan, nous atteignons le nombre de 11 coupoles intrusives pour une superficie d'environ 13 500 km$^2$, c'est-à-dire une coupole pour chaque 1 200 km$^2$. Cette densité plutôt élevée n'est certainement pas caractéristique de la seule côte toscane mais elle est typique pour certaines zones de subsidence successive à la période paroxistique de tous les cycles orogénétiques.

Les six coupoles formées de roches très acides (granodiorites à granites) se sont introduites dans les sédiments du géosynclinal apenninien de la période comprise entre le trias et l'oligocène tout en provoquant de vastes phénomènes de métamorphisme thermique et de minéralisation. En outre, les sédiments sont recoupés par des filons granitiques, aplitiques et microgranitiques et, dans le cas de la coupole de Campiglia, certaines fractures filoniennes sont arrivées à la surface en donnant ainsi naissance à une vaste couverture ignimbritique.

Il y a de nombreuses données géologiques qui permettent d'établir que la mise en place de ces coupoles est d'autant plus ancienne qu'elles sont plus occidentales. On rapportera ici les données principales.

1) Le soulèvement de la chaîne des Apennins se poursuit d'ouest en est, et les phénomènes d'ultramétamorphisme et de granitisation sont donc plus anciens dans la partie plus occidentale de la chaîne montagneuse.

2) La dénudation des coupoles intrusives est plus accentuée dans la partie occidentale (Monte Capanne à l'île d'Elbe et île de Montecristo) que dans les parties plus orientales (Campiglia et Gavorrano).

3) La coupole plus occidentale, c'est-à-dire celle du Monte Capanne, était évidemment en partie dénudée pendant le messinien, puisqu'on trouve en abondance dans les conglomérats fossilifères messiniens sur la côte toscane des galets provenant du magmatisme de l'île d'Elbe. Le même conglomérat est au contraire recoupé par des filons hydrothermaux à sphalerit et galène dans la zone au nord de Campiglia, c'est-à-dire que la mise en place de la coupole granitique de Campiglia était encore en cours au début du pliocène.

4) La détermination chronologique relative des diverses coupoles intrusives de la Toscane, qui a été faite avec la méthode des halos pléochroïques dans la biotite, a permis d'établir avec précision l'âge moins élevé des intrusions plus orientales.

Les données mentionnées ci-dessus, ainsi que d'autres arguments géologiques que pour abréger nous ne rapportons pas, portent à considérer désormais comme certain l'âge toujours plus jeune des petits massifs intrusifs au fur et à mesure qu'on s'approche de la partie actuellement soulevée de la chaîne des Apennins.

Voyons à présent les connaissances que nous avons au sujet de la chronologie absolue. Les données géologiques nous fournissent uniquement des informations limitées et précisément nous disent que la coupole du Monte Capanne à l'île d'Elbe (et peut-être l'île de Montecristo, apparue du même âge par la méthode des halos pléochroïques) est du

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prémessinien, et qu'au contraire toutes les autres coupoles sont du postmessinien. Une datation très précise a été possible pour le Monte Capanne et pour l'île de Montecristo avec la méthode Rb/Sr à cause de la grande quantité de Rb de la biotite de Montecristo, et de la lépidolite et de la pollucite de l'île d'Elbe. Cet âge est compris entre 6 et 7 millions d'années.

On sait que d'après les tables chronologiques de Holmes (1947) et de Kulp (1960) les données de l'âge des divers niveaux du néogène sont très peu précises; cela a peu d'importance quant aux buts de cette communication, tandis qu'il est très intéressant de constater que les plus anciennes des coupoles intrusives qui affleurent en Toscane se sont mises en place à une époque bien plus récente qu'on ne croyait auparavant.

Ces données nous portent logiquement à supposer que dans les zones plus orientales par rapport aux petits massifs intrusifs affleurants, il y en a d'autres qui ne sont pas encore dénudés par l'érosion et quelques-uns encore en cours de refroidissement. Ici même par la suite nous essaierons de fournir toutes les données existantes en faveur de cette hypothèse.

Considérons toute la partie de la Toscane et du Latium occidental limitée au nord par la vallée de l'Arno, au sud par la vallée du Tibre et à l'est par la ligne Empoli-Sienne-lac Trasimène-vallée de la Paglia. Toute cette zone est justement intéressée par une tectonique disjonctive due à la subsidence postorogénétique. Ici s'est développé, à partir de la fin du pliocène, une notable activité volcanique, qui a atteint son maximum pendant la glaciation rissienne. Nous pouvons nettement diviser cette activité dans les deux catégories suivantes.

1) Volcanisme acide très peu différencié d'origine anatectique directement lié à la remontée des masses granitisées. Ce volcanisme a donné origine à des couvertures ignimbritiques plus ou moins étendues et, en moindre partie, à des coulées de lave (Campiglia, Roccastrada, Monte Amiata en Toscane, et La Tolfa, Manziana, Monte Cimino dans le Latium).

2) Volcanisme hybride provenant probablement des zones profondes granitisées du Sial et en partie aussi du Sima. Ce volcanisme, typique à chambres superficielles et avec un cycle de différenciation très accentué, a engendré de nombreux appareils volcaniques avec de grandes quantités de produits pyroclastiques et coulées de lave (Radicofani en Toscane, Monti Sabatini et Monti Vulsini dans le Latium).

Bien qu'il soit évident qu'une partie seulement des intrusions superficielles ont engendré un phénomène volcanique, la présence d'une couverture ignimbritique dans une zone où est connue une remontée de stocks nous donnera toutefois un indice important de la présence d'une intrusion superficielle qui n'affleure pas.

Mais il y a beaucoup d'autres arguments au regard de cette zone, outre la présence des couvertures ignimbritiques, pour supposer qu'il y a des intrusions superficielles encore en cours de refroidissement. Énumérons ici les principaux:

1) Soulèvement des assises pliocéniques. La couverture pliocénique dans la zone examinée se trouve à une altitude variable entre 100 et 300 mètres; dans certains endroits elle monte à une bien plus grande altitude. En particulier dans la zone de Larderello et du Monte Cimino, elle arrive à environ 600 m et dans la zone du Monte Amiata elle dépasse 900 m.

2) En correspondance exacte avec ces soulèvements post-pliocéniques très localisés, il y a de fortes anomalies négatives de gravité. Dans ce cas aussi, c'est dans la zone du Monte Amiata qu'on remarque davantage ce phénomène.

3) Les axes de la tectonique régionale sont bien troublés dans les zones dont parlent les points 1 et 2.

4) Dans toutes les zones 1, 2 et 3 on note de nombreuses minéralisations de divers types. Dans les zones où l'on suppose que les coupoles ont atteint une distance moindre de la surface, on a retrouvé par suite de travaux miniers des roches certainement thermométamorphiques.

5) Une méthode isotopique basée sur la mesure des rapports $O^{16}/O^{18}$ et $C^{12}/C^{13}$ dans les calcaires, et dont la validité a été contrôlée sur des roches provenant des bordures des coupoles granitiques affleurantes, a fourni une preuve de la présence de coupoles enfermées dans la zone considérée et elle en a localisé d'autres pas encore prévues. Une telle méthode apportera certainement une aide importante pour la recherche des petits massifs intrusifs non affleurants, surtout dans les zones où les connaissances géologiques régionales sont insuffisantes.

Les données ci-dessus mentionnées semblent suffisantes pour accepter l'hypothèse de la présence des coupoles en cours de refroidissement soit dans la zone de Larderello, où manquent les manifestations volcaniques, soit dans celle du Monte Amiata, couverte par les ignimbrites.

Mais il est évident que toutes les coupoles ensevelies dans la zone ne sont pas à un même stade de refroidissement, et elles ne seront pas toutes capables de donner une forte anomalie thermique localisée; en outre, la présence de l'anomalie thermique ne sera certainement pas une condition suffisante pour le formation d'un champ géothermique.

Dans le but d'éclaircir ce que doivent être les conditions de gisement d'une coupole intrusive pour qu'il y ait possibilité de formation d'un champ géothermique, nous résumerons ici brièvement les données sur la série sédimentaire et sur les niveaux de cette série atteints par les diverses coupoles intrusives connues en Toscane.

La série sédimentaire de la fosse géosynclinale des Apennins commence en Toscane avec l'ingression triasique sur les sédiments continentaux ou saumâtres du permocarbonifère. Ce trias, au début formé de quartzites conglomératiques et quartzites schisteuses, passe ensuite à une série évaporitique avec une forte épaisseur d'anhydrites suivies de dolomies et de calcaires qui, dans le cas fréquent de transformation partielle ou totale en gypse et dissolution de l'anhydrite, se sont transformés en cargneules très poreuses. Cette formation triasique est suivie d'une série mésozoïque calcaire, puis d'une série marneuse du crétacé-éocène et enfin de grès oligocéniques. Quelquefois, pour des causes de nature tectonique, on trouve directement sur le trias une série flyschoïde d'époque qui varie entre le jurassique supérieur et l'oligocène constamment riche en argile.

La sédimentation du géosynclinal s'arrête vers la fin de l'oligocène ou vers le miocène inférieur avec la phase du soulèvement. On trouve ensuite de façon discontinue sur ces sédiments de fosse une série nettement transgressive messinienne et pliocénique, qui ne revêt aucun intérêt dans le but de la présente communication.

En résumant donc, là où l'érosion et la dénudation tectonique n'ont pas découvert les terrains plus vieux, la série toscane est formée d'un trias poreux (quartzites fracturés et anhydrites) ou même très poreux (cargneules vacuolaires), recouverte d'une série génériquement imperméable ou tout au moins assez peu perméable par rapport au trias qui se trouve au-dessous.

La remontée des stocks peut atteindre les niveaux les plus divers de cette série, en provoquant des phénomènes variés par rapport à la porosité de la série même. Sur la connaissance des coupoles qui se montrent à la surface ou presque, nous pouvons distinguer trois types sûrs de phénomènes et en arguer un quatrième. Ces quatre types sont ici même reportés avec la suite des phénomènes provoqués par l'intrusion.

1) La remontée de la coupole est arrivée à faire intrusion parmi les assises de la couverture flyschoïde imperméable (Monte Capanne à l'île d'Elbe et île de Montecristo). On constate de vastes phénomènes d'autométamorphisme dans les roches magmatiques (en particulier dans les microgranites) et l'absence presque totale de minéralisation dans la couverture rejointe par les roches intrusives. Probablement les intenses phénomènes de métamorphisme thermique ont aussi éliminé la porosité de la série triasique qui se trouve au-dessous.

2) La remontée de la coupole intrusive a traversé la série poreuse triasique et est arrivée jusqu'aux premiers niveaux de la série calcaire mésozoïque (Campiglia). La série poreuse a été partiellement imperméabilisée par le métamorphisme thermique. Des minéralisations, nombreuses mais peu importantes, de haute et moyenne température (cassitérite, skarn avec sulfures de Cu, Pb, Zn) se trouvent dans les calcaires mésozoïques avec suites de plus basse température à plus grande distance de la coupole granitique.

3) La remontée de la coupole intrusive a atteint le permocarbonifère ou la seule partie inférieure de la série triasique (quartzites) [Elbe orientale, île de Giglio, Gavorrano, Prata près de Massa Marittima]. La partie très poreuse a été peu ou pas du tout intéressée par les phénomènes de métamorphisme thermique; elle a été par conséquent le siège des grandes minéralisations pyrométasomatiques ou hypothermales avec skarn, magnétite, pyrrhotine, ologiste et surtout pyrite. De même la couverture imperméable qui se trouve au-dessus a été intéressée par des phénomènes de minéralisation de type filonien, mais toujours de haute ou moyenne température.

4) La remontée de la coupole intrusive s'est arrêtée à des niveaux plus bas par rapport aux couches poreuses triasiques (Larderello, Monte Amiata, La Tolfa, Monte Cimino, etc.). Les minéralisations de haute et moyenne température ne sont pas connues; elles se sont peut-être développées à des niveaux inconnus au-dessous du trias poreux. Dans les séries triasiques et plus récentes, il est uniquement arrivé quelquefois une minéralisation de type épithermal avec des phénomènes étendus de silicisation, melnikovite, marcasite, cinabre et stibine. La forte anomalie thermique a activé des courants de convection dans les eaux d'origine superficielle qui imprègnent la série poreuse. Dans le cas où la série poreuse est couverte d'une épaisseur convenable de sédiments imperméables, ces courants de convection porteront à la formation de champs géothermiques.

Tandis qu'il est évident que les types 1, 2, 3 sont directement et clairement visibles soit sur le terrain, soit dans le sous-sol, étant donné la grande activité minière en Toscane, le type 4 est hypothétique. Il faut pourtant considérer qu'en acceptant l'hypothèse qu'il y a une coupole intrusive en cours de refroidissement dans les zones de Larderello et du Monte Amiata, il est certain que cette coupole doit se trouver à une grande profondeur au-dessous de la série poreuse triasique. En effet, dans les nombreux forages qui ont été faits pour la recherche et l'exploitation des champs géothermiques soit dans la zone de Larderello, soit dans celle du Monte Amiata, on n'a jamais trouvé dans la série triasique ni minéralisations de moyenne et haute température, ni phénomènes de métamorphisme thermique, même pas dans la partie basale de cette série, parfois atteinte par les forages.

## Conclusions

A cause des connaissances actuelles sur la géologie des champs géothermiques, il est fort probable que de tels champs puissent s'engendrer de façons diverses, et en particulier que l'anomalie thermique indispensable à la formation de ces champs puisse avoir des origines différentes, quoique toujours dans le milieu des phénomènes magmatiques.

Toutes les données existantes pour établir l'origine plus probable des champs géothermiques de la Toscane, ainsi que les modalités géologiques générales pour retrouver de semblables conditions en d'autres zones de la surface terrestre, ont été exposées dans cette communication. En bref, les conditions à chercher devraient être les suivantes.

1) Zone de subsidence postorogénétique de l'époque la plus récente possible (néogène);

2) Récente grande activité magmatique avec présence de coupoles intrusives acides de type circonscrit et qui se montrent à la surface en petites étendues (stocks);

3) Présence de couvertures ignimbritiques très récentes formées de magmas d'anatexie (et pas de différenciations acides simatiques);

4) Présence de petits massifs intrusifs ne se montrant pas à la surface, mais facile à reconnaître avec des méthodes géologiques, géophysiques et probablement surtout avec des méthodes géochimiques;

5) Présence d'une série sédimentaire poreuse avec une couverture imperméable;

6) Absence de minéralisations de haute et moyenne thermalité dans la zone de la supposée coupole;

7) Présence d'une anomalie thermique (manifestations thermales, chaleur anormale en surface et en profondeur, etc.). Le développement de ce dernier point n'est pas dans les buts de cette communication. D'autre part, il sera commun à la recherche de tous les champs géothermiques, quelle que soit leur genèse.

### *Résumé*

L'auteur résume et coordonne les connaissances actuelles sur les intrusions acides récentes en Toscane, par rapport aux événements géotectoniques de la région. La subsidence postorogénétique du versant occidental de la chaîne des Apennins a porté en temps successifs à la mise en place d'une série de petites coupoles toujours plus récentes en progressant de l'ouest vers l'est. Les deux intrusions les plus occidentales, et donc les plus anciennes (granite de l'île de Montecristo et granodiorite du Monte Capanne, île d'Elbe), remontent seulement à 6 millions d'années environ; encore plus jeunes sont celles affleurant près de la côte toscane. Il semble donc logique de supposer la présence d'intrusions plus orientales pas encore dénudées par l'érosion et encore en phase de refroidissement. L'auteur rapporte toutes les données actuellement connues sur les anomalies des soulèvements postpliocéniques, sur les anomalies gravimétriques et d'autres encore qui justifient l'hypothèse de l'existence de coupoles profondes en cours de refroidissement, soit dans les deux zones vaporifères de la Toscane, soit en d'autres zones de la même région et du nord du Latium. Quelques observations et considérations sur les terrains de la série sédimentaire traversés de stocks ont permis de formuler certaines hypothèses capables d'expliquer les raisons pour lesquelles dans les assises autour des coupoles, il y a dans certains cas d'importantes minéralisations, dans d'autres des champs géothermiques et enfin dans d'autres encore ces types de manifestations manquent complètement ou bien sont extrêmement réduites.

## THERMAL ANOMALIES AND GEOTHERMAL FIELDS RELATED TO RECENT PLUTONISM IN TUSCANY

### *Summary*

The author summarizes the present knowledge of recent acid intrusions in Tuscany (Italy) and relates it to the geo-tectonic events of this region. The post-orogenic subsidence of the western slope of the Apennine chain caused the formation of a series of relatively small stocks, more and more recent from west to east. An age of only six million years has been established for both the most westerly, and therefore the oldest intrusions (granite of the Montecristo island and granodiorite of the Monte Capanne, Elba island); those intrusions occurring along the Tuscany coast appear to be of more recent formation. Therefore, the presence of more easterly intrusions which have not yet been uncovered by erosion and which are still cooling may be assumed.

The author gives all the presently known data concerning the anomalies of post-pliocenic mountain raising, the gravimetric anomalies and other anomalies which confirm the validity of the assumption of the presence of cooling stocks occurring deep in both the geothermal fields of Tuscany and in other zones of the same region, and also of the northern Latium.

Some remarks and observations on rocks of the sedimentary series which are crossed by the stocks allow the author to formulate some hypotheses in order to explain the reasons for which, in the zones of emplacement of stocks, sometimes important ore deposits, sometimes geothermal fields occur, and sometimes neither of these phenomena.

# GEOLOGY OF THE GEYSERS THERMAL AREA, CALIFORNIA

*James R. McNitt**

The first commercial use of geothermal power in the United States began in June 1960, when the 12 500 kw Geysers power plant was put on steam. Although the power output at The Geysers represents only a small fraction of the total electrical power produced in California by conventional means, the success of the Geysers project may stimulate the development of this source of energy elsewhere in the United States. The efficiency and success of future development, however, will greatly depend on knowledge of the geologic factors controlling the generation of natural steam. This report presents, and attempts to interpret, geologic data concerning The Geyser thermal area which may be of value in determining the future power potential of similar thermal areas.

The Geysers thermal area is located in the coast ranges of California, approximately 130 km. north of San Francisco (figure 1). Steam wells were first drilled for the purpose of generating electric power at The Geysers in 1921, and by 1925 eight wells were completed. Although sufficient steam was produced at that time to establish the feasibility of the project, there was as yet no market for the steam, and the project was abandoned. Since 1955, Magma Power Co. and its partner Thermal Power Co. have drilled 12 more wells, ranging from 800 to 1 000 feet in depth. The steam from these wells is now being used to operate the Geysers power plant which was completed by the Pacific Gas and Electric Co. in 1960.

The regional geologic map above (figure 2) is a compilation of mapping done by Anderson (1936), Brice (1953), and the present writer. The geology of The Geysers thermal area (figure 3) was mapped by the writer on a topographic base of 1 : 12 000 during the summer of 1958.

Gratitude is expressed for the helpful co-operation given by the personnel of the Thermal Power Co. and the Pacific Gas and Electric Co., whose efforts are responsible for much of the data presented in this report.

## Regional geology

### Geologic history

1. There are four kinds of rocks in the Clear Lake region (figure 2): marine geosynclinal rocks of Jurassic and Cretaceous age; serpentine, which intrudes the Jurassic rocks; Pleistocene and Recent volcanic rocks; and fresh-water gravels and silts of Plio-Pleistocene age.

2. Geosynclinal deposition ceased in early Tertiary time when the Mesozoic rocks were uplifted and gently folded. General stability of the region during late Tertiary time is indicated by an extensive Pliocene erosion surface which truncated the folded Mesozoic rocks. This erosion surface was then coated with continental silts and gravels of Plio-

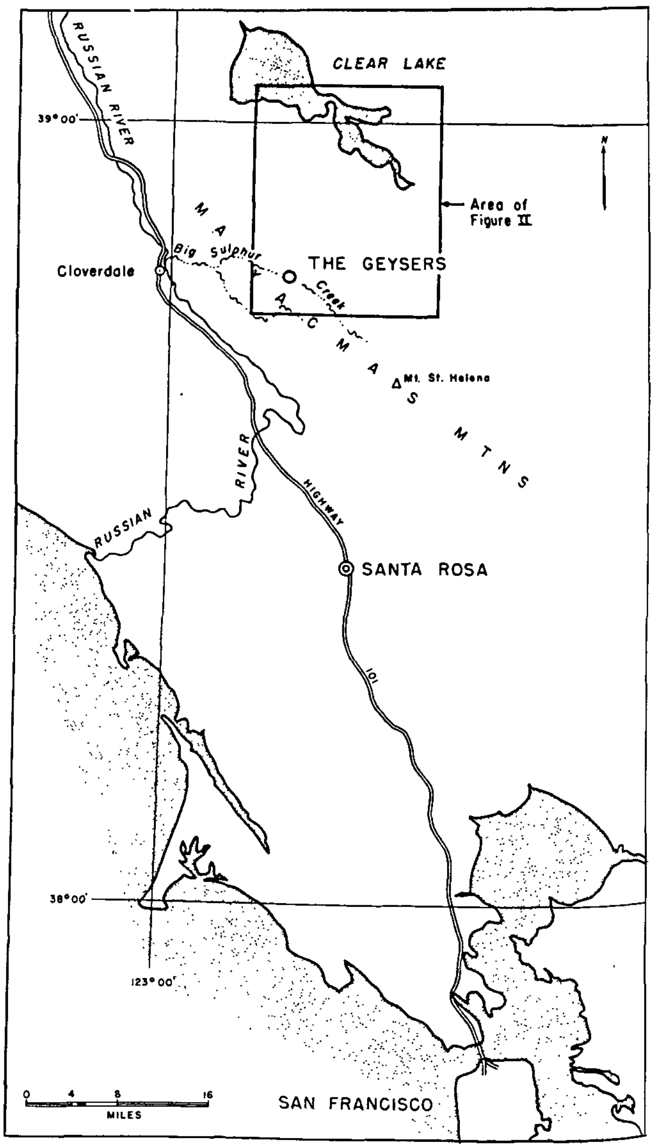
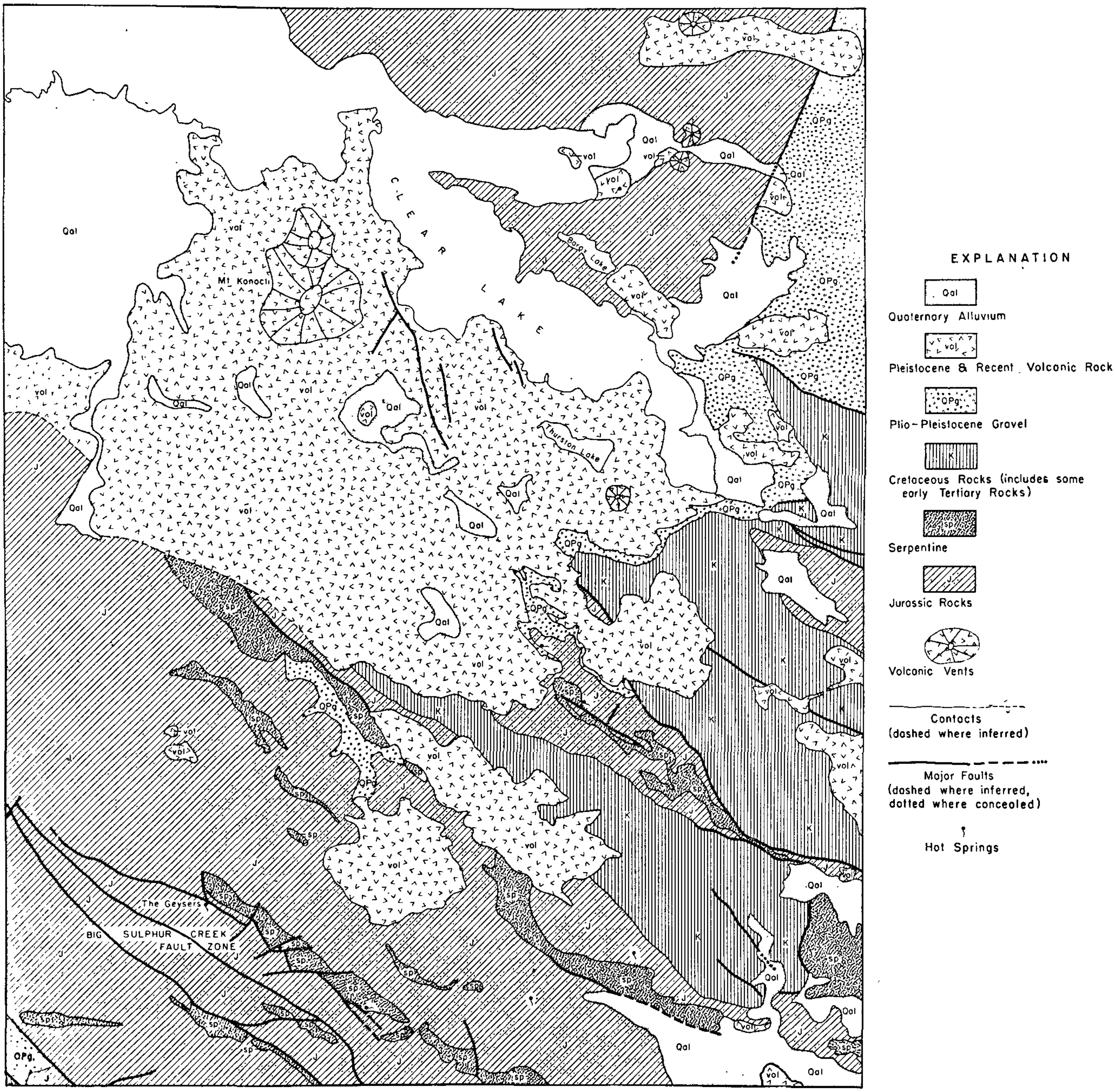



Figure 1. Index map

* California Division of Mines, San Francisco.




GEOLOGIC MAP OF CLEAR LAKE AREA

After Anderson, Brice, McNitt

0 1 2 3 4 Miles

Scale

**Figure 2**

Pleistocene age which grade upwards into tuffaceous sediments interbedded with thin layers of olivine basalt. Pleistocene and Recent volcanic rocks erupted onto this series of sediments and olivine basalt.

3. A period of normal faulting, beginning no earlier than Pliocene time, was followed by right-lateral faulting which is probably continuing to the present day. The thermal areas shown in figure 2 are located on, or close to, the surface trace of these faults.

## Mesozoic rocks

1. The Mesozoic rocks of the Clear Lake area are divided into the Franciscan formation, which in this area is of probable Upper Jurassic age; the Knoxville formation of uppermost Jurassic age; and undifferentiated Cretaceous rocks. The Franciscan formation, which is at least 28 000 feet thick, consists of interbedded graywacke and spilitic basalt plus minor amounts of shale, conglomerate and chert.

The Knoxville formation has a probable maximum thickness of 5 000 feet, but not all of this is exposed in the Clear Lake area. The Knoxville formation is a thin-bedded sequence of graywacke and shale, which occur in the ratio of 1:4.

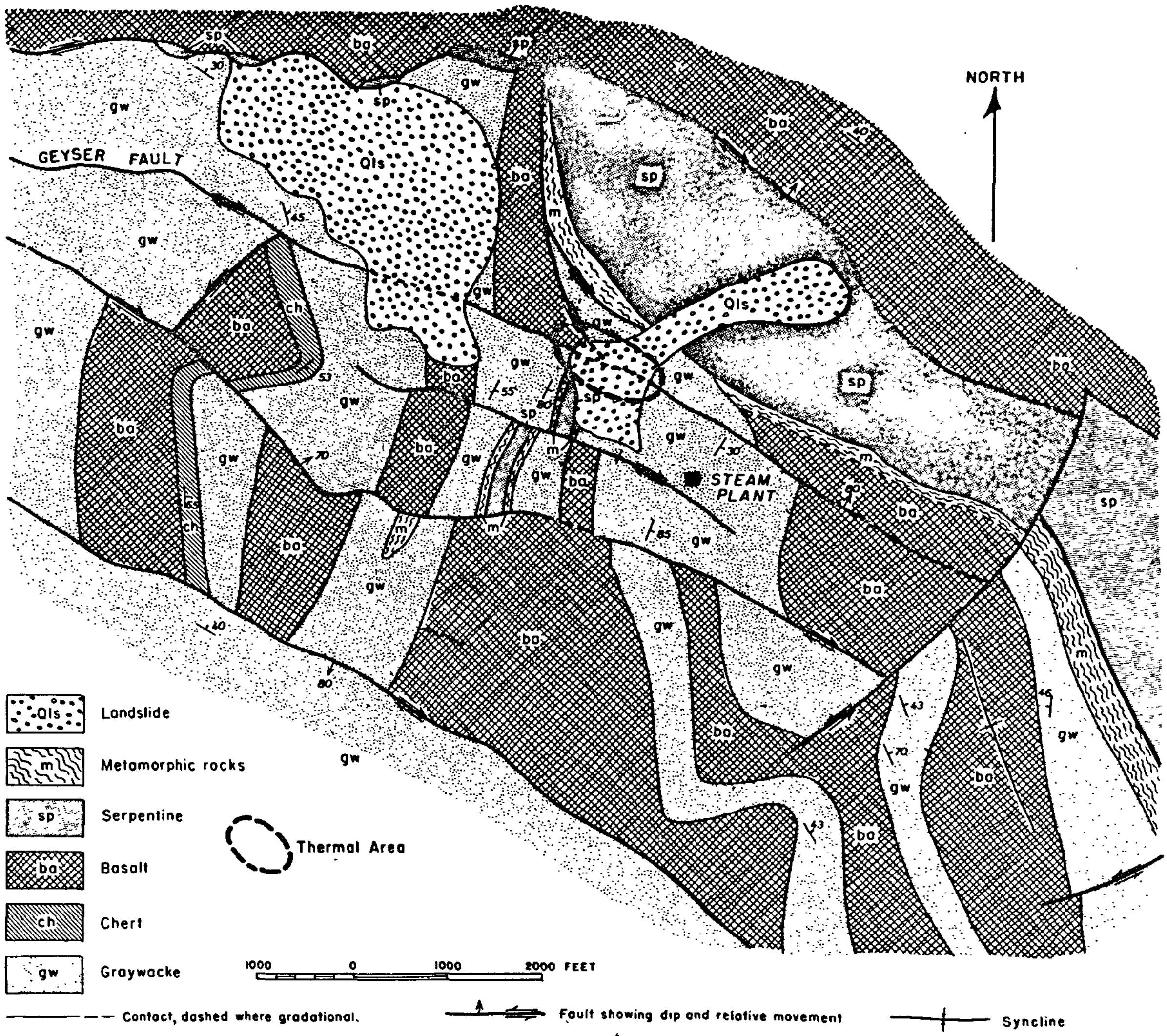
2. Serpentine sills, which intrude both the Franciscan and Knoxville formations, range from 500 to 1 000 feet in thickness and are from 2 000 feet to more than 4 miles in length. Amphibole schists, including glaucophane schists, occur in narrow zones along the margin of the serpentine bodies and are considered to be the product of contact metamorphism of spilitic basalt by the ultra-basic intrusives.

3. Approximately 5 000 to 10 000 feet of undifferentiated Cretaceous rocks overlie the Knoxville formation. This sequence consists of massive yellow-brown sandstones and gray shales, interbedded in about equal proportions.

PLEISTOCENE AND RECENT VOLCANIC ROCKS

1. Rhyolitic flows and tuffs, obsidian, basaltic lavas, and lavas of dacitic and andesitic composition, are represented in the Clear Lake area (Brice, 1953). The age relationship of these flows is difficult to determine because several of the flows are isolated from the main volcanic mass, located in the south-west shore of Clear Lake (figure 2), and because contact relationships are obscured by landslides and faults. The association of olivine basalt with the gravels that underlie a major portion of the volcanic rocks, however, indicates that the first flows were of basaltic composition.

2. The major vent in the volcanic field is Mt. Konocti, a composite cone standing 2 000 to 2 500 feet above the surrounding terrain and located on the west side of Clear Lake (Anderson, 1936). In addition to this vent, three Recent cinder cones are located on the east and one on the south side




Geologic Map of The Geysers Thermal Area
James R. McNitt

Figure 3

of Clear Lake. The rhyolite flow which caps Cobb Mountain, 3 km north-east of The Geysers, is underlain by 200 feet of rhyolite tuff, suggesting the presence of a local explosion vent in that area. The scarcity of volcanic vents that might represent large feeders, the fact that many of the flows are isolated from the vent at Mt. Konocti, and the general north-west trend of the flows, suggest that "lavas were apparently extruded from a system of north-west-trending fissures, the different flows no doubt rising along separate fissures" (Brice, 1953).

### Structure

1. Gentle folding of the Mesozoic rocks has produced a regional north-west strike and dips which y rarelexceed 50°. Although the average width of the folds is probably several miles, a more accurate estimate of width is not possible because the folds have been displaced by several fault zones which also trend north-west (figure 2). The volcanic rocks are only rarely displaced by the faults, indicating there has been no significant post-eruptive fault movement. These faults not only act as conduits for present-day thermal fluids, as indicated by the location of hot springs (figure 2), but have also controlled the location of numerous mercury mines and prospects in the Clear Lake area.

2. Both vertical and horizontal displacements have been demonstrated on the faults in this region. The Big Sulphur Creek fault zone, on which The Geysers is located, is a strike-slip fault zone with a right-lateral sense of movement. A set of minor north-east-striking faults, with apparent left-lateral displacement, are associated with the major north-west-striking faults of the Big Sulphur Creek fault zone (see figure 2). Blocks between north-west and north-east faults are rotated clockwise about a vertical axis, indicating that although the dominant movement was right-lateral on the north-west set, a minor amount of left-lateral movement must have taken place on the north-east set. Right-lateral movement on the Big Sulphur Creek fault zone is also indicated by the geometric relationship between fault deflections and the occurrences of mercury ore at their deflections, i.e., right-lateral movement was necessary to produce "open" structures at these points. It can be demonstrated from structural evidence that the Big Sulphur Creek fault zone is no older than Pliocene time, and it is probable that major fault movement was contemporaneous with Pleistocene and Recent volcanism.

## Geothermal activity at The Geysers

### Structural control

1. The only fault in the Big Sulphur Creek fault zone that conducts thermal fluid to the surface is the Geyser fault (figure 3). This fault strikes N 70° W and dips 70° to 80° north-east, and, like the other north-west-striking members of the Big Sulphur Creek fault zone, is believed to be right-lateral.

2. The most active thermal area on the Geyser fault is at The Geysers itself. The surface geology of The Geysers is obscured by sliding and extensive alteration, but faults and bedding attitudes can be extrapolated into the thermal region from the surrounding area. The Geysers area is located on a steeply plunging shear zone caused by the intersection of a left-lateral fault, which strikes N 8° W, with the Geyser fault. Two of the steam wells are located immediately north of the trace of the Geyser fault on the small wedge of basalt which extends into the thermal area from the north-west. These wells passed from basalt into greywacke at approximately 300 feet, thus confirming the 70° NE dip of the Geyser fault.

3. Three less active areas are located along the Geyser fault to the north-west: one at approximately 1 500 feet, another at 4 000 feet and a third at 5 500 feet from the west end of The Geysers area (figure 3). These areas may be located on cross faults similar to the cross fault at The Geysers, but surface exposures are too poor to verify this assumption.

### Surface expression

1. The Geysers thermal area, as defined by the effects of hydrothermal rock alteration at the surface, is about 1 300 feet long and 600 feet wide. The longer dimension approximately parallels the north-west-striking Geyser fault.

2. Most of the natural thermal activity is confined to Geyser Creek, which occupies a narrow canyon crossing the western part of the area from north to south. Although this canyon contains numerous hot springs, whose temperatures range between 50°C and the boiling point, there are only two rather feeble fumaroles. A third fumarole, also quite small, plus a few hot springs, occurs in the area east of the canyon.

3. Allen and Day (1927) measured the discharge from hot springs in Geyser Creek and found the flow to range between 2 770 gal/hr. in the wet season and 1 775 gal/hr. in the dry season. Because these authors estimate this discharge to be "at least half if not considerably more" than the total hot spring discharge from The Geysers area, an average year-round flow could be estimated at 3 000 gal/hr. Allen and Day concluded that their measurements clearly show that a body of ground water, varying in volume with the season, is constantly reaching the surface along Geyser Creek, and that therefore part of the water from these springs is of surface origin.

4. No significant chloride content has been found in the hot spring waters, and the springs have been classified as the sodium-bicarbonate type by White (1957).

### Alteration

1. Surface alteration of greywacke, which is the only altered rock type exposed at The Geysers, has resulted from intense acid leaching. Original

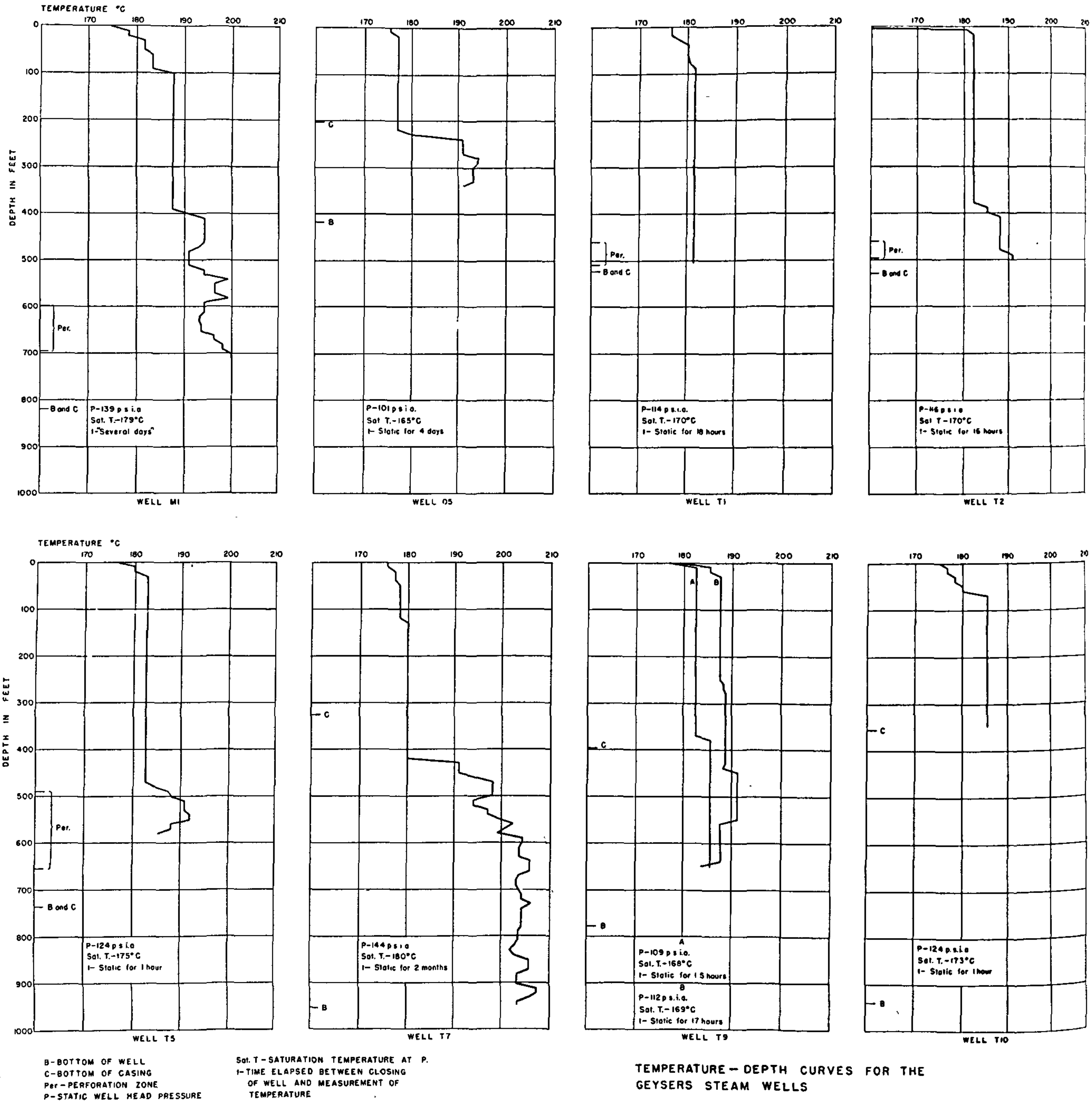



**Figure 4**

rock textures are completely destroyed and the remaining porous mass consists essentially of alunite, opal, and residual quartz. A small amount of dickite was also found in a few localities. Eleven sulfate minerals, in addition to alunite, have been identified from The Geysers (Vonsen, 1946, p. 288). The precipitation of sulfates is due to the oxidation and hydration of $H_2S$ to sulfuric acid in the steam condensate and surface water.

2. All the wells at The Geysers were drilled into Franciscan greywacke, except for two which penetrated approximately 200 feet of diabase at a depth of about 100 to 300 feet. The greywacke has been altered by the formation of pyrite, sericite, carbonate, and quartz. The pyrite occurs as irregular grains 2 or 3 mm in diameter disseminated throughout the altered rock. Sericite has replaced the albite feldspar as well as a considerable part of the fine grained groundmass. Unlike the disseminated occurrence of pyrite, sericitization is restricted to narrow zones which are controlled by small fractures. In zones of poor core recovery, however, the greywacke is completely disintegrated to a mass of quartz and sericite. The carbonate and quartz are predominantly

vein-filling minerals in the altered greywacke, but some carbonate replaces the greywacke groundmass. The predominant carbonate, by far, is calcite; in a core taken from 750 feet, however, small veins of siderite were also present.

3. The altered diabase penetrated by two of the wells represents a diabasic facies of the large north-striking basalt body which crops out north-west of the well area. The original diabase texture is well preserved in the altered rock, but the mineralogy has been drastically changed. The centres of the plagioclase laths have been extensively sericitized, but the original composition can be determined as labradorite. Bands of clear K-feldspar surround the sericitized labradorite. Pyrite is disseminated throughout the altered rock; titaniferous magnetite is replaced by leucoxene; and chlorite replaces augite. As in the altered greywacke, calcite and quartz veins are common, and quartz is considerably less abundant than calcite. Numerous apatite crystals are present in the K-feldspar and are believed to be secondary in origin. Although the occurrence of the calcium zeolite, wairakite, has been reported in material thrown from a blowing steam well at The Geysers (Steiner, 1958), this mineral has not been identified in the present investigation.

## Steam reservoir

1. On 21 and 22 April 1960, temperature logs were run by the Thermal Power Co. on eight steam wells. These temperatures were taken with an iron-constantan thermocouple after the wells had been shut off for periods ranging between one hour and two months. The resulting temperature-depth plots for these wells are shown in figure 4. The static wellhead pressure recorded during the time of temperature measurement and the elapsed time between well shut-down and temperature measurement are indicated for each well.

2. A striking characteristic of these logs is the interval of constant temperature encountered in the upper part of the wells. In only one of the wells, T7, does this constant temperature interval represent saturation conditions at the measured pressure. In all the other wells, the constant temperature shows various degrees of superheat, ranging from 8°C to 19°C, indicating that a liquid phase does not exist over the interval measured. There is a distinct temperature increase at the bottom of the constant temperature zone in six of the wells (figure 4). The maximum temperature below this temperature "break" is 207.5°C, which was recorded in well No. T7.

3. The surface representing the bottom of this constant temperature zone is shown by contours in figure 5A. Because geologic mapping indicates that steam is conducted to the surface through a steeply plunging fracture system, it is not probable that the surface shown in figure 5A, which dips only 25°, corresponds to one of these steam-conducting fissures.

4. It is known that a body of groundwater overlies the superheated steam zone. Therefore, it is suggested that the base of the constant temperature zone corresponds to a steam-water interface at the bottom of the body of ground water. Immediately after closing a flowing well, a film of condensed water should form on the wall of the well where superheated gas comes in contact with ground water or with the well casing, which is in contact with ground water. As heat is absorbed by the surrounding groundwater, the temperature of the gas in the well will decrease until saturation conditions for the pressure in the well are obtained. At any time between the shut-down of the well and the final attainment of saturation conditions, the temperature in that part of the well which is in contact with ground water should not vary with depth. This is due to the fact that the temperature at which steam will condense on the wall of the well is dependent on the steam pressure, which, under static conditions, would be essentially constant with depth. The validity of this proposed explanation for the constant temperature zone is supported by the fact that the only well in which saturation conditions exist in the constant temperature interval is well No. T7. This well had been closed for the longest period of time before the temperatures were measured, suggesting that all the wells would eventually reach saturation conditions within the depth interval of constant temperature.

5. If the steam reservoir is essentially static, i.e., there is no driving pressure from beneath the reservoir forcing the steam to the surface (other than the expansive force of the steam itself), then the static wellhead pressure should be equal to the hydrostatic pressure of the overlying body of ground water. Therefore, the height of the overlying water body at the point at which the well is drilled may be computed from pressure data. This hypothesis has been tested by calculating the height of a column of water which would produce the static wellhead pressure given in figure 4, and adding this height to the elevation of the temperature "break" at the bottom of the constant temperature interval. The surface thus defined, contoured in figure 5B, should represent the top of the groundwater body which overlies the steam. Two features of the surface defined in this manner support the static reservoir hypothesis: (*a*) there is a general similarity in configuration between the topography of The Geysers area (figure 5C) and the configuration of the upper boundary of the proposed ground water body (figure 5B), thus indicating a relationship which would be expected between the two surfaces; (*b*) the elevation of the surface shown in figure 5B ranges between 1 500 and 1 600 feet, which corresponds to the range in elevation of the principal natural springs in Geyser canyon (Waring, 1915).

6. Figure 5D is a cross-section through The Geysers area illustrating the spacial relationship between the ground surface, the top of the ground-water body, and the steam-water interface, as defined by the method described above.

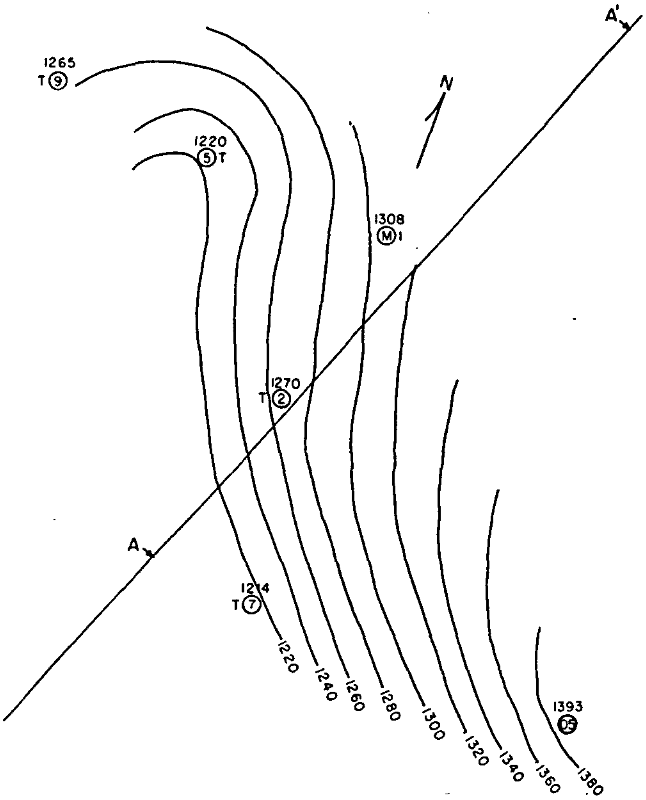



**Figure 5A. Contours drawn on bottom of constant temperature zone**

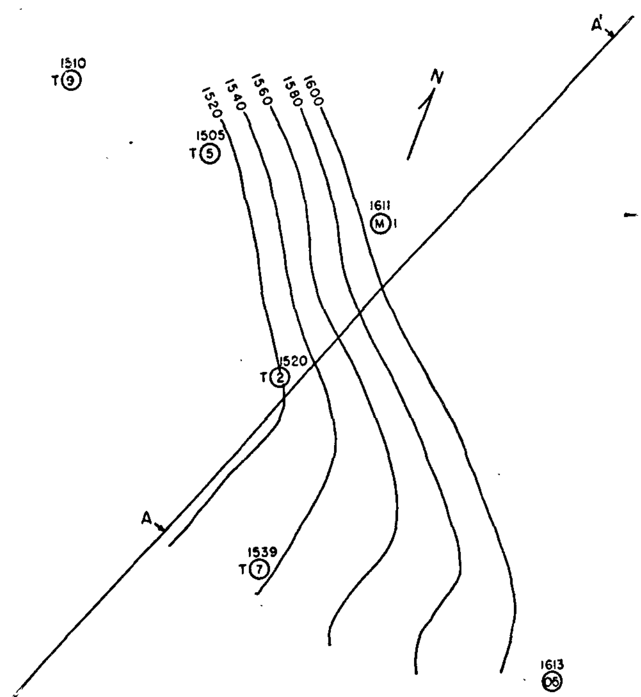



**Figure 5B. Contours drawn on top of ground water zone as defined by calculations described in text**

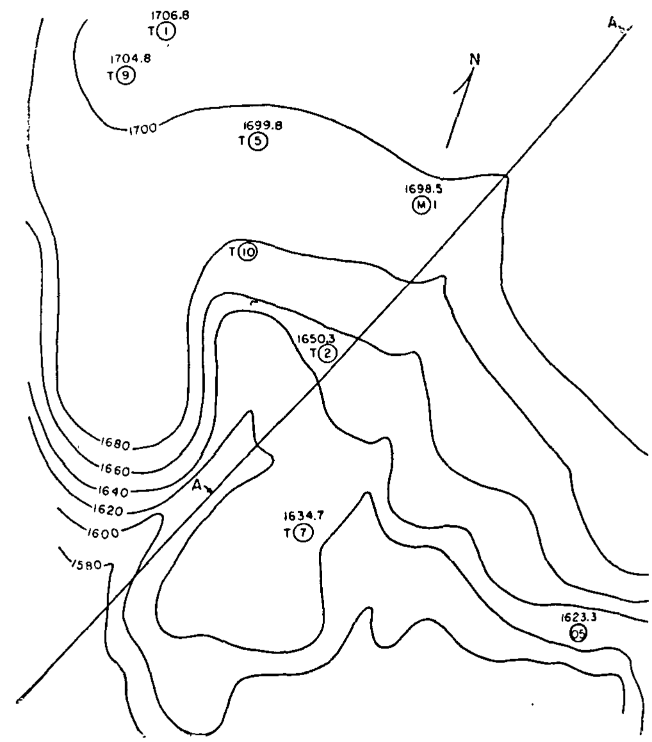



**Figure 5C. Surface contours of The Geysers thermal area**

7. If the steam reservoir pressure is lowered by releasing the steam through drill holes, the steam-water interface does not sink, but rather it rises because of water boiling off the interface as a result of the lowering of the saturation pressure. This effect is demonstrated in well No. T9 where two consecutive temperature logs were run, the first $1\frac{1}{2}$ hours and the second 17 hours after shut-down of the well (figure 4). Instead of moving upwards with time because of increasing steam pressure, the steam-water interface actually moved downwards 70 feet in $15\frac{1}{2}$ hours due to condensation at the steam-water inter-

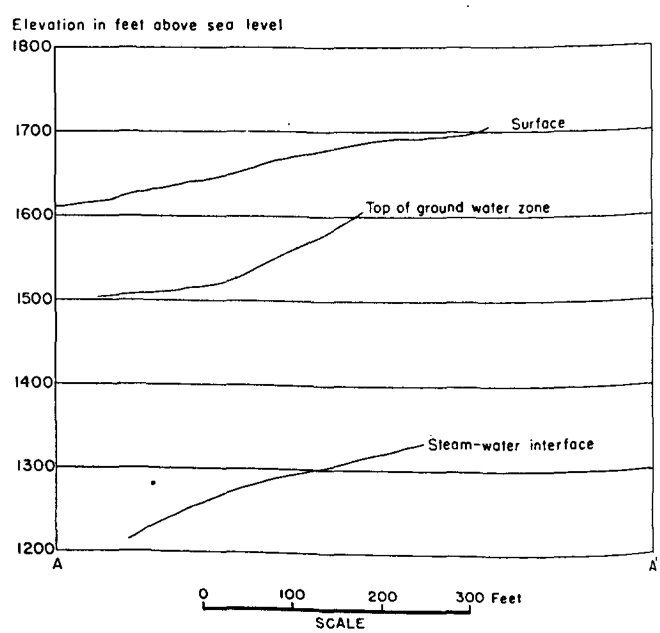



**Figure 5D. Section across A-A**

face. In this regard it is important to note that if the pressure of the hydrostatic head became greater than saturation pressure at the maximum steam temperature (207.5°C), the steam-water interface would move downwards indefinitely, and only saturated steam and hot water could be produced. A hydrostatic head equivalent to approximately 730 feet of boiling water would be necessary to produce this condition at The Geysers. The present ground water zone has a maximum thickness of approximately 300 feet.

8. A "quenching" of this nature could occur, however, only if the steam enthalpy is less than 670 cal/gm. At a constant enthalpy greater than 670 cal/gm, an increasing water-head could not produce a condensed phase in the steam, but would cause a supercritical gas phase to form when the hydrostatic head reached a depth of about 10 000 feet.

## Heat flow

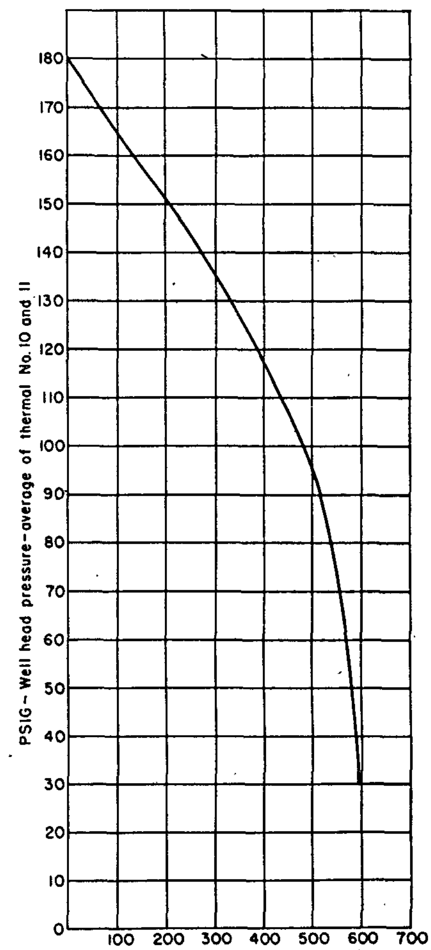
1. Although the static pressure of the steam is dependent upon the hydrostatic head above the steam, the height of this water column is principally determined by the rate of heat flow into and out of the overlying water body. This water body is a mixture of meteoric water, originating in the immediate vicinity of The Geysers, and condensed steam from below. Under natural conditions, heat is released from this ground-water body by flow of hot water from the springs in Geyser Canyon, and the rate of this water-flow is determined by the porosity of the fracture zone. Evaporation of water must also be an important cause of heat loss because water in the ground water body is at, or very near, its boiling point throughout its pressure range. The rate of heat loss from the ground water body must be equal to the rate at which heat is supplied at the steam-water interface. If the rate of heat flow into the water body were greater than the rate of heat loss, the water would "boil away" and superheated steam would escape directly to the surface. If the rate of flow of cold meteoric water into the ground water body increased, the rate of heat flow into the water body by steam condensation would also increase because of the necessity of raising a greater volume of water to its boiling point. Eventually, the rate of heat flow into the area would be limited by the physical dimensions of the feeding fractures and, on continued inflow of cold meteoric water, the system would be "quenched" as described in paragraphs 7 and 8.

2. The natural heat flow from The Geysers thermal springs can be estimated in the following manner. The natural thermal spring water, which is derived from the ground water body, is a mixture of meteoric water and steam condensate. The enthalpy of the meteoric water is approximately 20 cal/gm and the enthalpy of the steam is 667 cal/gm. Mixing of these two waters results in a water body having an enthalpy of approximately 100 cal/gm. Water is released from this body at the approximate rate of 3 000 gal/hr. If $x$ is the percentage of condensed steam in the natural spring flow, then the following equation expresses the above conditions:

$$670\,x + 20\,(1 - x) = 100$$

and $x = 12$ per cent.

3. Therefore, under natural conditions, approximately one pound of steam is condensed in one second. At the average enthalpy of 667 cal/gm, this estimated steam flow gives an estimated natural heat flow from The Geysers thermal area of $3 \times 10^5$ cal/sec. This figure, however, does not include heat loss by evaporation from the ground water body.




TOTAL STEAM FLOW FROM WELLS AT THE GEYSERS

After A.W. BRUCE

P.G. & E. Co. March 2, 1961

Figure 6

4. An estimated limit for the maximum rate of heat flow through the steam wells at The Geysers is shown in figure 6, which is a steam flow — wellhead pressure curve computed for all the producting wells. Water loss from natural spring flow (approximately 25 000 lb/hr), from evaporation, and from an

uncontrolled "blowout" were not included in the computation of this curve. If these other factors are considered, a conservative estimate for maximum total steam flow from the area would be about 800 000 lb/hr. At an average enthalpy of 667 cal/gm, this estimated steam flow gives a maximum estimated heat flow of $7 \times 10^7$ cal/sec. Comparing this figure with the calculated natural heat flow shows that drilling the wells makes it possible to increase the rate of heat flow from the thermal area by approximately 230 times the rate of natural heat flow.

## Origin of the thermal fluid

The steam from The Geysers may be derived from either of two sources: (*a*) deep circulating ground water which becomes heated at depth by conduction from hot rocks, or (*b*) primary water which is released at depth and which arrives at the surface mixed, to a greater or less degree, with meteoric water. Primary water may be metamorphic, connate, or magmatic in origin.

The fact that The Geysers thermal area can produce, essentially instantaneously, a rate of heat flow 230 times the natural rate, indicates that a heat reservoir exists at depth and from which heat is released by convective flow, rather than by the much slower process of conductive flow through rock. It is conceivable that this heat reservoir consists of a body of meteoric water existing at its boiling point somewhere at depth below the present steam water interface. If this body of water were fed directly from the surface through open channels, a reservoir pressure would be obtained equivalent to the hydrostatic head existing between the surface and the deep heat reservoir. At a depth of only 1 km the static pressure in the heat reservoir, if open to the surface, should be approximately 1 400 psi.

Such a pressure, however, is 10 times the maximum static reservoir pressure measured at The Geysers. It is improbable, therefore, that an open convective system exists in which meteoric water is fed directly to the heat reservoir, raised to its boiling point, and then returned to the surface as steam.

The steam enthalpy is another factor which suggests that the thermal discharge is not in equilibrium with meteoric water. These enthalpies, computed from the wellhead pressures and maximum temperature recorded in the wells, are shown in table 1.

**Table 1. Enthalpies of thermal fluid**

| *Well No.* | *Enthalpy in cal/gm* |
|---|---|
| T1 | 669 |
| T10 | 669 |
| T2 | 673 |
| T5 | 673 |
| T9 | 674 |
| M1 | 676 |
| O5 | 678 |
| T7 | 681 |

Although the average steam enthalpy measured at the turbine is only 667 cal/gm, the steam enthalpies computed in the above manner are significantly higher. There are two reasons for this discrepancy: (*a*) the rate at which heat will be absorbed from flowing steam by evaporation at the water-steam interface is much greater than the rate of heat absorption by the same process under static conditions; (*b*) a small amount of heat loss occurs while the steam is being transported from the bottom of the well to the turbine.

**Table 2. Enthalpies of primary fluid with corresponding percentage of primary fluid in thermal discharge**

| *Enthalpy of primary fluid in cal/gm* | *Per cent of primary fluid in discharge* |
|---|---|
| 1 000 | 63 per cent |
| 900 | 71 per cent |
| 800 | 81 per cent |
| 700 | 94 per cent |

Superheated steam with an enthalpy greater than 670 cal/gm cannot be in equilibrium with a liquid phase. The fact that the steam enthalpy in six of the wells is greater than 670 cal/gm therefore supports the hypothesis that the steam is of primary rather than meteoric origin. If the steam is of meteoric origin, then a mechanism must exist whereby the meteoric water is first heated to the boiling point, then separated from the source of meteoric water, and finally heated again to produce a fluid with an enthalpy greater than 670 cal/gm. It is possible that a restricted flow of meteoric water could enter the system below a zone of hot rock, and then become superheated on its passage upwards through the hot rock to the surface, thus accounting for both the low reservoir pressure and the superheat. The existence of such a natural system, however, would be quite fortuitous.

If the heating of meteoric water by primary water is the dominating mechanism responsible for the thermal activity, then it is possible to calculate the approximate ratio of primary to meteoric water in the steam well discharge by making the following assumptions. A reasonable geothermal gradient in this area, discounting the presence of a near-surface heat source, would be approximately 30°C/km (Birch, 1954). Therefore, if groundwater succeeded in penetrating down the Geyser fault to a depth of slightly over 3 km, it would have an enthalpy of approximately 100 cal/gm due to a normal geothermal gradient. If water having an enthalpy of 100 cal/gm is heated by primary water to produce a fluid having an enthalpy of 667 cal/gm, which is the average enthalpy of The Geyser's steam measured at the turbine, the ratio of primary to primary + meteoric water may be found by evaluating the following equation :

$$ax + 100(1 - x) = 667$$

where $a$ is the enthalpy of the primary water and $x$ is the ratio of primary to primary + meteoric water. White (1957) states that steam at any likely volcanic temperature cannot have an enthalpy of more than 1 000 cal/gm. Table 2 gives the evaluation of $x$ in the above equation for enthalpies of primary steam from 1 000 cal/gm to 700 cal/gm.

Provided that the assumptions stated above are valid, these calculations suggest that at least 60 per cent of the fluid now issuing from the steam wells is of primary origin.

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## *Summary*


Natural steam is being utilized to generate 12 500 kw of electric power at The Geysers thermal area, which is located 130 km north of San Francisco in the coast ranges of California.

This region is underlain by a eugeosynclinal sequence of greywacke and spilitic basalt of Jurassic age, and sandstone and shale of Cretaceous age. The Jurassic rocks have been intruded by numerous serpentine sills. Geosynclinal deposition ceased in early Tertiary time when the Mesozoic rocks were uplifted and gently folded. A Pliocene erosion surface truncates the folded Mesozoic rocks. Pleistocene volcanic rocks, including rhyolitic flows and tuffs, obsidian, basaltic lavas, and lavas of dacitic and andesitic composition were erupted onto this surface. The volcanic field is approximately 24 km long and 9 km wide.

A north-west-trending, right-lateral fault zone crosses the Jurassic rocks 3 km south-west of the volcanic field. This fault zone, which has been mapped for a length of 40 km, is no older than Pliocene time, and movement has probably continued into Recent time. Several thermal areas, of which The Geysers appears to be the most active, plus a considerable number of mercury mines and prospects, are located on the fault zone.

The Geysers thermal area, which is about 0.2 km in diameter, is located on a steeply plunging fracture zone caused by the intersection of a major member of the north-west-trending fault zone with a minor north-trending fault. Natural thermal activity consists of numerous hot springs whose temperature ranges between 50°C and the boiling point plus three small, feeble fumaroles. Although the volume of flow from these springs varies with the season, an average year-round flow is estimated at 3 000 gal/hr. These springs are of the sodium-bicarbonate type and have no significant chloride content.

Surface hydrothermal alteration, consisting of intense leaching of the Jurassic greywacke by sulfuric acid, has resulted in a porous mass of alunite, opal, and residual quartz. Sulfuric acid is formed by the oxidation and hydration of $H_2S$ in the steam condensate and surface water. Below this zone of oxidation, as disclosed by the steam well cores, the greywacke has been hydrothermally altered, resulting in the formation of disseminated pyrite and sericite and of vein calcite and quartz. K-feldspar, rimming sericitized labradorite, was found in cores from a diabase body which was penetrated by two of the wells. The augite of the diabase is replaced by chlorite.

The steam wells range from approximately 160 to 300 metres in depth. Under static conditions, individual wellhead pressures range from 101 to 144 psia, and maximum temperatures in the wells, measured with an iron-constantan thermocouple, range between 182°C and 208°C. These data indicate that The Geysers steam is superheated and has an enthalpy ranging from 669 cal/gm to 681 cal/gm.

The depth-temperature curves are characterized by a constant temperature zone which extends from approximately 30 metres to 115 metres in depth. Interpretation of these depth-temperature curves strongly suggests that the base of the constant temperature zone corresponds to the base of a ground water body which is overlying the superheated steam reservoir. If it is assumed that the static wellhead pressures are equivalent to the hydrostatic pressure of the overlying water body, then the

thickness, as well as the elevation of the upper boundary, of the ground water body may be calculated. This assumption is supported by the fact that the range in elevation of the upper boundary of the ground water body, thus calculated, corresponds to the range in elevation of the principal thermal springs in the area. It can be concluded, therefore, that the static steam reservoir pressure is due to the overlying hydrostatic head, rather than to a reservoir "drive" pressure originating at depth.

The position of the steam-water interface is determined by the fact that the rate of heat flow into the overlying ground water zone must be equal to the rate of heat loss from this zone under equilibrium conditions. If the rate of heat flow into the water body became greater than the rate of heat loss, less steam would be condensed, the interface would move upwards, and the reservoir pressure would decrease.

If the rate of flow of cold meteoric water into the ground water body increased, more steam would be condensed, the interface would move downwards, and the reservoir pressure would increase. If the hydrostatic head became great enough to condense the steam at the highest steam temperature, the steam-water interface would move downwards indefinitely, and a completely saturated system would result.

The natural rate of heat flow from The Geysers area due to condensation of the superheated steam is approximately $3 \times 10^5$ cal/sec. The maximum rate of heat flow from the area through the wells can be estimated at $7 \times 10^7$ cal/sec. Drilling the steam wells, therefore, makes it possible to increase the rate of heat flow by 230 times the natural rate.

Considerations concerning the physics of this natural hot spring system suggest that 60 per cent to 80 per cent of the steam is from primary water and that the remainder is of meteoric origin. This primary water could be metamorphic, connate or magmatic.

## CONSIDÉRATIONS GÉOLOGIQUES AU SUJET DE LA RÉGION THERMIQUE DITE « THE GEYSERS » EN CALIFORNIE

### *Résumé*

On fait usage de vapeur naturelle pour la production de 12 500 kW d'énergie électrique dans la zone dite The Geysers, située à 130 km au nord de San Francisco, dans la chaîne côtière de Californie.

La masse sous-jacente se caractérise, dans cette zone, par des grauwackes et des basaltes spilitiques d'âge jurassique en série géosynclinale, avec des grès et des ardoises du crétacé. On trouve nombre de nappes d'intrusion dans les roches jurassiques, constituées par de la serpentine. Les dépôts géosynclinaux ont cessé au début du tertiaire, époque à laquelle les roches mésozoïques furent soulevées et légèrement repliées. Une surface d'érosion appartenant au pliocène tronque les couches mésozoïques ainsi plissées. Des roches volcaniques du pléistocène, notamment des écoulements et des tufs de rhyolite, de l'obsidienne, des laves basaltiques et des laves d'une composition dacitique et andésique ont fait éruption sur cette surface. Le champ volcanique a quelque 24 km de long et 9 km de large.

Une zone de failles à côtés droits et à orientation générale vers le nord-ouest traverse les roches jurassiques à 3 km au sud-ouest de la région volcanique. Cette région de failles, dont on a fait un relevé cartographique sur une longueur de 40 km, ne remonte pas à une époque antérieure au pliocène et certains mouvements s'y sont probablement poursuivis jusqu'à l'époque actuelle. Plusieurs zones thermiques, dont celle de The Geysers semble être la plus active, plus un grand nombre de mines de mercure en exploitation ou à l'état de possibilité se trouvent dans la zone des failles.

Le champ thermique de The Geysers, dont le diamètre est de l'ordre de 0,2 km, est situé dans une zone de fractures à plongée rapide, dont la présence s'explique par l'intersection d'un membre important de la zone des failles à orientation générale nord-ouest avec une faille mineure orientée vers le nord. L'activité thermique naturelle est constituée par nombre de sources chaudes, dont la température s'échelonne entre 50 °C et le point d'ébullition, plus trois petites fumerolles peu actives. Bien que le débit de ces sources varie avec les saisons, on évalue sa moyenne horaire annuelle à 3 000 gallons. Ces sources sont du type à bicarbonate de sodium, sans teneur appréciable en chlorures.

Les altérations hydrothermiques superficielles, constituées par un intense lessivage de la grauwacke du jurassique par l'acide sulfurique, ont donné lieu à la formation d'une masse poreuse d'alunite, d'opale et de quartz résiduel. L'acide sulfurique est formé par l'oxydation et l'hydratation du $SH_2$ présent dans les produits de condensation de la vapeur et dans l'eau de surface. Au-dessous de cette zone d'oxydation, ainsi que l'indiquent les échantillons prélevés dans les puits de vapeur, la grauwacke a fait l'objet d'une altération hydrothermique aboutissant à la formation de pyrites et de séricites disséminées, avec veines de calcite et de quartz. Un feldspath potassique situé en bordure d'une labradorite transformée en séricite a été trouvé dans les carottes prélevées sur un corps de diabase pénétré par deux des puits. L'augite de la diabase y est remplacée par de la chlorite.

La profondeur des puits débitant de la vapeur s'échelonne entre 160 et 300 m. Dans des conditions statiques, les pressions individuellement relevées à la bouche des puits vont de 101 à 144 livres par pouce carré et les températures maximums, prises dans ces puits avec un thermocouple fer-constantan, vont de 182 à 208 °C. Ces données indiquent que la vapeur trouvée à The Geysers est surchauffée et que son enthalpie s'échelonne entre 669 cal/g et 681 cal/gm.

Les courbes profondeur-température se caractérisent par un plateau à température constante qui s'étend, en profondeur, de 30 à 115 m environ. L'interprétation de ces courbes donne fortement à penser que la base de la plage à température constante correspond à celle d'une nappe d'eau souterraine située au-dessus du réservoir de vapeur surchauffée. Si on admet que les pressions statiques à la bouche des puits sont équivalentes à la pression hydrostatique de la masse d'eau située au-dessus de ce réservoir, on peut calculer l'épaisseur de cette masse d'eau en même temps que la cote de son niveau supérieur. Cette hypothèse est appuyée par le fait que les variations de la cote ainsi calculée correspondent à la gamme des hauteurs des principales sources chaudes de la région. On peut donc en conclure que la pression statique du réservoir de vapeur est due à la pression hydrostatique située au-dessus d'elle, plutôt qu'à une pression « motrice » émanant du réservoir même et trouvant son origine en profondeur.

La position de la face de séparation vapeur-eau est déterminée par le fait que le débit de la fourniture de chaleur à la zone d'eau souterraine sous-jacente doit être égal au taux des pertes de chaleur dans cette même zone quand l'équilibre règne. Si le régime de fourniture de chaleur à la masse d'eau est plus élevé que celui des pertes, la condensation de vapeur diminue, la surface de séparation se déplace vers le haut et la pression qui règne dans le réservoir diminue.

Si le taux d'écoulement de l'eau météorique froide vers la masse d'eau souterraine augmente, il se condense plus de vapeur, la surface de séparation se déplace vers le bas et la pression augmente dans le réservoir. Si la pression hydrostatique devenait suffisante pour condenser la vapeur à la plus haute température possible pour celle-ci, la surface de séparation vapeur-eau se déplacerait indéfiniment vers le bas et on aboutirait à un système complètement saturé.

Le débit naturel de chaleur donné par The Geysers en raison de la condensation de la vapeur surchauffée est de l'ordre de 300 000 calories par seconde. Le débit maximum de cette chaleur, dans le même champ, tel qu'il s'établit avec des puits, peut être évalué à 7 millions de calories par seconde. En fonçant des puits pour recueillir la vapeur, par conséquent, on multiplie le débit naturel de chaleur par un facteur de 230.

Les considérations physiques ayant trait à ce système de sources chaudes naturelles donnent à penser que la proportion de la vapeur en provenance de l'eau primitive varie entre 60 et 80 p. 100, le reste étant d'origine atmosphérique. Cette eau primitive peut être d'origine métamorphique, fossile ou magmatique.

# ÉCHANTILLONNAGE ET ANALYSE DES GAZ DES SOURCES NATURELLES DE VAPEUR

*Renzo Nencetti**

Toutes les études géochimiques concernant la définition des caractères d'un événement ou d'un phénomène superficiel ou souterrain donné exigent la fixation en qualité et en quantité des composants chimiques des roches, des minéralisations, des eaux, des gaz et des matières végétales que l'on retrouve dans la zone sous examen.

Les différences qualitatives et quantitatives résultant des enquêtes de laboratoire, qu'elles soient chimiques ou physico-chimiques, contribuent à définir les caractères de diagnostic d'une zone déterminée. Elles offrent au géologue un moyen extrêmement utile de compléter ses connaissances des études géologiques, géophysiques, minéralogiques, pétrographiques, etc. Dans le cas qui nous occupe, l'application de la recherche géo-chimique aux composants du fluide endogène n'est pas seulement utile à l'ingénieur géologue, mais également à l'ingénieur chimiste; en effet, celui-ci a intérêt à récupérer les composants chimiques prisés comme l'acide borique, l'ammoniaque, l'hydrogène sulfuré. Et encore sert-elle à l'ingénieur thermotechnicien, puisque c'est du contenu des incondensables du fluide endogène que dépend le cycle thermique de l'exploitation énergétique de celui-ci.

En particulier, l'apport en connaissance venant d'une étude de ce genre aide à définir les multiples aspects d'un phénomène endogène pendant son cycle d'évolution, ainsi que les problèmes liés à l'allure même de ce phénomène.

Dans le champ géothermique de Larderello, le fluide endogène se présente comme un mélange intime de vapeur non saturée surchauffée et de gaz divers, ayant la composition moyenne en poids indiquée au tableau 1.

**Tableau 1. Composition moyenne en poids du fluide endogène**

| | | p. 100 |
|---|---|---|
| Vapeur d'eau | $H_2O$ | 955,62 |
| Acide borique | $H_3BO_3$ | 0,30 |
| Ammoniaque | $NH_3$ | 0,30 |
| Anhydride carbonique | $CO_2$ | 42,65 |
| Hydrogène sulfuré | $H_2S$ | 0,88 |
| Gaz combustibles | $CH_4 + H_2$ | 0,19 |
| Azote | $N_2$ | 0,16 |
| Gaz rares | H + A | 1 cc |
| | | 1 000,00 |

* Larderello, S.p.A., Pise (Italie).

Étant donné que l'emploi de n'importe quel fluide endogène, soit au stade de l'exploitation énergétique, soit au stade de l'exploitation chimique, est lié directement et indirectement au partage partiel ou total des gaz du fluide endogène à disposition, lorsque nous parlons de gaz endogène nous voulons pratiquement nous rapporter à ce qui reste après condensation totale de la phase vapeur. Naturellement de petites fractions gazeuses peuvent se trouver dissoutes dans la vapeur condensée; dans ce cas les analyses séparées du gaz et du contenu gazeux des vapeurs condensées donneront la composition totale du mélange gazeux.

Ainsi qu'il est indiqué au tableau 1, le mélange gazeux est constitué d'anhydride carbonique, qui est son constituant principal du point de vue quantité, de $H_2S$, de $H_2$, de $CH_4$, de $Na_2$, de Ar, de He.

Les autres constituants chimiques, comme l'acide borique et l'ammoniaque contenus également dans le fluide des soufflards, demeurent presque entièrement dissous dans l'eau du condensé.

## Prélèvement des échantillons de fluide total

L'échantillonnage du fluide total pour les analyses demande que l'on prélève, de manière séparée ou combinée, les deux phases composant le système, vapeur condensée et gaz, opération qui devra être effectuée toujours en même temps.

Les deux systèmes de prélèvement peuvent être employés suivant les besoins de la recherche. Et précisément le premier (échantillonnage séparé) est employé lorsque l'on veut effectuer des recherches sur des quantités abondantes de vapeur condensée pour les analyses de détail dans les phases vapeur. La deuxième méthode est employée pour la routine normale de laboratoire.

### Prélèvement séparé des phases : vapeur condensée et gaz

La figure 1 présente le dispositif employé. Il se compose d'un condensateur *A*, d'un séparateur *B*, d'un réfrigérant *C*, d'un échantillonneur à gaz *D* et d'un échantillonneur à vapeur *E*.

Le système est raccordé, moyennant un tuyau en caoutchouc, à une prise munie d'un robinet *R*, placé dans la conduite de décharge de la tête du puits ou du vapeur-duc, normalement employé pour le relèvement de la pression dynamique du fluide.

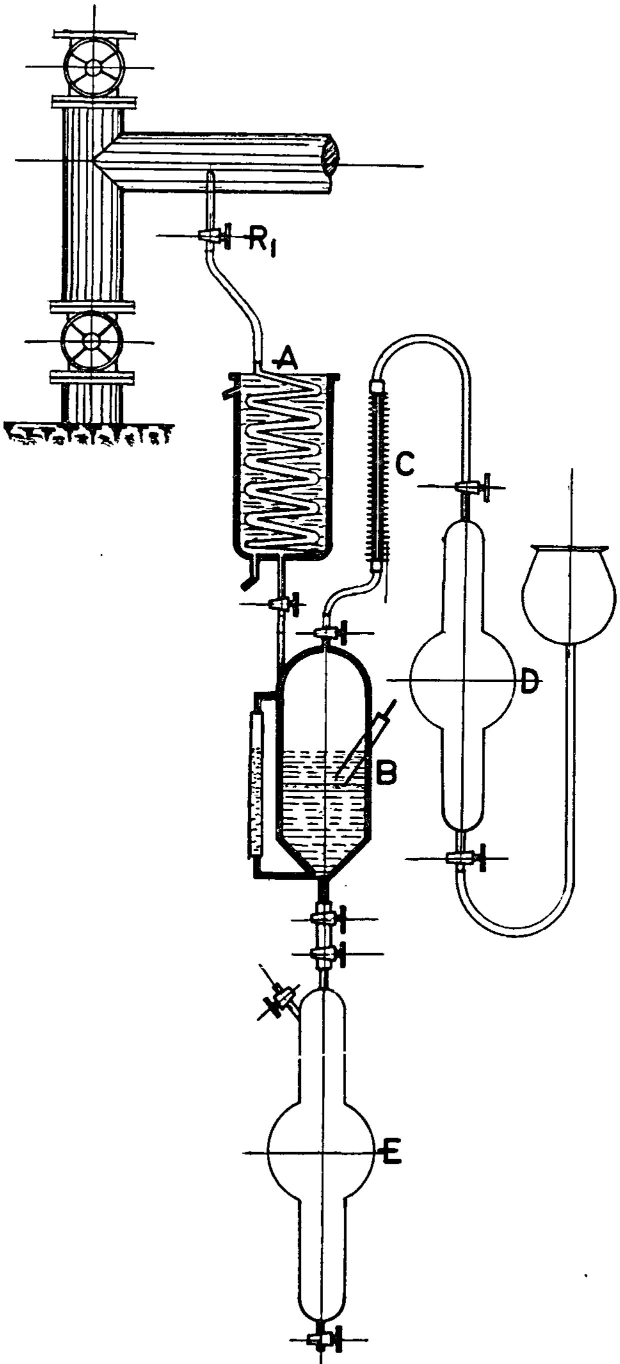


**Figure 1. Dispositif pour l'échantillonnage du fluide total en phases séparées**

Naturellement, tout le système, jusqu'au robinet *R*, doit se trouver sous vide, de manière à éviter toutes contaminations d'atmosphère. L'opération de démarrage doit se faire en tenant légèrement ouvert le robinet *R*. Lorsque des situations particulières rendraient impossible l'emploi de pompes à vide, il faudra chasser tout l'air pouvant se trouver à l'intérieur du système, en faisant passer des quantités abondantes d'eau et de gaz à travers les deux échantillonneurs.

PRÉLÈVEMENT COMBINÉ DES DEUX PHASES

Le dispositif pour ce type d'échantillonnage se réduit, comme il est indiqué à la figure 2, à un condenseur *A*, un réfrigérant *B* et un échantillonneur *C*. Dans ce cas également, tout le système doit être placé sous vide afin d'éviter toutes contaminations de l'atmosphère.

## Prélèvement d'échantillons de gaz résiduaire

Ainsi qu'il a été mis en évidence dans les pages qui précèdent (tableau 1), le mélange gazeux présente des concentrations de constituants principaux, comme $CO_2$ et $H_2S$, de telle nature que le dosage quantitatif des autres gaz n'en devient que plus difficile. De plus, il est tout aussi difficile de recouvrer séparément ces gaz, aux fins des recherches ultérieures concernant la fixation de leur composition isotopique.

Nous avons déjà dit que dans les différents champs de production, on a des écarts dans les valeurs du rapport gaz/vapeur et dans le pourcentage des mélanges gazeux. On peut tirer généralement d'un soufflard de 10 à 30 litres de gaz (à 0 °C à 760 mm Hg) par kilo de vapeur condensée. De l'ensemble de ce volume gazeux, environ 88-95 p. 100 se composent d'anhydride carbonique, de 2 à 3 p. 100 d'hydrogène sulfuré, et la fraction restant, de 2 à 9 p. 100, est constituée des autres gaz (azote, hydrogène, méthane et gaz rares qui sont indiqués sous la dénomination conventionnelle « gaz résiduaire »).

Sur la base de ces données, il faudra éliminer pendant le prélèvement de l'échantillon de 900 à 950 litres de $CO_2$ et de 20 à 30 litres de $H_2S$ (en tout 1 m$^3$ environ), pour obtenir le volume d'à peu près 50 litres nécessaire pour travailler quelques centimètres cubes de gaz nobles.

Il est évident que l'élimination de ces gaz doit se faire de manière à ne pas permettre l'absorption des divers constituants gazeux de ce mélange résiduaire.

A cette fin, nous avons éliminé des absorptions liquides, telles que des solutions à 10 p. 100 de KOH ou de NaOH, et des solides tels que NaOH et KOH en morceaux et chaux soudée, car ils étaient apparus peu économiques et demandaient des récipients encombrants et d'un transport difficile.

Le système que nous employons se compose d'une série d'adsorbeurs à cribles moléculaires Linde type 5A, suivant le schéma porté à la figure 3.

Ce système se compose d'un condenseur *A*, d'un séparateur *B* pour la vapeur condensée, d'un réfrigérant *C*, de deux adsorbeurs à cribles moléculaires *D*, d'un échantillonneur *E* et d'une bouteille à niveau *F*. Le liquide employé pour le remplissage des parties *E* et *F* est une solution très alcaline pour NaOH, de pyrogallol, surmontée d'un voile d'huile de vaseline afin d'empêcher des solutions éventuelles de gaz dans le liquide de transport. Le manomètre *G* sert à suivre le remplissage régulier de l'échantillonneur *E*. Au moment du prélèvement, l'échantillonneur *E* doit être placé sous vide ou être plein du liquide

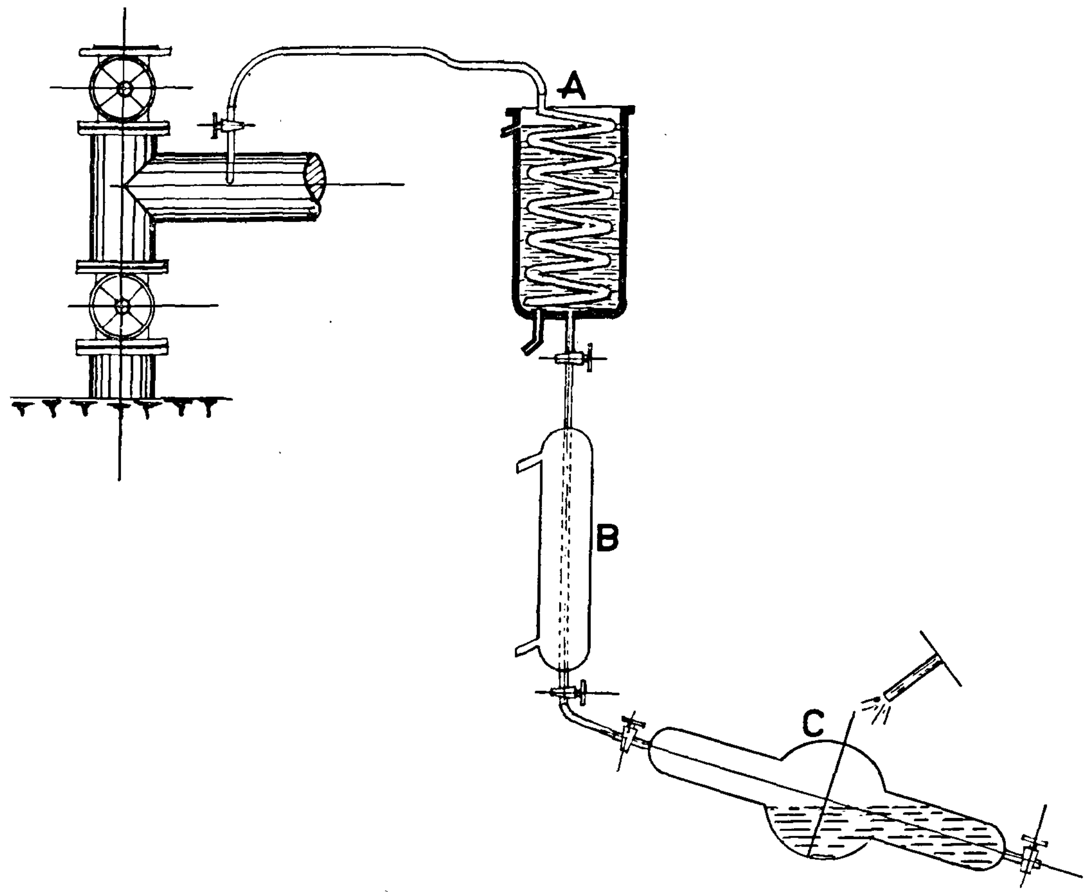


Figure 2. Dispositif pour l'échantillonnage du fluide total en phases combinées

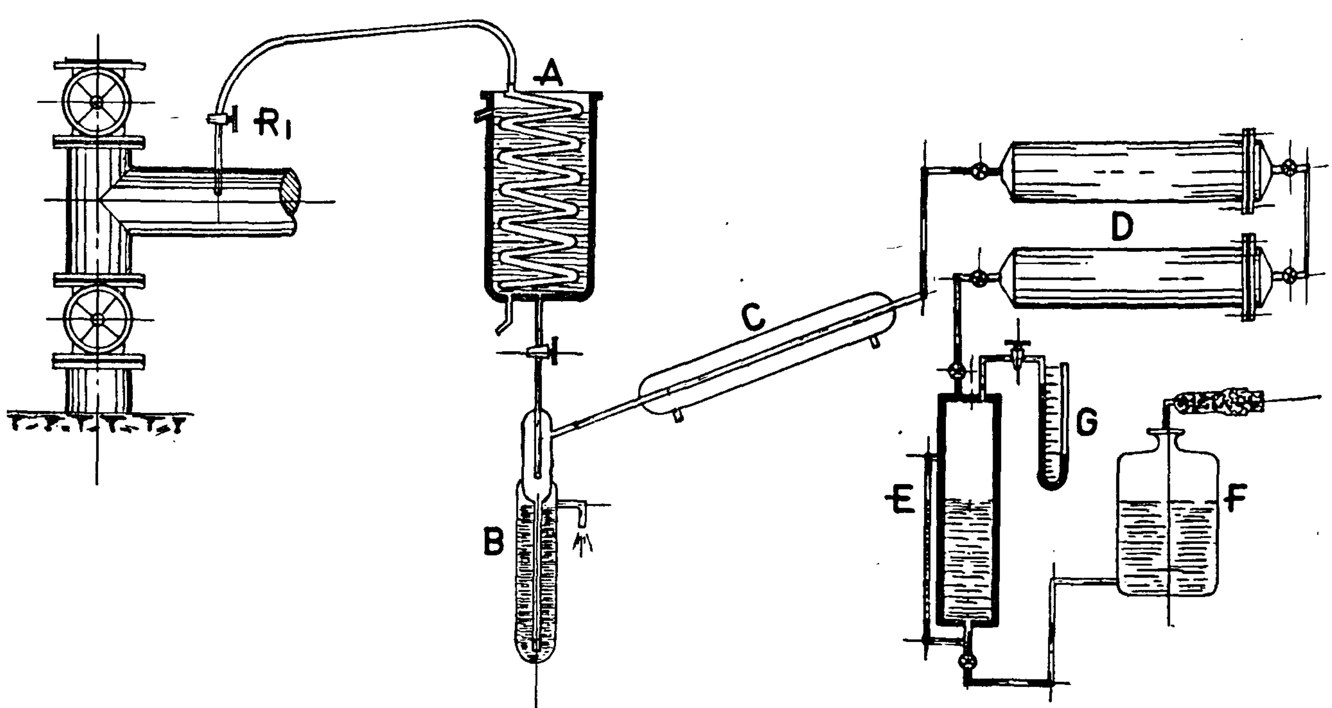


Figure 3. Dispositif pour l'échantillonnage du gaz résiduel

de déplacement. Tout le système sera d'ailleurs placé sous vide jusqu'au robinet *R*.

### Régénération des cribles moléculaires

Le système à cribles moléculaires pour l'adsorption de $CO_2$ et de $H_2S$ n'est pas seulement d'un emploi facile en raison de l'encombrement moindre des équipements à transporter, mais il est aussi extrêmement économique, puisqu'il peut être régénéré convenablement moyennant des opérations successives. La régénération s'effectue moyennant soufflage d'air chaud (300 °C), en sens inverse au chemin parcouru par le gaz en phase d'absorption de $CO_2 + H_2S$. L'opération de désorption devra être prolongée pendant plus d'une heure.

## Analyse des gaz

Comme suite à ce que nous venons de dire, les échantillons de gaz qui se présentent aux analyses de laboratoire sont de trois types :

1) Des échantillons de gaz totaux;

2) Des échantillons de gaz résiduaires;

3) Des échantillons de gaz dissous dans la vapeur condensée.

Nous allons donc exposer les méthodes d'analyse suivies pour l'étude des divers types d'échantillons.

### Analyse sur échantillons de gaz totaux

L'échantillonneur contenant les gaz prélevés comme il est dit plus haut est étudié à l'aide d'un gaz-chromatographe Fractovap C.-ERBA-mod. B (fig. 5 et 6).

Dans ce dispositif, les gaz constituant les échantillons *A* sont placés en très petites quantités à la base d'une colonne chromatographique et transportés le long de cette colonne, à l'état de vapeur, moyennant un courant de gaz neutre *B*. Les divers composants de ce mélange gazeux (fig. 6) traversent ainsi une colonne chromatographique constituée d'huile de vaseline sur célite gardée en chambre thermostatique *D*.

Pour les diverses affinités que présentent les divers composants gazeux aux substances de remplissage de la colonne chromatographique, ces composants émergeront de la colonne, en des temps successifs, ce phénomène étant fonction de la vitesse avec laquelle les composants parcourront la colonne, vitesse qui à son tour est fonction du coefficient de partage.

A la sortie de la colonne chromatographique, les fractions séparées et différentes de gaz traversent un révélateur formé de deux cellules (*F* et *G*) à l'intérieur de l'une desquelles passe le gaz de référence, tandis que dans l'autre (*G*) passe le mélange gazeux du gaz partagé avec le gaz de transport.

Chacune de ces cellules contient des éléments thermiques à coefficient de température élevé, chauffés à courant continu. Chaque gaz, en passant à travers le révélateur, absorbe une certaine quantité de chaleur, qui est fonction de sa conductibilité thermique. Il s'ensuit un refroidissement des éléments thermiques qui se manifeste par une variation de la résistance de ces éléments.

Le pont de Wheatstone (*H*) se rapportant aux deux cellules supporte dès lors un déséquilibre, d'autant plus important que la différence entre la conductibilité thermique du gaz de transport et celle du gaz sous examen est elle-même plus grande. Le signal du pont, convenablement amplifié, est reçu par un enregistreur (*I*) et marqué par un fléchissement de la plume.

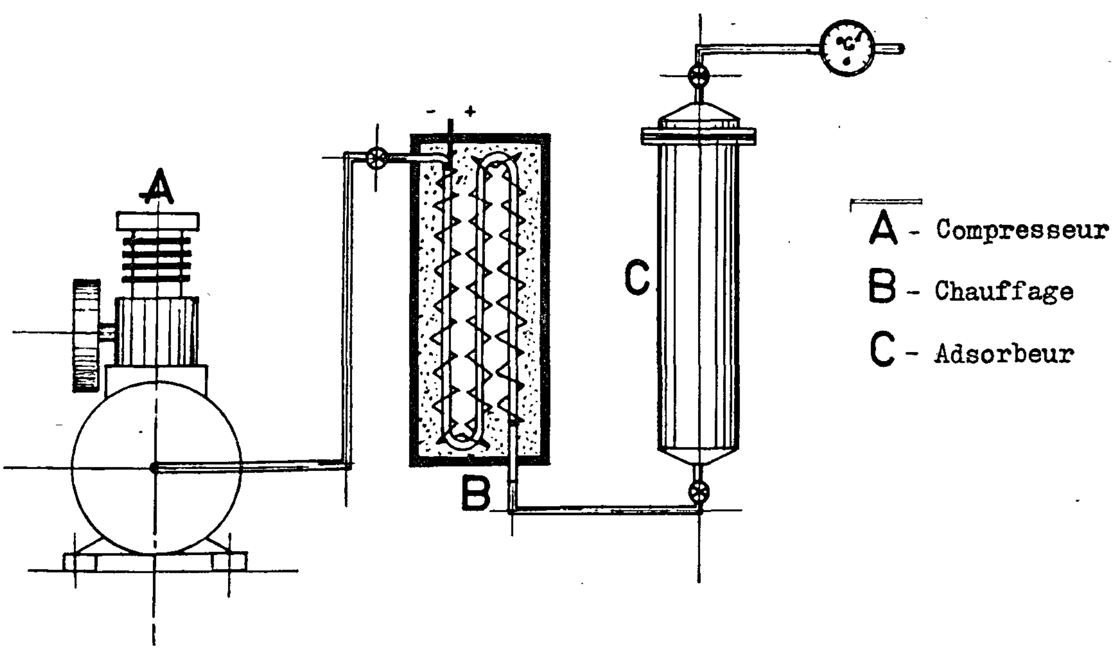


**Figure 4. Dispositif pour la régénération des adsorbeurs à cribles moléculaires**

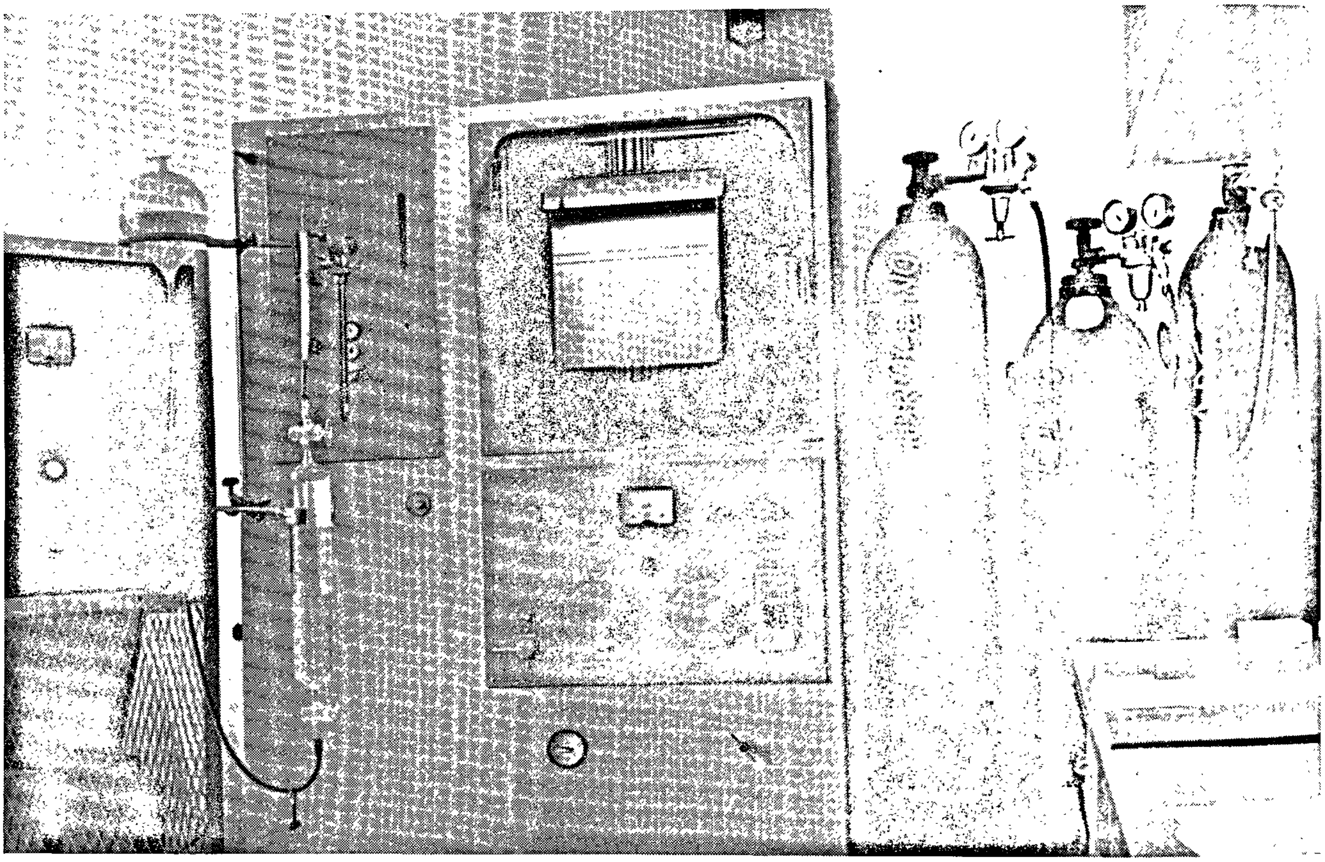

**Figure 5. Appareil gaz-chromatographe C. Erba, modèle B**

A la fin des analyses, on a une série de pointes comme celles portées à la figure 7. On en calcule alors la surface.

Moyennant des courbes d'étalonnage convenables de l'appareil pour les divers gaz, on pourra obtenir une lecture correcte des pourcentages s'y référant.

Il est connu que les colonnes chromatographiques de partage permettent de fixer rapidement les composants plus lourds. Par conséquent, ces colonnes ne permettent pas de séparer les gaz permanents ($O_2$, $H_2$, CO et hydrocarbures jusqu'à 5 atomes de carbonium). En effet ces gaz sont peu solubles dans n'importe quel liquide de partage. L'analyse de ce gaz est effectuée au moyen d'une colonne remplie de matière chromatographique de type adsorbant (charbon-cribles moléculaires) et les hydrocarbures y sont retenus irréversiblement ou éliminés après une longue période de temps. Il ressort de ce qui précède que l'analyse chromatographique de nos gaz doit encore se faire sur deux temps successifs, en employant deux colonnes dont les caractéristiques sont différentes. Les difficultés se rapportant à la substitution des colonnes sont résolues grâce à un dispositif spécial donnant la possibilité d'aménager la colonne à cribles moléculaires à l'extérieur de l'appareil, mais pouvant être incluse ou exclue moyennant un robinet sans rien changer aux conditions opérationnelles de la chambre thermostatique.

### Analyses des gaz nobles

Grâce à l'appareil dont nous allons faire la description au paragraphe suivant, à partir de volumes de gaz résiduaire connus, on élimine les constituants combustibles ($CH_4$, $H_2$). On obtient ainsi à la fin un mélange de $N_2$ et de gaz nobles dans des concentrations telles qu'il devient facile de fixer les contenus en Ar et He au moyen d'un gaz-chromatographe.

En vue de cette détermination, on emploie une colonne chromatographique de 5 mètres de long, avec remplissage à cribles moléculaires Linde 5Å, plongée dans un bain frigorifère à — 15 °C. Le gaz de transport employé est l'hydrogène.

Si l'on calcule le facteur d'enrichissement du $N_2$ dans l'échantillon des gaz nobles, on peut remonter à la concentration réelle de ceux-ci sur gaz naturel.

L'utilité de cette méthode d'analyse consiste d'une part dans sa précision et dans sa vitesse, et d'autre part dans le fait qu'elle permet d'effectuer un contrôle fort utile des déterminations quantitatives pouvant être obtenues même avec l'appareil dont il sera parlé au paragraphe suivant.

### Échantillonnage séparé des constituants du mélange gazeux

Les études concernant la genèse des divers gaz contenus dans un fluide endogène rendent nécessaire la détermination de la composition isotopique de chaque constituant gazeux. Les gaz rares comme Ar et He ont un intérêt tout particulier.

Tandis que la séparation des constituants principaux ne pose pas de problème particulier, car il est facile de les fixer sélectivement par absorption avec des solutions de Ba $(OH)_2$ et de $(CH_3\ COO)_2$ Pb, pour ce qui est des gaz combustibles et rares, il faut par contre disposer d'un équipement capable d'effectuer la combustion fractionnée des premiers et une séparation sélective des autres.

Pour ce faire, nous avons construit dans nos laboratoires de recherche un appareil à vide élevé suivant le schéma des figures 8 et 9. Avant toute opération avec pompe à huile et pompe à diffusion, on effectue un vide extrêmement poussé dans toutes ses parties.

L'échantillon de gaz résiduaire contenu dans le gazomètre $G$ est déplacé au moyen du niveau $L$, dans un dépurateur à chaux soudée $D$, pour l'élimination de traces éventuelles de $CO_2$. A partir de celui-ci, moyennant la trappe $T_2$ (plongée dans un mélange frigorifère de neige carbonique et d'acétone, pour fixer des traces éventuelles d'humidité), grâce au piston $P_1$, on aspire un certain volume de ce gaz résiduaire. Ce volume de gaz est ensuite déplacé à l'intérieur du four $F_1$ (préalablement thermostaté à 300 °C et contenant de l'oxyde de cuivre et un peu de bioxyde de cérium) où l'hydrogène agit en

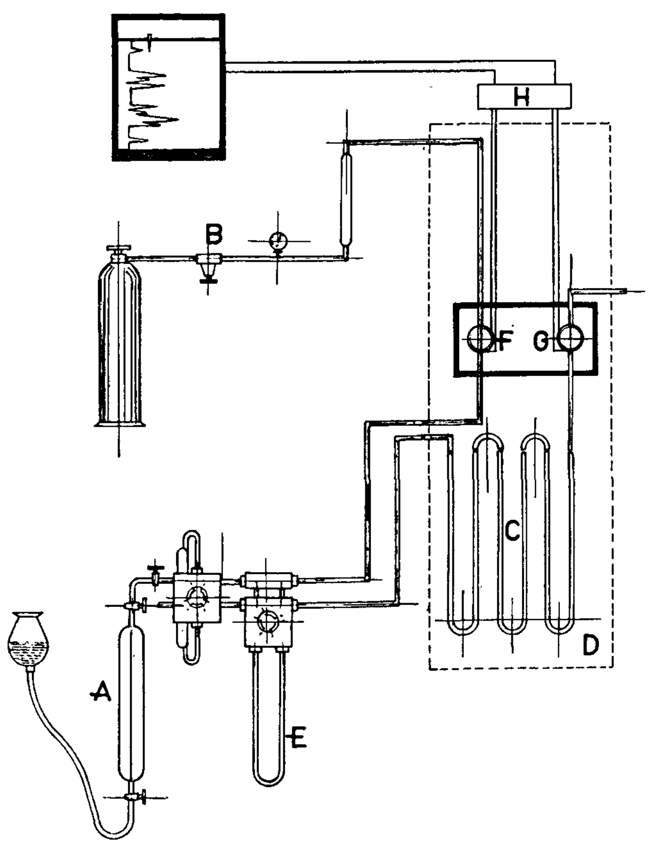


**Figure 6. Représentation schématique du cycle du gaz-chromatographe**

réduisant le sel de cuivre donnant lieu à la formation d'eau, celle-ci étant, à son tour, retenue dans le tube $W_1$ contenant une substance déshydratante ($P_2O_5$ ou driérite).

En travaillant avec les pistons $P_1$ et $P_2$, le gaz est soumis à des passages avant et arrière à travers le four $F_1$ jusqu'à ce qu'il n'y ait plus de lectures constantes pour le volume de gaz sortant de ce four, ce qui indiquera la combustion totale de l'hydrogène.

A partir de ce piston $P_2$, le gaz résiduaire est déplacé vers le four $F_2$ (contenant du rhodanate de potassium $K_2C_rO_4$ en grains et thermostaté préalablement à la température de 700 °C), où l'on obtient l'oxydation du métal $CH_4$ en anhydride carbonique $CO_2$. Celui-ci, après avoir absorbé l'eau de réaction avec le tube $P_2O_5$ ($W_2$) peut être prélevé grâce à l'échantillonneur $C$, pour des examens spectrométriques ultérieurs, ou bien être bloqué dans la trappe $T_3$ des immersions dans un bain frigorifère d'air liquide. Des passages successifs effectués avec des pistons $P_2$ et $P_3$ assureront l'oxydation complète du méthane.

Une fois l'hydrogène et le méthane éliminés du mélange, le volume gazeux restant contient de l'azote et des gaz nobles. L'azote est ensuite fixé dans le four $F_3$, contenant des copeaux de calcium métallique avec de petites quantités de sodium métallique comme catalyseur, thermostaté à 700 °C. La circulation du gaz à travers le four, effectuée grâce à des pistons $P_3$ et $P_4$, est continuée jusqu'au fixage complet de l'azote par le calcium embrasé.

Avant de passer au traitement des gaz nobles restants, il est bon de s'assurer si les autres gaz ($H_2$, $N_2$ et $CH_4$) ont été complètement absorbés. A cette fin, il convient de porter les fours $F_1$, $F_2$, $F_3$ à une température d'environ 700 °C et de faire circuler encore une fois le gaz restant; celui-ci sera finalement recueilli dans le piston $P_4$, en manœuvrant convenablement ses robinets jusqu'à atteindre en $F_1$, $F_2$, $F_3$ le vide le plus poussé possible.

### Séparation et échantillonnage des gaz nobles

Une fois le gaz collecté dans le piston $P_4$, l'on procède à séparer l'hélium et l'argon par la méthode Dewar. A cette fin, le dispositif employé est celui indiqué de manière schématique à la figure 9. Naturellement, cet appareil fait corps avec tout le système de séparation des gaz; nous le présentons à part pour les besoins de l'exposé.

Comme le montre la figure 9, le dispositif prévoit l'emploi de deux tuyaux à charbon actif pour l'adsorption des gaz nobles. Il faut souligner qu'avant toute opération d'adsorption les deux tuyaux à charbon actif doivent être chauffés sous vide pendant quelques heures, de manière à désorber des traces éventuelles d'air ou d'autres gaz adsorbés précédemment, pour être bien sûr d'avoir obtenu le vide le plus parfait.

En tenant fermé le robinet $R$ placé en aval desdits tuyaux, le gaz est envoyé lentement à travers le charbon actif. On plonge ensuite ces tuyaux dans de l'air liquide. De la sorte, seulement l'argon et

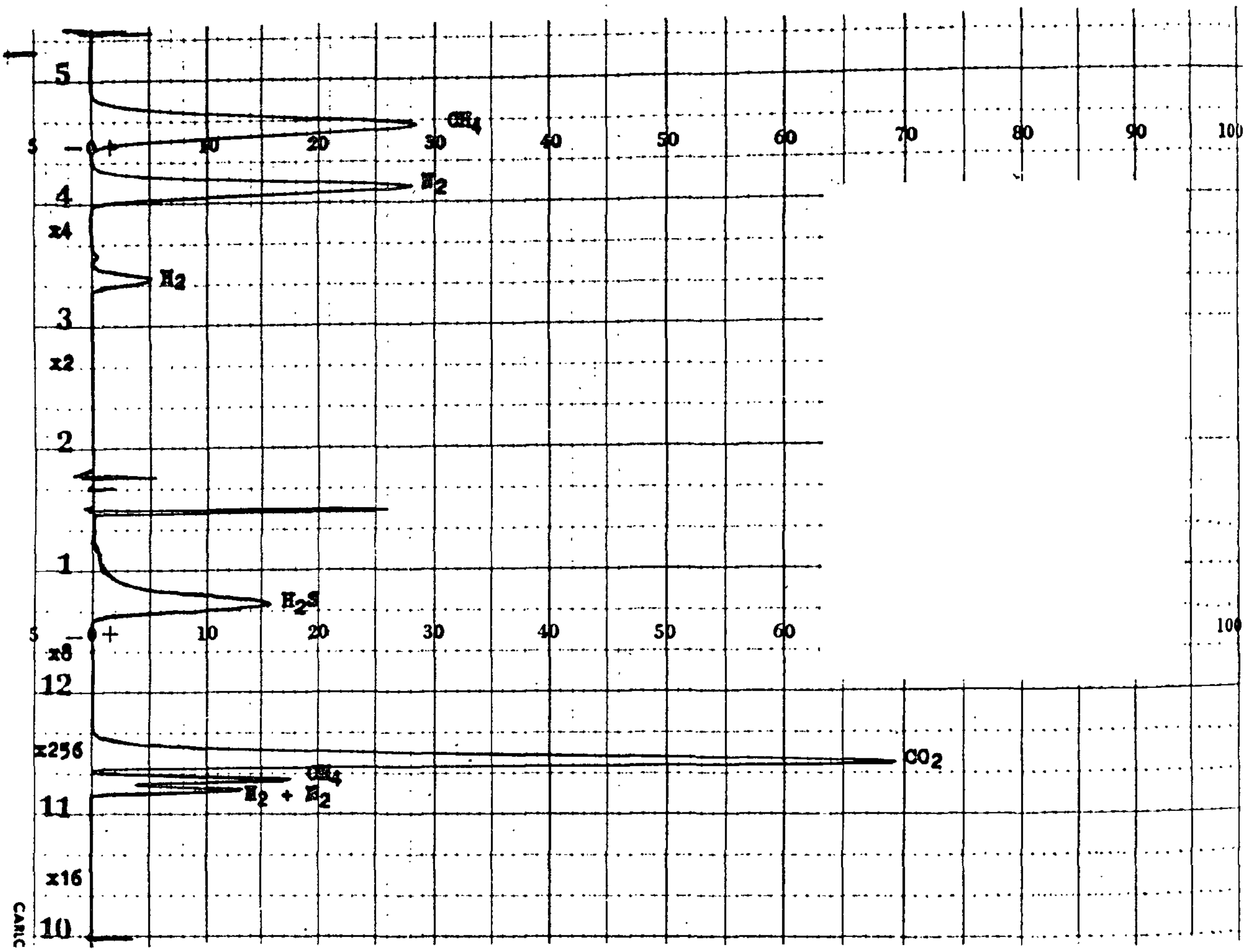


**Figure 7. Chromatographe typique du gaz résiduel**

les traces éventuelles d'azote seront adsorbés, tandis que l'hélium demeure libre.

Après un certain temps, en ouvrant le robinet $R$, on met ces tuyaux en communication avec la Geissler $S_1$ où l'hélium viendra se placer. Dans cette Geissler, on peut voir, grâce à des observations spectroscopiques, s'il reste des impuretés d'argon. Dans cette hypothèse, on répétera l'opération d'adsorption en prolongeant le temps d'immersion dans l'air liquide. Après avoir chassé les traces éventuelles d'argon, l'hélium pourra être recueilli dans l'échantillonneur $C_3$ pour des analyses ultérieures, ou être éliminé à travers l'appareil à vide.

Si nous enlevons à présent les tuyaux à charbon actif du bain d'air liquide, il nous faudra attendre un certain temps avant que le charbon actif acquière la température ambiante, désorbant ainsi l'argon et l'azote adsorbés.

Nous devons souligner que, malgré tous les traitements soignés de l'argon et de l'hélium, avec calcium ardent dans le four $F_3$, il reste toujours dans le mélange des gaz nobles une petite trace d'azote, et cela même après adsorption sur charbon actif.

Il est donc nécessaire, avant de prélever l'échantillon d'argon, de travailler au four $F_4$ (toujours à calcium métallique ardent) en obtenant un fixage ultérieur de ce gaz dans le four, comme il a été fait pour l'hélium, par passages répétés. On en contrôle la pureté par observation spectroscopique dans la Geissler $S_2$; finalement on prélève l'échantillon dans l'échantillonneur $C_4$.

## Remarques

Le dispositif que nous avons présenté aux figures 8 et 9 tel qu'il a été conçu, permet également de mesurer quantitativement les volumes gazeux au fur et à mesure qu'ils ont été séparés; c'est ce qu'on obtient par différence entre le volume du gaz, au début de tout traitement, et le volume restant après traitement; les mesures de pression sont relevées par la lecture des manomètres installés.

Nous devons souligner également qu'en réalité l'appareil est bien moins compliqué qu'il ne paraît aux schémas; en effet, dans les figures nous avons dû répéter beaucoup de dispositifs, dans le but de rendre notre explication autant que possible claire et faire comprendre le fonctionnement de tout l'ensemble d'analyse.

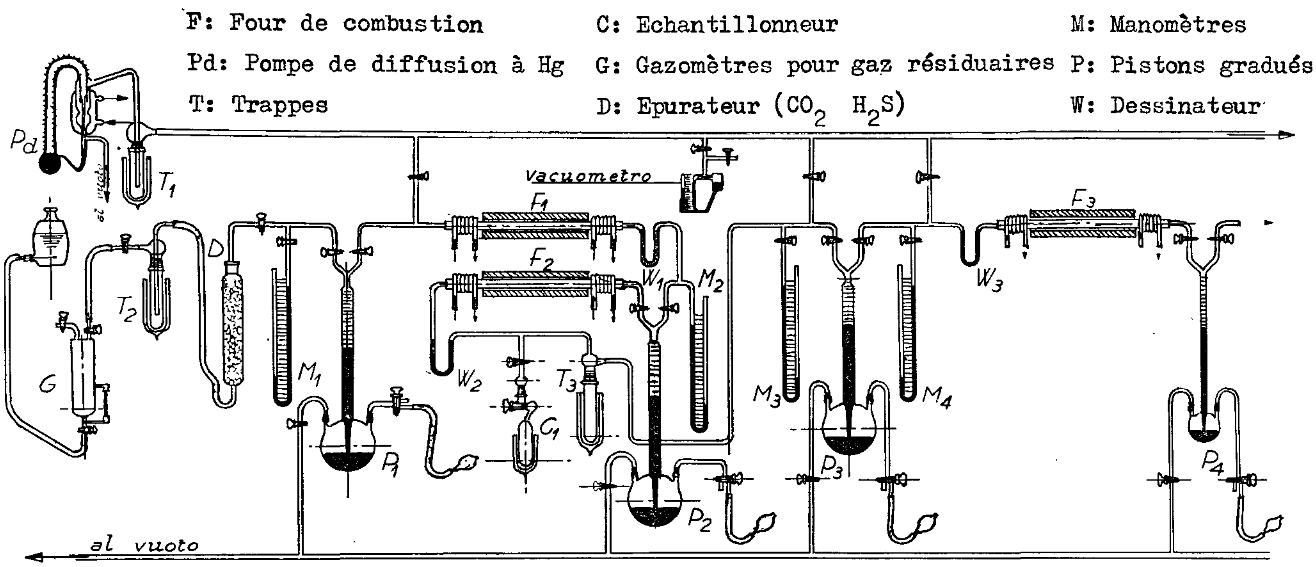


**Figure 8. Représentation schématique de l'appareil à haut vide pour la séparation et la récupération sélective des constituants du gaz résiduel**

C'est pour ces mêmes raisons de recherche de simplicité que nous avons laissé de côté le système de pompes nécessaires pour assurer le vide le plus poussé possible, et que la pompe à chute de mercure entre le piston $P_4$ et la partie demeurant n'a pas été présentée, bien qu'elle soit nécessaire pour prélever complètement le gaz restant après élimination de l'hydrogène, du méthane et de l'azote.

Au cas où l'on voudrait employer un dispositif analogue à celui présenté rien que pour obtenir la séparation des gaz nobles des autres gaz, cet appareil serait beaucoup plus simple. En effet, les différentes opérations d'élimination de l'hydrogène, du méthane et de l'azote peuvent être effectuées dans un four unique contenant les réactifs nécessaires et chauffé à la température de 700 °C.

Pour l'analyse des concentrations en gaz nobles, il suffira donc de mesurer le volume initial du gaz envoyé dans le four et de soustraire de ce volume de gaz initial le volume restant après traitement.

La séparation de l'argon à partir de l'hélium doit être faite d'après le schéma de la figure 9.

En ce qui concerne l'établissement des dimensions des diverses parties du dispositif, il faudra évidemment se baser sur les concentrations en gaz nobles du gaz résiduaire à traiter et sur le volume des gaz nobles séparés que l'on se propose d'obtenir à la fin des différentes opérations.

En ce qui concerne les concentrations en gaz nobles présents dans les gaz du fluide endogène du champ vaporifère de Larderello, il faut prélever en moyenne 40 litres de gaz résiduaire, ainsi qu'il est dit à la page 305 si l'on veut obtenir un volume de gaz rares d'environ 20 à 30 cc.

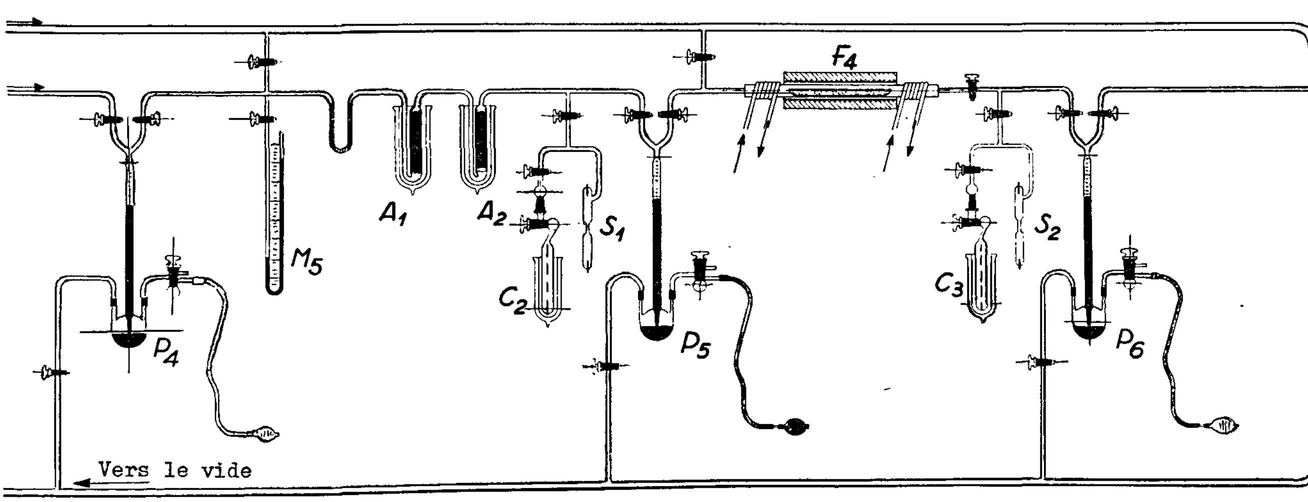


**Figure 9. Vacuomètre vers le vide**

## Enregistrement des résultats

Les résultats des analyses peuvent être enregistrés sous forme de concentrations en volume de gaz naturel, ou de concentrations par kilo de fluide total.

L'enregistrement des résultats, effectué d'une manière plutôt que de l'autre, aura comme conséquence la variation des rapports de composition. En effet, les quantités de gaz naturel mélangées à un kilo de vapeur varient d'un puits à l'autre et d'un champ à l'autre. C'est ainsi que tandis que le premier type d'enregistrement met en évidence exclusivement les caractéristiques de la phase gaz et les rapports d'abondance s'y rattachant, le deuxième type d'enregistrement nous représente la composition réelle du fluide endogène débité au sondage. Il appartiendra donc à l'analyseur d'adopter un enregistrement plutôt que l'autre, suivant le type de recherche qu'il voudra accomplir et suivant les buts que cette recherche visera.

A titre d'exemple, nous présentons au tableau 2 deux types d'enregistrement des données pouvant être adoptés : les valeurs indiquées se rapportent au fluide débité par le même sondage.

Ainsi qu'on peut le remarquer, dans nos tableaux nous avons indiqué aussi les quantités d'acide borique et d'ammoniaque qui, présents dans le fluide des soufflards, demeurent presque totalement dissous dans l'eau de la vapeur condensée, avec de petites quantités d'anhydride carbonique, d'hydrogène sulfuré et des traces d'autres constituants gazeux. Les quantités de gaz dissous varient suivant les conditions de température et de vitesse de condensation relevées au cours du prélèvement de l'échantillon. Dans des conditions normales, pour 100 cc d'eau de vapeur condensée, on a environ 50 cc de $CO_2$ et 3,5 cc de $H_2S$ (rapportés à 0 °C, 760 mm Hg). Si l'on considère que, selon les différents puits de vapeur, pour 100 cc d'eau de vapeur condensée on obtient de 1 500 à 3 000 cc de gaz séparé (c'est-à-dire de 1 400 à 2 700 cc de $CO_2$ et de 30 à 75 cc de $H_2S$), on peut en tirer la conclusion que la quantité de gaz dissous est très petite (de 3 à 18,5 p. 100 pour $CO_2$ et de 1,66 à 4,66 p. 100 pour $H_2S$).

Naturellement, il faudra tenir compte de ces petites quantités dissoutes lorsque l'on considérera la composition complète du fluide. Par contre, elles pourront être négligées lorsque l'on s'occupe du gaz séparé de la vapeur. Aux fins de l'analyse du contenu en gaz dissous dans les eaux, en général, nous renvoyons au mémoire G/73 du même auteur.

## Quelques remarques à caractère économique

L'équipement pour le prélèvement des échantillons de gaz ne demande qu'une dépense relativement modeste. Il se compose en effet de condenseurs à eaux, de séparateurs de vapeur condensée d'échantillonneurs en verre à étanchéité parfaite sous vide. Exception faite de ces derniers appareils fragiles, l'autre matériel nécessaire peut être entièrement en métal. Il convient que les serpentins du condensateur et le séparateur de vapeur condensée soient faits avec des matières capables d'éviter les inconvénients découlant de l'attaque chimique par les constituants acides.

L'équipement est transporté sur car muni d'un réservoir d'eau pour alimenter les condensateurs. Les opérations d'échantillonnage pour les gaz soit totaux, soit résiduaires, doivent être effectuées lentement, de manière à permettre une condensation excellente de la phase vapeur et une séparation plus exacte des gaz de la vapeur condensée.

En général, les temps employés pour échantillonner 1 000 cc de gaz sont de 10 minutes pour le gaz naturel et de 50 minutes pour le gaz résiduaire. Ces temps ne tiennent pas compte du montage (5 minutes environ) du dispositif condensateur-séparateur commun aux deux types d'échantillonnage et du temps de charge en $CO_2$ et $H_2S$ de l'adsorbeur à cribles moléculaires (45 à 60 minutes environ). Les opérations doivent être effectuées par au moins deux ouvriers, le nombre des prélèvements faits dans la journée étant fonction de la distance entre les différentes manifestations naturelles à échantillonner.

## Analyses isotopiques

La chaîne pour le recouvrement par sélection des différentes fractions gazeuses a permis d'obtenir un ensemble intéressant de connaissances portant sur la genèse des gaz naturels endogènes, grâce à la fixation de la composition isotopique de ceux-ci. En effet, on examine ainsi la distribution des isotopes stables d'un certain élément, dans les divers composés naturels contenant cet élément.

La composition isotopique mesurée est rapportée généralement à un standard approprié que l'on emploie comme échantillon de référence et qui s'exprime par la quantité :

$$\delta \text{ p. } 1\,000 = \frac{R \text{ échantillon} - R \text{ standard}}{R \text{ standard}} \times 1\,000,$$

où $R$ est le rapport en atomes entre l'isotope le plus lourd et l'isotope le plus léger.

Dans quelques cas particuliers, il suffira d'exprimer la valeur du rapport isotopique absolu. C'est ce que donne la formule : $\alpha = \dfrac{R \text{ échantillon.}}{R \text{ standard}}$

Dans cette hypothèse, $\alpha$ est appelé « facteur d'enrichissement ».

## Hydrogène et deutérium

Puisque les isotopes stables de l'hydrogène, du protium et du deutérium ont une importance considérable en géochimie, car ils sont séparés et fractionnés moyennant des processus géologiques et cosmologiques en des quantités plus importantes que n'importe quel couple d'isotopes stables, Boato,

### Tableau 2. Exemple de transcription des dates analytiques

2a) *Concentration du gaz (p. 100 du gaz total)*

| *Zone et puits* | *Débit (t/h)* | *Température (°C)* | *Rapport gaz-vapeur* | *p. 100 de vapeur par poids* | | *Volume de $NH_3$ pour 100 volumes de gaz naturel* | *p. 100 de gaz naturel (volume)* | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | *$H_3BO_3$* | *$NH_3$* | | *$CO_2$* | *$H_2S$* | *Résidu* | *$H_2$* | *$CH_4$* | *$N_2$ plus gaz nobles* | *He* | *A* |
| Larderello : | | | | | | | | | | | | | | |
| Puits A . . . . | 210 | 185 | 29,3 | 0,065 | 0,014 | 0,621 | 93,35 | 2,45 | 4,20 | 1,58 | 1,67 | 0,95 | 0,0025 | 0,00097 |

2b) *Composition par kg de vapeur naturelle*

| *Zone et puits* | *Débit (t/h)* | *Température (°C)* | *Composition par kg de vapeur naturelle* | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | *$H_3BO_3$* | *$NH_3$* | | *Gaz naturel* | *$CO_2$* | *$H_2S$* | *Résidu* | *$H_2$* | *$CH_4$* | *$N_2$ plus gaz nobles* | *He* | *A* |
| | | | *Grammes* | | | *Litres normaux Nl (à 0 °C et 760 mm Hg)* | | | | | | | *N cc 0 °C et 760 mm/Hg* | |
| Larderello : | | | | | | | | | | | | | | |
| Puits A . . . . . | 210 | 185 | 0,65 | 0,14 | 0,182 | 29,3 | 27,35 | 0,718 | 1,230 | 0,463 | 0,489 | 0,278 | 0,7310 | 0,2842 |

Careri et Volpi[1] ont effectué des recherches sur les rapports $HD/H_2$ des gaz de Larderello.

L'analyse de l'hydrogène des divers échantillons a mis en évidence des contenus en *D* plutôt bas et tellement rapprochés les uns des autres qu'il était possible d'allouer une valeur commune de 0,79 ± 0,05 à l'hydrogène des différents puits.

Ce fait peut être attribué à une séparation du gaz par diffusion dans le sous-sol ou à la réaction d'échanges entre l'hydrogène et l'eau lourde suivant la formule : $H_2O + HD = HDO + H_2$, cette réaction pouvant être catalysée en profondeur avant que la vapeur n'arrive à la surface.

Par voie de conséquence, il devrait y avoir une concentration en deutérium dans la phase eau et un appauvrissement de celui-ci dans le gaz. En effet, le facteur d'enrichissement en deutérium dans l'eau des vapeurs condensées n'est pas si différent de celui de l'eau ordinaire et a une valeur égale à 1 ± 0,1.

Harter et Suess (1949), dans leurs recherches sur le contenu en deutérium de l'hydrogène de l'atmosphère, ont découvert que celui-ci était supérieur à celui de l'eau de surface (prise comme standard), en raison de phénomènes de fuite du protium dans les couches supérieures de l'atmosphère. Ils en ont conclu que dans les eaux juvéniles, il faudrait donc trouver un contenu en deutérium inférieur à celui des eaux de surface.

La valeur obtenue pour les vapeurs condensées, égale à la valeur de l'eau de surface, doit donc être considérée comme une conséquence de la dilution des eaux du sous-sol profond avec des eaux de surface qui y ont pénétré.

## Méthane et anhydride carbonique (c)

Les mesures effectuées sur le carbone du méthane ont donné des valeurs de $\delta$ c approchant une valeur moyenne de — 35. Cette valeur indique une dérivation organique pour ce constituant gazeux et, par voie de conséquence, une contamination due à des roches sédimentaires. Les mesures relevées pour le carbone de l'anhydride carbonique ont donné des valeurs de $\delta$ c près de la valeur moyenne — 7.

On suppose que cette valeur est attribuable, en partie au moins, à $CO_2$ provenant de la décomposition thermique des roches carbonatiques profondes.

## Argon

L'argon est un produit de désintégration naturelle du $K^{40}$ et le rapport $Ar^{40}/Ar^{36}$ dans l'atmosphère est de 296 ± 1 (Nier).

Les dosages effectués sur argon contenu dans les gaz naturels du champ géothermique de Larderello mettent en évidence qu'il y a un enrichissement remarquable en $Ar^{40}$.

Les valeurs obtenues pour $\alpha$, suivant la formule :

$$\alpha = \frac{Ar^{40}/Ar^{36} \text{ gaz nat.}}{Ar^{40}/Ar^{36} \text{ atmosphère}}$$

sont compris dans l'écart 1,174 ÷ 1,580 (d).

Cela signifie que dans quelques cas l'enrichissement en $Ar^{40}$ peut être même remarquable. Cet enrichissement est, de toute évidence, attribuable à la température élevée à laquelle sont soumises les roches intéressées par l'eau remontant vers la surface à l'état de vapeur.

En effet, une source thermale d'eaux boriques (Saturnia), située à quelque distance seulement du champ géothermique de Larderello, contient de l'argon ayant la même composition isotopique que l'argon de l'atmosphère.

Il faut donc en tirer la conclusion que les eaux intéressées à ce phénomène représentent le moyen de transport d'une certaine quantité d'argon de l'atmosphère, et qu'une température assez élevée est nécessaire pour produire une perte de quantités importantes d'$Ar^{40}$ dans les roches potassiques.

Les causes pouvant déclencher un phénomène d'enrichissement plus ou moins poussé d'$Ar^{40}$ pourraient donc se résumer comme suit :

*a*) Le volume des roches potassiques intéressé par la circulation profonde des eaux météoriques;

*b*) La température à laquelle ces roches potassiques sont soumises, déclenchant des pertes plus ou moins grandes d'$Ar^{40}$ pour autant que ces valeurs seront plus ou moins importantes;

*c*) La quantité d'eau, et partant d'argon atmosphérique, les variations de cette quantité pouvant donner lieu à différents types de dilution d'$Ar^{40}$ produit par les roches potassiques.

En théorie, il est à prévoir qu'entre le débit du sondage et la dilution d'$Ar^{40}$ le rapport est direct.

Bien que les données que nous possédons semblent confirmer cette attente, il est peu probable qu'elle saurait être confirmée dans tous les cas, étant donné la variété des raisons de trouble tectonique en place pouvant se manifester dans le sous-sol en créant des situations différentes d'un puits à l'autre.

## Remerciements

L'auteur désire remercier chaleureusement le professeur Tongiorgi, Directeur du Laboratorio di Geologia Nucleare du Comitato Nazionale Energia Nucleare (C.N.E.N.) de Pise et ses collaborateurs de l'aide précieuse qu'ils ont bien voulu donner à la mise en place du programme de recherches isotopiques.

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## *Résumé*

L'auteur expose dans ce mémoire les méthodes d'échantillonnage et d'analyse employées aux Laboratoires de recherche de la société Larderello, S.p.A. Les échantillons de gaz et de vapeur sont prélevés séparément ou en combinaison, suivant les buts de l'enquête que l'on veut poursuivre. Le prélèvement des gaz résiduaires est d'un intérêt tout particulier lorsqu'il s'agit de fixer du point de vue quantitatif les contenus en gaz rares Ar, He.

Les gaz résiduaires formés de $CH_4$, $H_2$, $N_2$ et les gaz rares sont récupérés après adsorption préalable des constituants gazeux principaux comme $CO_2$ et $H_2S$. L'adsorption est effectuée au moyen de colonnes à cribles moléculaires aménagées à la suite du condensateur.

Le gaz naturel total est analysé au moyen d'un appareil de chromatographie de partage en phase vapeur, sur deux phases successives. En premier lieu on détermine les contenus en $CO_2$ et $H_2S$ en employant des colonnes chromatographiques remplies d'huile de vaseline sur support inerte maintenues dans une chambre thermostatique à la température de — 5 °C.

Le gaz de transport est He. Les contenus en $CH_4$, $N_2$, He sont déterminés sur une seconde portion de l'échantillon gazeux en employant une colonne auxiliaire extérieure remplie de cribles moléculaires type Linde 5A. Dans ce cas encore le gaz de transport est He.

Description est faite ensuite du cycle de travail d'un équipement à vide élevé pour l'enrichissement des contenus en gaz rares. Cet enrichissement est effectué au moyen d'un procédé de combustion fractionnée du $CH_4$ et $H_2$.

Le mélange gazeux restant, formé à présent seulement de $N_2$, Ar et He, est analysé par chromatographie de partage en phase vapeur, par emploi d'une autre colonne extérieure à cribles moléculaires (d'une longueur de 5 m), plongée dans un bain frigorifère.

L'équipement à vide élevé, dans sa partie finale, est muni d'un four électrique rempli de copeaux de Ca et Na métalliques. A la température de 700 °C on a la consommation du contenu en $N_2$. Ce traitement rend possible la récupération des fractions pures de Ar et de He, soit en mélange soit séparément.

Sont ensuite rapportés quelques résultats obtenus lors des analyses isotopiques des divers constituants gazeux récupérés séparément pendant le cycle de travail dans l'appareil à vide élevé.

Pour les divers puits, les données les plus courantes sont les suivantes :

*a*) Les gaz endogènes révèlent un enrichissement en $Ar^{40}$ par rapport à l'argon atmosphérique; cet enrichissement varie de 1,174 à 1,580.

*b*) Le rapport $HD/H_2$ assume la même valeur $(0{,}79 \pm 0{,}05)$.

*c*) La composition isotopique du $CH_4$ ($\delta$ c = — 30) indique une origine organique de ce gaz;

*d*) La composition isotopique du $CO_2$ ($\delta$ c = — 7) indique une certaine contamination de $CO_2$ découlant de la décomposition thermique des calcaires.


# SAMPLING AND ANALYSIS OF GASES IN NATURAL-STEAM WELLS


## *Summary*

This paper reviews the methods of gas sampling and analysis used by the research laboratories of Larderello, S.p.A. The gas and steam samples are collected after the geothermal fluid has been cooled in water coolers.

The gas and liquid phases can be collected together or separately, according to the object of the analysis. The collection of the residual gases for the quantitative determination of noble gases (Ar, He) is of special interest. The residual gases, consisting of $CH_4$, $N_2$, $H_2$, and noble gases, are recovered by adsorption of the main gaseous constituents, $CO_2$ and $H_2S$.

This adsorption is accomplished by molecular sieves in columns, connected to the cooler outlet. The natural gas is analysed by gas-chromatographic methods in two separate stages. $CO_2$ and $H_2S$ are first determined in graphic columns filled with vaseline oil in an inert packing in a thermostat maintaining the working temperature of $+5$°C. Helium is the carrier gas. $CH_4$, $H_2$ and $N_2$ are then determined in a second gas portion, using an external auxiliary column filled with molecular sieves, Linde 5A. Helium is the carrier gas. The author also describes the working cycle of a high-vacuum gas-line for the enrichment in noble gases. This is accomplished by separate combustion of $CH_4$ and $H_2$.

The residual gas mixture, now consisting only of $N_2$, Ar and Helium is analysed with the gas-chromatograph, using another external column (containing molecular sieves Linde 5A), 5 m long, immersed in a cooling bath.

The high-vacuum gas-line, in its last part, has an electric furnace filled with shavings of metallic Ca and Mg. At the working temperature of 700°C, the nitrogen is absorbed.

This makes it possible to recover the pure Ar and He fractions, either mixed or separated.

The author also presents some results obtained from isotopic analyses of the various constituents, separately recovered during the working cycle of the high-vacuum gas-line.

For various wells, the present data indicate that :

(*a*) The $Ar^{40}/Ar^{36}$ ratio is higher in the well gases than in the atmosphere by a factor of 1.174 to 1.580.

(*b*) The $HD/H_2$ ratio for hydrogen is almost the same value ($0.79 \pm 0.05$).

(*c*) The isotopic composition of $CH_4$ ($\delta$ c = $-30$) indicates the organic origin of this gas.

(*d*) The isotopic composition of $CO_2$ ($\delta$ c = $-7$) indicates a certain contamination by $CO_2$ from limestone (thermal decomposition).

# ÉCHANTILLONNAGE ET ANALYSE DES EAUX DE SOURCES THERMALES OU PROVENANT DE MANIFESTATIONS VAPORIFÈRES

*Renzo Nencetti* *

Un des aspects les plus caractéristiques d'une zone intéressée de quelque façon que ce soit par des phénomènes endogènes liés à des activités du type volcanique ou plutonique, est l'aspect touchant à la présence de manifestations hydrothermales et gazeuses ou vaporifères apparaissant en surface suivant des sources distinctes ou associées. En particulier, ce sont : la composition chimique de ces manifestations, la caractéristique saillante d'un ion déterminé, l'enrichissement relatif de celui-ci par rapports aux autres, la température, le pH, etc., qui sont autant d'éléments d'enquête nécessaires si l'on veut mettre en vedette les facteurs prééminents des eaux distribuées par les sources ou si l'on veut classer ces eaux en fonction de leurs caractéristiques chimico-physiques plus saillantes et avancer des hypothèses quant à leur genèse probable.

Un autre aspect intéressant d'une prospection hydrogéochimique concerne la distribution topographique des températures de déversement et des constituants chimiques. Cette distribution peut être exprimée sur carte topographique au moyen de contours réunissant toutes les sources ayant soit la même concentration par rapport à un ion commun, soit le même rapport d'abondance entre un ion prééminent et les ions secondaires. Bien sûr, cette préparation des données doit se faire à l'aide d'une étude géologique de la zone sous examen. En effet, les différences de composition dépendent aussi des différentes méthodes de mélange entre les eaux d'horizons divers, mais elles dépendent aussi de divers facteurs de milieu du sous-sol, tels que :

*a*) Le type ou système de circulation des eaux dans le sous-sol;

*b*) Les temps de circulation;

*c*) La situation tectonique et les conditions de perméabilité et de porosité des roches intéressées;

*d*) La nature et le type des roches;

*e*) Le degré d'altération chimique des roches par l'effet des phénomènes d'hydratation, d'hydrolyse, d'oxydation et de réduction, ainsi que de l'action d'acides aussi bien organiques qu'inorganiques, etc.;

*f*) La dilution par les eaux météoriques, marines, fossiles, magmatiques et métamorphiques.

Ces facteurs agissent à leur tour différemment et à un degré variable suivant les conditions de l'état physique et les équilibres chimiques des eaux au moment où elles prennent une part active à l'un ou à l'autre des facteurs susindiqués.

Il apparaît dès lors évident que l'étude des eaux ne saurait se borner à celles qui se trouvent à la surface, mais qu'elle doit se poursuivre à l'égard des eaux souterraines, lorsque les situations particulières des forages en donnent la possibilité.

Enfin, l'analyse des eaux ou des vapeurs condensées acquiert un caractère d'un intérêt technologique lorsqu'on veut récupérer les contenus prisés pouvant être exploités sur échelle industrielle.

C'est ce qui arrive en effet dans la zone géothermique de Larderello, où les contenus en acide borique et ammoniaque sont récupérés aux fins d'un emploi successif dans la production de sous-produits chimiques, comme l'acide borique, le borax, les boro-dérivés inorganiques et organiques et le carbonate d'ammoniaque.

## Types et modalités dans le prélèvement des échantillons

Il ressort de ce qui précède que l'enquête hydrogéochimique se base sur deux types de prélèvements d'échantillons : en surface et en profondeur. Dans les prélèvements de surface sont compris aussi les échantillons de vapeur condensée provenant de

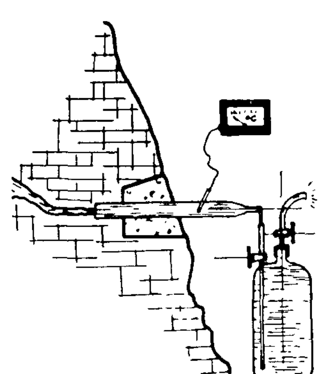

**Figure 1. Prélèvement d'eau de source**

manifestations naturelles, de sondages, etc. Le prélèvement des échantillons de surface ne présente pas de difficultés particulières; les méthodes et les récipients employés ne doivent pas donner lieu à des pertes de gaz dissous ou à des souillures venant

* Larderello, S.p.A., Pise (Italie).

de l'air. Les figures 1, 2, 3, 4 et 5 montrent divers dispositifs que nous employons pour la prise de sources et de manifestations vaporifères naturelles, ainsi que pour les prélèvements en bassins et pour les sondages. Nous tenons à souligner que la fermeture des échantillonneurs est effectuée, au cas de la figure 1,

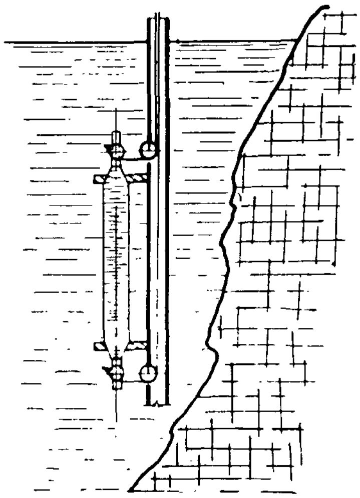

**Figure 2. Dispositif pour le prélèvement d'eau à température élevée en bassins**

quelques heures après le débit de la source et dans le cas des figures 3 et 4, après quelques jours.

Le dispositif de la figure 2 est employé pour des prélèvements dans des eaux thermales à température élevée; dans le cas d'eaux à température normale, la fermeture de l'échantillonneur est effectuée à la main, mais toujours dans des conditions d'immersion complète de celui-ci.

Le prélèvement d'échantillons, à partir des eaux de profondeur, ou de sondages, est effectué au moyen d'un dispositif expliqué par le schéma de la figure 5. Il se compose d'un cylindre $A$ en acier inoxydable ou en résine thermorésistante, muni de deux robinets $R_1$, $R_2$ qui en assurent l'étanchéité parfaite, même sous vide. Le cylindre est relié au câble d'une grue par un dispositif de blocage excentrique. Une fois atteinte la profondeur à laquelle on veut prélever l'échantillon, on ferme les robinets en laissant tomber le poids $P$ le long du câble de soutien de l'échantillonneur. Ce poids, en heurtant contre le dispositif d'arrêt des petits câbles en nylon (qui tiennent en position d'ouverture les deux robinets) fait coulisser vers le bas la tige $B$, en dégageant les anneaux terminaux des petits câbles. Les ressorts $M_1$ et $M_2$ assurent la fermeture des robinets.

Le dispositif d'arrêt excentrique permet d'accrocher au câble de transport autant d'échantillons que l'on veut aux distances fixées au programme.

La fermeture des échantillonneurs disposés en série a lieu successivement, c'est-à-dire après celle de l'échantillonneur le plus proche de la surface. A la figure 5, il est possible de remarquer que le dispositif de butée, qui retient les anneaux auxquels aboutissent les fils de nylon des robinets, tient un troisième anneau relié à un autre poids $P_1$, lui aussi mis en place sur le câble de la grue.

Cependant, lorsque le premier poids fait stopper les anneaux, le deuxième est libre de tomber à son tour pour débloquer le dispositif d'arrêt des anneaux de l'échantillonneur suivant; et ainsi de suite jusqu'au dernier échantillonneur.

Il suffira dès lors de retirer lentement le câble pour récupérer les échantillons d'eau.

## Procédés analytiques

La méthodologie analytique que nous avons appliquée pour la fixation des constituants chimiques dissous et gazeux est la méthode classique, adoptée par tous les laboratoires de recherche et prévue pour la spectrophotométrie de flamme, la spectrophotométrie d'adsorption, la polarographie et la chromatographie en phase vapeur.

Au moment du prélèvement, l'on effectue quelques déterminations telles que pH, $H_2S$, alcalinité, qui sont influencées par des pertes éventuelles de gaz dissous.

Aussi bien le pH que l'alcalinité sont mesurés au moyen de potentiomètres, la seconde en solution titrée de HCl et en observant les virages aux valeurs de pH pour phénolphtaléine et pour méthylorange.

Le $H_2S$ est déterminé par précipitation avec acétate de cadmium et titrage iodométrique du précipité, en milieu acide pour l'acide acétique.

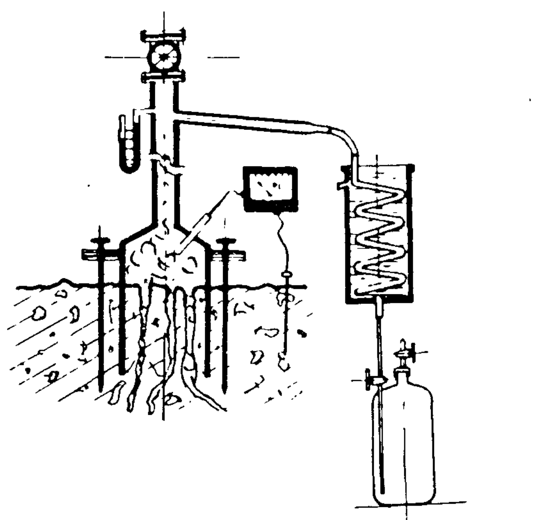

**Figure 3. Dispositif pour le prélèvement de manifestations vaporifères naturelles en fond mou**

Au cas de concentrations basses, cette détermination est effectuée par spectrophotométrie, suivant Sands, avec la méthode au bleu de méthylène (745 mμ).

En particulier, les déterminations en laboratoire suivent l'ordre et les méthodologies que nous résumons ci-après.

### Fer

Une portion de l'échantillon est traité avec du rhodanate de potassium pour la reconnaissance des qualitatifs. Lorsque le résultat est positif, on procède au dosage spectrophotométrique, avec orthophénantroline et hydroquinone tamponnées à pH 4,5, en mesurant l'intensité d'absorption à 510 mμ.

### Gaz dissous

Ils sont dosés au moyen de l'appareil indiqué à la figure 6 où, avant de commencer, on a fait le vide grâce à une pompe à huile $P_o$ et à une pompe à diffusion $P_d$.

L'eau sous examen, contenue dans un récipient $C_1$ de 200 cc et échantillonnée séparément, est envoyée égoutter dans un ballon de dégazage $A$. Les gaz qui se sont séparés, mélangés à de la vapeur d'eau, passent ensuite dans la trappe $T$, plongée dans un mélange frigorifère formé de neige carbonique et d'acétone. C'est dans cette trappe que les vapeurs d'eau sont bloquées, tandis que les gaz, aspirés par le piston $P_1$ sont collectés et mesurés dans le piston $P_2$. En manipulant bien les robinets de ces pistons, on parvient à transférer du piston $P_1$ au piston $P_2$ toutes les portions de gaz qui se sont dégagées même après avoir agité l'eau du ballon $A$ et décongelé la trappe $T_1$.

L'opération prend fin lorsque l'eau de l'échantillonneur $C_1$ étant épuisée, on ne remarque pas de variations dans le niveau de la colonne de mercure du piston $P_2$. Le gaz récupéré est ensuite transféré à l'échantillonneur $C_2$, dont le volume est connu; on mesure à présent la pression (en mm Hg) du gaz qu'il contient aux fins de report successif de son volume à 0 °C et 760 mm Hg.

Le gaz échantillonné est examiné au chromatographe en phase de vapeur, suivant le système expliqué par l'auteur dans son mémoire G/76 concernant l'analyse des gaz endogènes. De cette manière, on obtient également la mesure du $CO_2$ dissous.

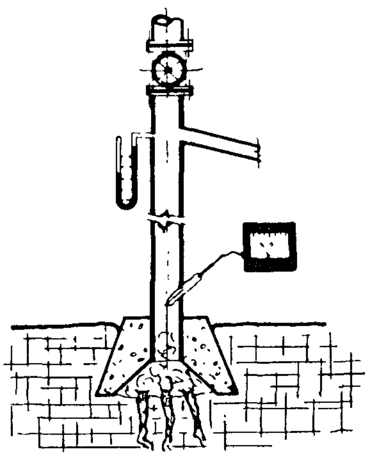

**Figure 4. Dispositif pour le prélèvement de manifestations vaporifères naturelles en fond dur**

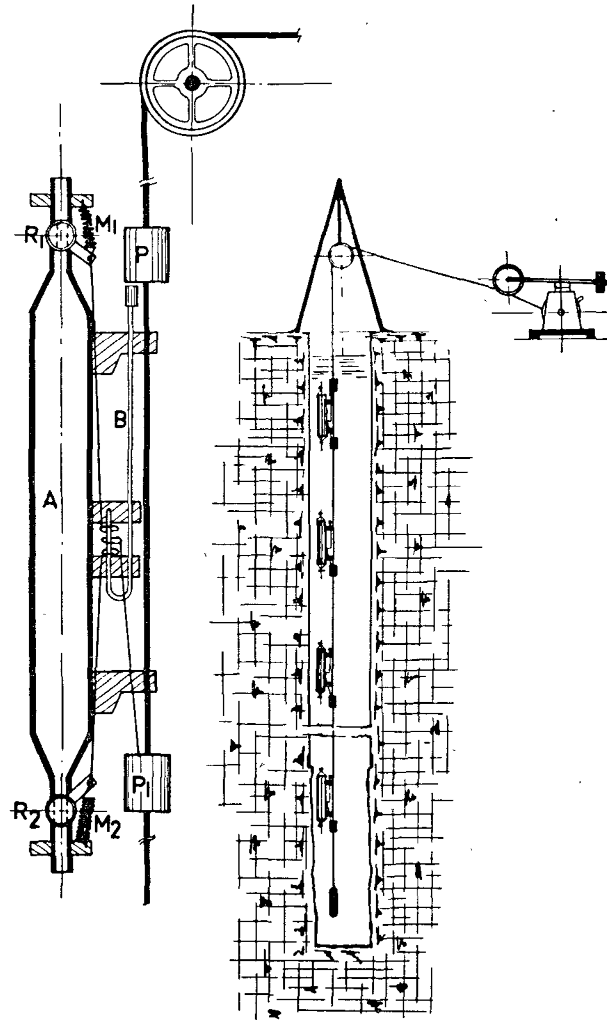


**Figure 5. Dispositif pour l'échantillonnage des eaux profondes**

### Carbonates et bicarbonates

Ce même ballon $A$, contenant l'eau dégazée à laquelle sont ajoutées à présent quelques gouttes de méthylorange, est placé dans l'appareil de la figure 7. Cet appareil est donc formé :

*a*) Du ballon $A$ où se trouvent la décharge de la burette $C$ et le tube d'évolution $S_1$;

*b*) D'une fiole $B$ dans laquelle sont placés un tube d'évolution $S_2$ et la décharge de la burette $D$;

*c*) D'une Drechsel $E$ contenant de l'hydroxyde de baryum, montée en dérivation sur le système.

Avant d'agir, on met en mouvement la pompe $P$, et l'air, obligé de circuler à circuit fermé, passe à travers la Drechsel à l'hydroxyde de baryum pour bloquer le $CO_2$ atmosphérique. Après quelques minutes de circulation, on exclut la Drechsel $E$, et l'air contenu dans l'appareil continuera à circuler à cycle fermé dans le système formé par la pompe, le ballon et la fiole.

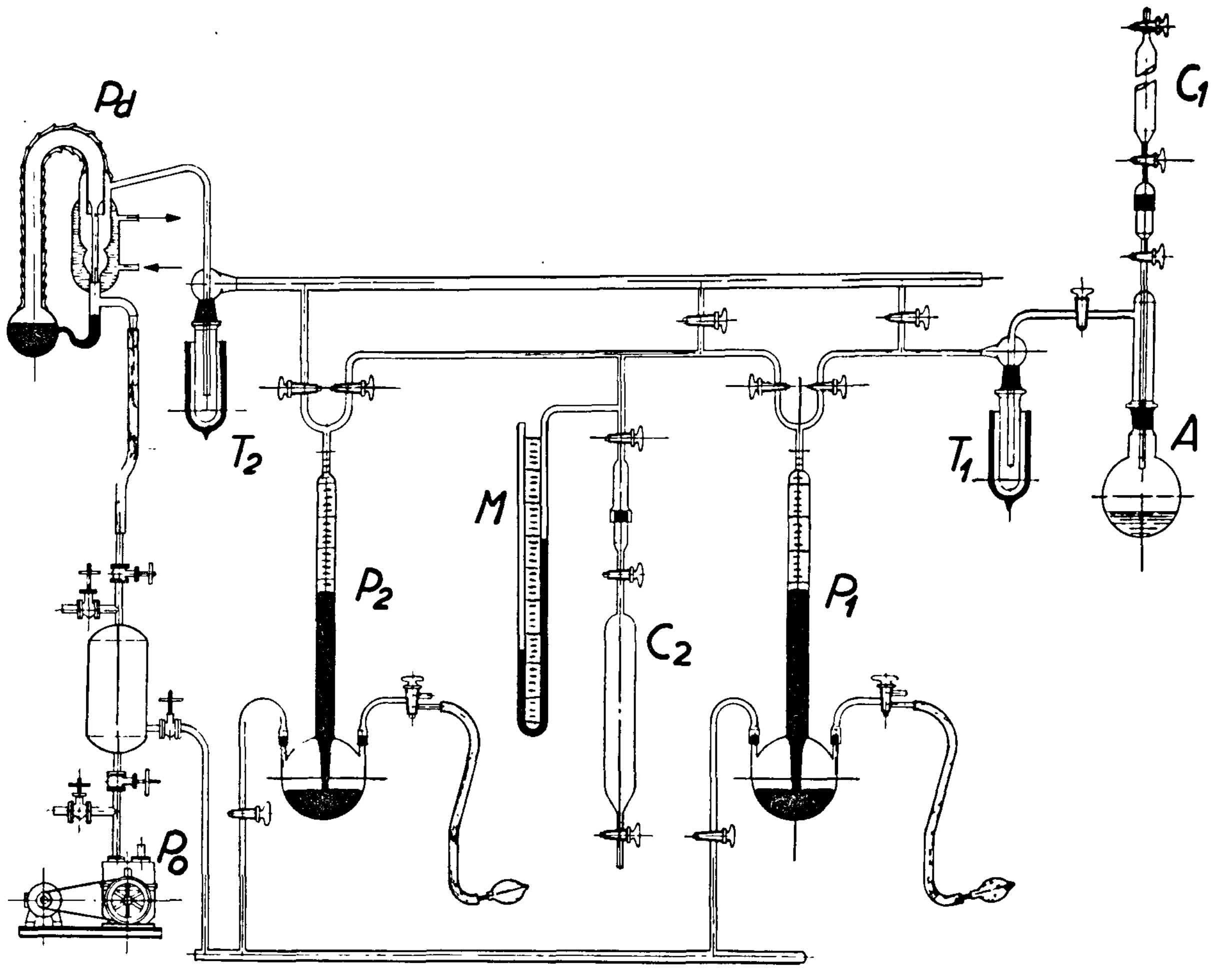


Figure 6. Appareil de laboratoire pour la récupération des gaz dissous

A ce moment, on fait tomber de la burette *D* dans la fiole *B* un volume connu de $Ba(OH)_2$, N/50, et de la burette *C* dans le ballon *A* de petites doses successives de $H_2SO_4$, N/10. L'adjonction de l'acide est poursuivie jusqu'à virage du méthylorange et jusqu'à excès de 20 cc.

Le $CO_2$ est obligé de barboter dans l'hydroxyde de baryum contenu dans la fiole *B* ($CO_2$ se dégage par l'action de l'acide sur les carbonates et les bicarbonates). L'opération prend fin lorsqu'on a soumis l'eau à une brève période d'agitation et de rechauffage.

Après un temps de circulation convenable, qui est nécessaire pour l'absorption complète de $CO_2$ par la solution d'hydroxyde de baryum, on arrête la pompe et on titre cet excès, au moyen d'une solution N/50 de HCl jusqu'à virage de la phénolphtaléine.

Si nous indiquons par *V* le volume en cc d'acide correspondant au volume de la solution d'hydroxyde de baryum employé, et par *v* le volume en cc de l'acide chlorhydrique N/50 utilisé pour le titrage, on a :

$(V\text{-}v) \times 3{,}5 = CO_2$ total en ppm, comme $HCO_3$

$(V\text{-}v) \times 3 = CO_2$ total en ppm, comme $CO_3$

### Silice

Elle est fixée gravimétriquement par insolubilisation, à l'état partiellement déshydraté, en présence d'acide chlorhydrique et au moyen d'une insolubilisation complète par calcination. Au cas de basses concentrations, la détermination est effectuée par spectrophotométrie, en mesurant l'absorption, à 430 m$\mu$, de l'ensemble silico-molybdique à pH 1,6 pour l'acide sulfurique.

### Oxydes

Dans ce groupe, on comprend les oxydes de Fe, Al, Mn, fixés d'après les méthodes classiques décrites plus haut. Des contrôles successifs effectués par polarographie pour Fe et Mn permettent d'obtenir Al par différence. Mais pour Mn, on effectue un contrôle supplémentaire spectrophotométrique à 525 m$\mu$.

### Calcium

Le calcium est fixé par le moyen complessométrique avec EDTA.

### Magnésium

Le magnésium est fixé dans une solution d'ammoniaque avec un indicateur Eliochrome *T*.

### Sodium, magnésium, lithium, strontium et césium

La détermination de ces métaux alcalins est effectuée au moyen d'un spectrophotomètre à la flamme, aux longueurs d'onde respectives de 589 mµ, 766 mµ, 670,8 mµ, 460,7 mµ et 452,1 mµ, en exécutant, pour chaque détermination, l'étalonnage de l'instrument avec des solutions standard. En outre, on fait des dilutions successives sur les échantillons sous examen, aux fins d'obtenir une lecture des valeurs comprises dans l'intervalle de l'étalonnage de l'instrument.

### Ammoniaque

Elle est fixée au moyen de l'appareil de Kjeldahl par déplacement avec NaOH et distillation successive et recueil sur solution titrée de HCl.

### Sulfates

La détermination est effectuée par la méthode gravimétrique par précipitation du sulfate de baryum en un milieu légèrement acide, ou encore par spectrophotométrie, par la méthode au chloroanilate de baryum, en mesurant l'absorption à 53 mµ.

### Phosphates

Ils sont déterminés par spectrophotométrie en mesurant l'absorption du complexe bleu de molybdène à 725 mµ. Cette détermination doit être effectuée après élimination au préalable de la silice, en raison de son interférence.

### Iodures

Ils sont déterminés grâce au potentiomètre, en effectuant, directement sur l'eau, le titrage avec $AgNO_3$, par emploi d'une électrode Ag/AgCl et d'une électrode de verre.

### Chlorures

Ils sont déterminés par la même méthode que ci-dessus. De la quantité de $AgNO_3$, consommée par le virage il faut enlever les cc de $AgNO_3$ exigés par la précipitation des iodures (premier virage) et des bromures éventuels (2e virage).

### Fluorures

Ils sont déterminés par le chloro-anylate de thorium dissous dans du méthyl-Cellosolve (glyco mono-

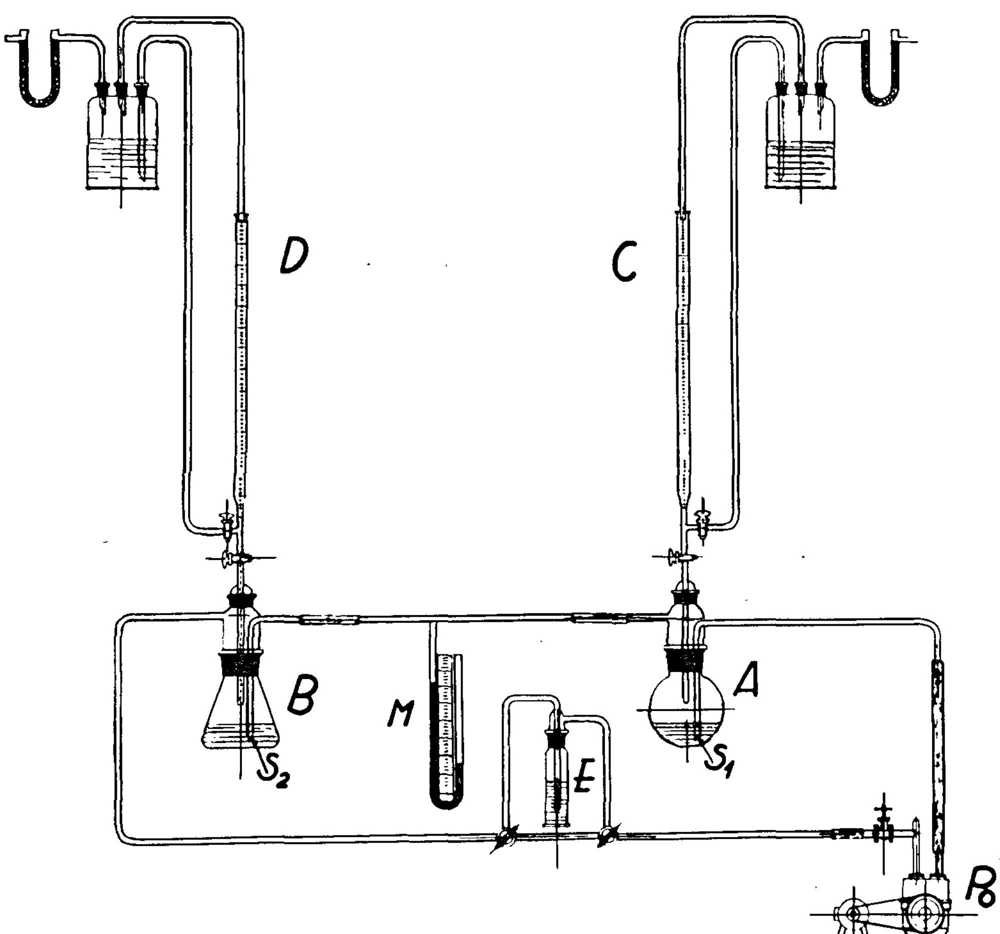


**Figure 7. Appareil de laboratoire pour la détermination des carbonates et des bicarbonates**

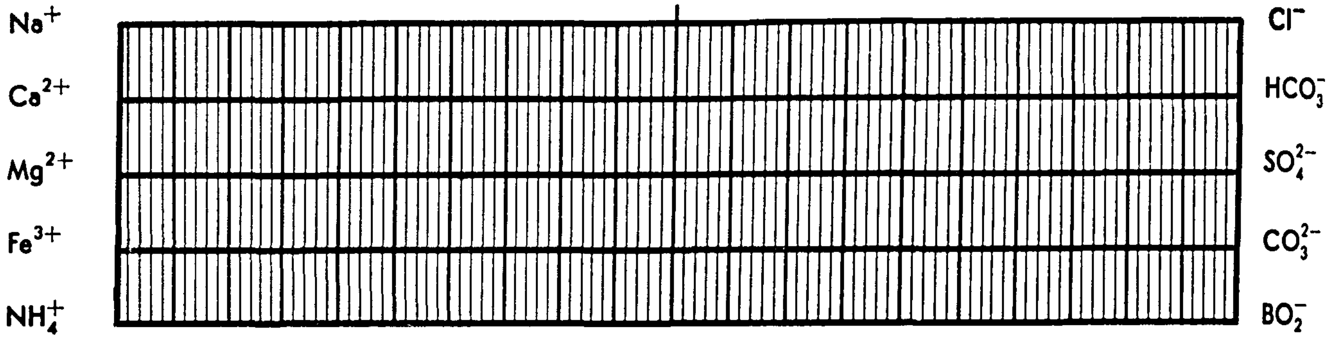


**Figure 8. Réticule pour la représentation graphique des résultats de l'analyse chimique des eaux (représentation graphique d'après Stiff)**

méthyl-éther) tamponné à pH 4,5, en mesurant l'absorption à 540 mμ.

Acide borique

La détermination est effectuée par potentiométrie en employant une électrode de verre. Le pH de l'eau sous examen, stabilisé à 7,2 et successivement baissé par l'adjonction de mannite pour la formation d'acide mannito-borique, est reporté à sa valeur de départ, avec solution titrée de NaOH. Cette méthode d'une part est très rapide et soignée, et d'autre part n'est pas affectée par des interférences, pourvu que soient éliminés au préalable les composants pouvant faire changer le pH de l'eau.

## Représentation géographique

Pour détecter et mettre en évidence les caractéristiques de toute eau le plus rapidement et le plus clairement possible, différentes méthodes de représentation graphique ont été examinées. Nous avons considérée comme étant la plus convenable la méthode suggérée par Stiff. Cette représentation n'est rien plus que l'enregistrement en diagramme des valeurs de réaction obtenues au moyen de l'équation :

$$\text{Nombre de réaction} = \text{quantité en ppm}\ \frac{\text{valence}}{\text{poids atomique}}$$

Le rapport valence/poids atomique est, pour chaque élément, une constante facile à calculer. Il est l'inverse, comme valeur mathématique, de l'équivalent chimique. Pour la représentation graphique nous nous servons d'un réticule (figure 8) où sont reportées en abscisse, les valeurs de réaction de chaque ion, à partir du centre du réticule, marquée par la droite du zéro, et en allant vers l'extrémité avec des valeurs de plus en plus grandes.

Sur l'ordonnée, on enregistre à droite du zéro les symboles des anions, et à gauche ceux des cations.

En réunissant tous ces points, représentant les valeurs du nombre de réaction pour les différents ions, on obtient des formes polyédriques donnant la « silhouette » de l'eau sous examen.

L'échelle des valeurs peut être variée afin de mettre en évidence n'importe quel constituant retenu fondamental aux fins de la détection du type d'eau; il suffit tout simplement de changer le dénominateur de la fraction d'ions, normalement suivant des multiples décimaux.

Nous avons ajouté au diagramme type les paramètres $NH_4^+$ et $BO_2^-$, car ce sont eux qui caractérisent les eaux de la zone vaporifère de Larderello.

Les systèmes suggérés par Palmer et Tickell, tout aussi intéressants, n'ont cependant pas été retenus chez nous en raison de certains désavantages qu'ils présentent.

En effet, dans la représentation graphique de Palmer, la concentration des ions est changée en valeur de réaction en pourcentage. Elle est donc inadéquate aux fins d'une détection rapide du type d'eau sous examen.

En second lieu, les valeurs de réaction en pourcentage peuvent amener à considérer comme étant identiques des eaux qui ont le même caractère chimique, mais une concentration ionique différente.

La méthode de Tickell, fondée sur un diagramme étoilé à six axes, avec des concentrations exprimées en valeurs de réaction en pourcentage, présente les inconvénients relevés pour le système de Palmer, étant donné qu'on ne tient pas compte de la concentration réelle des ions.

Après avoir obtenu de cette façon les « silhouettes » des eaux, il devient très facile et d'une vitesse immédiate, d'une part, d'établir la subdivision des eaux mêmes sous forme graphique, d'autre part, d'exprimer les rapports réciproques éventuels devant être approfondis par suite à l'aide des connaissances géologiques, minéralogiques, pétrographiques, etc.

## Constituants chimiques des eaux de vapeur condensée

Les eaux provenant de vapeurs condensées sont caractérisées, en général, par une prééminence marquée des anions $HCO_3^-$ et $BO_2^-$ et du cation $NH_4^+$. Le rapport $HCO_3^-/BO_2$ varie de 0,2 à environ 5. Les concentrations du $NH_4^+$ varient de 130 à 1 600 ppm. Le fluore est totalement absent. Les anions $Cl^-$ et $SO_4^{--}$, s'ils sont présents, ne le sont qu'en de très faibles concentrations, ne dépassant jamais

1 ppm. Ce n'est qu'en quelques cas que le $Cl^-$ atteint une valeur maximum de 30 ppm.

Les métaux alcalins et alcalino-terreux en général sont présents en de très faibles concentrations, ne dépassant jamais 1 ppm; ce n'est que le calcium qui fait exception, et les eaux, lorsqu'elles le contiennent, révèlent des concentrations comprises entre 9-90 ppm.

Le pH de ces vapeurs condensées est toujours compris dans l'intervalle 6-7, 5. Ce n'est que dans quelques cas que le pH a des valeurs inférieures, mais jamais au-dessous de 5,1. La conductibilité électrolytique est comprise dans l'intervalle (1-10). $10^{-3}$ ohm$^{-1}$/cm$^{-1}$.

Sur la base des caractéristiques chimiques, ces eaux peuvent être considérées du type « bicarbonate borique ».

## Constituants chimiques des eaux de sources thermominérales

Le développement du plan d'exploitation des bassins vaporifères de la zone géothermique de la société Larderello, S.p.A., a eu comme conséquence d'épuiser beaucoup de manifestations naturelles de vapeur, de gaz et d'eaux thermominérales jadis très diffusées.

Malgré cela, quelques sources d'eau ont continué leur activité même avec des débits très limités.

Les constituants chimiques caractéristiques de ces eaux sont dans ce cas également les anions $HCO_3^-$, $BO_2^-$ auxquels s'ajoutent $Cl^-$ et $SO_4^{--}$, en des concentrations sensibles.

Pour ces eaux, le rapport B/Cl est compris dans l'écart 0,2-0,9; celui $HCO_3/Cl$ dans l'écart 0,8-80; celui $SO_4/Cl$ dans l'écart 0,4-5; celui $SO_4/HCO_3^-$ dans l'écart 0,1-6.

Les concentrations des alcalins sont variables avec une prééminence du sodium; le rapport K/Na varie à l'intérieur de l'écart 0,02-0,2 et celui Li/Na à l'intérieur de l'écart 0,02-0,2.

Parmi les alcalino-terreux, le calcium prime le magnésium avec un rapport Ca/Mg compris à l'intérieur de l'écart 2-20. Le rapport Ca + Mg/G + Na varie dans les limites de 2 et 90.

Aucune de ces eaux n'a un caractère décidément acide, le pH variant dans un intervalle allant de 6,5 à 8.

Pour ce qui est de la classification génétique des eaux en fonction de leur composition chimique, nous nous bornons à un renvoi aux ouvrages de Clarke, White, et autres (voir la bibliographie figurant à la fin du présent mémoire).

## Recherches isotopiques

Les recherches isotopiques (Professeur Tongiorgi) menées sur des calcaires et des vapeurs condensées, et prélevés dans la zone géothermique de Larderello, ont mis en évidence les valeurs des rapports $O^{18}/O^{16}$ au point qu'il était fondé de supposer que la vapeur débitée des bassins de Larderello était constituée dans sa presque totalité d'eau météorique, intéressée dans un phénomène de circulation profonde.

Cette circulation trouverait un accroissement à la puissance dynamique de son mouvement de convexion, suite aux remarquables quantités de chaleur cédées aux masses d'eau circulante par les roches directement intéressées par le plutone réchauffant, roches avec lesquelles ces masses d'eau viennent en contact.

Ces masses d'eau finiraient donc par acquérir une énergie suffisante pour vaincre la résistance de la pression statique ambiante et trouveraient dans les roches juxtaposées les voies pour remonter vers la surface. Cette phase de retour serait d'autre part facilitée du fait de la capacité d'agression chimique accrue des eaux sur les roches environnantes, suite aux enrichissements en matériaux acides volatiles ($CO_2$ et $H_2S$) de provenance soit magmatique, soit métamorphique. Pendant cette remontée, les valeurs de la pression statique ambiante étant moins grandes, ces eaux se gazifieraient pour finalement émerger en surface à l'état de vapeur surchauffée.

Il faudrait fixer à présent en combien de temps le cycle complet est bouclé.

A cette fin, les études seront poussées à l'avenir, et porteront sur le contenu en tritium des vapeurs endogènes condensées, afin de confirmer la valeur obtenue par Libby (1953) pour le rapport $T/H$ dans nos vapeurs condensées.

Libby a trouvé que ce rapport prenait la valeur $T/H = 0{,}4 \times 10^{-18}$ atomes.

Sur la base de la semi-période de cet isotope instable, le temps de circulation des eaux serait supérieur à 40 années.

Par rapport au contenu en $D$ de l'eau de la vapeur condensée des différents puits ($c$, $d$, $e$), il est apparu que ce contenu ne s'éloignait pas beaucoup du contenu normal de l'eau de surface. Le facteur d'enrichissement défini comme

$$\alpha = \frac{D/H \text{ échantillon}}{D/H \text{ eau commune}}$$

est apparu égal à $1 \pm 0{,}1$.

## Remerciements

L'auteur désire remercier les membres du Laboratorio di Geologia Nucleare du Comitato Nazionale Energia Nucleare (C.N.E.N.) de Pise, pour l'assistance donnée au cours des études isotopiques.

Un remerciement tout particulier est dû à M. le professeur E. Tongiorgi, directeur du Laboratoire susdit, pour sa collaboration constante et précieuse à la mise en place des différents problèmes et pour la part qu'il a eu dans la discussion des résultats.

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## *Résumé*

Dans le présent exposé, l'auteur illustre dans quelle mesure les études hydro-géochimiques ont contribué à la prospection d'une nouvelle zone géothermique.

Maintes sources thermales et manifestations naturelles de vapeur, associées à des émanations gazeuses, caractérisent les zones touchées par des phénomènes géothermiques liés à l'activité volcanique ou plutonique.

La composition chimique de ces manifestations, l'abondance d'un certain élément, l'enrichissement relatif de celui-ci par rapport aux autres, etc., sont autant de données extrêmement utiles pour posséder les éléments de diagnostic permettant d'établir une distinction entre les différents types d'eaux. Les analyses chimiques ont aussi un intérêt technologique pour la récupération industrielle des constituants chimiques prisés; les installations chimiques de la société Larderello, S.p.A., utilisent en effet les contenus en $H_3BO_3$, $H_2S$ et $NH_3$ du fluide endogène aux fins d'une vaste production de sous-produits chimiques.

L'auteur passe en revue les méthodes employées pour l'échantillonnage des eaux des sources thermales et des vapeurs condensées, soit des « soufflards » soit des manifestations naturelles de surface. Dans le prélèvement de ces échantillons, on recommande la plus grande attention pour éviter toute contamination de l'atmosphère qui provoquerait une évaluation inexacte du contenu en gaz dissous et quelques altérations dues à des processus d'oxydation.

En outre, description est faite d'un appareil employé pour le recouvrement des gaz dissous. Ceux-ci sont analysés par une méthode de chromatographie de partage en phase vapeur.

Après avoir rapidement décrit les méthodes analytiques employées, illustration est donnée de quelques éléments tirés des analyses chimiques des vapeurs condensées. L'auteur conclut par l'exposé de quelques résultats fournis par les déterminations isotopiques.

Celles-ci donnent un contenu en deutérium très voisin de celui des eaux de surface et un contenu en tritium inférieur à $0{,}4 \times 10^{-18}$ atomes. D'après les analyses isotopiques des calcaires et des eaux de condensation des vapeurs, il apparaît raisonnable d'accepter l'hypothèse d'une origine météorique des masses de vapeur de Larderello. Les valeurs du rapport $O^{18}/O^{16}$ peuvent s'expliquer du fait d'un vaste système de circulation des eaux dans le sous-sol, où a lieu un échange isotopique intense entre les eaux négatives de surface et les calcaires du sous-sol profond.

Ce système de circulation comporte un contact des eaux circulantes avec les zones profondes directement chauffées par l'intrusion magmatique et un retour à la surface de ces mêmes eaux sous forme de vapeur surchauffée. Des valeurs du rapport $T/H$ il est possible de déduire le temps de circulation, supérieur certainement à 40 ans.

# WATER COLLECTION AND ANALYSIS FROM THERMAL SOURCES AND VAPOUR MANIFESTATIONS

## *Summary*

In this paper, the author illustrates the contributions of hydro-chemical studies to the prospecting works of a new geothermal area.

Many thermal springs, low or high in temperature, or natural steam manifestations with associated gas flows, occur in areas interested by endogenous phenomena, connected with volcanic or plutonic activity.

The chemical composition of these thermal manifestations, the abundance of certain elements, their relative enrichment in respect to others, etc., are very useful in order to have some diagnostic terms for distinguishing different types of waters.

Chemical analyses have also a technological interest for industrial recovery of valued constituents; the chemical plants of Larderello S.p.A. are utilizing

the $H_3BO_3$, $NH_3$, and $H_2S$ contents for a wide production of chemical by-products. The author reviews the different methods used for collecting waters from thermal springs and condensed steam, either from boraciferous steam jets or from natural manifestations.

Particular care is recommended in order to avoid any possible atmospheric contamination which may produce unreliable valuations of dissolved gas contents and some alterations due to the oxidation processes. The laboratory apparatus for the recovery of dissolved gas, which is subsequently examined by a gas-chromatographic apparatus, is also described. After a brief exposition of the analytical methods used, some data obtained from chemical analyses of condensed steam are also given.

The author concludes by showing some results of the isotopic determinations. These indicate a Deuterium content very close to the surface waters and a Tritium content as low as $0.4 \times 10^{-18}$ atoms. From isotopic analyses of limestones and condensed waters, it seems reasonable to assume a meteoric origin for the Larderello steam masses.

The $O^{18}/O^{16}$ ratio values may be explained by a very wide water circulation system underground, whereby an intense isotopic exchange between negative surface waters and limestones takes place.

This circulation system involves a contact of circulating waters with the deep zones directly heated by magmatic intrusion, and a return of the same to the surface as superheated steam.

As we may deduce from the T/H ratio value, the circulation time would be in excess of forty years.

# MÉTHODES ET DISPOSITIFS DE MESURE EN TÊTE DES PUITS EMPLOYÉS AU CHAMP GÉOTHERMIQUE DE LARDERELLO APRÈS ÉRUPTION D'UN SONDAGE

*Renzo Nencetti**

L'exploitation tant chimique qu'énergétique des masses de fluide endogène détectées ainsi que l'essor des études portant sur le potentiel de production d'une zone vaporifère donnée appellent l'emploi de méthodes et d'équipements spéciaux de mesure du débit de chaque composant et aussi (mais voudrions-nous dire, surtout) de détermination, pour les différentes valeurs de pression.

*a*) Des variations du débit de chaque composant et de leurs caractéristiques physiques;

*b*) Des variations de l'état physique probable des constituants et de leurs proportions.

Ces deux problèmes sont également liés l'un à l'autre; en effet, d'une part, l'état chimique des composants détermine le mélange, d'autre part, les conditions d'équilibre de ces composants sont remarquablement influencées par les conditions physiques du fluide.

Les pages qui suivent se proposent de faire rapidement le point des systèmes et des méthodes de mesure mis en œuvre au champ géothermique de la société Larderello, S.p.A., aux fins du relèvement des caractéristiques dont il a été parlé ci-dessus.

## Mesure du rapport gaz/vapeur

La nature particulière du fluide endogène débité par les soufflards exige une mesure précise des quantités des phases, condensable et incondensable, qui le composent.

Étant donné que les mesures absolues des deux quantités ne permettraient pas d'établir des comparaisons et des corrélations, nous exprimons le rapport entre le gaz et la vapeur condensée au moyen d'une unité pratique. Cette unité est Nl/kg et représente les litres de gaz (à 0 °C et 760 mm Hg) par kilogramme de vapeur condensée obtenue.

L'appareil employé pour la fixation du rapport gaz-vapeur est présenté à la figure 1. Il se compose de :

*a*) Un condensateur à serpentin *A*, alimentable en eau froide moyennant le récipient *B;*

*b*) Un séparateur de vapeur condensée *C*, muni d'une gaine à thermomètre *T*, d'un niveau *L*, d'un robinet de déchargement *R* et d'un tuyau de sortie des gaz *U;*

*c*) Un gazomètre *G*, muni d'un manomètre à eau *M*, d'une gaine de thermomètre *T*, d'un niveau *L*, d'un tuyau d'amenée des gaz *E*, et d'un robinet d'écoulement $R_1$. Ce gazomètre aura été préalablement étalonné avec précision, de manière à marquer la valeur du volume en litres pour les différentes hauteurs correspondantes du liquide au niveau $L_1$, pour la zone occupée par le gaz provenant du séparateur *C*.

### Manière de procéder

Après avoir aménagé le dispositif comme il est indiqué à la figure 1, on ouvre le robinet à la tête du puits $R_2$, de manière à ce que l'eau de la vapeur condensée sortant du séparateur *C* soit suffisamment froide. On ferme alors le robinet *R* du séparateur *C*. On assure le raccord, avec un tuyau en caoutchouc, entre le tuyau de sortie des gaz *U* sortant du séparateur et le tuyau d'amenée au gazomètre *E*. En même temps, on ouvre le robinet de déchargement $R_1$ du gazomètre, de manière à ce que dans les deux portions du manomètre *M* il n'y ait pas de différence de niveau ($p = o$). Lorsque le liquide déplacé par le gaz a atteint, dans l'indicateur de niveau, la hauteur correspondant au volume $Vg$ (par exemple, 20 litres), on ferme en même temps tous les robinets. On mesure alors le volume $Vc$ de l'eau de vapeur condensée obtenue. On prend note de la température existante dans le gazomètre et de la pression atmosphérique.

Le volume total de fluide traité sera donc donné suivant la formule :

$$Vg + Vc = V \text{ (volume total du fluide traité)}$$

Si nous supposons une densité $d = 1$, pour l'eau de vapeur condensée collectée, on peut calculer le volume à $t$ °C de gaz correspondant à 1 000 g de vapeur condensée.

Ce volume s'exprime suivant la formule :

$$(Vg - Vc) : Vc = Vt : 1\,000;$$

$$Vt = \frac{Vg - Vc}{Vc} \times 1\,000$$

En appliquant l'équation caractéristique des gaz parfaits et compte tenu de la tension de vapeur d'eau pour la température enregistrée, nous aurons

* Larderello, S.p.A., Pise (Italie).

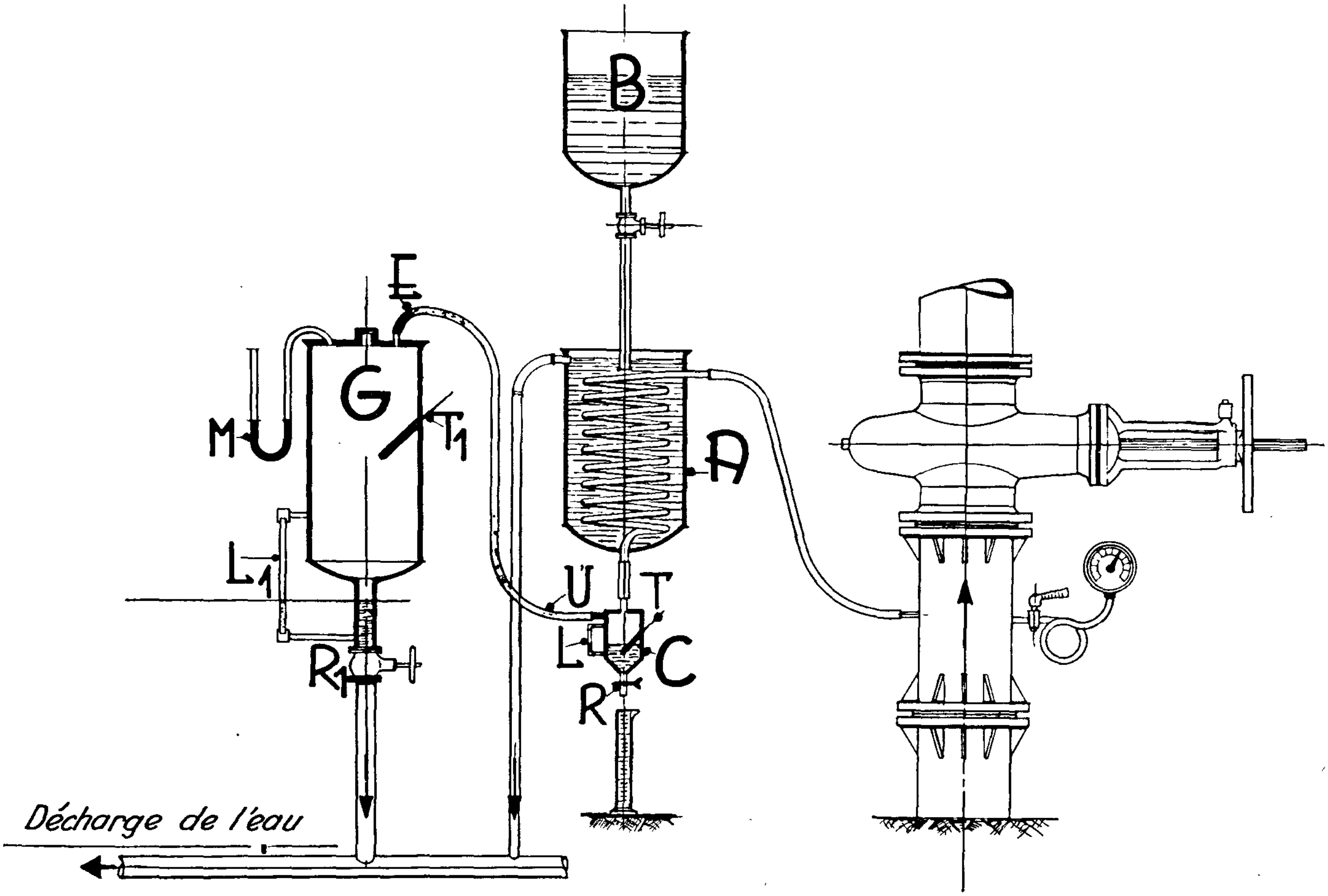


**Figure 1. Appareil pour la détermination du rapport gaz/vapeur**

le volume de gaz rapporté à 0° et 760 mm Hg., suivant la formule :

$$Vc = \frac{(P_1 - h) \times Vt \times T}{Po \times (T = t_1)}$$

où $Vo$ = volume du gaz à 0 °C et 760 mm Hg;
$P_1$ = pression atmosphérique en mm Hg;
$h$ = tension de vapeur d'eau pour la température enregistrée en mm Hg;
$t_1$ = température expérimentale en °C

Par conséquent, $Vo$ sera le volume de gaz en Nl par kilo de vapeur condensée. Il y a lieu d'ajouter à ce volume celui des gaz qui sont restés dissous dans la vapeur condensée, rapporté à 0° et 760 mm Hg. Pour les dosages des gaz dissous, nous renvoyons au mémoire du même auteur portant sur l'analyse des eaux (G/73).

## Mesures de débit

Nous présenterons maintenant les méthodes employées à la société Larderello, S.p.A., pour le relèvement du débit, c'est-à-dire des quantités en poids passant à travers la section d'un dispositif d'étranglement dans le temps unitaire. La valeur du débit est exprimée en kg/h.

Les équipements employés sont de deux espèces : le cône étalonné; le diaphragme circulaire.

Le premier dispositif est employé en général pour mesurer les quantités de fluide débitées par un sondage, quelques jours après son éruption en surface. Les différentes mesures, obtenues en variant les diamètres de sortie, ne servent qu'à donner des indications générales sur le potentiel de production du nouveau sondage.

Le dispositif à diaphragme circulaire est par contre employé pour avoir les valeurs définitives et pour tracer la courbe représentative du sondage; ou encore la valeur du régime d'écoulement du sondage, en fonction des variables pression/débit, auxquelles il faut ajouter encore les déterminations correspondantes de température et du rapport gaz/vapeur.

Nous faisons remarquer que les mesures avec le cône étalonné sont exécutées sur le dispositif placé en tête du puits à basse pression, employé normalement au cours du forage, et relié à la bride de la conduite, au moyen de la vanne $V_1$ à haute pression ($PN$ 40 $\Phi$ 350).

Les vannes $V_2$ et $V_3$ sont du type à basse pression, la vanne $V_4$ est le *blow-out preventer* (fig. 2).

### Dispositif du cône étalonné

Ce dispositif se compose (voir fig. 2) d'un tronçon de tuyau $A$ muni de raccords pour l'établissement des pressions statique et dynamique, d'une gaine pour thermomètre $T$ et d'un cône étalonné $B$. Ce cône a un orifice de sortie de diamètre connu et inférieur à celui du tuyau $A$, et cela aux fins d'obtenir la réduction du diamètre nécessaire pour l'étranglement du courant du fluide sortant. Les vannes $V_2$, $V_3$ sont à basse pression et servent aux manœuvres de distribution du fluide nécessaires pour assurer la substitution des divers cônes de mesure employés.

Cette mesure est effectuée en maintenant entièrement ouverte la vanne de tête du puits $V_1$, de manière à diriger toute la quantité de fluide vers le dispositif d'étranglement.

En ouvrant le robinet de raccord pour la pression dynamique, on mesure le niveau $h$ dans les deux tronçons du manomètre à colonne de mercure et l'on prend note de la température.

Étant donné que la pression et la température, après amenée du fluide vers le dispositif de mesure, tendent l'une et l'autre à un accroissement sensible, il faudra attendre un temps suffisant pour que les oscillations du liquide manométrique cessent.

Pour le calcul du débit en kg/h, on applique la formule ci-après de Bendermann :

$$G = 71{,}64 \times S_1 \times \sqrt{P_1} \times \sqrt{\gamma m},$$

où $G$ = débit du fluide en kg/h;

$S$ = surface (en cm²) de l'orifice d'écoulement dont le diamètre est connu;

$P_1$ = pression absolue en ata, obtenue à partir de $\dfrac{H + h}{735{,}5}$ où H est le dénivellement manométrique et h est la pression barométrique en mm de Hg;

$\gamma m$ = poids spécifique du mélange fluide en fonction de la pression, de la température et du rapport gaz/vapeur.

### Dispositif du diaphragme étalonné

La mesure du débit, avec manomètre différentiel, est fixée d'après les normes dictées par le Consiglio Nazionale delle Ricerche pour les mesures de débit des fluides au moyen de diaphragmes, portées aux *Tabelle dell'Ente Nazionale per l'Unificazione dell'Industria* (U.N.I. 1559-1605, a).

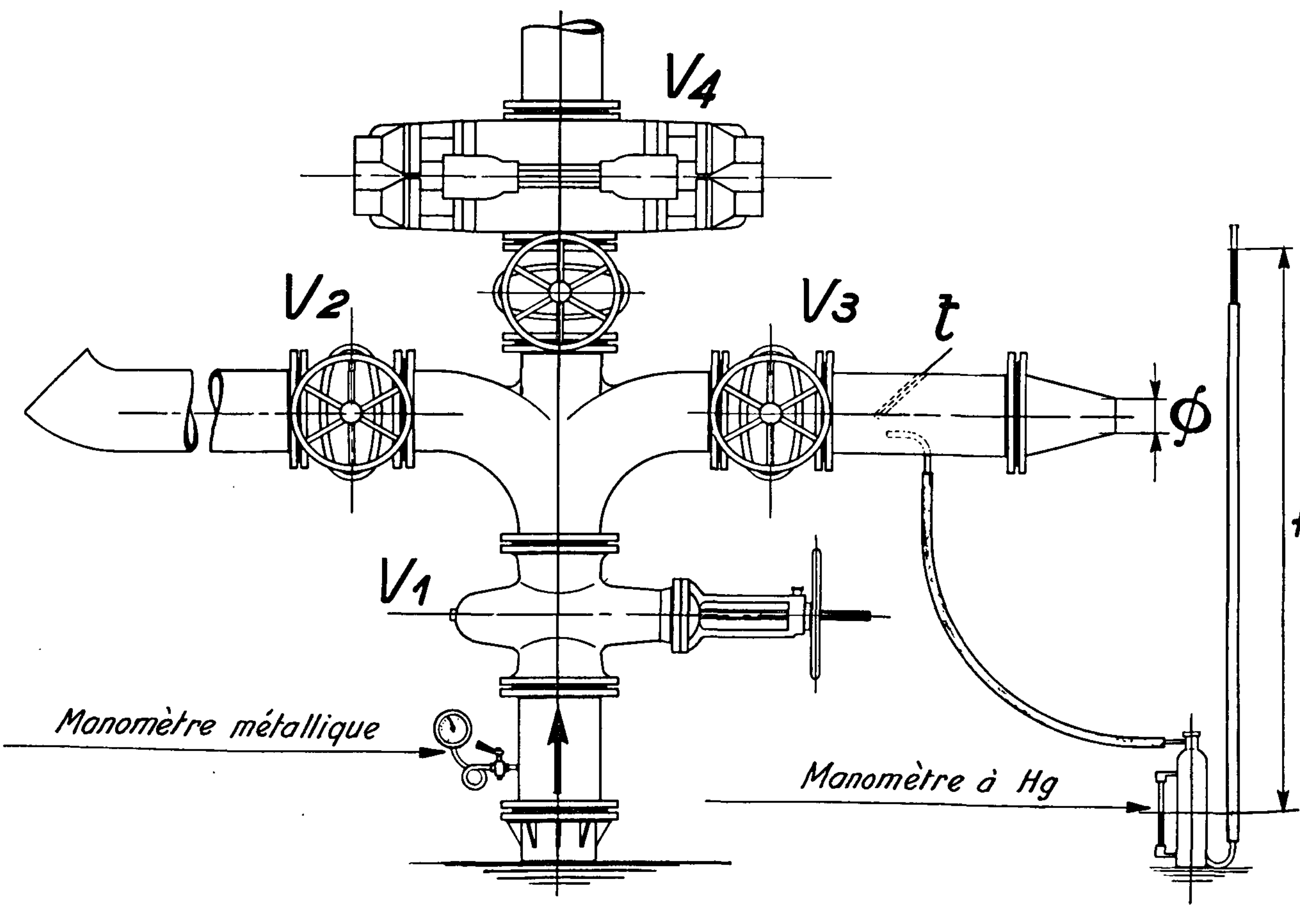


**Figure 2. Dispositif à cône pour la mesure du débit**

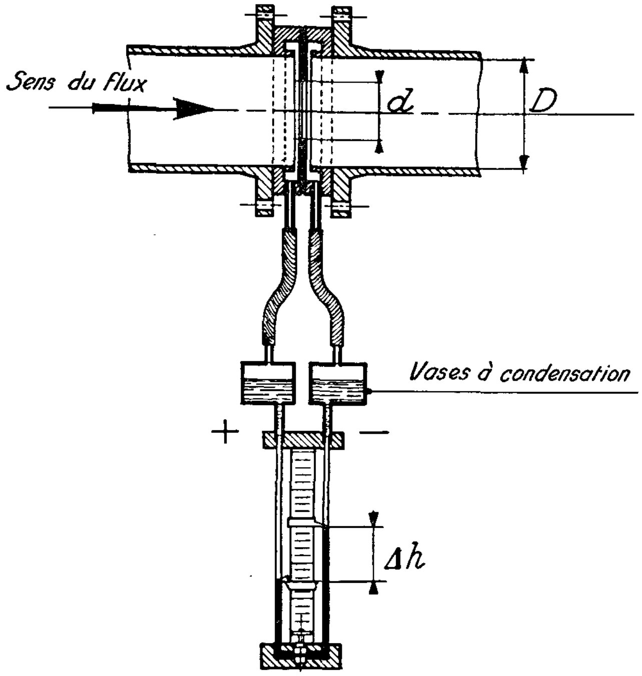


Figure 3. Dispositif à diaphragme circulaire pour la mesure du débit

En particulier, le dispositif que nous employons prévoit l'emploi d'un diaphragme en acier Inox du type 10/C/13, résistant à l'attaque chimique et ayant des rapports d'étranglement compris dans l'écart 0,5 - 0,7, afin de ne pas rendre les pertes de pression propres au diaphragme trop importantes.

Pour le calcul du débit en poids (kg/h, en employant du mercure comme liquide manométrique) des fluides compressibles, en particulier de la vapeur surchauffée, on applique la formule suivante :

$$G = 0{,}04436\ \alpha\ d^2\ \varepsilon \sqrt{\gamma\ m}\ \sqrt{\Delta\ h}$$

où $\alpha$ = coefficient expérimental d'écoulement, fonction du rapport d'étranglement $m$ [6]

$\varepsilon$ = coefficient de compressibilité, fonction de $\Delta\ h$ (en mm Hg), P (ata) et $m$.

## Dispositif pour relever les données d'établissement de la courbe débit/pression

Le dispositif de mesure est celui à diaphragme étalonné (comme ci-dessus) avec l'adjonction d'une vanne de contre-pression $V_4$ placée dans la partie finale de la conduite de déchargement.

L'ensemble de ce dispositif à basse pression est accouplé (fig. 4, 5 et 6) à une tête de puits à haute

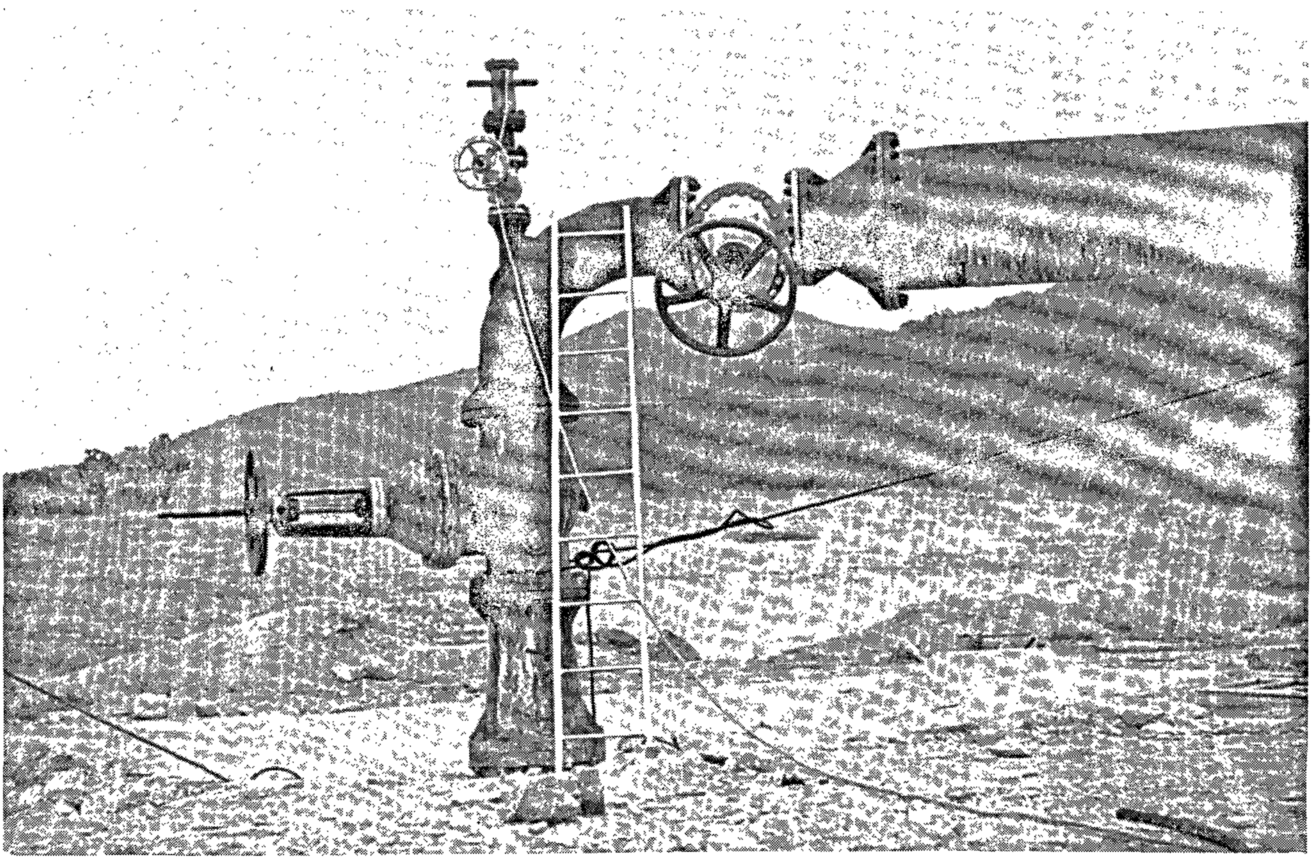

Figure 4. Dispositif à haute pression à la tête du puits pour les mesures du régime de production d'un sondage

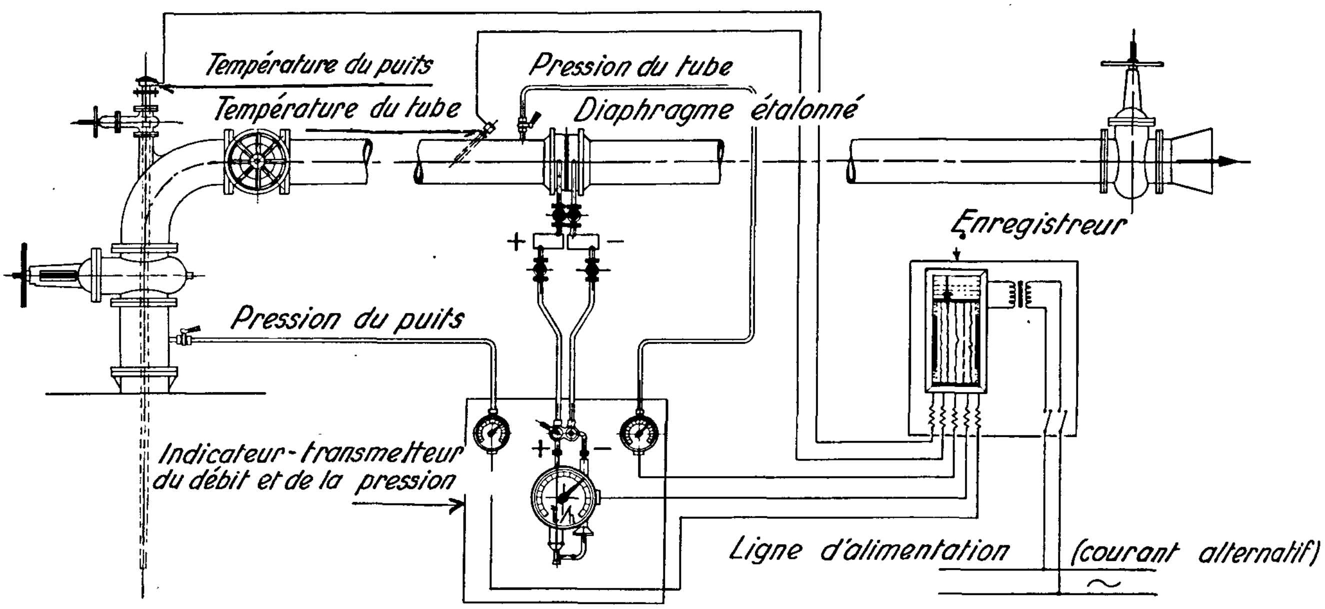


**Figure 5. Représentation schématique du dispositif de mesure avec indicateurs automatiques et enregistreur électrique**

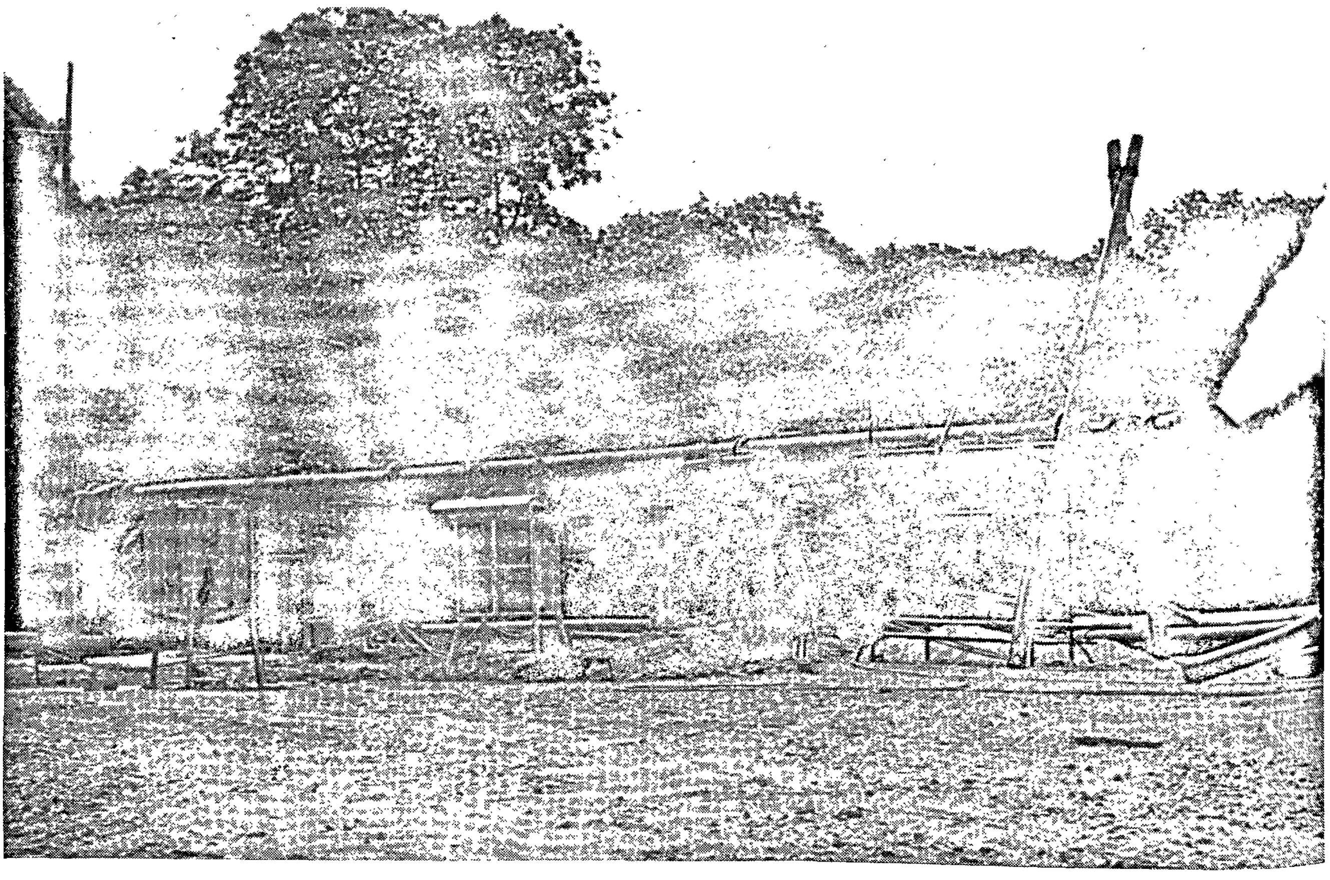

**Figure 6. Dispositif de mesure avec indicateurs automatiques**

pression constituée de deux vannes à haute pression $V_1$ et $V_3$ et d'une cornière en acier munie d'une vanne à haute pression $V_2$ qui sert à l'introduction d'un thermomètre électrique de 4,5 m.

Cette longueur est nécessaire parce qu'elle permet de relever les valeurs des températures réelles du fluide. En effet, étant donné que les résistances terminales de celui-ci se trouvent à l'intérieur du sondage et au-dessous du plan du sol pour environ 3 m, on ne ressent pas les oscillations dues aux différents types de dispersion de la chaleur qui se manifestent, par contre, sur les dispositifs aménagés le long de la conduite en surface.

L'appareil que nous venons de présenter permet de relever des mesures pour les différentes valeurs de pression mesurée à la tête du puits.

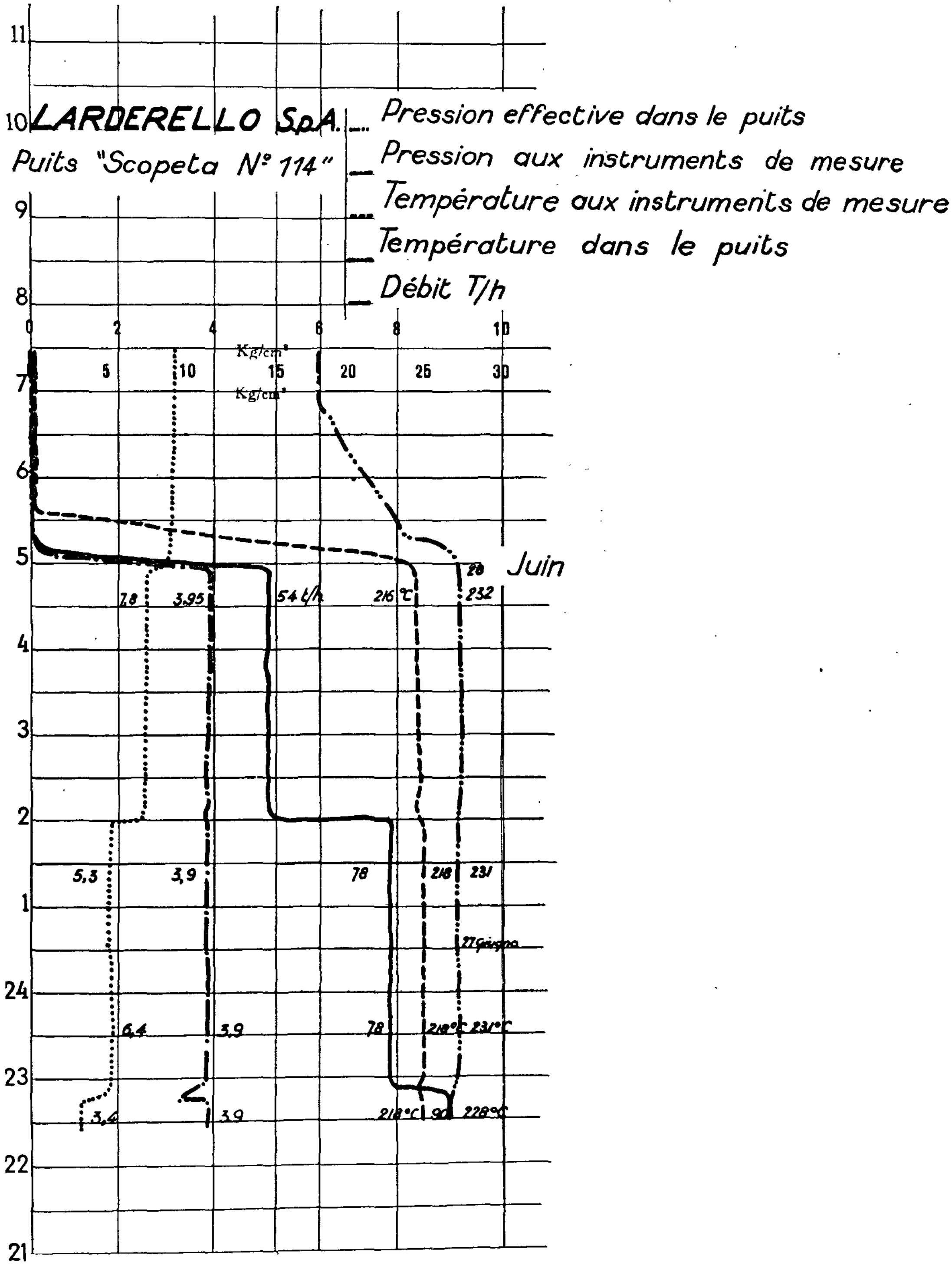


Figure 7. Diagramme multiple obtenu par l'enregistreur automatique

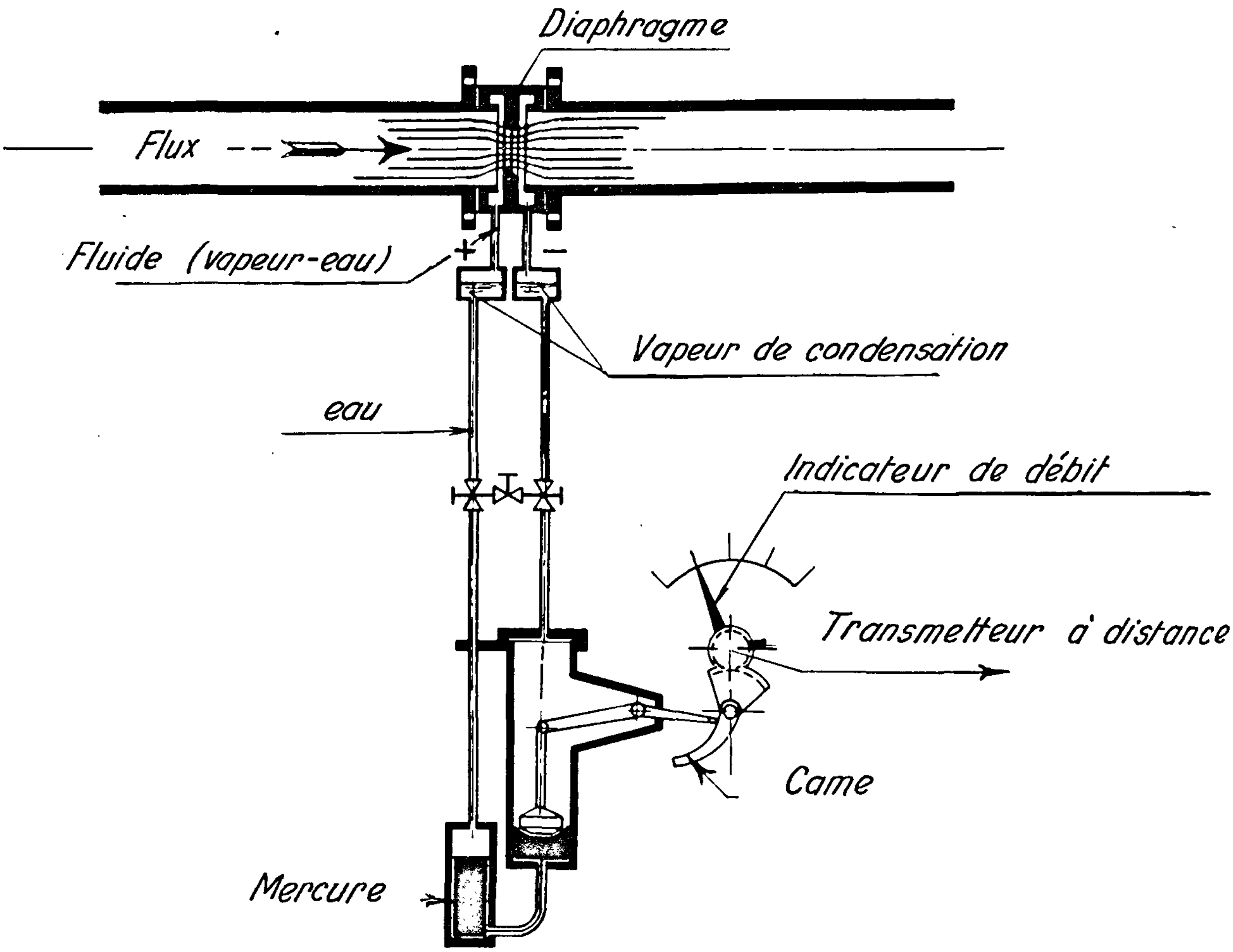


**Figure 8. Indicateur automatique à balance différentielle**

Il est évident que les manœuvres nécessaires d'étranglement servant à accroître la pression à la tête du puits seront faites à l'aide de la vanne $V_3$, étant donné que la vanne $V_1$ sera constamment ouverte en raison de la présence du thermomètre à l'intérieur du puits. Le relèvement des valeurs de la pression effectué à l'intérieur du puits pour les différentes conditions d'ouverture de la vanne $V_3$ est fait au moyen d'un manomètre aménagé un peu avant la vanne $V_1$.

La vanne de contre-pression $V_4$ aménagée, comme nous venons de le dire, après le diaphragme étalonné, sert à assurer le maintien de valeurs constantes de la pression à l'intérieur de la conduite à basse pression du dispositif de mesure, dans le but de rester autant que possible près des valeurs d'étalonnage des appareils de mesure. A toute variation de la pression à la tête du puits correspond une variation du débit du courant du fluide.

Le relevé des données se fait au moyen d'appareils automatiques fournissant une indication visuelle et au moyen de transmetteurs électriques spéciaux qui assurent un enregistrement continu des valeurs de mesure (fig. 6).

Ces équipements permettent donc de suivre à tout instant l'allure du débit du sondage sous examen. En effet, ils fournissent le diagramme multiple (fig. 7) et continu des courbes respectivement de : temps, débit, température et pression. Ces dernières sont données soit pour le dispositif de mesure soit pour la tête du puits.

L'indicateur de débit basé sur le principe de la balance différentielle (fig. 8) a été étudié en général pour des mesures sur vapeur surchauffée d'un poids spécifique donné.

Puisque le fluide endogène contient aussi une quantité sensible de gaz naturel, il est nécessaire que les valeurs de débit soient corrigées d'un certain facteur $C$ donné par $C = \dfrac{\sqrt{\gamma\, m}}{\sqrt{\gamma\, v}}$

où $\gamma\, m$ = poids spécifique du mélange gaz/vapeur;
$\gamma\, v$ = poids spécifique de la vapeur surchauffée pour des valeurs données de $p$ et de $t$.

Finalement, on mesure le rapport gaz/vapeur pour chaque valeur de la pression à la tête du puits.

Les données collectées sont ensuite portées au diagramme, comme il est indiqué à la figure 9. On fait le relèvement des valeurs, en fonction de la pression à la tête du puits ($P$) en ata, du débit ($G$)

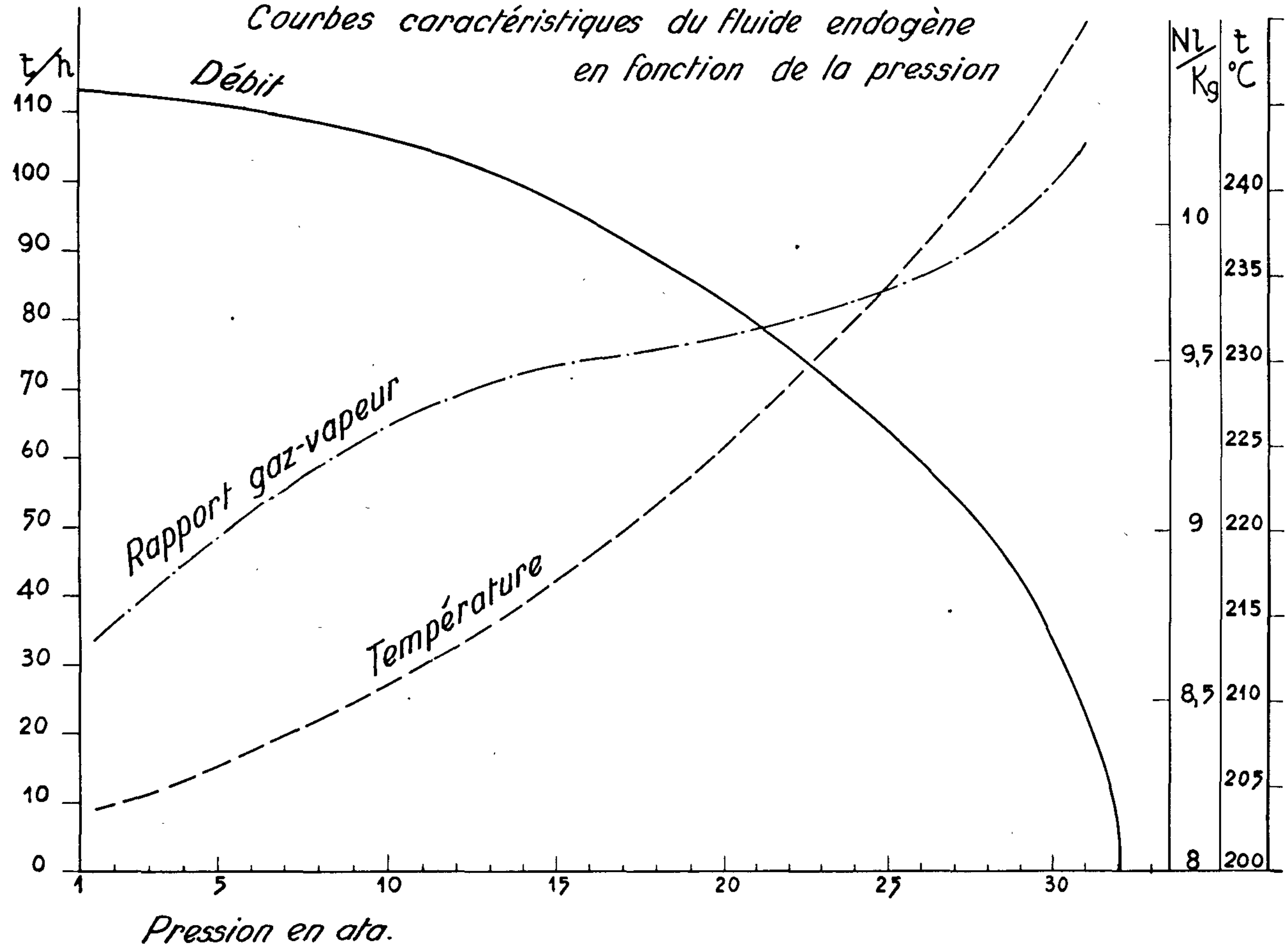


Figure 9. Diagramme typique du régime de production d'un sondage

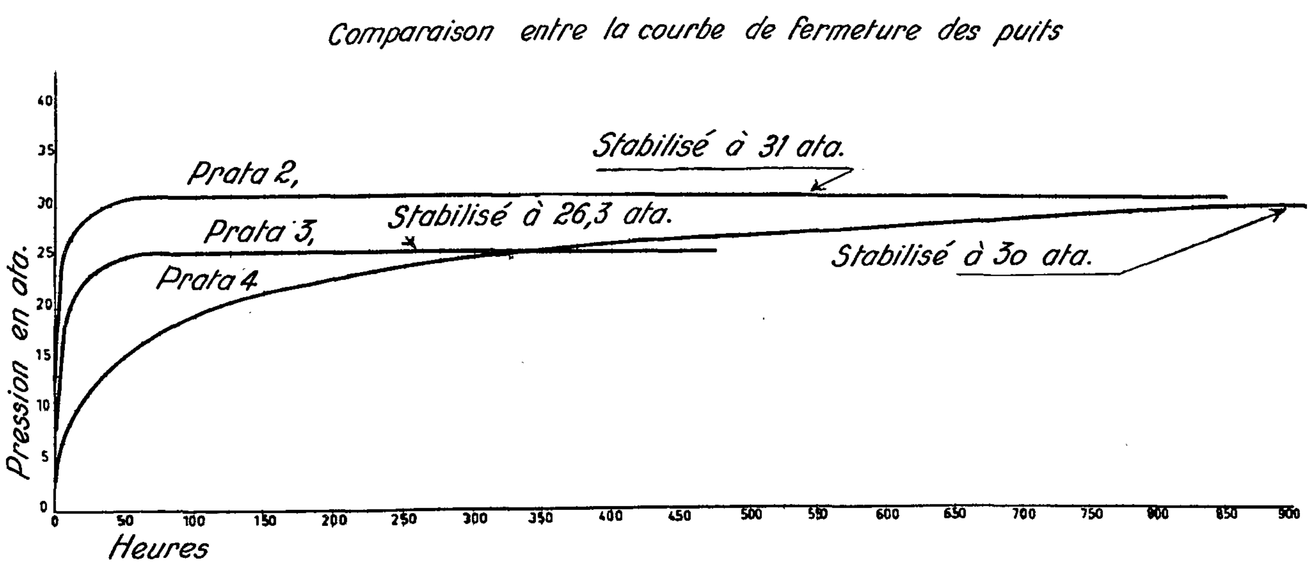


Figure 10. Courbes de fermeture pour trois sondages

en tonnes/h, de la température ($t$) en °C, du rapport gaz/vapeur ($R$) en Nl/kg. La courbe représentative rencontrera l'abscisse ($P$) avec la valeur de la pression de fermeture ($G = 0$).

La détermination de la valeur de la pression de fermeture est donc l'opération finale du programme des mesures. Ce relèvement se fait en des temps successifs, à partir de l'instant qui suit immédiatement la fermeture complète de la vanne $V_3$. En effet, les données intéressantes que l'on peut tirer sont les suivantes :

*a*) Valeur limite stabilisée par la pression de fermeture;

*b*) Temps employé pour atteindre cette valeur stabilisée.

Il apparaît dès lors évident (fig. 10) que les valeurs limites de la pression de fermeture stabilisée peuvent être atteintes en des temps très différents. Mais les deux valeurs — temps de stabilisation et pression de fermeture stabilisée — acquièrent leur intérêt important d'évaluation, car elles permettent de faire ressortir une caractéristique donnée d'un bassin productif donné, la pression de fermeture, ainsi qu'un caractère distinctif — le temps de stabilisation — entre les différents sondages d'un bassin vaporifère ayant une certaine valeur de la pression de fermeture.

**Temps de stabilisation pour mesures de débit**

Le relèvement des valeurs des paramètres nécessaires pour établir la courbe débit-pression peut amener à des courbes absolument erronées pour une allure particulière du phénomène endogène.

En effet, au moment où, par variation de la surface d'efflux de la vanne d'étranglement, on varie la pression à la tête du puits, c'est le débit qui supporte des variations bien plus grandes que celles qui correspondent à l'accroissement de pression.

En un premier temps, on a même de fortes oscillations du débit (pouvant amener des erreurs lorsqu'on étudie ce phénomène), étant donné que l'axe zéro de ces oscillations ne coïncide nullement avec le point établi après un temps de stabilisation convenable.

Plus précisément, une fois la première période d'oscillations terminée, le débit et la pression (rien n'étant changé quant à la surface de la vanne régulatrice) continuent leur variation pour une période très longue allant, sauf exception, d'un minimum de 48 heures à un maximum pouvant atteindre quelques centaines d'heures.

On ne connaît pas bien la cause de ce phénomène, de même qu'on ne connaît pas bien soit la genèse, soit les conditions de montée du fluide endogène

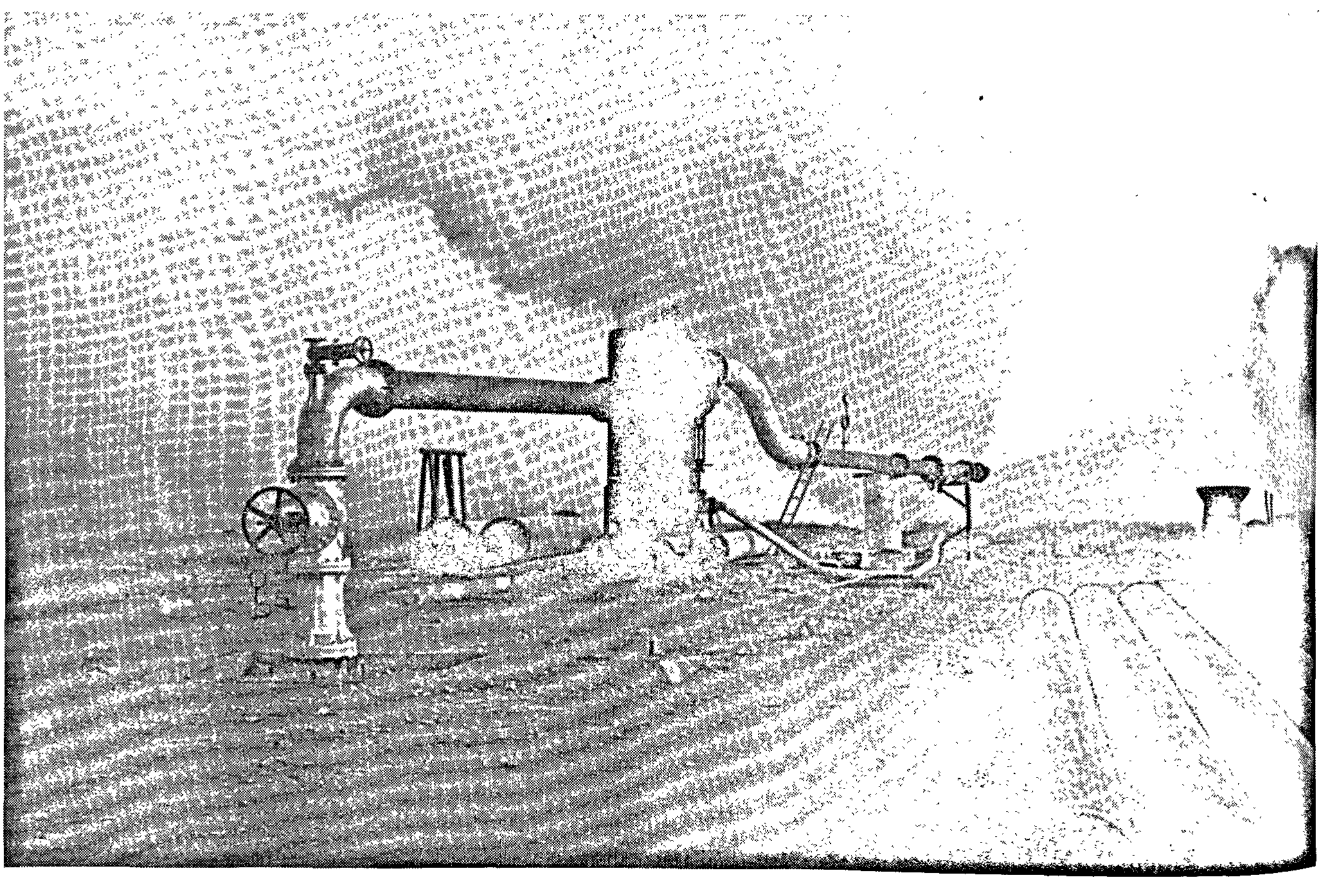

**Figure 11. Cyclone vertical avec dispositif de mesure**

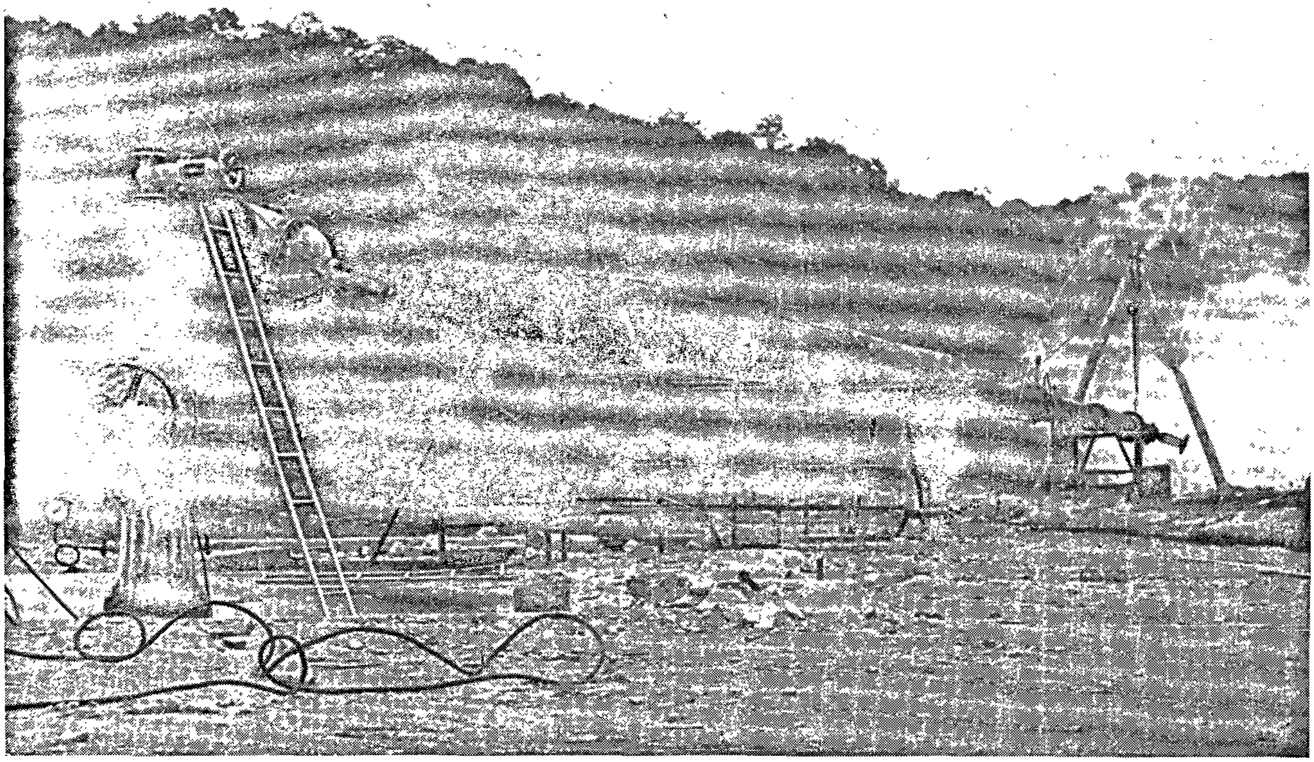

**Figure 12. Cyclone axial avec dispositif de mesure**

intimement lié à cette cause. En tout cas, il est intéressant pour nous de relever qu'en fixant les couples G et P, après un temps suffisamment long à partir du moment où la stabilisation est atteinte, on obtient un diagramme débit-pression absolument erroné.

Par ailleurs, il est impossible que l'opérateur parvienne à s'apercevoir de l'erreur, car la variation de ces deux grandeurs — avant d'atteindre un couple de valeurs parfaitement stabilisées — est extrêmement lente, presque insensible, alors que sa dérivée est, par contre, constante et peut agir, comme nous venons de le dire, sur plusieurs semaines.

Par conséquent, avant de procéder à la lecture du couple *G-P*, et donc avant de passer à une nouvelle variation de la surface d'efflux de la vanne de régulation, il faut s'assurer qu'au moins 48 heures plus tard les deux valeurs de *G* et de *P* sont restées exactement les mêmes.

## Mesures sur mélanges eau-vapeur

Ces mesures sont faites avec les mêmes méthodes et les mêmes appareils que ceux que nous avons déjà indiqués. Il faudra cependant placer en amont du dispositif de mesure, un séparateur eau-vapeur (fig. 11 et 12). Il faudra ajouter aux formules établies par les normes U.N.I. des facteurs de correction, fixés par voie d'expérimentation pour condensation totale. Sans entrer dans les détails de construction

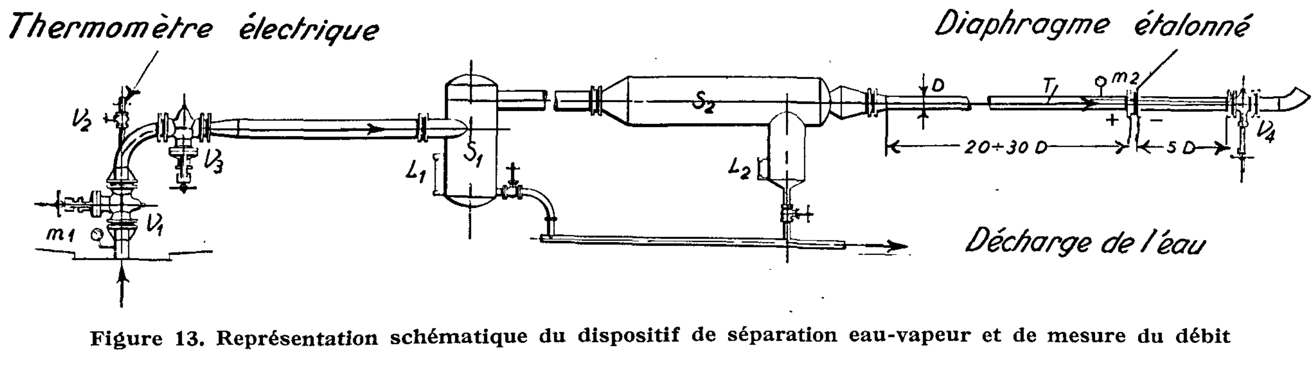


**Figure 13. Représentation schématique du dispositif de séparation eau-vapeur et de mesure du débit**

de ces séparateurs, nous dirons que ceux que nous avons employés sont du type à cyclone vertical et axial à pouvoir de séparation élevé, même pour les brouillards, et sont faciles à transporter. Pour des débits d'eau importants, ils sont placés en série, en aval de la vanne de fermeture (fig. 13). Le premier séparateur, du type vertical, sert à écouler de l'élément aériforme la plupart des abondantes quantités d'eau débitée par le soufflard (60 à 250 tonnes/h). Par contre, l'autre type, axial (modèle Larderello, brevet principal 341054, Confédération suisse) sert à obtenir une séparation poussée du résidu d'humidité à partir même de composants axiaux des vitesses de la masse globale du fluide, de l'ordre de 25 à 30 m/sec.

Cette caractéristique est indispensable pour nous, à moins que nous ne recourrions à des dimensions qui seraient trop grandes pour nous permettre le transport de l'équipement. En effet, les débits du fluide à traiter à basse pression peuvent atteindre des valeurs de 200-250 tonnes/h.

L'humidité en aval du séparateur axial ne dépasse pas, en général, 0,4-0,6 p. 100.

L'ensemble de cet appareil de séparation ne dépasse pas le poids de 2,5 tonnes, cette condition étant nécessaire et indispensable pour permettre le transport et la mise en place aisée et simple de l'équipement lui-même.

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## *Résumé*

L'évaluation des caractéristiques fondamentales d'une nouvelle source de fluide endogène, ainsi que le développement des recherches nécessaires aux fins de l'exploitation tant énergétique que chimique de celui-ci, appellent une série de déterminations chimiques et physiques portant sur les masses du fluide débitées.

Ces déterminations sont effectuées après un certain temps de l'éruption du sondage, de manière à permettre une auto-épuration du déchargement, à partir du fluide de forage, des déchets, etc. Ces déterminations sont toujours réalisées conformément à un programme de travail qui démarre avec une mesure générale, ayant caractère de simple indication, du débit total du fluide détecté.

Le dispositif employé pour effectuer cette mesure est appelé « cône étalonné » (figure 2). Il se compose d'un tronçon de tube $A$ muni de raccords pour le relèvement des pressions statique et dynamique, d'une gaine pour thermomètre $T$, d'un cône $B$. Ce dernier a un orifice d'écoulement de diamètre donné, inférieur à celui du tube $A$, afin d'obtenir une réduction du diamètre nécessaire pour l'étranglement du courant du fluide. La vanne $V$ est la vanne d'arrêt à haute pression.

Après drainage du fluide vers le dispositif de mesure, il faut attendre un temps suffisant de stabilisation des valeurs de pression et de température, car celles-ci tendent, au début, à subir des accroissements significatifs. Pour le calcul du débit, on applique la formule indiquée par le mémoire.

Pour le relèvement de la valeur du rapport gaz/vapeur, on emploie le dispositif de la figure 1, au moyen duquel on peut procéder séparément à la détermination quantitative des phases condensable et incondensable constituant le fluide naturel.

La valeur de ce rapport, calculée suivant des équations données, est exprimée en Nl/kg, litres de gaz (à 0 °C et 760 mm Hg) par kilo de vapeur condensée.

Il y a lieu d'ajouter à la mesure du volume séparé celle des gaz dissous dans la vapeur condensée, fixée au laboratoire tout de suite après prélèvement de l'échantillon, avec les contenus en $H_3BO_3$ et $NH_3$ à peu près complètement dissous dans la vapeur condensée.

Le programme des mesures définitives est exécuté après remplacement de la tête de puits à basse pression par une autre du type à haute pression — comme à la figure 5. Deux autres vannes ($V_2$ et $V_3$) y sont installées, en plus de la vanne $V_1$.

La vanne $V_2$ sert à l'introduction d'un thermomètre électrique, $V_3$ aux manœuvres nécessaires pour l'étranglement du courant fluide, aux fins d'avoir des valeurs différentes de pression à la tête du puits.

Le thermomètre à résistance est long de 4,5 m et permet de relever les valeurs réelles de température que le fluide acquiert pour les différentes valeurs de la pression à la tête du puits.

Le dispositif de mesure pour relever les valeurs définitives est un diaphragme étalonné (en acier INOX-10/C/13) ayant un rapport d'étranglement compris à l'intérieur de l'écart 0,5-0,7, pour ne pas rendre sensibles les pertes de pression propres du diaphragme.

Le débit est calculé suivant ce qui est dit aux *Norme del Consiglio Nazionale delle Ricerche*, portées aux *Tabelle dell'Ente Nazionale Unificazione Industria*, U.N.I., 1559-1605.

Dans la partie finale du tuyau de déchargement du dispositif, on place une autre vanne à basse pression $V_4$, servant à assurer le maintien des valeurs constantes de pression, à l'intérieur de la conduite à basse pression du dispositif de mesure. Cela dans

le but d'approcher autant que possible les valeurs d'étalonnage des appareils de mesure.

Pour les variations successives de la surface d'écoulement de la vanne $V_3$ et partant de pression de la tête du puits, on relève les données nécessaires pour construire le diagramme débit/pression et les autres du rapport gaz/vapeur.

Tandis que pour les valeurs du rapport gaz/vapeur l'on suit les méthodes et les calculs indiqués, les valeurs concernant, par contre, le diagramme débit/pression sont relevées directement d'après les indications automatiques ou à partir d'un diagramme multiple continu, tracé par un enregistreur. Celui-ci doit recevoir et marquer, à des intervalles réguliers, les données envoyées par des transmetteurs électriques reliés à des instruments à lecture directe.

La dernière valeur à relever, dans l'ordre du temps, est celle concernant la pression de fermeture. Les données obtenues sont portées au diagramme, comme il est indiqué à la figure 9. A partir de celui-ci, en fonction de $P$ en ata, on obtient les valeurs de $G$, $t$ et $R$.

Concernant les valeurs des paramètres nécessaires pour l'accomplissement de la courbe caractéristique, l'auteur fait remarquer que celles-ci devront être relevées seulement après que se sera écoulé un temps de stabilisation suffisamment prolongé.

En effet, au moment où l'on fait une variation de la pression à la tête du puits, le débit subit des écarts de beaucoup supérieurs à ceux correspondant à l'accroissement de la pression s'y rapportant.

D'habitude, en une première phase, les valeurs de débit et de pression subissent des oscillations considérables, suivies de variations continues, parfois extrêmement faibles, pour un temps allant, sauf exception, d'un minimum de 48 heures à un maximum de centaines d'heures. Il est cependant opportun, avant de passer à des variations ultérieures des conditions de débit, de vérifier que les valeurs obtenues pour $G$ et pour $P$ sont restées exactement les mêmes, au moins pendant 48 heures, et cela dans le but d'obtenir une courbe pour autant que possible représentative.

En ce qui concerne les mesures à effectuer sur des fluides composés de mélanges eau/vapeur, l'auteur décrit un équipement type, employé à ce but aux champs d'exploitation de la société Larderello, S.p.A., lorsque les conditions s'y prêtent. Sur le dispositif normal à diaphragme étalonné, on monte l'appareil séparateur qui peut être fait d'un seul appareil (fig. 11 et 12) ou de deux séparateurs montés en série (fig. 13), suivant le débit du sondage. Les séparateurs sont de deux types : l'un du type vertical, servant à exporter du fluide la plupart de la quantité d'eau débitée, tandis que le second, du type axial, sert à effectuer une séparation poussée du résidu d'humidité qui est maintenu dans l'intervalle 0,4 à 0,6 p. 100.

## METHODS AND APPARATUS USED FOR WELLMOUTH MEASUREMENTS IN THE LARDERELLO GEOTHERMAL ZONE WHEN A NEW WELL COMES IN

### *Summary*

The fundamental characteristics required for assessing a new steam well, and the studies and development necessary for its chemical and energetic utilization demand a series of technical determinations on the fluid discharged.

These determinations are made after the lapse of a certain time from initial gush, so that the discharge can naturally purify itself from drill cuttings, mud, water, etc.

The measuring programme is initiated by approximate measurement of steam flow, based on the relationship between the discharge pressure and the exit-orifice area. The apparatus used is the calibrated nozzle (or cone), shown in figure 2, installed on the drilling well-head.

The gas-steam ratio, or the gas volume corresponding to a given weight of condensed steam, is measured with the apparatus shown in figure 1. The value is expressed in Nl/kg (litres of gas at 0°C and 760 mm Hg per kg of condensed steam).

The volume of gas separated must be added to the condensed gas content of the condensed steam; this value is determined by laboratory apparatus, at the same time as the $NH_3$ and $H_3BO_3$, nearly all of which is dissolved in the condensate.

The definitive measurement programme is undertaken after the drilling wellhead is replaced by another of high-pressure type (figure 5) provided with three H.P. valves. Valve 1 is the shut-in valve; valve 2 is a valve through which a resistance thermometer is passed and lowered to well-bottom; valve 3 is the regulating pressure valve.

The measuring apparatus consists of a thin-plate orifice, with a throat ratio ranging from 0.5 to 0.7, to hold the pressure drop to minimum values.

The flow is calculated in accordance with Norme del Consiglio Nazionale delle Ricerche (Standards of National Research Council) in Tabelle dell'Ente Nazionale Unificazione Industria, U.N.I. 1559-1605.

A back-pressure valve is installed in the last part of the discharge line; this serves to hold the pressure in the measuring line constant and as close as possible to the calibration data of the measuring instrument.

The flow surface of the valve 3, and therefore the well-head pressure, is progressively decreased

to obtain data for plotting flow (in tons/h) against wellhead pressures (in atm), as shown in figure 9.

The graph also shows the gas-steam ratio and temperature corresponding to each well-head discharge pressure.

All the data, except the gas-steam ratio, are directly obtained by reading either the automatic indicators or a multiple continuous record (figure 7), traced at constant time intervals, by a 6-curve electric recorder, connected to the above indicators by electrical transmitters.

The last reading is the shut-in pressure. In regard to the parameters required for plotting the flow curve, the author notes that these should be recorded only after a sufficiently long stabilization period. In fact, after a well-head pressure change, the flow fluctuates very widely up to the values corresponding to the pressure increase. Usually, at first, flow and pressure changes are followed by other continuous variations, sometimes very small, for a time which, except in special cases, runs from 48 hours to several hundred hours.

Therefore, before modifying the discharge conditions, it appears to be necessary to make sure that the obtained values found for G and P have remained constant for almost 48 hours.

In regard to determination of the shut-in pressure, it is useful to note the pressure at regular time intervals, in order to have another interesting indicator of well conditions, represented by the slope of the shut-in pressure curve.

In order to have the most accurate means of measurements for a producing well giving a water-steam mixture, the steam must be separated from the water and each must be separately measured.

In reference to this problem, the typical separating and measuring equipment in use at the Larderello geothermal area is shown in figures 11 and 12. Depending on the well flow, the cyclone and axial separators may be installed in series or separately. The two-separator system shown in figure 13 is used for producing wells. The former is a cyclone separator which removes most of the water; the latter is an axial cyclone which extracts the residual water from the initial separation, leaving a residual humidity of 0.4 to 0.6 per cent.

Original : Russian

# THE HYPERTHERMAL WATERS OF PAUZHETSK, KAMCHATKA, AS A SOURCE OF GEOTHERMAL ENERGY

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The thermal waters of active volcanic areas include a number of characteristic types of varying chemical composition (gas and salt content) and origin.

One of the most characteristic types of these waters, found in many such areas and of very great value for power production, are the hyperthermal, high-pressure abyssal waters formed under highly reducing conditions and under the abnormally high temperatures and pressures due to contemporary magmatic chambers.

Their chemical composition differs from that of other thermal waters, their flow is greater, and their heat content is highest of all. Characteristic representatives of this type are the waters of Wairakei, New Zealand; Krisuvik, Iceland; and a number of large groups of springs in the Kurile-Kamchatka volcanic region : the springs of Geyser Valley, the Pauzhetsk waters, and the springs of Goryachy Plyazh.

They are all of almost the same composition, containing nitrogen, carbon dioxide, chlorides, and sodium, with relatively low total mineral content (under 5 g/l), and high silica (as much as 600 mg/l of $H_2SiO_3$). Boron is often present, and total gas content is low — usually under 200 ml/l (table 1). Their temperature ranges from 200 to 300°C in a number of known fields.

In spite of their very high temperature, these waters are as a rule in the liquid state at depths as shallow as a few hundred metres, owing to the hydrostatic pressure there, and their motion in all respects obeys the usual hydrogeological laws that govern the behaviour of high-pressure underground water. It is only in areas of natural discharge of the waters, or where they gush from wells, that a vapour phase is formed, resulting in a steam-water mixture and giving the specific dynamics of water outflow. The most rapid circulation and discharge of these waters occur primarily in zones of young tectonic comminution.

The data on the chemical composition, geological conditions of occurrence, and hydrogeological features of these thermal waters allow us to consider them to be, for the most part, of atmospheric origin, formed by infiltration, and owing their composition to complex processes of leaching of igneous and igneous-sedimentary rocks, impregnation with gases of magmatic and thermometamorphic origin, and to certain other processes. The occurrence of these waters is probable in the deep horizons of many active volcanic areas, and, in particular, in the eastern volcanic region of Kamchatka and the Kurile Islands.

Their high heat content, great yield, and often their considerable head make precisely this type of thermal water the most promising as major sources of heat and power; and geothermal power stations based on them exist or are being planned in a number of countries.

During the last few years in the Union of Soviet Socialist Republics, the Academy of Sciences and the Ministry of Geology and Subsurface Resources have been doing work of this kind in south Kamchatka, at the Pauzhetsk hot springs, which are a very characteristic example of a field with the waters we have just described (figure 1).

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**Table 1. Chemical composition of abyssal hyperthermal waters of active volcanic areas (typical examples)**

| *Region* | *Deposits* | *Total mineral content of waters (g/l)* | *Formula for ionic composition (equiv. per cent)* | *$H_2SiO_3$ (g/l)* | *pH* |
|---|---|---|---|---|---|
| Kamchatka, USSR . . . | Pauzhetsk | 3.3 | $Cl_{95}/(Na+K)_{92}$ | 0.216 | 8.1 |
| | Geyser | 2.4 | $Cl_{83}/(Na+K)_{94}$ | 0.332 | 8.7 |
| Kunashir Island, USSR . | Goryachy Plyazh | 4.6 | $Cl_{96}/(Na+K)_{93}$ | 0.309 | 8.1 |
| New Zealand. . . . . . | Wairakei | 3.9 | $Cl_{97}/(Na+K)_{95}$ | 0.502 | 8.6 |
| Iceland . . . . . . . . | Krisuvik | 2.2 | $Cl_{87}/(Na+K)_{94}$ | 0.648 | 9.1 |


**Figure 1. Map showing location of Pauzhetsk Springs on Kamchatka Peninsula**

## The geological structure and hydrogeological conditions of the Pauzhetsk deposit

The discharge area of the Pauzhetsk thermal waters, located at the southern end of Kamchatka, is a very promising site for harnessing high-grade hydrothermal resources. This area of about 400 sq km displays intense and varied hydrothermal activity, manifested by various hot springs and great jets of gas and steam. The greatest natural discharge for thermal waters in this area takes place at Pauzhetsk.

In geological structure, the area is located in an ancient (early Quaternary) trough, with a maximum width of 25 km and an amplitude of downwarping of the order of 1 000 m. During the Quaternary period, the central part of this depression underwent considerable upheaval, forming a great anticlinal structure, the Kambalny mountain range, with elevations over 1 000 m, complicated by a series of tectonic faults. This range shows considerable Quaternary volcanism, together with contemporary hydrothermal activity in the form of numerous gas-steam jets.

The south-west part of the trough has the great Quaternary massif of the Koshelev volcano, which also exhibits jets of gas and steam.

The plateaux surrounding the trough have surfaces of ancient Quaternary volcanic rocks, underlain by volcanogenous-sedimentary Tertiary deposits (aleurolites and tufaceous sandstones), which are 650 m below the surface at the Pauzhetsk hot springs and are covered by a thick layer of Quaternary volcanic rocks.

The discharge centre of the Pauzhetsk hot springs consists of a small thermal field (800 × 400 m) at the NW foot of the Kambalny range, in the valley of the Pauzhetka River, at about 100 m elevation. The total discharge of the natural outlets of the Pauzhetsk hot springs, including several large boiling springs and two small geysers, was 35 l/sec up to the commencement of exploration, and the total discharge of thermal waters into the Pauzhetka River through the alluvial deposits was estimated at 100 l/sec.

A detailed temperature survey showed the thermal field to have three main zones of heat liberation, striking NE, and associated with tectonic dislocations pitching SE. The principal Pauzhetsk springs are 250 m from the central zone, which is the largest and is distinctly defined. This zone, to which those springs correspond, coincides with a belt of thermometamorphic rocks detected magnetometrically at the E slope of the Pauzhetka valley. The E zone of heat liberation manifests itself on the slope of the valley in intense hydrothermal alterations of the rocks, and in steam jets (figure 2).

Exploratory drilling was commenced at the Pauzhetsk thermal field in 1958 with a deep rotary well (800 m), and was continued in 1959-1960 with shallower (300-500 m) core-wells (15 in all). Most of it was done in the above main heat-liberation zone and SE of it.

The exploratory drilling disclosed the following geological section (enumerated from top to bottom):

1. From 0 to 50-70 m. Grey ash rock and tuffites, of dacitic composition, with a large number of fine intercalations of aleuritic material as thin as 1 cm.

2. From 50-70 to 270-300 m. Agglomerate lithoclastic tuffs of andesitic-dacitic composition, of low porosity, consisting of fragments of lavas, pumice and volcanic glasses, with ash cement. A group of strong tuff breccias runs through the tuffs at depth 170-200 m, and consists of fragments of dacites, hornblende andesites and pyroxene andesites and andesito-basalts. These tuff breccias form a marker horizon within the deposit.

3. From 270-300 to 390 m. Andesitic tuff breccias, dense and dark coloured, consisting of fragments of andesitic and basaltic lavas, with ash cement.

4. From 390 to 570 m. Crystalloclastic dacitic tuffs, very dense and consisting of crystals of quartz, plagioclase, hornblende, and fragments of volcanic glass.

5. From 570 to 650 m. Andesitic basaltic tuff breccia in large blocks.

All the above groups of rocks are arbitrarily classified as Quaternary deposits.

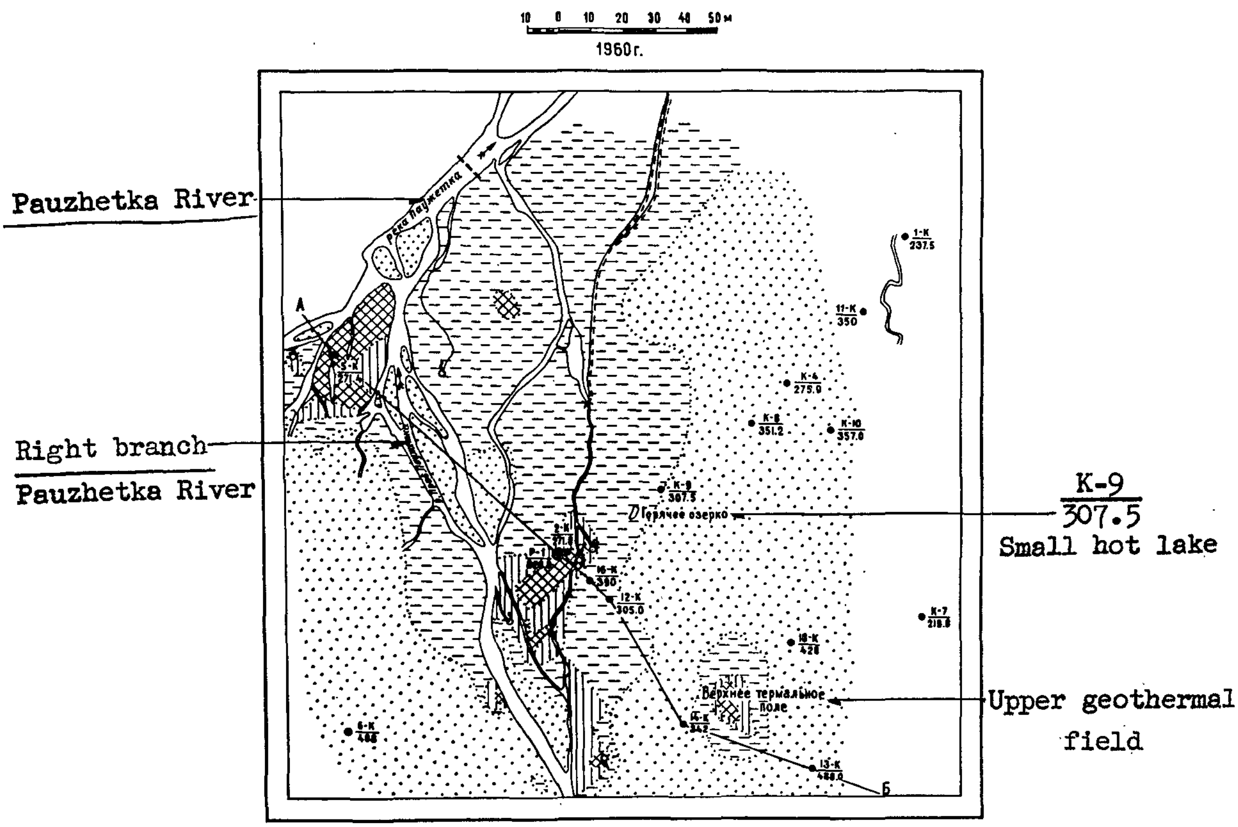
6. From 650 to 800 m. Tufaceous sandstones, greenish grey in colour, intercalated with aleurolites. These rocks belong to the Tertiary deposits, which are several thousand metres thick in this area.

As will be clear from the geological section (figure 3), the rocks in the above thermal field are almost horizontal, but are dissected into individual blocks by a system of pitching faults, mainly NE in strike. The major fissures are evidently associated with these faults, which are the routes for the most active circulation of the thermal waters.

The tufaceous facies holding the thermal waters were subjected to hydrothermal metamorphism of character and intensity varying with depth. Mineralization was most intense in the lithoclastic tuffs. The section of the rocks encountered by a deep rotary borehole shows the following zonal distribution of the hydrothermal alterations :

Depth 0-5 m. Kaolinization. The red clays near the surface give way to grey clays at depth.

Depth 30-250 m. Zeolitization and feldspathization. Adular is prevalent in the upper part of the zone,




LEGEND

Temperature of rock at depth 1 m below earth's surface (1957)

- Under 20°C
- From 20 to 50°C
- From 50 to 80°C
- From 80 to 100°C

Principal thermal springs

BOREHOLES

- Rotary
- Core well

8-K / 351.2 — Borehole No. / Depth of borehole

Figure 2. Outline map of Pauzhetsk Thermal Field

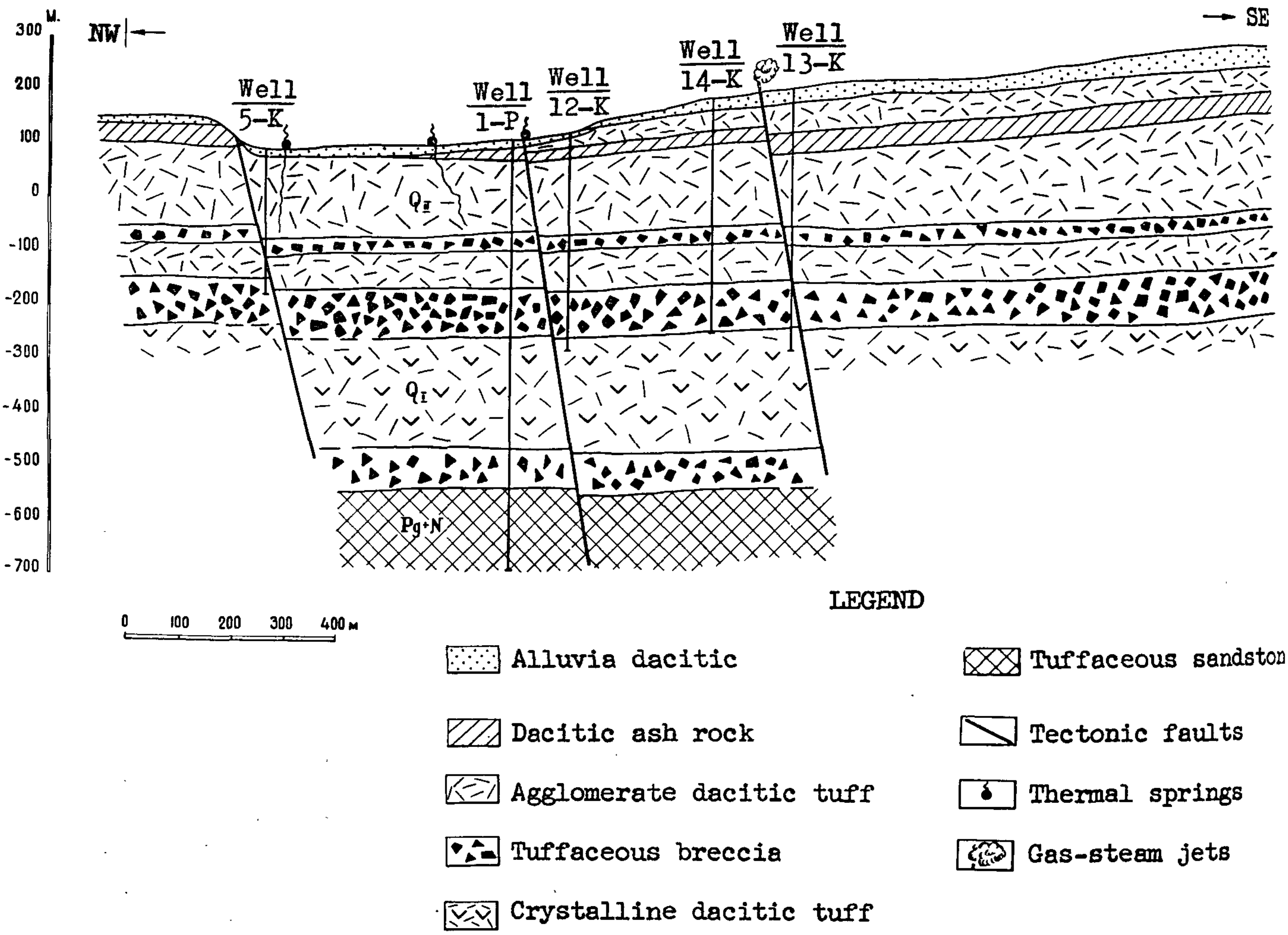



**Figure 3. Schematic geological section of Pauzhetsk Thermal Field (along line A-B)**

zeolite of the Lomonite group in the lower. Calcite, chlorite, pyrite and apatite are present in smaller quantities.

Depth 250-800 m. Propylitization. Recent formations of chlorite, carbonate, pyrite are disseminated with local concentrations of hydromica, anhydrite, zeolite, quartz, adular, and epidote.

By 1961, drilling had furnished the following principal hydrogeological data :

1. The high-pressure hyperthermal waters (temperature over 130-150°C) circulate throughout the complex of Quaternary and Tertiary rocks traversed by the wells, although the formations relatively richest in water are the agglomerate tuffs of the Pauzhetsk suite, overlain by almost water-impermeable ash rock.

2. The greatest inflow of water, up to 20-40 kg/sec, was in the wells traversing large fissures in the agglomerate tuffs. In areas where the rock fissures are minor, the discharge from the wells is not over 6-8 kg/sec, since the filtering power of the tuffs themselves is very poor (of the order of 0.01 m/day).

3. The hydrostatic head of the water in the wells located in the main zone of heat liberation is 10-20 m above the surface of the ground and increases regularly in the SE direction.

4. In the main zone of heat liberation and SE of it, the water temperature in the boreholes increases with depth to 170-195°C. However, in the central part of the thermal field tapped by the deep rotary well (W of the main heat-liberation zone), a rise of temperature to 180-185°C is noted only down to depth 400 m. Still farther down, the temperature declines to 130-140°C.

This is apparently to be explained by the fact that the main zone of heat liberation dips SE and, consequently, the deep borehole is further from the highly heated zone.

5. All the wells on gushing eject a steam-water mixture and operate by vapour-lift. Discharge is constant, pulsating, or of geyser type, depending on the abundance of water in the wells and on their diameter. The high-discharge wells gush at a constant rate throughout the possible pressure range to the well mouth. Pulsating of geyser flow is characteristic only of wells with a small discharge.

## Studies of steam-water wells

The rotary method was used in drilling all wells. A continuous core was removed, using the conventional clay drilling fluid and continuous flushing so as to cool the bore and avoid sudden ejection of the steam-water mixture.

In developing sampling and testing methods for the Pauzhetsk steam-water wells, account was taken of the successful experience of Italian research on hyperthermal waters, and also, especially, that in the Wairakei area of New Zealand, where the geological and hydrogeological conditions very closely resemble those at Pauzhetsk.

The research programme on the Pauzhetsk wells included the following principal subjects, data on which were essential to any satisfactory hydrogeological and energy appraisal of the Pauzhetsk deposit of thermal water.

*Thermophysical data*

(*a*) Temperatures in wells with steady heat conditions;
(*b*) Heat content of steam-water mixture leaving the wells;
(*c*) Steam pressure at well mouth.

*Hydrodynamic data*

(*a*) Hydrostatic head of the thermal waters;
(*b*) Discharge of steam-water mixture at various pressures at well mouth;
(*c*) Depth of steam formation in wells.

*Chemical data*

(*a*) Ionic and salt composition of thermal waters;
(*b*) Gas composition of vapour phase and gas content of waters;
(*c*) Changes in the chemical composition of the waters in gushing from the wells.

The temperatures in the wells — including the temperatures during gushing — were measured with bimetallic thermometers provided with a clockwork mechanism, and by special maximum mercury thermometers with a scale to 250°C (slow-recording where necessary). The latter gave entirely successful results.

The heat content and the discharge of the steam-water mixture of the exploration wells were both determined calorimetrically. It proved technically inadvisable to use a large stationary separator for sampling such wells. The samples of water and steam for chemical analysis were taken instead with a miniature cyclone separator connected by a special pipe to the pipe discharging the steam-water mixture.

Recording manometers were used to register the steam pressure and water pressure at well mouth. The data so obtained on the head of the thermal water in the wells furnished a very important indicator of its direction of motion, and, in conjunction with the geothermal data, also served as a basis for further guidance of the exploratory drilling.

The depth of steam formation was determined in a number of gushing wells by measuring the temperatures at various depths. (The water temperature falls when steam is formed, thus changing the slope of the temperature curve). These data are important for assessing the efficiency of well operation and the hydrogeological conditions in the individual sections of the field.

During the drilling of the deep rotary well, the geological section encountered was sampled at regular intervals by the method of test discharge of the steam-water mixture. During this operation, the separate depth intervals of the well were covered by the casing, and the space around the casing was cemented. This method of sampling was so complicated and time-consuming, however, that it subsequently had to be adandoned in favour of sampling all the core-wells only on completion of drilling, taking only the total flow from the entire well section not covered by the casing. The data so obtained were interpreted, in particular the ranges of depth at which water and inflow was intense by comparing the results of the sampling with those of the electric logging and temperature survey, and also with the observations during drilling (absorption of drilling fluid, percentage of core yielded, drilling quality of the rock strata).

## Chemical composition, heat content, and reserves of the Pauzhetsk thermal field

The chemical studies showed that all the thermal waters of the Pauzhetsk field belonged to the same type. They are nitrogen-carbon dioxide, sodium chloride, siliceous and boron-containing thermal waters, with a total mineral content of 3.3 g/l on discharge, an alkaline reaction (pH 8.1), and a very low total gas content (less than 100 ml/l).

Deep in the ground, however, before the beginning of steam liberation (and of degassing), which leads to a certain concentration of the water, their total mineral content is lower (by 12-15 per cent), and they are poorer in certain components (table 2). Their reaction is probably weakly acid. The gas composition of the vapour phase (per kg of steam) is : $CO_2$ : up to 500 mg; $H_2S$: up to 25 mg; $NH_3$: up to 15 mg.

A more detailed study of the chemical composition of the well water shows that the Pauzhetsk field has two sub-types of thermal water, which differ in certain respects.

The principal high-discharge, high-pressure waters, coming from great depths through tectonic fissures which feed the principal Pauzhetsk springs and the most productive wells, differ in having a higher total mineral content, a lower sulphate content, and, accordingly, a higher $Cl/SO_4$ ratio.

The less heated waters, circulating in the Quaternary volcanic tuffs, especially in the underlying

Table 2. Brief characterization of the chemical composition of the thermal waters of certain Pauzhetsk wells

| Spring or well No. | Sampling interval, m | Date of analysis | On discharge at surface, g/l | | | At depth, before beginning of steam liberation (calculated), g/l | | | $Cl/SO_4$ |
|---|---|---|---|---|---|---|---|---|---|
| | | | Total minerals | Cl | $SO_4$ | Total minerals | Cl | $SO_4$ | |
| *Principal deep high-temperature waters* | | | | | | | | | |
| Spring No. 1 | — | 25 Oct. 58 | 3.27 | 1.667 | 0.077 | 2.87 | 1.462 | 0.067 | 21.7 |
| Well No. 2 | 49.0-271.0 | 4 May 60 | 3.27 | 1.606 | 0.080 | 2.82 | 1.384 | 0.069 | 20.2 |
| Well No. 12 | 30.0-305.0 | 9 Oct. 60 | 3.38 | 1.633 | 0.079 | 2.93 | 1.420 | 0.069 | 20.6 |
| *Deep high-temperature waters with admixture of waters of Quaternary tufaceous suite* | | | | | | | | | |
| Well No. 4 | 21.5-275.9 | 4 May 60 | 2.72 | 1.322 | 0.070 | 2.45 | 1.119 | 0.063 | 18.8 |
| Well No. 8 | 23.0-351.2 | 6 Oct. 60 | 3.08 | 1.480 | 0.113 | 2.77 | 1.347 | 0.105 | 13.1 |
| Well No. 10 | 70.0-357.0 | 2 Nov. 60 | 3.06 | 1.558 | 0.110 | 2.73 | 1.391 | 0.098 | 14.4 |
| *Waters from Upper Tertiary deposits* | | | | | | | | | |
| Well R-I | 300.0-800.0 | 2 Nov. 60 | 2.55 | 1.038 | 0.354 | — | — | — | 2.9 |

Tertiary deposits, have a somewhat lower mineral content, a higher sulfate content, and a lower $Cl/SO_4$ ratio (table 2). For this reason, during the gushing of a number of Pauzhetsk wells, which operate by vapour-lift, with the formation of deep depression funnels, waters of the second sub-type are drawn into the principal deep waters, thus somewhat modifying their composition and lowering their heat content.

It is also important to note that, as the abyssal hyperthermal waters rise to the surface through the fissures in the rocks, the gas content of these waters is decreased by steam formation and degassing, while gas and steam are liberated at the surface. The presence there of free gas and steam is thus an indicator of the existence of hyperthermal waters at great depths. A detailed study of the composition of the gas-steam emissions in the eastern part of the Pauzhetsk thermal field showed them to be the gas-vapour phase of the abyssal Pauzhetsk thermal waters.

Our present hydrogeological and hydrochemical data allow us to consider the Pauzhetsk thermal waters to be formed by infiltrating atmospheric waters which acquire their chemical composition primarily by leaching the igneous and igneous-sedimentary rocks and by becoming impregnated at depth with gases of thermometamorphic and, in part, of magmatic origin.

The data obtained up to now on the thermal conditions in the wells, the heat content of the steam-water mixture, the steam pressure, and the discharge of the wells (table 3), permit the conclusion that the high-pressure abyssal thermal waters arrive from the SE at the centre of their natural discharge, through a system of tectonic fissures, and come from deep-seated Tertiary sediments on the side of the Kambalny range, deep under which the geothermal values are abnormally high, owing to phenomena of contemporary volcanism.

In this connexion the Pauzhetsk thermal field must be considered the marginal NW part of an extensive Pauzhetsk deposit of thermal waters, which has, as yet, been prospected by drilling only to an insignificant extent.

The reserves of thermal waters thus far disclosed by boreholes as a result of the first stage of prospecting the edge of the Pauzhetsk field, with a total discharge of about 150-200 kg/sec and a heat content of 160-188 kcal/kg are thus merely a small part of the thermal waters that can be discovered in the deeper eastern part of the Pauzhetsk field.

Table 3. Temperature, heat content, pressure and discharge of certain exploration wells of the Pauzhetsk field

| Well No. | Well depth, m | Maximum temperature in well, °C | Heat content of steam-water mixture, kcal/kg | Maximum steam pressure at well mouth, atm | Discharge of well, kg/sec, at various pressures at well mouth | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | 1/atm | 2/atm | 3/atm | 4/atm | 5/atm | 6/atm |
| 2 | 271 | 187 | 177 | 4.6 | 6.0 | 3.9 | 2.8 | 2.1 | — | — |
| 4 | 276 | 174 | 160 | 5.4 | 40.0 | 33.0 | 27.0 | 20.0 | 14.0 | — |
| 7 | 220 | 180 | 177 | 5.4 | 4.7 | 3.0 | 2.6 | 2.4 | 1.9 | — |
| 8 | 351 | 168 | 159 | 4.1 | 8.6 | 6.8 | 5.6 | 3.5 | — | — |
| 10 | 358 | 179 | 164 | 5.2 | 23.5 | 20.2 | 16.8 | 12.7 | 8.4 | — |
| 12 | 306 | — | 175 | 5.5 | 7.3 | 6.0 | 4.6 | 3.1 | 1.5 | — |
| 14 | 342 | 195 | 188 | 6.7 | 20.5 | 16.5 | 14.5 | 12.5 | 10.3 | 8.5 |

### *Summary*

For power production, the hyperthermal, high-pressure, abyssal waters found in active volcanic areas are the most valuable known type of thermal waters. Their heat content is very high (running up to 200-300 kcal/kg), the yield of the wells is high, and their chemical composition varies little, so that they can in fact be used to generate power. Characteristic examples are the thermal waters at Wairakei, New Zealand, Krisuvik, Iceland, and, in the Kurile-Kamchatka volcanic zone, at the Pauzhetsk Geyser, and several other fields.

Since 1958 the USSR Academy of Sciences and the Ministry of Geology and Subsurface Resources of the USSR have been conducting combined prospecting and exploration at this Pauzhetsk field, in southern Kamchatka, USSR, to locate steam supplies sufficient to operate a pilot geothermal power station. During this period they have run geological surveys, conducted geophysical exploration (by electrical prospecting and magnetometry), made temperature and hydrochemical surveys of the thermal field, drilled fifteen exploration wells 200 to 800 m deep, conducted geothermal measurements in the wells with maximum mercury and bimetallic thermometers, and studied the ionic, salt and gas composition of the waters.

The Pauzhetsk thermal field is located in an active volcanic region, and is associated with the NW end of the Kambalny mountain range, a great anticlinal structure formed in an early Quaternary trough filled with a thick layer of Quaternary volcanic rocks (tuffs and tuff breccias) and underlying volcanogeno-sedimentary Tertiary deposits (aleurolites and tuffaceous sandstones). The natural discharges of thermal waters and gas-steam jets that form the Pauzhetsk thermal field are in the valley of the Pauzhetka river and are associated with a zone of tectonic dislocations of NE strike, pitching SE.

Hydrogeological, geothermal and hydrochemical data indicate that the thermal waters arrive from the SE at the centre of their natural discharge, coming from deep horizons of the Tertiary deposits of the Kambalny range, where the geothermal values are abnormally high in consequence of contemporary volcanism.

The drilling at this stage has tapped water at temperatures up to 195°C, with a heat content ranging from 160 to 188 kcal/kg, and yielding steam pressures up to 6.7 atm at well mouth. The wells gush a mixture of steam and water. The flow is constant when the discharge is substantial; otherwise the flow is pulsating or geyser-like. The steam is low in $CO_2$ and $H_2S$. The total discharge of thermal waters and steam by all the wells is estimated at 150 kg/sec, which would be enough to operate a small geothermal power station.

The exploration up to now has revealed only the marginal (NW) part of the vast Pauzhetsk thermal field. Considerably larger reserves of thermal waters, with higher parameters, can be found in the eastern, deeper part of this field.

## LES EAUX HYPERTHERMIQUES DE PAOUJETSK, DANS LA PRESQU'ILE DU KAMTCHATKA, SOURCES D'ÉNERGIE GÉOTHERMIQUE

### *Résumé*

De tous les types de ressources hydrothermales présentant une certaine importance en tant que source d'énergie, ce sont les eaux à haute température et à haute pression, formées en profondeur dans les régions caractérisées par leur activité volcanique, que l'on retiendra. Elles se distinguent très nettement des autres par leur richesse calorifique (qui atteint 200 à 300 kilocalories par kg), leur gros débit et leur composition chimique nettement définie, toutes caractéristiques permettant leur exploitation comme sources de force motrice. On citera, comme exemples types de ces eaux thermales, celles de Wairakei en Nouvelle-Zélande, celles de Krizuvik en Islande et, dans la région volcanique des Kouriles et du Kamtchatka, en URSS, celles des champs de Paoujetsk, de Geyser et de plusieurs autres.

Depuis 1958, un ensemble de projets de prospection et d'exploration est en voie de réalisation pour les gîtes d'eaux thermales de Paoujetsk, dans le Kamtchatka méridional, sous les auspices de l'Académie des sciences de l'URSS et du Ministère de la géologie et de la conservation des ressources du sous-sol, dans le but de trouver des ressources de vapeur suffisantes pour la réalisation d'une centrale électrique géothermique expérimentale. On procède, depuis cette date, à des relevés géologiques, des recherches géophysiques (par des méthodes relevant de l'électricité et de la magnétométrie), des sondages thermométriques et hydrochimiques des champs, des forages d'essai (15 puits dont les profondeurs s'échelonnent entre 200 et 800 m), des mesures géothermiques dans les puits (au moyen de thermomètres à maximum des types à colonne de mercure et à élément bimétallique) et à une étude de la composition des eaux (ions, gaz, sels).

Le gîte de Paoujetsk se trouve dans une région de volcanisme actif. Il est associé à l'extrémité nord-ouest de la chaîne de Kambalny, puissante

structure anticlinale formée dans une dépression remontant au début du quaternaire et remplie d'une couche épaisse de formations volcaniques quaternaires (tufs, brèches) et de roches sous-jacentes appartenant au tertiaire, du type sédimento-volcanique (aleurolithes et tufs arénacés). Les jaillissements naturels d'eaux thermales et les écoulements de gaz et de vapeur qui constituent le gîte géothermique de Paoujetsk se trouvent dans la vallée de la rivière du même nom et sont liés à la zone des accidents tectoniques orientée vers le nord-est et s'abaissant vers le sud-est.

Les données hydro-géologiques, hydrothermiques et hydrochimiques recueillies jusqu'à présent témoignent du foyer d'origine de ces eaux au sud-est du champ, en de profonds horizons des formations tertiaires de la chaîne de Kambalny, caractérisée par son régime géothermique anormalement intense, manifestation d'un volcanisme contemporain.

Les sondages exécutés jusqu'à présent indiquent que les eaux ont des températures allant jusqu'à 195 °C, avec une valeur thermique de 160 à 188 grandes calories par kg et une pression de vapeur qui peut atteindre 6,7 atmosphères à la bouche des puits. Ces derniers débitent un mélange d'eau et de vapeur. Leur régime d'écoulement est stable pour les principaux, mais intermittent ou pulsé pour les plus petits, qui prennent le caractère de geysers. La vapeur se caractérise par sa faible teneur en $CO_2$ et en $H_2S$. Le débit global des puits, mesuré en eau et en vapeur, est évalué à 150 kg/s, ce qui suffirait à alimenter une petite centrale électrique géothermique.

Les travaux de recherches menés jusqu'à présent ont été limités aux confins nord-ouest de la région en cause. Il existe dans la partie est et plus profonde de ce champ des ressources hyperthermiques beaucoup plus importantes, avec des paramètres plus élevés.

# RESULTS AND POWER GENERATION IMPLICATIONS FROM DRILLING INTO THE KILAUEA IKI LAVA LAKE, HAWAII

*Donald E. Rawson* and Walter P. Bennett†*

In November 1959, the volcanic eruption in the Kilauea Iki crater produced a lava lake containing about 100 million metric tons of molten lava. Prior to this eruption the Kilauea Iki crater was about a mile long and 700 feet deep. The outbreak of the eruption was along a fissure on the south-west wall of the crater, roughly halfway between the floor and the rim (figures 1 and 2). During the many eruption phases lava flowed into the crater, filling it to above the vent elevation. In the interim periods of the eruption cycles, lava flowed back into the feeding conduit.

The resulting lake of molten rock covered by a crust of solidified lava offered a unique opportunity to attempt a drilling experiment through rock at

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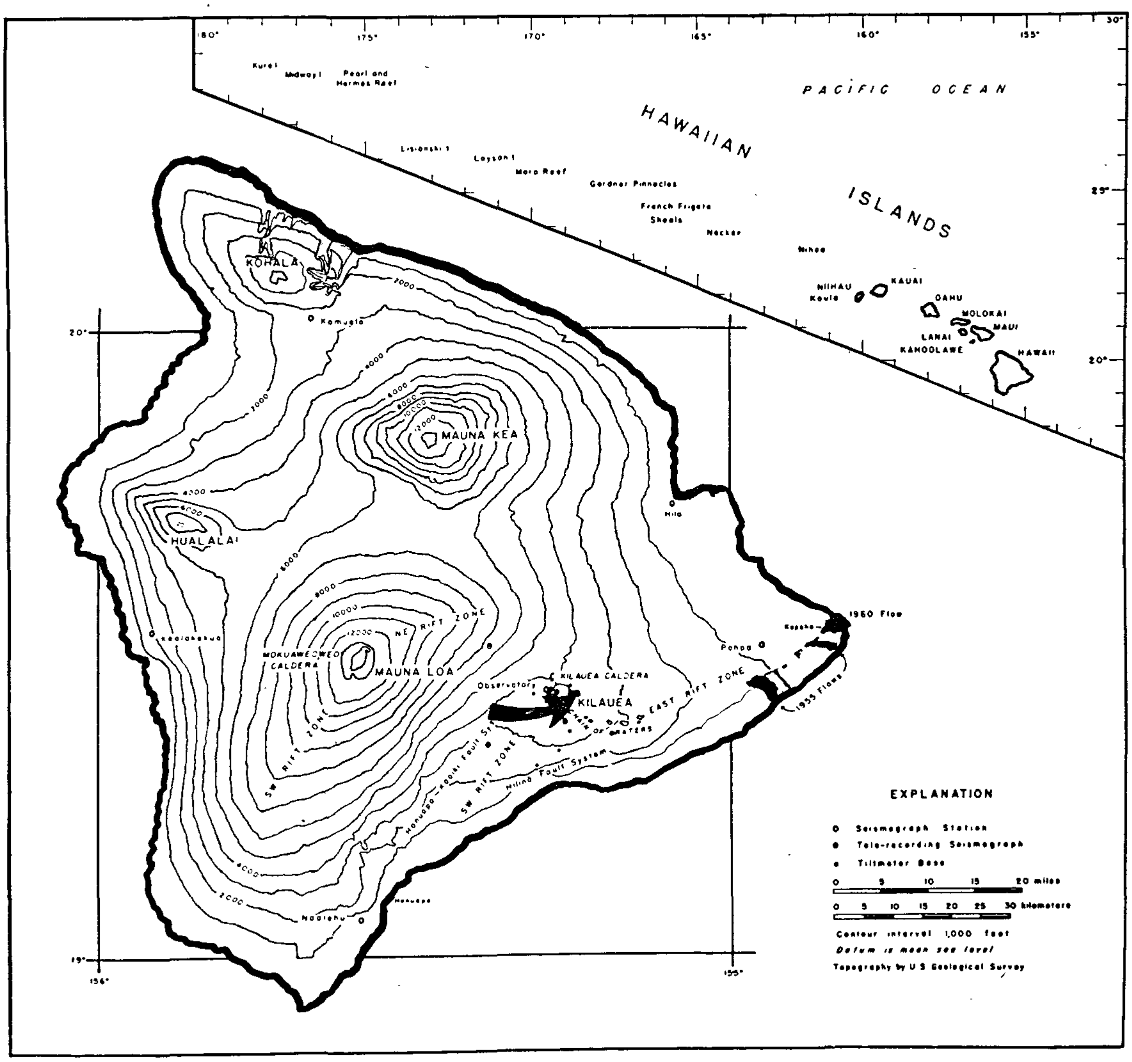


Figure 1. The Hawaiian Islands: arrow marks the location of the Kilauea Iki drilling experiment (reproduced from *Science*, vol. 132, No. 3243)

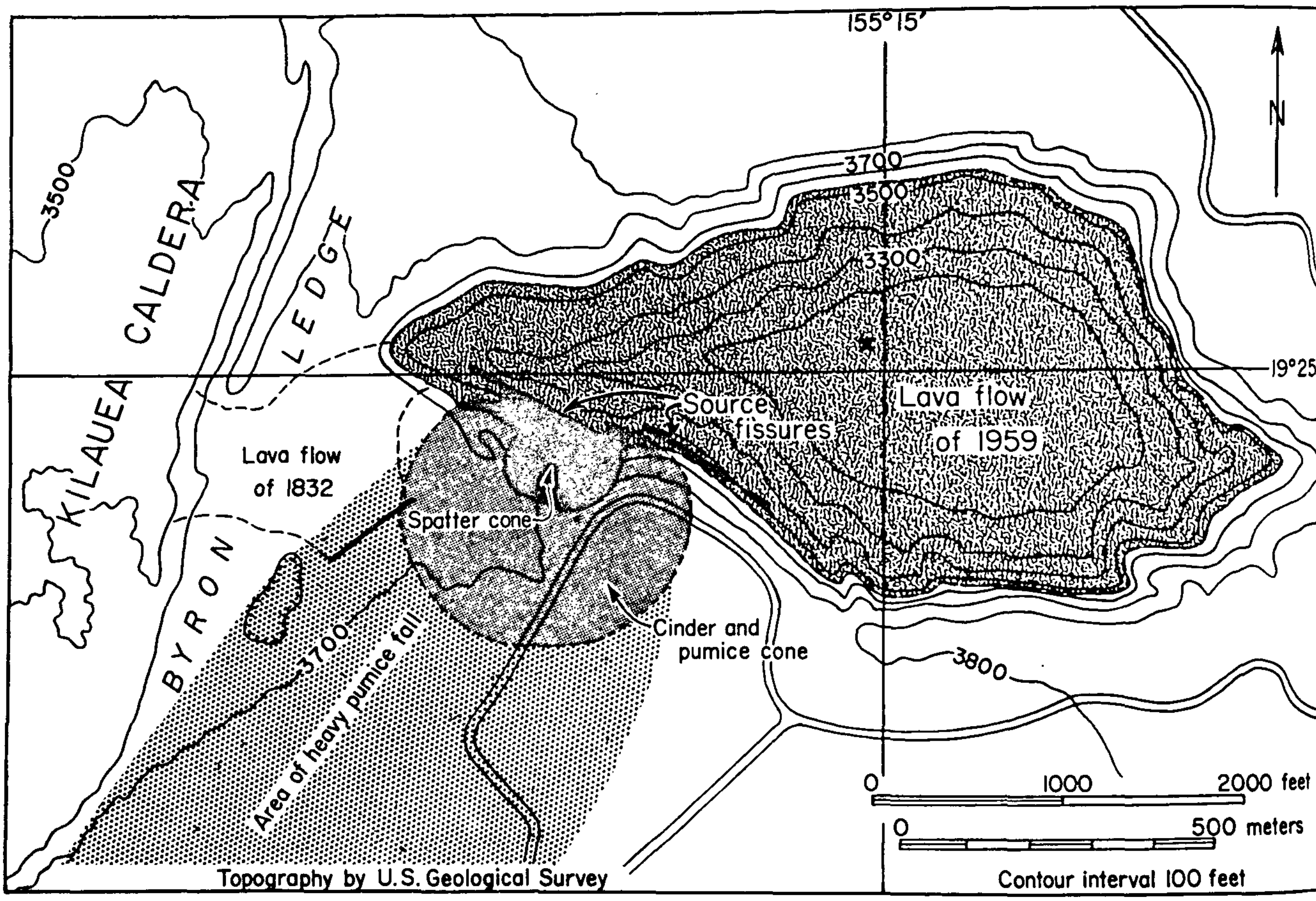


**Figure 2. Kilauea Iki Lava Lake : X marks the drill location (map provided by G. A. Macdonald)**

temperatures exceeding 1 000°C into molten lava (figure 3). The experiment was conducted to obtain knowledge of the problems encountered when drilling into a melt and to obtain as much volcanological data as possible. This paper covers primarily what was learned from the drilling experience.

## Drilling equipment

Part of the experiment was to test the temperature limitations of standard drilling equipment. A Concore type E5 portable core-drilling rig was used because of its flexibility in the field (figure 4). The rig has a manual control screw-fed feature so that the operator can feel possible difficulties developing during drilling; this feature proved quite valuable. An air compressor located on the crater rim was used to supply air circulation. About 1 400 feet of air line connected the compressor to the drill. A cable and winch was used to transport equipment to and from the crater floor. Table 1 lists the drill bits used during the operation.

## Drilling operation

The hole was started with NX core bits drilling a 3-inch-diameter hole, using compressed air to cool the drill tools and remove the cuttings. Several types of bits were tried to determine their effectiveness. At 8 feet the bit size was reduced to AX size, drilling a $1\frac{7}{8}$-inch-diameter hole. This was done to reduce drilling vibration and increase the efficiency of the air coolant. The hole was cored AX size, and then reamed NX size, to 14 feet, to accommodate installation of a 2-inch-diameter casing. The casing was installed to reduce air communication with the hole through cracks in the crust, so that gas samples taken when melt was tapped would not be badly diluted. AX coring bits were used to drill from 14 feet to the final depth of 20 feet.

Air was selected as the coolant medium for two major reasons : (1) to determine the feasibility of using air as a coolant where temperatures exceeded 800°C, and (2) to avoid water contamination of gas samples obtained upon reaching the melt. Drilling with air progressed satisfactorily to a depth of 12 feet (850°C), and with difficulty to 16.8 feet (1 025°C). At that depth, owing to slow drilling progress and excessive damage to the bits, it was decided to use water to cool the hole. (It should be noted that the bits were not specifically designed for air drilling, that air circulation was not optimum since the compressor was located 1 400 feet from the drill rig, and that the fresh basalt rock was extremely hard — about 6 on Mohs' scale — and not friable.) With the drill tools out of the hole,

Table 1. Drill bits used

| No. | Size | Description |
|---|---|---|
| 1. . . . . . . . . . | NX[a] | Homemade Kennametal[b] core bit |
| 2. . . . . . . . . . | NX | Sawtooth Kennametal core bit |
| 3. . . . . . . . . . | NX | Carboloy core bit |
| 4. . . . . . . . . . | NX | Used diamond core bit |
| 5. . . . . . . . . . | NX | Diamond core bit |
| 6. . . . . . . . . . | BX[a] | Rock cutter bit |
| 7. . . . . . . . . . | NX | Hawthorne finger bits |
| 8, 9, 10, 11 . . . . | AX[a] | Homemade Kennametal core bits (figures 6 and 7) |
| 12 . . . . . . . . . | AX | Diamond core bit |
| 13, 14 . . . . . . | AX | Used diamond core bits |
| 15, 16, 17 . . . . . | AX | Hawthorne finger bits |
| 18 . . . . . . . . . | AX | Homemade Kennametal bit, teeth mounted with a Nicoro[c] weld |
| 19 . . . . . . . . . | AX | Special Kennametal bit using a Nicoro weld to mount teeth in a bit blank of 4140 steel (figure 7) |

[a] Outside diameter is 2 15/16 in. for NX bits, 2 5/16 in. for BX bits, and 1 27/32 in. for AX bits.

[b] The Kennametal used for the teeth is an alloy of tungsten, titanium, and carbon with a cobalt binder.

[c] Nicoro is an alloy of 35 per cent gold, 62 per cent copper, and 3 per cent nickel, that was used to vacuum-braze the teeth to the bit blank.

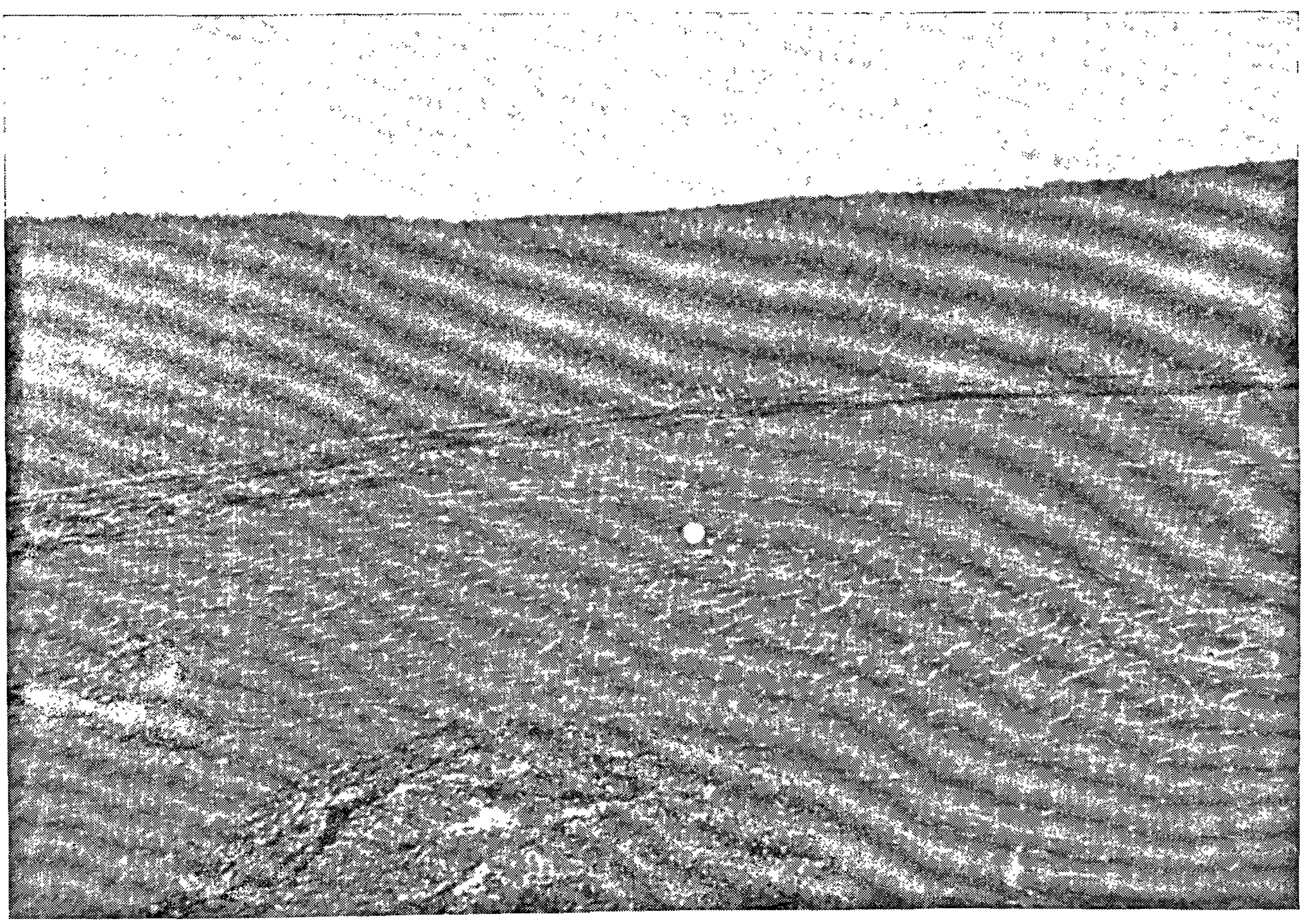

Figure 3. Kilauea Iki Lava Lake: white dot in centre marks the drill location

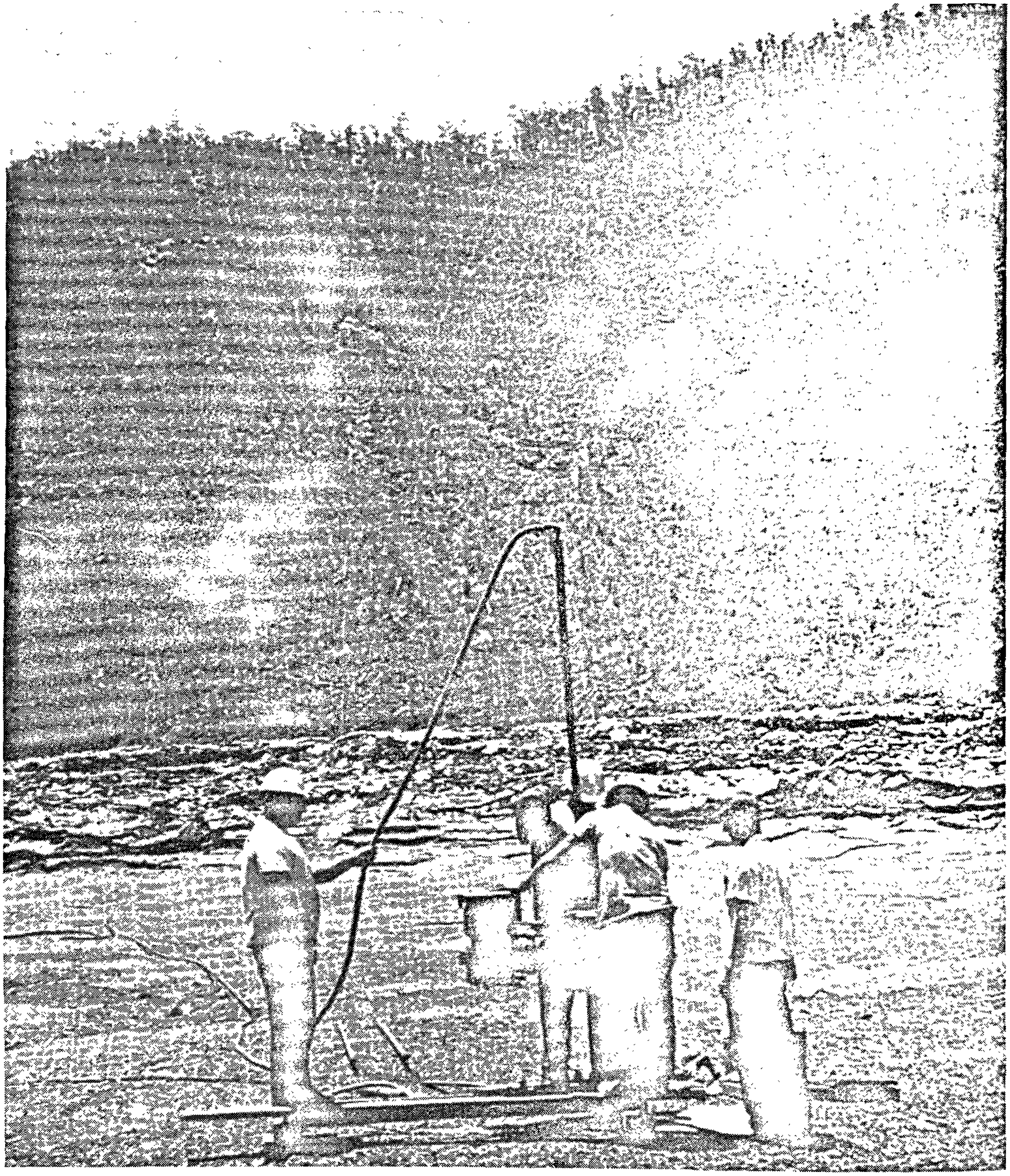

Figure 4. Drill crew and rig on the crater floor

about 5 gallons of water were slowly poured into the hole to cool the rock. The tools were then lowered for drilling, and water was periodically injected into the compressed-air line (figure 5). After 6 or 8 inches of drilling, the cycle was repeated. This air-water vapor coolant worked quite well, and the drilling rate increased from 1.5 feet in 8 hours to one foot per hour. Core recovery was poor, but there was little damage to the drill bit.

The crust-melt boundary was encountered at about 19 feet, and the melt was quite fluid at 20 feet. At 19.1 feet the drilling operator reported a dragging or sticking action at the drill bit, suggesting it was not cutting firm rock. At a depth of 19.5 feet the tools slowly dropped into the hole of their own weight. Apparently the coolant quenched a protective crust around the bit, and as the tools were lowered fresh melt would be exposed and quenched; this formed a protective sheath around the drill tools. The first core of melt was obtained by cutting off coolant circulation, allowing the silver solder around the teeth on the bit to melt so that the teeth could close inward. Circulation of coolant was then restored to quench the melt while pulling the tools. A 2-inch-long core of melt was trapped in the bit and a slight coating of sulfur was deposited on its surface by the outgassing melt (figure 6). Later it was found that samples of melt could be obtained by attaching a "shoe", a tapered cylinder, to the drill rods and driving it into the melt by hand. The core of melt recovered could then be tapped out of the shoe. At 20.4 feet, further removal of melt did not deepen the hole because of the increased fluidity at that depth. Within 48 hours, melt had risen in the hole from a depth of 20.4 feet to a depth of 18.7 feet; a capped stainless steel pipe was therefore installed to receive a thermocouple package to study the cooling history of the crust.

Table 2 is a log of the daily drilling progress. The major drilling problems encountered were excessive chipping and rapid wearing of the Kennametal and Carboloy teeth and shattering of diamond teeth (figure 7). Chipping was partly due to vibration of the small drilling rig when using air circulation for cooling. Much of the damage was due to inadequate removal of heat from the hole by the compressed air coolant, since bit wear greatly decreased, and the drilling rate significantly increased, when water was used to cool the drill string and the hole. Occasionally, circulation ports would clog with core and rock chips; then, from lack of cooling, the diamond teeth would shatter and the silver solder weld for the Kennametal would melt. Progress was also hindered at a depth of 15 feet because threads on the core barrel and drill bits "froze" owing to thermal expansion of the metal. This problem was eliminated by lubricating the threads with powdered graphite.

As was previously noted, this drilling was conducted as an experiment to learn the difficulties in drilling very hot rock. With improved selection of drilling equipment it is probable that air drilling would work satisfactorily to 1 000°C with standard drilling equipment. The drill rig should be larger than the one used, the air compressor should be close to the rig, and bits specially designed for optimum air circulation should be used. Water could be used as a drilling fluid (in place of the air-water vapour system) if the rig were equipped with a packer on the exhaust to divert the steam or hot water produced and to trap the drill cuttings.

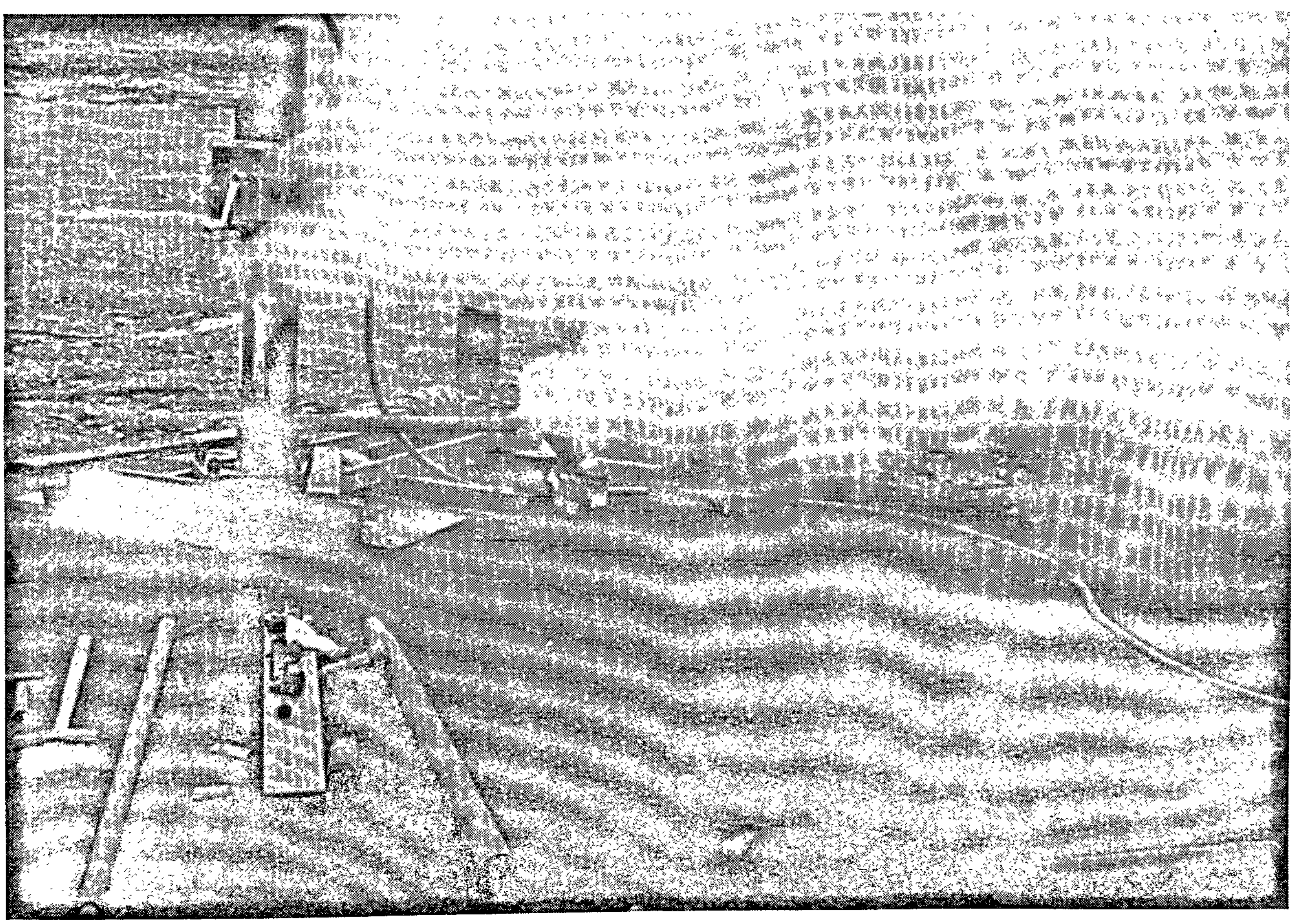

Figure 5. Steam produced by drilling with air-water vapour as the coolant

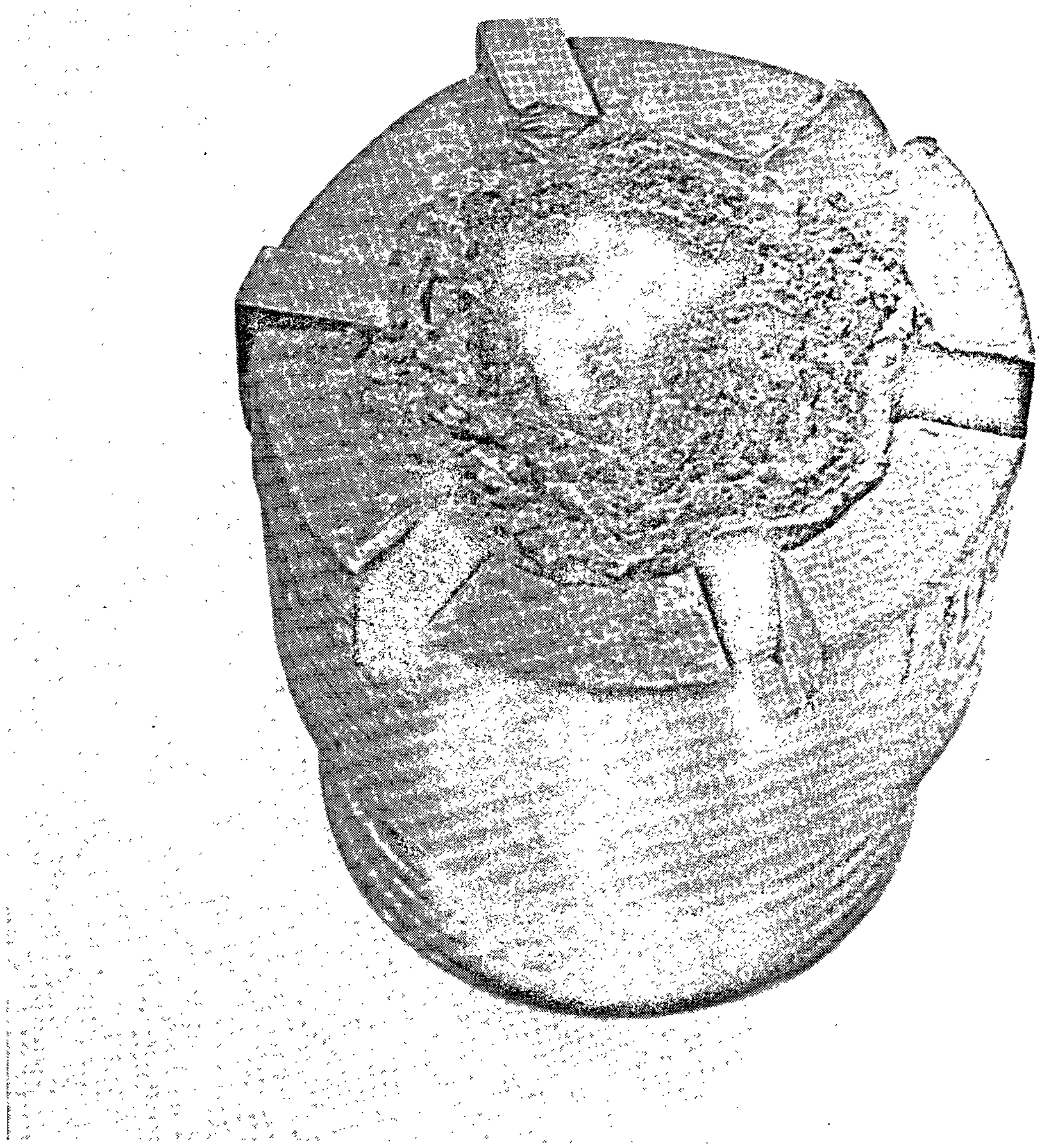

**Figure 6. A sample of molten lava trapped and quenched in drill bit No. 11 (note the lack of wear or chipping of the teeth remaining in the bit)**

## Power generation implications

The Kilauea Iki lava lake is a significant energy source, containing about $2 \times 10^9$ kilowatt-hours of recoverable power, according to the estimates of Kennedy and Griggs.[1] This drilling experiment demonstrates that conventional equipment can drill into molten rock, enabling possible testing of power recovery schemes. As indicated by Kennedy and Griggs, some of the properties of the melt that should be known to evaluate power recovery schemes are: (*a*) the gas content and composition, (*b*) the viscosity of the melt at different temperatures and degrees of solidification, (*c*) the thermal profile deep into the melt, and (*d*) the heat released as a function of viscosity and the degree of solidification of the melt. It is the opinion of the authors that properly designed experimental pipes could be pushed into

[1] Kennedy, G. C. and Griggs, D. T., Power Recovery from the Kilauea Iki Lava Pool, Rand Report No. RM-2696-AEC, dated 12 December 1960, Rand Corporation, Santa Monica, California. See appendix for a condensation of this paper.

the molten lava and later recovered, making possible the determination of many of the above properties of the lava. Difficulties would be encountered in the selection of materials to withstand temperatures up to 1 250°C with the associated corrosion problems, and in the possibility of equipment becoming bound in the melt by strong convection currents or an excessive build-up of lava on the pipes. Certainly a thermocouple package could be pushed deep into the lake, and melt samples could be obtained from various depths. Schemes for obtaining viscosity measurements and undiluted gas samples are being designed with the hope that they can be tested at some future date.

While the filling of a natural depression with lava is an occurrence that would rarely be expected throughout the world, it is not beyond conception that specially engineered craters could be constructed to trap the outflow of lava along known rift zones in active volcanic areas. The lava basins could be located around a central generation station and, in a sufficiently active region, could supply continuous power. Kennedy and Griggs estimate the natural cooling time of the Kilauea Iki pool to be in excess of 75 years.

## Thermal measurements

Figure 8, showing the thermal profile in the hole, is a plot of the most reliable temperature measurements. The peak temperature of 1 064°C, obtained with an optical pyrometer, is probably a little low because of gases emanating from the melt. Before melt was encountered, there was close agreement between the optical pyrometer and thermocouple measurements. The melt-crust contact in figure 8 is where the rock became noticeably fluid. Microscopic examination of core from a depth of 19.7 feet shows that the "melt" was 60 per cent crystalline. The remaining 40 per cent was glass formed by quenching the liquid portion of the lava.

Obtaining reliable temperature readings from a drill hole at temperatures in excess of 1 000°C proved more difficult than had been anticipated. At first, 20-gauge Chromel-Alumel thermocouples with a high-temperature silica fabric insulation were tried but were found unsatisfactory once heated. Ceramic insulators were then used with 40-gauge Chromel-Alumel wires, but again the wires broke or shorted owing to twisting and differential expansion between the wires and the insulators. Platinum-platinum 90 per cent, rhodium 10 per cent thermocouples were obtained and installed in ceramic insulators, and similar problems occurred with the long lengths. Several readings were obtained that showed no indication of failure, and these are used to define the thermal profile through the crust. The final thermocouple package installed in the hole to follow the cooling history of the crust consists of platinum-platinum 90 per cent, rhodium 10 per cent thermocouples with ceramic insulators. The thermocouple measuring the bottom hole temperature was installed in a $\frac{1}{8}$-inch stainless steel tube closed at the bottom.

**Table 2. Daily log of drilling activity**

| *Date (July 1960)* | *Footage drilled* | *Core recovery (per cent)* | *Bits used* [a] | *Remarks* |
|---|---|---|---|---|
| 19 . . | 0-8 ft | ~30 | 1,2,3,4 | Several bits were tried, to see if core recovery would improve. Bits suffered some chipping |
| 20 . . | 8-13.9 ft hole reamed 8.5-11.9 ft | ~2 plus chips | 1,2,3,4, 5,7,8,9,13 | Several bits were again tried to obtain core. AX bits were used to drill, and the hole was reamed with NX bits. Bits were thermally damaged when circulation was impaired |
| 21 . . | Hole reamed 11.9-13.9 ft and NX drilled to 14 ft | 0 plus chips | 6,2 | A 2-inch casing was installed to depth, grouted with a refractory cement near the bottom and ordinary cement at the top |
| 22 . . | 14-15.5 ft | ~5 plus chips | 18,5,10 | The Nicoro weld withstood the heat but silver solder melted, losing the teeth to the hole |
| 23 . . | 15-16.8 ft | ~10 plus chips | 15,19,14,16 | Hawthorne finger bits were tried with no success. The mal-expansion of tools and severe chipping of teeth caused considerable delay |
| 25 . . | 16.8-20 ft | 0 plus chips | 11,12 | Air-water vapour circulation was used, drilled into melt and sampled. Bit No. 12 was tried only to attempt retrieving some core |

[a] See table 1.

Table 3. Preliminary gas analyses [a]

| | *Sample No. 3* [b] | *Sample No. 4* [b] | *Local air* [c] |
|---|---|---|---|
| $N_2$ | 73.3 | 61.9 | 77.82 |
| $H_2O$ | 17.7 | 30.9 | 0.86 |
| $H_2$ | 5.3 | 5.4 | 0.04 |
| Ar | 1.0 | 0.8 | 0.86 |
| $O_2$ | 0.16 | 0.7 | 20.31 |
| $CO_2$ | 1.0 | 0.3 | 0.11 |
| $SO_2$ | trace | trace | — |

[a] Analysts: R. W. Crawford and C. J. Dooley, Lawrence Radiation Laboratory, Livermore, California.

[b] Results given in volume or mole per cent; water was determined by weight; other gases were determined by volume and pressure measurements and by mass spectroscopy.

[c] Local air collected at the drilling location and analysed by mass spectroscopy.

The space between the insulated wires and the tubing was filled with powdered aluminium oxide. Two shorter thermocouples were attached to the outside of this tube, and the whole package was lowered into the stainless steel receiving pipe already installed in the hole. Commercially available Chromel-Alumel or platinum-platinum/rhodium thermocouples in ceramic insulation surrounded by Inconel sheathing would probably work satisfactorily.

## Gas analyses

After the drill penetrated the melt, a series of gas samples was taken into 34-litre stainless steel tanks. The tanks were connected to a stainless steel pipe extending to the bottom of the hole. The hole was sealed to the sampling pipe with Duxseal, an asbestos-base plastic sealing compound, to prevent air leakage into the system. A vacuum pump pulled

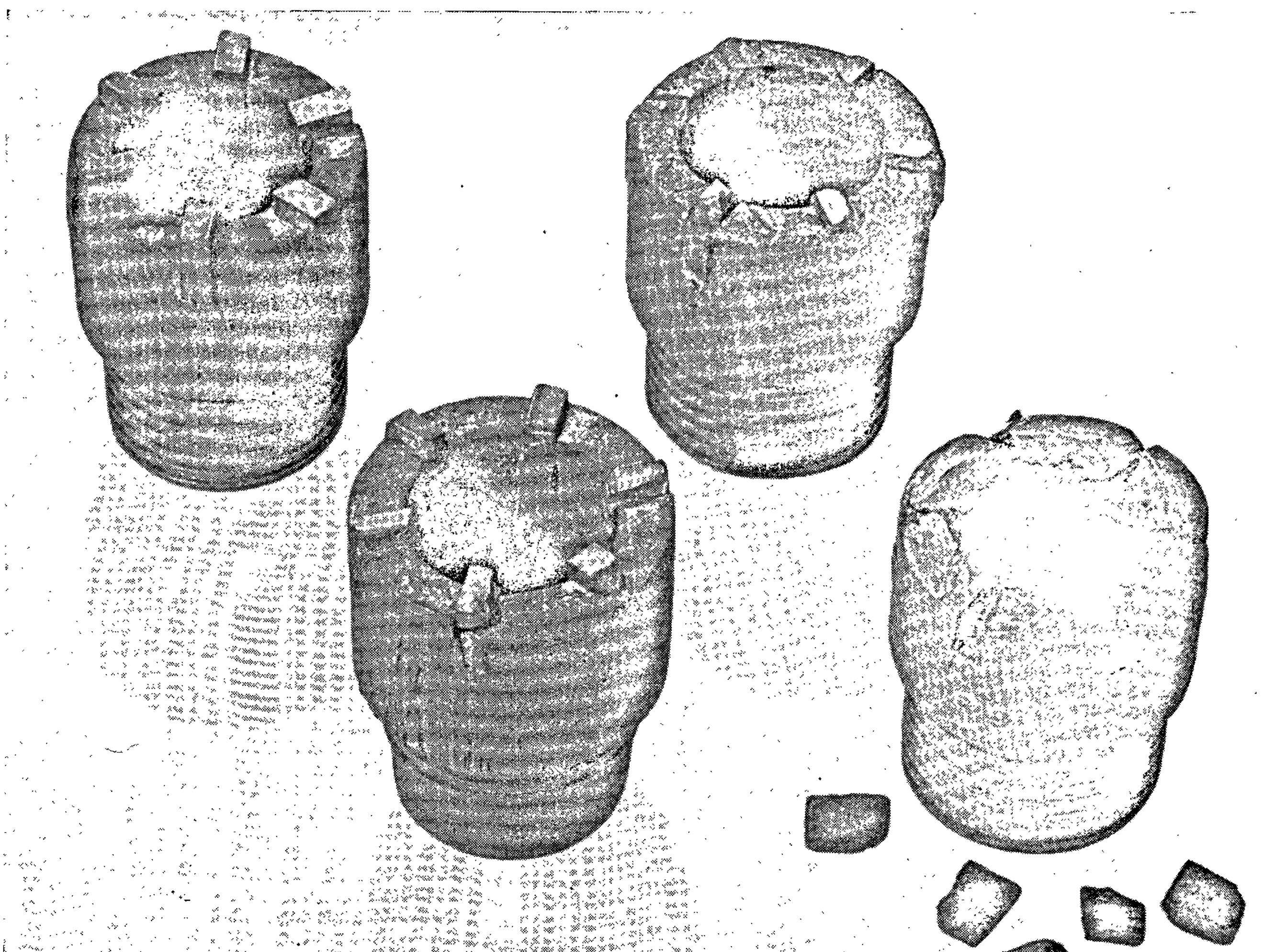

Figure 7. AX Kennametal core bits showing varying degrees of damage. In order from rear to front and from left to right: bits Nos. 8, 9, 19 and 10

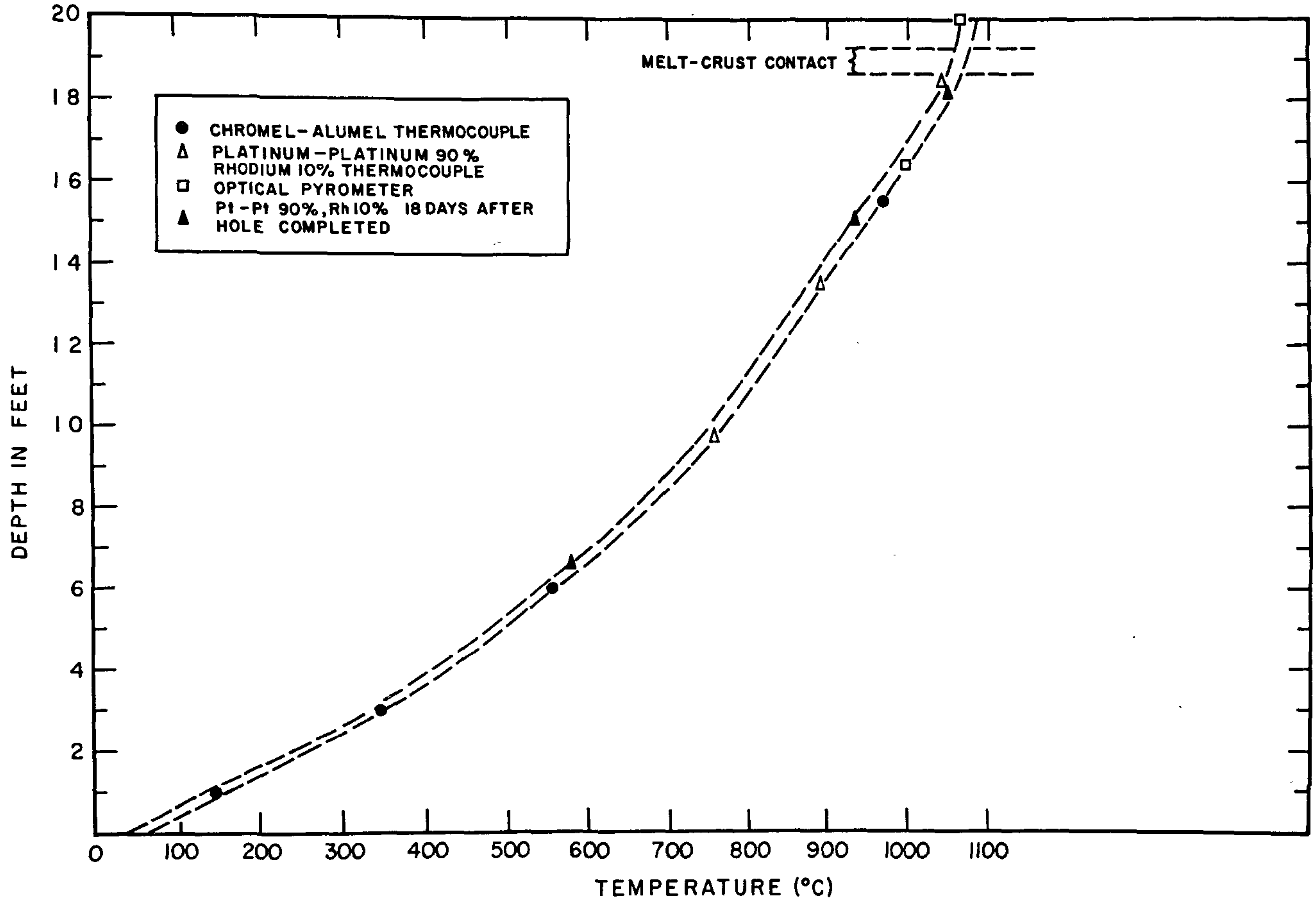


Figure 8. Temperature profile through the crust of the Kilauea Iki Lava Lake (the parallel dash lines indicate the spread of the data)

Table 4. Chemical analyses of crust and melt samples from drill hole in Kilauea Iki crater[a]
*(per cent)*

| | *1* | *2* | *3* | *4* | *5* | *6* |
|---|---|---|---|---|---|---|
| $SiO_2$ | 46.77 | 46.99 | 44.58 | 47.24 | 48.25 | 48.43 |
| $TiO_2$ | 2.28 | 2.24 | 1.73 | 2.20 | 2.52 | 2.98 |
| $Al_2O_3$ | 12.04 | 12.14 | 9.25 | 11.14 | 12.90 | 13.00 |
| $Fe_2O_3$ | 1.72 | 2.55 | 1.27 | 1.41 | 1.78 | 1.32 |
| FeO | 9.95 | 9.19 | 10.76 | 10.22 | 9.88 | 11.25 |
| MnO | 0.18 | 0.18 | 0.18 | 0.16 | 0.18 | 0.18 |
| MgO | 14.85 | 14.33 | 23.46 | 15.66 | 11.39 | 9.39 |
| CaO | 9.89 | 9.90 | 7.18 | 9.56 | 10.38 | 10.03 |
| $Na_2O$ | 1.53 | 1.51 | 1.10 | 1.53 | 1.75 | 2.10 |
| $K_2O$ | 0.38 | 0.40 | 0.29 | 0.39 | 0.45 | 0.60 |
| $H_2O+$ | 0.04 | 0.06 | 0.04 | 0.14 | 0.07 | 0.25 |
| $H_2O-$ | 0.19 | 0.28 | 0.10 | 0.23 | 0.35 | 0.04 |
| $P_2O_5$ | 0.24 | 0.25 | 0.19 | 0.15 | 0.28 | 0.32 |
| TOTAL (per cent) | 100.06 | 100.02 | 100.13 | 100.03 | 100.18 | 99.89 |

NOTES:
1-Depth 0 feet. A 2-cm surface crust (not core). Olivine-rich basalt.
2-Depth 4 feet. Core. Olivine-rich basalt.
3-Depth 7.5 feet. Core. Picrite-basalt (oceanite).
4-Depth 13.9 feet. Core. Olivine-rich basalt.
5-Depth 16.2-16.8 feet. Core. Olivine basalt.
6-Depth 20 feet. Melt core. Glassy basalt with a little olivine.
[a] Analyst: Takashi Katsura; results furnished by G. A. Macdonald.

**Table 5. Corrosion rates of test specimens immersed in molten lava and exposed to air at 1 300°C[a]**

| *Test specimens* | *Corrosion in lava (inches per year)* | *Corrosion in air (inches per year)* |
|---|---|---|
| Stainless steel (type 304) | 2.6 | 18 |
| Stainless steel (type 316) | 1.7 | 18 |
| Hot rolled steel | 10.0 | > 60 |
| Cold rolled steel | 22.0 | > 100 |
| Inconel | 3.0 | 5.4 |
| Hastelloy R-235 | 2.6 | 9.4 |

[a] Studies performed by R. L. Olson, Lawrence Radiation Laboratory, Livermore, California.

on the system for about 30 seconds to flush out air in the hole and raise the gas concentration for sampling. Results of two samples taken in sequence are shown in table 3. No corrections have been made for contamination.

An analysis of the rare gas fraction[2] indicates that the nitrogen and argon are primarily due to recent air contamination. This argon is distinctly not radiogenic. Air contamination probably occurred when the melt contacted air during eruption or possibly as the melt was en route to the surface. Much of the air's oxygen was taken up by the oxygen-deficient melt. The relatively low oxygen content with respect to nitrogen and argon and the constant nitrogen-argon ratio with varying amounts of oxygen indicate that most of the air contamination did not occur during sampling or analysing. The water content in these samples is low because of condensation in the pipe before entry into the tank. The hydrogen content is higher than previously reported in volcanic gas analyses, and it is not certain whether or not some hydrogen was released by water reacting with the stainless steel sampling equipment.

The rather high hydrogen content in the gas and the high ratio of FeO to $Fe_2O_3$ in the melt make for rather strong reducing conditions with respect to oxygen or water (table 4). This might retard corrosion by oxide formation. Analyses for various sulfur and halogen compounds are not complete; therefore comments about corrosion by these gases cannot be made.

## Corrosion studies

A few simple corrosion experiments were performed as part of the design of equipment for measuring viscosity and temperature in the melt.

[2] Wasserburg, G. J., private communication.

Corrosion effects were observed on several metal strips partly immersed in molten lava for 90 minutes at 1 300°C (dry Kilauea Iki basalt becomes completely molten at about 1 230°C). The upper portion of the metal strips was left exposed to air. The corrosion rates were estimated by comparing both the immersed and the air-exposed samples for weight loss and appearance with corroded specimens of the same metals having previously determined corrosion rates (table 5). Type 316 stainless steel, type 304 stainless steel, Hastelloy R-235, and Inconel have maximum corrosion rates of 1.5 to 3 inches per year where the metal is immersed in molten lava. It is notable that in every case air attack at 1 300°C was significantly greater than melt attack. Considering the expected reducing conditions of both the melt and the gas at field operation temperatures of less than 1 200°C, the corrosion rates determined in the laboratory are probably higher than would be met in the field.

The most serious corrosion would probably be caused by the action of high temperature steam on pipes; however, steam corrosion is not expected to be so severe as to prohibit testing of power recovery schemes. The injection of small amounts of a reducing agent, such as hydrogen gas, could further reduce corrosion.

## Acknowledgements

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# Appendix

## Condensation of report[3] "Power recovery from the Kilauea Iki lava pool"

*by George C. Kennedy and David T. Griggs, University of California, Los Angeles, California*

The lava pool created by the eruption of Kilauea Iki in 1959 contains nearly 100 million tons of molten lava. This presents a unique opportunity to learn how to make industrial use of sub-surface pools of molten rock such as those that might be formed by deep underground nuclear explosions or from underground magma reservoirs that might exist in active volcanic regions. This report proposes scientific probing of the Kilauea Iki lava pool and suggests some potential methods of electric power production.

The Kilauea Iki pool is estimated to contain $3 \times 10^{16}$ calories. To melt such a quantity of rock with a nuclear explosion would require about 100 megatons yield. If only the latent heat of fusion were recovered ($0.75 \times 10^{16}$ cal) and converted to electricity at a thermal efficiency of 25 per cent, this would yield $2 \times 10^9$ kilowatt hours. At 5 mills per kWh, this would have a value of $10 million. It is thus clear that the Kilauea Iki lava pool and similar sized molten rock bodies represent significant natural resources.

In order to assess fully the feasibility of the various possible schemes of power recovery, it is necessary to know some properties of the lava pool. The gas content and composition must be known so that its corrosive effect may be properly assessed. The present degree of solidification of the lava must be ascertained; and the heat released, as solidification proceeds, should be determined as a function of degree of solidification and viscosity of the mix.

Three general methods of power recovery are considered. The first is drilling a lattice of cased holes which are used as counter-current-flow heat exchangers to heat fluids pumped in through a central coaxial pipe and collected from the exterior region of the same pipe. The second is bubbling water from the lower end of a pipe inserted to the bottom of the lava pool and tapping steam which will collect nearby under the crust. The third is the formation of a thin horizontal bubble over the whole top of the pool under the crust, with central injection of water and peripheral collection of steam.

Each method is considered as though it were used to recover heat from the whole lava pool. It is assumed in each case that the volume of an elliptical cylinder $800 \times 500 \times 100$ m can be processed ($3.1 \times 10^7$ m$^3$, or $8 \times 10^7$ metric tons). Since the time for natural solidification is 75 years, the time to process this volume must be much less than 75 years. It will be arbitrarily assumed that all the available heat is recovered in 10 years, at a constant power level.

The total heat in $8 \times 10^7$ tons at 1100°C is about $3 \times 10^{16}$ cal' $1.3 \times 10^{17}$ joules, $4 \times 10^{10}$ kWh, or $4 \times 10^6$ kilowatt years. The latent heat to freezing is 1/4 of this (100 cal/gm) or $10^6$ kWy, from which electrical power at 25 per cent efficiency could be produced at an average rate of 25 000 kW for 10 years. If the heat could be removed from all this lava in such a way as to cool it down to an average temperature of 700°C (giving final working fluid temperatures of about 500°C), then one could recover about 200 cal/gm, or twice the above power. The installed power capacity of a power-station is usually about four times the average power, so that this lava pool would operate a 100 000 kW plant for 10-20 years at the normal duty cycle. This is sufficient power for 200 000 people at the Los Angeles rate of consumption.

### The water-tube boiler

In this method of power recovery, gas-tight tubes would be inserted vertically through the crust to the bottom of the lava pool. Water would be pumped in through a small internal pipe, would be heated by conduction through the wall of the tube, and the steam would be piped from the top of the tube to the turbine. As heat is removed, lava is solidified around the outside of the tube so that further heat must be transmitted by thermal conduction through this solid concentric shell. The poor thermal conductivity of solid basalt is the major limiting factor in this method. It would be necessary to install a lattice of such tubes. A reasonable compromise of ideal heat recovery with the installation expense requires that tubes be spaced every 10.7 m (67 ft centre-to-centre spacing). The cost of the tubes alone is estimated to be several million dollars. In addition, there would be large costs in surface piping, valving, manifolding, etc. This scheme is therefore considered to be uneconomical.

Despite this apparent drawback, this scheme is subject to less uncertainties than either of the other two presented, and lends itself to easy testing and more certain cost-analysis. It is perhaps worthwhile to make a more thorough engineering study of feasibility and cost.

### The bubbler

In this method of power recovery, it is proposed to sink a pipe at the centre of the lake to a point near the bottom. Liquid water is pumped down the pipe and bubbles up through the molten lava, collecting in a large bubble under the crust which is then tapped for highly superheated process steam. It is hoped that this bubbling process will stir and promote convection in the whole lake and thus extract from one input and one output hole the latent heat of freezing of the whole lava pool.

The pressure of the output steam will be that due to the crust — approximately 1.75 bars. The temperature will be somewhat lower than that of the molten lava — approximately 1000°C. The pressure of the input water will be slightly greater than the hydrostatic head of the lava — 20 bars at a depth of 75 m.

The process of bubble formation will be a complex combination of the effects of heat flow into the water, surface tension, buoyancy, and hydrodynamic instability. We have as yet been unable to make a meaningful analysis of this process.

We believe that the easiest way to test this is to install a bubble tube and pump water at the full design rate (100 kg/sec) for a substantial period to observe its behaviour. It would be desirable to form a collecting chamber first, by injection of air below the crust, and to install full-size vent lines with appropriate valves to handle the steam which will collect in this chamber as water is pumped down the long central pipe. Monitoring of the steam pressure fluctuations and temperature will give considerable evidence as to what is happening. Pulses of water injection will show time of rise and degree of vapourization and superheat as a function of the quantity of water injected at each pulse.

Other difficulties which have not been anticipated may occur in the actual bubbler, but it looks promising to us — sufficient

[3] Condensed from Rand Research Corporation report No. RM-2696-AEC, with the above title, Kennedy and Griggs, 12 Dec. 1960. This condensation was written by the D. E. Rawson and G. H. Higgins of the Lawrence Radiation Laboratory to emphasize the points of interest in the paper and does not necessarily represent the opinions or emphasis of Kennedy and Griggs.

to warrant experimental tests up to the full rate of flow for a short period, like a week.

### The pancake

In the pancake method, it is proposed to inject water or gaseous working fluid through a central pipe just below the crust. This will form a thin horizontal bubble at the pressure of the overburden (1.75 bars), which will expand as more water is injected until it covers the whole surface of the molten lava pool. Peripheral pipes will be emplaced to tap this bubble and remove the hot gas.

It is clear immediately that the pancake is a permutation of the bubbler configuration, for if steam is not rapidly withdrawn from the bubbler, a pancake of steam underneath the lava crust should form. Partial crystallization will thus take place at the top of the lava pool underneath the steam bubble and underneath the crust. As a result of the 10 per cent difference in density upon freezing the lava, we suspect that the cooled and partially frozen melt underneath the pancake will founder and sink to the bottom of the pool, presenting a continuous new surface of hot melt from which energy can be extracted.

Care must be taken in the initial generation of the bubble underneath the lava crust. Slow initial injection of air would develop a bubble under the viscous layer next to the solid crust. This viscous layer will seal any fractures that might develop in the crust and, if the gas flow continues, will freeze to form a strong container. Surface surveys to measure doming of the crust would show the thickness of the bubble at every point at any time. Questions of this sort could readily be answered by a small-scale experiment.

### Scientific implications

Not only would the testing of power recovery schemes at Kilauea Iki lava pool be of immediate engineering importance but a large number of important scientific results could be obtained from an experiment. Volcanology is a very primitive science; it has made few advances over the last few decades. We do not have sufficient knowledge about such facts as the viscosity of lava in a pool, the precise temperatures of lava, the primordial gas content, and we know little about the temperature interval over which crystallization in a lava pool takes place. Knowledge of the viscosity of basaltic melt would allow us to evaluate certain petrogenetic theories.

Volatile-free lava, of composition similar to that of the Kilauea Iki lava pool, melts in the laboratory at approximately 1200°C. The lava pool at Kilauea Iki is probably somewhat under this temperature owing to the effect of volatiles on depressing the freezing point of the lava. Knowledge of the true temperature of this lava pool would allow us to estimate the volatile content of the melt.

Basaltic lavas of this composition are believed to be *de novo* samples of material from the deep interior of the earth, coming from depths of about 200-400 kilometres. The gases they contain might either be primitive gases evolved for the first time to the surface of the earth, as new additions to our atmosphere and hydrosphere, or they may be gases acquired by the lava and distilled into the column of melt during its journey to the surface of the earth. Careful collection and analysis of the gases associated with this lava would go far towards answering some of the problems connected with the origin of the atmosphere and hydrosphere as well as the bulk composition of the earth. Extremely pertinent information could be obtained on the matter of chemical differentiation of rock melts by observing the temperature interval over which the lava pool freezes and the sequence of solid phases that appear as crystallization continues. Precise knowledge of thermal gradients and thermal history might afford clues as to the effect of radiative transfer of heat to the melt. Insight into the heat conduction mechanism could be obtained.

### Geothermal power implications

Assuming that power from molten lava could be proven to be economically converted to electrical power at Kilauea Iki, what are the long-range power implications? Kilauea volcano erupts every few years and its mean annual production is around 100 million cubic yards of melt. These eruptions are localized along the three main fractures that radiate out from the central part of the volcanic edifice. It seems extremely likely that reservoirs of molten rock are present between eruptions high in the volcanic edifice. A drilling programme to locate and explore the dimensions of these reservoirs of molten rock and the conduits leading to the main fracture zones would be of extreme pertinence. It seems within the realms of possibility that when these chambers or fingers of melt, standing high in the volcanic edifice, are located, the appropriate outlet and inlet tubes could be placed and power produced from the melt in the main volcano itself. One hundred million cubic yards of melt that flow out on an average yearly basis represent the excess energy escaping to the surface in this spot. It seems likely that if we could extract energy equivalent to this amount of molten rock on an annual basis, we might extensively lengthen or even stop the pattern of regular eruptions at Kilanea. These eruptions cause on an average many millions of dollars of damage per year owing to the fact that the ash and lava flood human habitations and destroy agricultural land. If such an objective could be achieved, we would have converted one of the hazards of mankind into a valuable natural resource. Similar reasoning may apply to other active volcanic regions.

## *Summary*

The November 1959 eruption at Kilauea Iki, Hawaii, produced a lava lake over 300 feet deep in the volcanic crater; it contained about 100 million metric tons of molten lava. This near-surface occurrence of naturally produced molten rock offers a unique opportunity for studying very hot underground energy sources. The Lawrence Radiation Laboratory participating in the Plowshare programme (the peaceful uses of atomic energy) conducted this drilling experiment into molten rock.[4] The knowledge gained is valuable to the engineering of equipment to study and to recover power from molten rock that might be formed by deep underground nuclear explosions or surface lava flows that might be trapped in man-made craters. The objectives of the experiment were to obtain knowledge of the drilling problems encountered while probing into hot and even molten lava; and, if drilling was successfully completed into the melt, to obtain samples and to study the thermal environment of interest to volcanology and to power recovery studies.

After drilling only nineteen feet, the crust of the

[4] This work was under the auspices of the United States Atomic Energy Commission.

lake was pierced; it was then possible to make temperature measurements in the melt and to collect samples of the molten lava and gases.

Completion of the experiment clearly demonstrated the feasibility of drilling into hard rock formations at temperatures up to 850°C, using standard core-drilling equipment and compressed air to cool the drilling tools and remove the cuttings. Using a mixture of water and air as the coolant, it is possible to drill with standard equipment into rock at temperatures exceeding 1 050°C. The major drilling problems encountered were: (1) excessive chipping and wearing of the bits resulting from the hardness of the material, high temperatures encountered in the hole, and vibration of the small drill rig due to use of air as the coolant; (2) inadequate compressed air circulation to remove heat properly when temperatures exceeded 850°C; and (3) binding of threads on the drill string owing to thermal expansion and contraction of the couplings. Binding of the threads on the drill string was overcome by use of powdered graphite as a lubricant for the couplings. Selection of more suitable drilling equipment (drill rig, bits, and air supply) would help overcome the vibration and heat problems.

The Kilauea Iki lava lake is a significant energy source, estimated to contain about $2 \times 10^9$ kilowatt-hours of recoverable energy. The drilling experience indicates that pipes could be pushed deep into the fluid melt, making it possible to field test power generation schemes and to measure many of the melt properties. Difficulties would be encountered in the selection of materials to withstand corrosion at temperatures up to 1 250°C and in the possibility of equipment becoming bound in the melt owing to strong convection currents or excessive build-up of viscous lava on the pipes. A few simple corrosion experiments were performed to aid the design of equipment for measuring various properties of molten lava and equipment for testing power recovery schemes. On the various metals tested, air attack was more severe than melt attack. The most serious problems would apparently be from the attack of steam on pipes at such high temperatures.

## RÉSULTATS DES FORAGES EXÉCUTÉS AU LAC DE LAVE DE KILAUEA IKI DANS L'ÉTAT D'HAWAII

## POSSIBILITÉS DE PRODUCTION D'ÉNERGIE RESSORTANT DE CES TRAVAUX

### *Résumé*

L'éruption de 1959 à Kilauea Iki (État d'Hawaii) [États-Unis] a formé, dans le cratère du volcan, un lac de lave ayant plus de 300 pieds (91 m) de profondeur et constitué par une centaine de millions de tonnes métriques de lave fondue. Cette formation naturelle de roche fondue à peu de distance de la surface terrestre offre une occasion unique d'étudier une source d'énergie souterraine à très haute température. Le Lawrence Radiation Laboratory a exécuté cette expérience de forage dans la roche en fusion au titre du programme « Plowshare » (utilisation de l'énergie atomique à des fins pacifiques)[4]. Les enseignements tirés de cette expérience seront utiles aux ingénieurs qui mettent au point le matériel destiné à l'étude et à la récupération de l'énergie contenue dans la roche en fusion qui pourrait être créée par des explosions nucléaires souterraines à grande profondeur ou dans des flux de lave en surface qui pourraient être captés dans des cratères artificiels. L'objet de cette expérience était de recueillir des données sur les problèmes de forage rencontrés dans les sondages des masses de lave chaude, voire en fusion, et, si le forage pouvait être mené à bonne fin — c'est-à-dire jusqu'à la masse en fusion — de prélever des échantillons et d'étudier le milieu thermique qui présente de l'intérêt pour la volcanologie et les études sur la récupération de l'énergie.

On traversa la croûte du lac en moins de 6 mètres (19 pieds). On se trouva alors en mesure de déterminer la température de la masse en fusion et de prélever des échantillons de lave fondue et de gaz.

En menant cette expérience à bien, on a démontré de façon probante que l'on peut foncer des puits dans des formations de roche dure à des températures allant jusqu'à 850 °C, en se servant de matériel de forage à carottage ordinaire et d'air comprimé pour refroidir les forets et chasser les débris. En employant un mélange d'eau et d'air pour le refroidissement, on peut forer avec du matériel standard dans des roches dont la température dépasse 1 050 °C. Les principaux problèmes auxquels on se heurta furent les suivants : 1) ébréchages et usure excessifs des forets en raison de la dureté du matériau traversé, des températures élevées trouvées dans le trou de sonde et des vibrations de la petite installation employée, causées par l'emploi de l'air comme fluide de refroidissement; 2) insuffisance du courant d'air comprimé pour éliminer convenablement la chaleur aux températures dépassant 850 °C; 3) coincement des filetages de la ligne de forage en raison des phénomènes de dilatation et de contraction des raccords causés par les variations de température. On surmonta ce problème en se servant de graphite en poudre comme lubrifiant pour les raccords.

[4] Ce projet a été exécuté sous les auspices de la Commission de l'énergie atomique des États-Unis.

Le choix d'un matériel de forage plus approprié (installation, forets et source d'air) aiderait à résoudre les problèmes tels que la vibration et l'échauffement.

Le lac de lave de Kilauea Iki représente une importante source d'énergie, évaluée à quelque 2 milliards de kWh récupérables. Les travaux de sondage qui viennent d'être décrits indiquent qu'il serait possible de foncer des tuyaux dans la profondeur de la masse fondue liquide, permettant de soumettre certains projets de production d'énergie à des essais sur place et de mesurer nombre des propriétés de cette masse en fusion. On se heurterait à des difficultés tenant au choix de matériaux capables de résister à la corrosion à des températures allant jusqu'à 1 250 °C et à la possibilité d'un coincement du matériel dans la masse fondue en raison de l'existence de forts courants de convection ou d'une accumulation exagérée de lave visqueuse sur les tuyaux. Certaines expériences simples de corrosion ont été exécutées pour aider à la mise au point de matériel devant servir à mesurer diverses propriétés de la lave en fusion et à évaluer quelques-unes des caractéristiques du matériel d'essai destiné à des programmes de récupération d'énergie. Pour les divers métaux soumis à l'essai, l'attaque par l'air a été plus grave que celle provoquée par la masse en fusion. Les plus graves des problèmes sembleraient avoir trait à l'attaque des tuyaux par la vapeur à ces températures exceptionnellement élevées.

# CHEMICAL ANALYSIS AND LABORATORY REQUIREMENTS: EXPERIENCE IN NEW ZEALAND'S HYDROTHERMAL AREAS

*J. A. Ritchie**

Though the most valuable property of a geothermal energy resource, the heat, cannot be assayed by the chemist, its chemical concomitants are of considerable interest. Discovery of their amount and relationships in naturally occurring thermal fluids can give valuable information about the origin and movement of those fluids and the heat they carry. Thus, the chemist has a valuable contribution to make in prospection, assessment and development of such a power resource.

Thermal waters are usually classified in terms of the ions which preponderate in them (1), but classification, involving determination of pH, chloride, sulphate, bicarbonate, sodium and calcium, is not enough — unless it be to reject certain types as not worth analysing further for the present purpose. Owing to the secondary origin of acid sulphate waters, for example, the relations of the ions in them give no useful information about the source of the heat. In fact, only waters carrying chloride ions are considered to merit fuller analysis. In addition to the ions already mentioned, potassium, lithium, ammonium, magnesium, fluoride, boric acid, silica and arsenic are of value in the prospecting stage. Others which have proved of interest in New Zealand include bromide, iodide, rubidium, caesium antimony and polythionates.

Fumarole exhalations, and gases from springs, are also of interest. Samples of these are analysed for carbon dioxide, hydrogen sulphide, hydrogen, methane and nitrogen; ammonia, boric acid and fluoride are determined in the condensates.

The sampling of springs and fumaroles and of drill-holes is dealt with in other papers (2, 3). Here it is stressed that taking a sample for analysis may properly be regarded as the first step, and perhaps a crucial one, in the analysis. It is therefore a concern of the chemist and should be under his control.

The main desiderata looked for in the choice of methods of analysis for this work have been sensitivity, so as to use small samples and cut down the volume to be collected in the field, and simplicity in operation so that the number of separate steps and the manipulation are kept to a minimum. Only a brief summary of the methods will be given here; unless modification is mentioned, it may be taken that the procedure given in the reference is followed exactly.

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## Methods of analysis

### Gas and condensate for gases

Acid gases, in the steam collection flasks, are extracted into the aqueous condensate phase with alkali, and the residual gases are pumped off for conventional gas analysis as described by Mahon (3). Carbon dioxide and hydrogen sulphide are titrated in the alkaline solution, which is unstable in air and should be analysed without delay.

### Titration of hydrogen sulphide

Run 20 ml of the alkaline solution slowly and with thorough mixing into 200 ml of solution containing 20 ml 2N sulphuric acid and 10.0 ml 0.01 N iodine; titrate the excess iodine with 0.01 N thiosulphate and starch indicator. Do a blank determination on the alkali used for the extraction.

### Titration of carbon dioxide

To 50 ml of the solution add 1 ml N silver nitrate and adjust to pH 8.25 with 2 N and 0.1 N hydrochloric acid, using a pH meter and magnetic stirrer; finish slowly, with gentle stirring. Most of the carbon dioxide is now present as bicarbonate; titrate to pH 3.8 with 0.1 N hydrochloric acid (4). Do a blank on the alkali used for the extraction. The silver nitrate overcomes interference by sulphide.

### Residual gases

These are analysed by the constant volume method using the apparatus of Bone and Wheeler ((5), and references therein) which, briefly, depends on measurement of the pressure of the residual gas, occupying a constant, fixed volume, after each constituent has been selectively removed by, or reacted with, a suitable reagent.

In case some carbon dioxide escaped extraction, test for it with potassium hydroxide and determine any present; then determine oxygen using chromous chloride, hydrogen by low temperature (250°C) reaction with copper oxide, saturated hydrocarbons by high temperature (600°C) reaction with Arneil reagent and nitrogen as residual gas.

### Gas samples from bubbling pools

These are best dealt with differently. In the field, 20 ml 5 per cent silver nitrate solution is added to the 600 ml bottle to fix hydrogen sulphide. In the laboratory the temperature and pressure of the gas are measured, the silver sulphide is washed out and weighed, and carbon dioxide is determined by the change in pressure after adding 20 ml 20 per cent sodium hydroxide. Residual gas is then pumped off for analysis.

#### DISCUSSION OF GAS ANALYSES

Gas mixtures of known composition have not been put through the over-all procedure, but internal evidence from a large number of carbon dioxide and hydrogen sulphide determinations on steam samples shows that the extraction and titrations provide a good determination of these gases. Difficulty has been experienced with air contamination, detected by the presence of oxygen in the residual gases, occurring in the sampling and/or in the transfer of the residual gas. Air contamination in sampling will lead to oxidation of sulphide, especially during the extraction with alkali, and the hydrogen sulphide results will be in error: a correction can be made by determining sulphate in the extract, provided a blank is done on the alkali. In high temperature fumaroles both sulphur dioxide and hydrogen sulphide may be present and sulphur gases have to be determined by other techniques.

Wilson and Wilson (6) have published a summary of results of a co-operative analysis, by the constant volume method, of a gas sample; this suggests that the accuracy of the residual gas analyses should be more than adequate.

### CONDENSATE FOR OTHER VOLATILE CONSTITUENTS

Absence of interfering ions simplifies the determinations made on these samples. A ready check for absence of spray contamination of steam samples is obtained by testing for sodium by flame photometry or for chloride by differential potentiometry.

#### AMMONIA

It is determined in the range 0.4-8 ppm by the phenate method of Crowther and Large (7): to a 10 ml aliquot add phenate and hypochlorite solutions, dilute to 25 ml and read the absorbance at 625 m$\mu$ after 20 minutes; do a blank determination on 10 ml distilled water.

#### FLUORIDE

Fluoride 0-2 ppm; method of Milton et al. (8), modified by use of a 0.02 per cent solution of chrome azurol S as indicator (9): titrate a 50 ml aliquot of sample, buffered with chloroacetate and with 1 ml indicator added, with 0.004 N thorium nitrate. Match the end-point to a blank containing 0.10 ml thorium nitrate. Titrate standard amounts of fluoride and draw a calibration graph of ml thorium nitrate v $\gamma$ fluoride. In careful work, matching is facilitated if two blanks, with 0.08 and 0.10 ml thorium nitrate, are used. Clean the Nessler glasses frequently with chromic acid, as a blue coating otherwise accumulates.

#### BORIC ACID

Boric acid, 0.2-20 ppm; after (10): acidify a 250 ml aliquot of sample to bromothymol blue, add 1 ml N sulphuric acid excess and blow air freed of carbon dioxide through it for 30 minutes. Use a pH meter and magnetic stirrer. Adjust carefully to pH 7.30 using carbonate-free sodium hydroxide solution; add 5 g mannitol and titrate back carefully to pH 7.30, with 0.025 N carbonate-free sodium hydroxide held in a burette assembly protected by soda lime tubes. Do a blank determination on distilled water and standardize the sodium hydroxide against boric acid at two or three levels in the range of interest.

### WATERS

The analysis of waters is complicated by the fact of higher mineralization and greater likelihood of interference. In hot spring waters, also, the range of composition may be very wide and the analyst must be prepared to find that a sample falls outside the limitations of the method in use. Sometimes use of a smaller aliquot will overcome the difficulty; otherwise special procedures have to be applied. In the development stage of a power project there will probably be many samples of fairly uniform composition from the field: greater accuracy can then be achieved, without more expenditure of time, by having standards covering a narrower range of concentration and closely approximating the composition of the samples.

The volatile constituents, hydrogen sulphide, bicarbonate and ammonia should be determined as soon as possible after sampling. For those determinations in which sulphide would interfere—e.g., chloride, sulphate—a sample, conveniently the remainder in the bottle used for the volatile constituents, is acidified to pH below 3 with a measured volume of 2 N nitric acid, and hydrogen sulphide is removed by bubbling nitrogen through it. The nitrogen is freed of oxygen by scrubbing with vanadyl chloride (11). The total volume is measured and determinations are corrected for dilution by the acid added.

#### TOTAL HYDROGEN SULPHIDE

Total hydrogen sulphide, up to 7 ppm : run 250 ml sample into 10 ml 0.01 N iodine acidified with 20 ml 2 N sulphuric acid and titrate the excess iodine with 0.01 N thiosulphate using starch indicator.

#### BICARBONATE, CARBONATE AND CARBON DIOXIDE

Take the temperature and measure the pH of a 100 ml aliquot of the sample. Add 1 ml 0.1 N silver nitrate and adjust the pH carefully to 8.25. Acidify to a pH below 3.8 with a measured volume of 0.02 N hydrochloric acid, bubble air freed of carbon dioxide through it for 15 minutes, then titrate back to pH 8.25 with 0.02 N carbonate-free sodium hydroxide. For a blank, acidify 100 ml distilled water, bubble to remove carbon dioxide, adjust to pH 8.25 and continue as with the sample. Estimate the concentrations of carbonate, bicarbonate and carbon dioxide from graphs relating the proportions of these species to pH at the temperature and ionic strength of the samples. The graph should refer to a temperature close to that at which the samples are analysed. This titration procedure gives more accurate results than does that of Tinsley et al. (4) in the presence of weakly ionised acids like silicic and boric.

### AMMONIA

Ammonia, 0-10 ppm; method of Kruse and Mellon (12). Treat 15 ml of sample with 2 drops 25 per cent acetic acid, 3 ml buffer and 0.3 ml chloramine T solution; after 90 seconds add 9 ml pyridine-pyrazolone solution, leave 60 seconds then shake with 25 ml carbon tetrachloride. Measure the absorbance of the extract at 450 m$\mu$. Sulphide does not interfere, but iron and aluminium, in acid waters, should be filtered off before adding the reagent. The reagent has to be prepared immediately before use, so batches of about ten samples are done together with one or two standards and a blank.

### CHLORIDE

Chloride is usually determined by Mohr titration of 25 ml of sample with 0.1 N silver nitrate. The potentiometric method of Kolthoff and Kuroda (13), in which the end-point is marked by attainment of a predetermined potential between a silver-silver chloride electrode and a reference electrode, is also satisfactory and has been used a lot. For chloride concentrations of over about 100 ppm both methods are equally accurate. Very low concentrations, 0.1-10 ppm, e.g., in condensate and surface water samples, are determined by the differential potentiometric method of Blaedel *et al.* (14) in which the potential between identical electrodes in unknown and standard solutions is compared.

### SULPHATE

Sulphate, 10-100 ppm, and more by dilution; photometric chromate method of Iwasaki et al. (15) modified: just neutralize a 5 ml aliquot of the sulphide-free sample to bromothymol blue; treat with acid barium chromate suspension, make ammoniacal and add alcohol. Heat under a cold thimble for 3 minutes on the steam bath, cool, filter and determine the absorbance at 400 m$\mu$. Sulphide and bicarbonate must be absent. In the presence of other foreign ions the sulphate results tend to be high; with Wairakei bore water the error does not exceed $\pm 10$ per cent.

Other methods for sulphate were tried: in the micro titration with barium perchlorate using thorin indicator, following removal of cations by ion exchange (16), the end-point was indistinct. The method of Fritz, Yamamura and Richard (17), in which two ion exchange columns are used to isolate the sulphate ions, is cumbersome for routine use. The nephelometric method of Steinbergs (18) gave good results in some hands but other workers had little success with it.

### BORIC ACID

Boric acid is determined by the same titration as is used for condensates, but a 50 ml sample is taken and diluted to 250 ml. Iron and aluminium in acid waters must be separated by double precipitation with sodium carbonate (10) or by ion exchange (19).

### FLUORIDE

Fluoride is determined by the same titration as is used for condensates, but for accurate results the fluorine must first be separated by distillation as hydrofluosilicic acid (20): evaporate a 100 ml sample, made alkaline with sodium hydroxide, to about 20 ml in a platinum basin, transfer to the distilling flask, treat with silver perchlorate and perchloric acid and steam distil; collect 200 to 250 ml distillate and use a 10-50 ml aliquot for the titration.

Ion exchange separation of the fluoride from thermal waters has not been successful. Direct titrations are affected mainly by sulphate and, to a lesser extent, by chloride. Distillation can be avoided, if sulphate is not too high, by applying corrections determined by titrating standard amounts of fluoride in presence of increasing amounts of sulphate and chloride. With bore waters of uniform composition, as occur at Wairakei, this technique can give quite accurate results. Interference by iron and aluminium in acid waters can only be overcome by distillation.

### SILICA

Silica, up to 500 ppm; standard method of the American Public Health Association (20), modified: heat a 5 ml sample with 0.5 ml N sodium hydroxide for 10 minutes in a platinum crucible on the steam bath; cool, add 0.5 ml N hydrochloric acid, transfer to a beaker and dilute to 50 ml. Treat with ammonium molybdate, hydrochloric acid and oxalic acid and measure the absorbance at 410 m$\mu$.The silica in thermal waters is mostly polymerized by the time samples are analysed and will not react with molybdate in the cold; the treatment with alkali converts it all to the ionic state.

### ARSENIC

Arsenic, standard method of the American Public Health Association (20): use 5-25 ml sample, taking not more than about 50 $\gamma$ arsenic; evolve arsenic as arsine, absorb in hypobromite solution and determine as the reduced arsenomolybdate. Measure the absorbance at 625 or 840 m$\mu$ according to the concentration. Arsenic should be determined on a sample which was filtered before bottling as, on standing, arsenic is carried down by any precipitate. If the sample used for analysis contains any precipitate, it should be well shaken and the aliquot treated to get insoluble matter into solution before proceeding with the determination.

#### Sodium, potassium, lithium

This is a flame photometric method: use the flame photometer in accordance with the manufacturer's instructions; compare the samples with standards which contain the alkali metals in proportions similar to those in the samples.

At the relative concentrations of the alkali metal and other ions in thermal waters, sodium has a considerable enhancing effect on the potassium emission and both sodium and potassium very slightly enhance the lithium emission; there are no other interferences (21). These effects are compensated for by making sets of standard solutions with various Na/K ratios covering the range in the samples; the set with ratio closest to that in the samples under examination is used; a correction can then be applied to the potassium result, if necessary, by interpolation. Lithium can be incorporated in the same standards. Samples with a total salt concentration exceeding about 7 500 ppm should be diluted rather than make more concentrated standards.

The accuracy obtained is a direct function of the amount of care put into the preparation of standards and matching them to the samples; in routine analysis of Wairakei bore waters the accuracy is estimated to be about $\pm 2$ per cent (22).

#### Calcium, magnesium

Calcium, magnesium, E.D.T.A. titration, method of Patton and Reeder (23), modified. For calcium, treat a 50 ml sample with sodium hydroxide, potassium cyanide and hydroxylamine hydrochloride and titrate using Cal Red (1 per cent Patton and Reeder's dye in sodium sulphate) as indicator. For calcium and magnesium treat a 50 ml sample with ammonia-ammonium chloride buffer, potassium cyanide and hydroxylamine hydrochloride and titrate using solochrome black as indicator; if little magnesium is present, add 1 ml 0.1 M magnesium — E.D.T.A. before the titration to improve the end-point. Some workers prefer a green end-point which can be got by screening the indicators with methyl red.

Iron and aluminium in the sample do not interfere in the calcium titration if triethanolamine is added before the sodium hydroxide; they should be separated for the calcium + magnesium titration.

#### Other ions

A number of other constituents, usually present in small amounts, are also of interest. Bromide and iodide have been successfully determined by the A.S.T.M. method D 1246-55 (24); rubidium and caesium by recording flame spectrophotometry with adjustment of sodium and potassium to a predetermined level in samples and standards (21); antimony by extraction and photometric determination (25).

## Equipment

No more can be done here than to mention the types of instrument and equipment which have been used and found satisfactory.

#### pH meter

A mains operated, direct deflection meter, calibrated 0-14 in 0.1 pH unit and with either manual or automatic temperature compensation, has been found entirely adequate. Such an instrument, combined with a magnetic stirrer, makes a very useful titration assembly. It can also be used for potentiometric titrations where high sensitivity is not required. The A.S.T.M. method E70-52T (24) sets out requirements which the pH meter should meet.

#### Photometer

A mains operated, direct reading filter photometer with glass colour filters, such as the Coleman model 9, is entirely satisfactory for determinations by established procedures; the accuracy of the results obtained is quite adequate. The limitations inherent in using broad band illumination must be borne in mind. Quartz prism and grating spectrophotometers — Beckman DU, Unicam SP500; Optika CF4 — are also in use, and an instrument of this type is indispensable if research is to be undertaken.

#### Flame photometer

A direct deflection filter instrument, with narrow band interference filters, the Eel, has been used a great deal for sodium, potassium and lithium determinations, and has proved very satisfactory. The flame attachment for the Beckman DU spectrophotometer is very useful and makes it possible to assay the alkalis just mentioned as well as the less common alkali and alkaline earth ions. In choosing a spectrophotometer with flame attachment, the ease with which the changeover can be made should be looked into.

#### Gas analysis apparatus, vacuum pump

The constant volume gas analysis apparatus of Bone and Wheeler is available commercially as a unit. An assembly incorporating a U-tube mercury manometer, a Töpler pump and a McLeod gauge is used for measurement and transfer of residual gases. A good rotary oil pump is also required. Gas handling techniques are specialized and some practice is needed: it will probably be found more convenient to undertake residual gas analysis only at a later stage.

SAMPLING EQUIPMENT

In the prospecting stage the main requirement is a large supply of bottles; these should be cleaned, for example, by steaming. When drill-holes are to be sampled, small stainless steel Webre cyclones, pressure gauges and pipe fittings are needed (3). Specially made pyrex glass flasks of 2-10 litres capacity having 2 diametrically opposed 10 mm o.d. tubular openings are used for the collection of gas + condensate samples.

## General

When the Wairakei geothermal power project was started, a new section was set up within the Dominion Laboratory in Wellington; sampling expeditions were made to the field and the analytical work was done in Wellington. Later, when drilling for production was under way, a field laboratory was set up at Wairakei and equipped for the analysis of the main constituents of the bore discharges; only residual gases are still sent to Wellington for analysis. Latterly the Wairakei laboratory, which is operated by, and as a branch of, the Dominion Laboratory, has been the centre for sampling and analysis in other parts of the thermal region. Special projects requiring major facilities are done in Wellington, using the Wairakei laboratory as headquarters for sampling trip.

It is desired to bring out the fact that in New Zealand experience the geothermal chemical laboratory has not been isolated but has been able to draw on a wide range of resources which were not provided as part of the power project. Such conditions may not obtain if a similar project is undertaken elsewhere.

The chemist may find himself cut off, and be helpless for lack of a reagent, apparatus or literature. A laboratory set up for this type of investigation, if it is to do more than purely repetitive analysis, must be well equipped, especially if far from well-found resources.

It may seem that a mobile laboratory would be useful in the prospecting stage. Such laboratories have been described and all the techniques required for the present analyses have been, or could be, used in them. However, when all the factors such as cost, laboratory work plan, likely accessibility of surface thermal manifestations etc. are considered, the sampling expedition from a permanent central laboratory is seen to offer greater flexibility and is more adaptable to a wide variety of conditions. This approach does not preclude, say, on-the-spot determination in the field of an unstable constituent like hydrogen sulphide.

Some 500 sq ft of floor space would provide adequate room for a laboratory; to equip it with chemical facilities would cost about £1 500 and it should be staffed by a well qualified chemist with at least one assistant. These estimates are necessarily approximate; they presuppose a programme of chemical investigation comparable in scope with that undertaken in New Zealand and that further resources, as discussed above, are accessible to the chemist.

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## *Summary*

The methods of analysis which have been successfully applied to hydrothermal fluids are detailed. In samples of condensate and gas, from fumaroles or separated steam, hydrogen sulphide and carbon dioxide are determined in an alkaline extract, the first by titration with iodine and thiosulphate, the second by titration with acid. Oxygen, hydrogen, hydrocarbons and nitrogen are determined by a constant-volume gas analysis method. In a second sample, fluoride is titrated directly with thorium; boric acid is titrated with alkali, using mannitol; and ammonia is determined photometrically with phenate.

For water samples the methods are: hydrogen sulphide, by iodine titration, bicarbonate, carbonate and carbon dioxide, by pH and acidimetric titration; ammonia, colorimetric with pyridine-pyrazolone; chloride, by titration with silver nitrate; sulphate, colorimetric with barium chromate; boric acid, by titration with alkali using mannitol; fluoride, volumetric with thorium, with or without distillation; silica, colorimetric as silicomolybdate; arsenic, colorimetric by molybdenum blue; alkali metals, by flame photometry, with standards of similar composition; calcium and magnesium, by titration with E.D.T.A. at pH $>13$ and at pH 10.

The equipment used includes: direct deflection pH meter; mains operated photometer of direct deflection type using coloured glass filters; direct deflection flame photometer with narrow band interference filters; gas transfer apparatus, vacuum pump and gas analysis apparatus; sampling equipment.

In the prospecting stage field sampling trips were made from Wellington; later a field laboratory was set up at Wairakei. About 500 sq ft floor space and £1,500 worth of chemical equipment are required.

# ANALYSES CHIMIQUES ET EXIGENCES QUANT AUX LABORATOIRES : EXPÉRIENCE ACQUISE DANS LES RÉGIONS HYDROTHERMIQUES DE LA NOUVELLE-ZÉLANDE

## *Résumé*

On donne le détail des méthodes d'analyse qui ont été employées avec succès pour les fluides des champs hydrothermiques. Sur les échantillons de produits de condensation et de gaz, en provenance de fumerolles ou de vapeur séparée, on détermine la teneur en hydrogène sulfuré et en anhydride carbonique en extrait alcalin : la première par titration avec de l'iode et du thiosulfate, la deuxième par la titration à l'acide. On détermine les teneurs en oxygène, en hydrogène, en hydrocarbures et azote par une méthode d'analyse des gaz à volume constant. Sur un deuxième échantillon, on fait un titrage direct des fluorures au thorium, celui de l'acide borique avec une base en se servant de mannitol et, finalement, on détermine photométriquement la teneur en ammoniaque au moyen d'un phénate.

Pour les échantillons d'eau les techniques sont les suivantes : hydrogène sulfuré par titration à l'iode, bicarbonates, carbonates et anhydride carbonique par la détermination du pH et la titration acidimétrique; ammoniaque, méthode colorimétrique avec la pyridinepyrazolone; chlorures par titration au nitrate d'argent, sulfates par une méthode colorimétrique avec du chromate de baryum; acide borique par titration avec une base en se servant de mannitol; fluorures, méthode volumétrique au thorium, avec ou sans distillation; silice, essai colorimétrique du silico-molybdate; arsenic, méthode colorimétrique par le bleu de molybdène; métaux alcalins, photométrie à flamme avec étalons de composition analogue : calcium et magnésium par titration à l'E.D. T.A. à un pH $>13$ et au pH 10.

Le matériel utilisé comporte un indicateur de pH à déviation directe, un photomètre alimenté par le courant du secteur du type à déviation directe qui fait usage de filtres en verre de couleur; un photomètre à flamme à déviation directe avec des filtres d'interférence à bande étroite; un dispositif de transmission du gaz, une pompe à vide et du matériel d'analyse des gaz, ainsi enfin qu'un matériel d'échantillonnage.

Pendant la phase de prospection, on a procédé à l'échantillonnage des chanps géothermiques à la suite de visites faites de Wellington; par la suite, on a organisé un laboratoire à Wairakei. Il faut environ 500 pieds carrés (46 m²) de surface pour les laboratoires et du matériel chimique estimé à 1 500 livres.

# KNOWN GEOTHERMAL FIELDS IN JAPAN

*Masatsugu Saito**

## Difficulties in Japanese geothermal prospecting

A large number of hot springs and fumaroles are known in Japan; they are mostly related to Quaternary volcanic activity (figure 1). Among the thermal areas of Japan, some are thought to be quite powerful.

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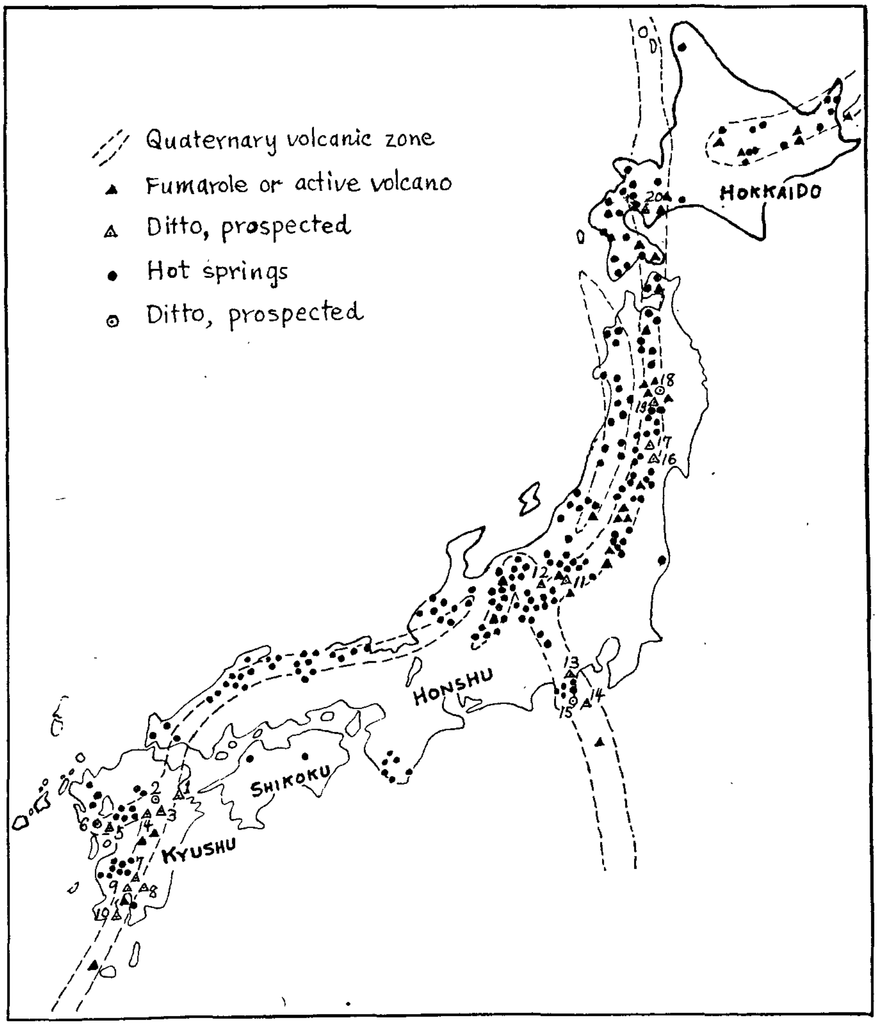
For many centuries, however, the hot springs of Japan have been used for bathing purposes. The Beppu area, for instance, displays strong surface phenomena, such as discharges of steam, geysers, hot water pools and boiling mud pools, which are possibly comparable to those to be seen at Geyser Valley in the Wairakei area of New Zealand. Beppu is now a large tourist city, however, with a population of more than 100 000, whose living depends directly




1. Beppu
2. Noya
3. Otake
4. Takenoyu
5. Unzen
6. Obama
7. Ebino
8. Yunono
9. Tearai
10. Ibusuki
11. Kusatsu
12. Yamanouchi
13. Hakone
14. Oshima
15. Atagawa
16. Narugo
17. Onikobe
18. Matsukawa
19. Takinoue
20. Showa-shinzan

**Figure 1. Hot springs and fumaroles, with the areas geothermally prospected in Japan (after H. Nakamura)**

or indirectly on the existence of hot springs; numerous wells, which supply a tremendous amount of hot water to the baths, have been drilled by hotel owners and others. Another example is the hot springs at Obama. About eighty wells which have been drilled in the area produce steam and hot water with a temperature of 130°C; the total output is reported to amount to 4 200 tons per hour, which would correspond to 70 000 kW if utilized for power generation. These sources, however, are being utilized for salt production (by evaporation of sea water) as well as for baths. Many other notable thermal areas known to exist are, almost without exception, already developed as hot spring resorts; usually, the larger the area, the larger the resort. In such areas, the exploitation of geothermal power is practically out of the question, since any exploitation likely to affect the surface phenomena which attract visitors, or the output of wells belonging to private concerns, has to be avoided. Consequently, geothermal explorations in Japan, unlike those in other countries, are handicapped by the fact that they cannot be carried on in the visibly promising areas; it may be possible, however, to discover new resources left untapped because of the scarcity of surface phenomena. These special circumstances have prevented the rapid development of geothermal fields in Japan.

## History of prospecting

The first prospecting well for geothermal power was drilled as early as forty years ago. It was not, however, until the post-war power supply crisis of 1947 that the possibilities of geothermal energy were seriously considered. Since then, government organizations, such as the Agency of Industrial Science and Technology (AIST) which includes the Geological Survey, electrical companies, and other private concerns have co-operated in exploring a number of the geothermal areas shown in figure 1 and listed in table 1. Among them, Beppu, Otake and Matsukawa are the areas where discharges from steam wells have been carefully measured.

In most areas the steam wells are still small in number, and, with a few exceptions, are less than 200 metres deep. All the steam from the wells is not superheated but, rather, saturated—that is, mixed with hot water. The steam is not satisfactory in amount, although it has the advantage of being only slightly corrosive, owing to small gas content.

In short, geothermal prospecting in Japan is still in the preliminary stage.

## Methods of prospecting

In the early days of post-war development, bore holes were simply drilled in places near natural fumaroles in steaming ground. Many such wells produced steam jets rather easily, but were not satisfactory for further exploration. Conventional geological mapping, chemical analysis of hot springs, surface temperature surveys, detection of gases and radioactivity contained in the soil, and horizontal electric prospecting were the most common research methods employed before drilling, but these methods dealt only with the superficial feature of the terrain and told little of the underground characteristics. The importance of studying geological structure in depth was, however, soon realized. Since then, geological mapping has been devoted to clarifying detailed structural features, including stratigraphic successions, folds, faults, joints, rock features such as density, porosity and permeability, and hydrothermal alteration. Seismic, gravity and vertical electric prospecting to suit the geothermal areas has been devised and applied according to the characteristics of the fields. During the well drilling, not only core and temperature logging, but also electric logging was used to determine rock characteristics. The physical and chemical characteristics of steam discharged from the wells have also been measured at most places.

## Examples of the geological structure of geothermal areas

In order to illustrate recent progress in geothermal prospecting in Japan, the geological structure of the Showa-shinzan, Onikobe and Matsukawa areas, which have been studied most thoroughly by the Geological Survey, are reviewed here.

### Showa-shinzan

Showa-shinzan is a volcanic dome newly formed about sixteen years ago as a parasitic dome of the Usu volcano. It is composed of dacitic rock, originally 1000°C and still more than 800°C in temperature. Geophysical prospecting has discovered the fact that the underground part of the dome mass inclines gently to the south and possibly extends at least as far as one kilometre away, where it becomes concealed at a depth of about 400 metres below the surface.

Surface manifestations of underground heat, such as fumaroles and hot springs, are poor in this area, except on the dome itself and the roof mountain near the dome. The drilling necessary to verify the above-mentioned underground structure and high temperature have not yet been undertaken. The country rocks into which the Showa-shinzan masses are intruded are Pliocene, Pleistocene and Holocene deposits consisting of lavas, volcanic ash, sand, lapilli, pumice, and other loose clastic sediments. Conditions likely to prevail at the point where the groundwaters contained in the porous country rocks come into contact with the hot underground masses represent a problem to be solved in order to know whether or not geothermal fluids are present in this area.

### Onikobe

Geothermal areas strong enough and large enough to be developed industrially should have adequate

**Table 1. List of geothermal prospections in Japan**

| Area | Geology | Method of survey | Test boring: Number | Test boring: Depth (m) | Test boring: Temp. (°C) | Product[b]: Temp. (°C) | Product[b]: Press. kg/cm² | Product[b]: Output[d] (metric tons/hr) and well dia. | Prospecting organization |
|---|---|---|---|---|---|---|---|---|---|
| Beppu[a] | Volcanic | Geologic, surf. temp., elect. prosp., temp. log., corrosion test. | 3 | 110 | 145 | 140* | 3.6* | S + W 2.4 (75 mm) | AIST, Geol. Surv., Electro. Technical Lab., Mechanical Lab. |
| Noya | Volcanic | Geologic, surf. temp., radioactive, chemical, elect. prosp., seismic, elect. log. | 1 | 200 | 100 | | | W | Geol. Surv., Kyushu Elect. Co. |
| Otake | Volcanic | Geologic, surf. temp., radioactive, elect. prosp., chemical | 4 | 900 | 185 | 144*<br>145* | 6.5*<br>5.0* | S 1.0, W 1.5 (65 mm)<br>S 6.0, W 3.0 (150 mm) | Kyushu Elect. Co., Geol. Surv. |
| Takenoyu | Volcanic | Geologic, surf. temp. | | | | | | | Kumamoto Pref. Govern., Yawata Iron Stell Co. |
| Unzen[a] | Volcano | | 3 | 30 | 120 | | | S | Geol. Surv. |
| Obama[a] | Volcanic | | about 80 | | | 130 | | S + W 4 700 in total | |
| Ebino | Volcano | Surf. temp., chemical, elect. prosp., magnetic | 3 | 75 | 108 | | | W 12 (125 mm) | Miyazaki Pref. Govern., Geol. Surv. |
| Yunono | Volcano | Geologic, surf. temp., chemical, elect. prosp., magnetic | 1 | 84 | 156 | 129 | | S + W | Geol. Surv. |
| Tearai | Volcano | Surf. temp., chemical | | | | | | | Geol. Surv. |
| Ibusuki[a] | Volcanic | Geologic, chemical | | | | | | S + W | Geol. Surv. |
| Kusatsu[a] | Volcanic | Surf. temp. | 2 | 200 | 100 | | | W | Tokyo & Chubu Elect. Co. |
| Yamanouchi[a] | Volcanic | | | | | 100 | | S + W | Tokyo & Chubu Elect. Co. |
| Hakone[a] | Volcano | | | | | | | S + W | Dowa Mining Co. |
| Oshima | Volcano | Geologic, elect. prosp. | 3 | | 70 | | | W | Dowa Mining Co. Geol. Surv. |
| Atagawa[a] | Volcanic | | | | | | | S + W | Tone Boring Co. |
| Narugo[a] | Volcanic, Tertiary | | 22 | 213 | 175 | 100∼175[c] | 2.6∼8.0[c] | S + W 1 ∼ 6 (45 mm) | Tone Boring Co. |
| Onikobe | Tertiary | Geologic, elect. log. | 3 | 255 | 185 | 110 | | S + W | Geol. Surv. |
| Matsukawa | Volcanic, Tertiary | Geologic, elect. prosp., seismic, elect. log., corrosion test | 10 | 450 | 189 | 154[c] | 5.1[c] | S + W 0.3 (45 mm) | Azuma-kako Co., Geol. Surv. |
| Takinoue | Tertiary | Geologic | | | | | | | Geol. Surv. |
| Showa-shinzan | Volcano | Geologic, surf. temp., chemical, gravity, seismic, elect. prosp., radioactive | | | | | | | Geol. Surv. |

[a] Developed as large hot spring resort.
[b] Products from the wells of steady dicharge are selected.
[c] When well closed.
[d] S, steam; W, water.

geological supporting conditions, as in the case of the Larderello area in Italy. Many Japanese fumarole areas are on volcanoes; in such places it is usually difficult to determine the deeper structures because of the thick covering of lava and volcanic eject. This is the reason that the Onikobe area, consisting of Tertiary rocks, has been opened as a field of geothermal prospection.

Topographically, the Onikobe area is an elliptical basin, 10 km and 8 km across the axes as determined by the river system of the area, shown in figure 2. Geologically, this basin is the result of crustal subsidence, probably late Miocene in age. The areas outside of and, in part, within the subsidence are made up of exposed pre-Neogene granite and a thick series of Miocene rocks, which are mostly volcanic and partly sedimentary. The remaining major part of the subsided area is covered with a formation deposited in a lake which once filled the basin from the Pliocene to Pleistocene epoch. This lacustrine formation is in loose deposits, and consists of the following: conglomerate, andesitic tuff-breccia and tuff, pumiceous tuff of dacitic character, and mudstone from the base upwards, though lateral changes of rock facies are remarkable. The total thickness of the formation is approximately 300 metres. At several places, the formation is penetrated by contemporaneous dacite domes.

Though the area is in a Quaternary volcanic zone, there is no recent volcano. However, hot springs, geysers, fumaroles, solfataras and native sulphur deposits occur sparsely in the subsided basin, and suggest the presence of deep-seated magma. Being at some distance from railways, the area has not been developed as a hot springs resort.

According to the topographic survey and regional geological mapping made in 1955, the alignment of thermal outcrops and hydrothermal alterations is probably controlled by the supposed fault-system in the Miocene and granite basement buried under the lacustrine formation. Three bore holes were drilled within the lacustrine formation to depths of 255, 250 and 192 metres (figure 3), each at a point a little away from the natural thermal outcrops.

So far as the explored depths are concerned, the geothermal character of the Onikobe area does not seem to be like that of Larderello in Italy, as had been expected, but is rather similar to that of Wairakei in New Zealand. That is to say, the faults in the basement of hard rocks act as feeders for the hot fluids ascending from the depths into the overlying lacustrine formation, in which the heating of ground water contained in the rock-pores as well as the cracks sets up a convective geothermal system.

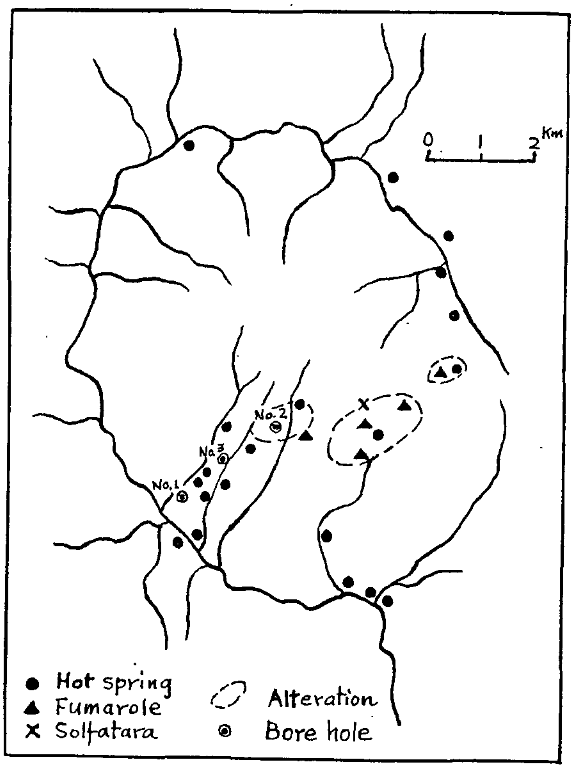


**Figure 2. Onikobe geothermal area (after H. Nakamura)**

The bore holes hitherto drilled are shallow. The lacustrine formation is much less thick than the reservoir rocks in the Wairakei area. In Onikobe, compact rocks of the Miocene series or granite may soon occur at greater depths, and the geothermal features may well be different from those of the shallow layers already explored.

## Matsukawa

Matsukawa is a small valley in the midst of a volcanic district where three active volcanoes and many other dormant volcanoes cluster, and a large number of hot springs, fumaroles, and some sulphur deposits are present. However, only one emergence of hot springs nearly at boiling temperature and some seepage of mineral waters a little higher than atmospheric temperature were originally known along the Matsukawa River. Here, the local people hoped to construct a new lodging house with hot baths; they have drilled seven wells at various points in the valley since 1953. Four of the wells produced steam instead of hot water at depths from 160 to 300 metres. Since then, the valley has been regarded as a noteworthy geothermal area, probably with an impervious cover.

The geologic mapping in 1957 determined the fact that this area is a dissected composite volcano consisting of somma and a central cone in a caldera (figure 4). The Matsukawa valley along which the thermal outcrops and steam wells are situated coincides with the southern margin of caldera collapse. The rocks occurring on the surface are only andesites: one constitutes the volcano, and the other underlines the volcano and stretches along the bottom of the valley and farther west to another Quaternary volcano.

The drill-cores preserved by the local people were reinspected. The upper columns of the cores are mostly of the above-mentioned lower andesite, which consists of lavas intercalated with pyroclastics. The lavas are very compact, and some reach as much as 50 metres in individual thickness. The lower columns below about 150 metres are composed of dacite, which is an accumulation of lavas and porous tuff containing fragments of pumice. Such dacite is common in the uppermost part of the Neogene system, which is exposed in neighbouring districts, such as the Takinoue thermal area seven kilometres to the south of Matsukawa.

Figure 5 represents the temperature-depth relations of steam wells. Three curves clearly show the sudden rise of temperature at depths from 140 to 180 metres. These depths correspond to the unconformity between the Quaternary andesite and the Pliocene dacite.

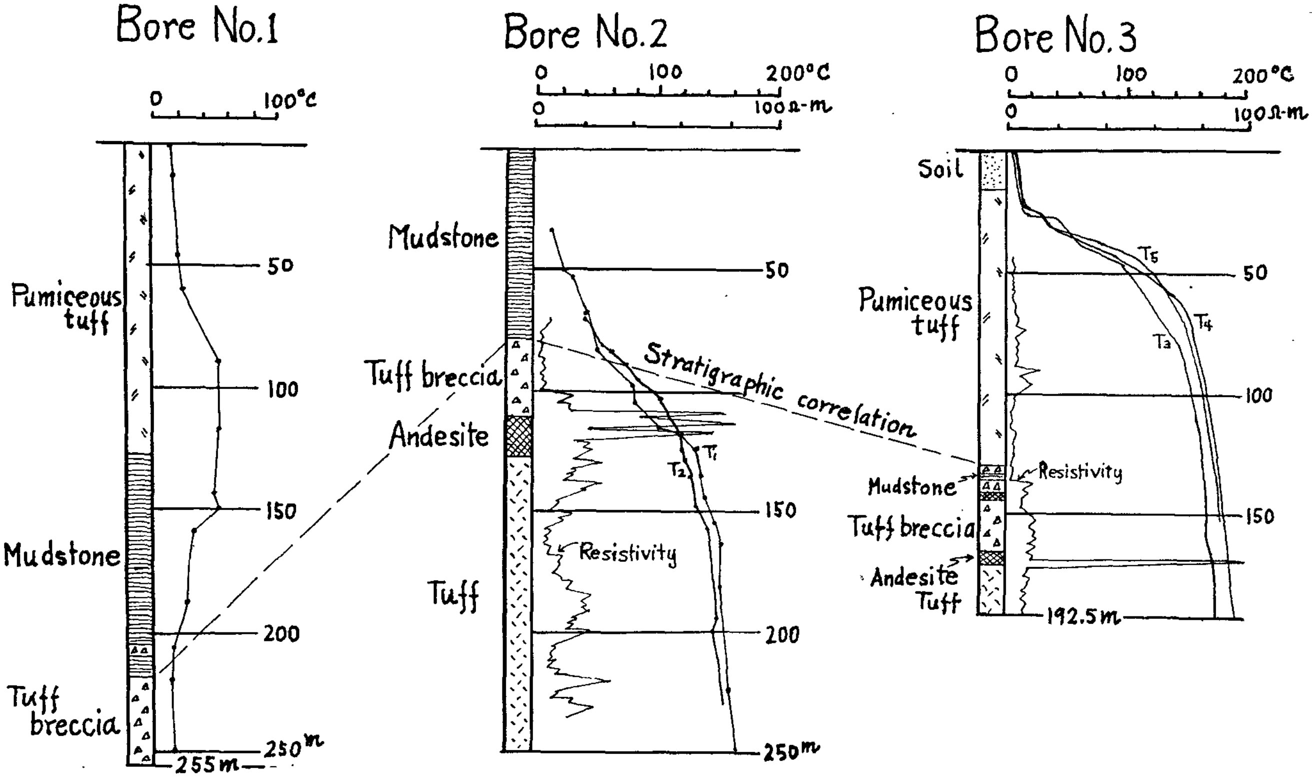



**Figure 3. Well loggings in Onikobe area**

*Note :* Bore No. 1 unexpectedly encountered a large outflow of cold ground water from the cracks traversing the mudstone and tuff breccia beds in the depths. Bore No. 2 and Bore No. 3 encountered high temperatures. The bottom temperatures of Bore No. 2 during the course of drilling (usually measured every morning after the nightly break in operation) show a rapid rise from 90°C to 130°C between the depths of 110 and 125 metres ($T_1$). This depth corresponds to the intercalation of compact andesite in the tuff-breccia bed as shown in the column of rock-cores. The resistivity curve obtained by electric logging shows steep peaks at this depth, indicating the presence of an impermeable rock. The compact andesite seems to play a role as a local cover against the geothermal fluids contained in the underlying porous pumiceous tuff. This rise in temperature was obliterated by convection in the well a few days after the completion of drilling ($T_2$). The temperature curves of Bore No. 3, measured intermittently over a few months ($T_3$, $T_4$, $T_5$), show typical convection curves. All lie below the theoretical boiling point depth curve. After artificial raising of the upper part of the water column, this well started to discharge steam mixed with hot water.

Seismic prospecting was undertaken in order to investigate the underground structure in the belt along the southern margin of the caldera. Although a complete assessment is not yet available, the data obtained harmonize with the physical characteristics of rocks lithologically determined, and moreover suggest latent rock formations much more than 1 000 metres thick which more or less correspond to the full successions of the Neogene system characteristic of the region. Some fractures were also detected, on a line close to the wall of the caldera.

On the basis of the geological, geophysical, and thermal data enumerated above, the geothermal condition of the Matsukawa area is believed to be as follows : the steep fractures related with the caldera conduct the magmatic heat from the depths. The porous dacite and cracks therein hold the geothermal fluids, which are supposed to be mainly of heated ground water. The compact andesite overlying the dacite prevents the geothermal fluids from flowing freely to the surface.

Hydrothermal alteration is observable along

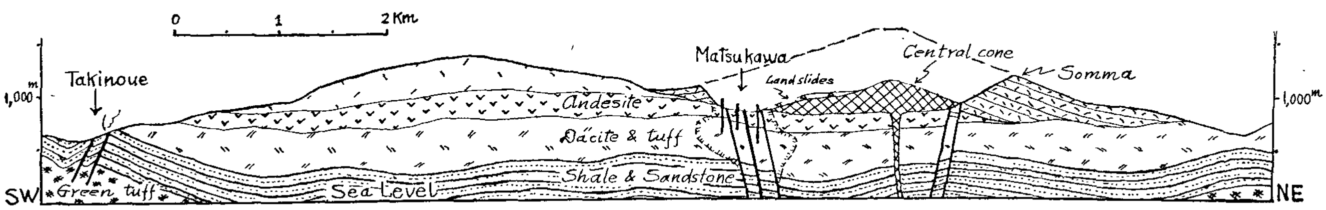



**Figure 4. Schematic profile of Matsukawa (after K. Sumi)**

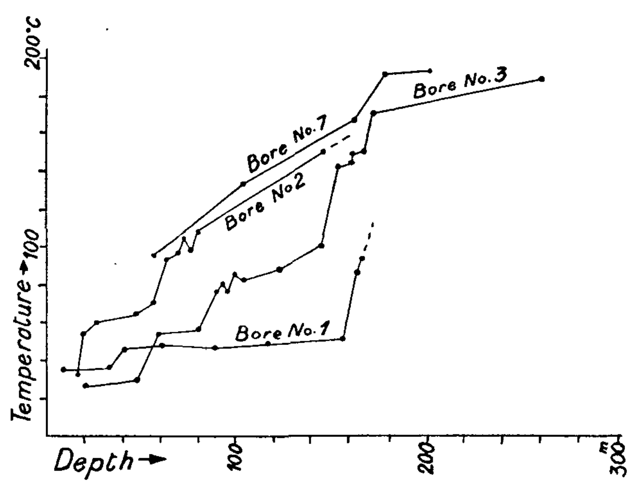



**Figure 5. Temperature measurement of steam wells in Matsukawa (reported by Azumakako Co. Ltd.)**

the Matsukawa River. It extends along the south bank, but is not clear on the north bank because of the thick cover of andesite boulders which are derived from the central cone of the volcano, probably as a result of land-slides. The results of electric prospecting on the northern bank suggest the extension of altered terrain beneath a covering approximately twenty metres thick. A new test bore drilled to a depth of 214 metres proves the actual presence of alteration, but demonstrates the fact that alterations do not always indicate the existence of geothermal fluids.

The discharges from one of the wells have been measured since 1957. They are of saturated steam, and contain gases less than 0.3 per cent in volume. In 1960, two new wells, 210 millimetres in diameter, were drilled to depths of 325 and 450 metres in the steam layers brought to light by the older wells. Electric loggings were employed at the time of drillings. The discharges are still under observation.

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## *Summary*

Many geothermal areas are known in Japan. Some are regarded as potentially powerful sources of power generation if developed, but they are now hot spring resorts unsuitable for intensive exploitation. The development of geothermal fields in Japan is handicapped at present because it is necessary to exclude known promising areas, and difficult to find important new sources where there are few surface indications.

A number of areas have been prospected since 1947 by government research institutions, such as the Geological Survey, and private concerns, such as electric companies, in combination. Test bores have been drilled, but they are few in number at most places and, except for a few wells, relatively shallow. The underground temperatures measured do not exceed 200°C. The quantity of steam produced is insufficient and it is mixed with hot water, although the chemical composition is favourable. Geothermal prospecting in Japan is still in the preliminary stage.

Geothermal prospecting during recent years, for instance in the Showa-shinzan, Onikobe, and Matsukawa areas, has paid special attention to the study of underground structures; the survey methods applied to these studies include detailed geological mapping, various kinds of geophysical prospecting, such as seismic, gravimetric, electric and magnetic prospecting, and electric logging, as well as rock-core inspections and thermal loggings conducted at the time of drilling.

Showa-shinzan is a new volcanic dome which appeared sixteen years ago. Physical prospecting has discovered that the underground temperature of the magmatic masses is still at 800°C. The geothermal features occutring at the point of contact between this hot mass and the ground water contained in the country rocks represent a problem still to be solved for practical purposes.

In the Onikobe area, the faults in the Miocene and granite basement conduct high temperature fluids from the depths into the overlying Pliocene beds of porous rocks, in which the ground water shows a convective geothermal system similar to that of the Wairakei area in New Zealand.

The Matsukawa area is a Quaternary composite volcano with caldera. The volcano rests on andesite lava of another volcano, which in turn is situated on a Tertiary basement. The fractures related to the caldera act as feeders for the heat from the deep-seated magma. The geothermal fluids are held in the porous beds of the uppermost Tertiary, and are covered by Quaternary andesite consisting mostly of thick and compact lavas.

# LES CHAMPS GÉOTHERMIQUES ACTUELLEMENT CONNUS AU JAPON


## *Résumé*

On connaît, au Japon, nombre de régions géothermiques. D'aucunes sont jugées comme capables de représenter de puissantes sources d'énergie si on les met en œuvre, mais sont actuellement des stations thermales qui se prêtent mal à l'exploitation intense de l'énergie thermique. Le problème auquel on se heurte actuellement au Japon dans ce domaine est constitué par la difficulté qu'il y a à exclure les régions dont on sait dès à présent qu'elles promettent d'être utilisables et à découvrir de nouvelles ressources importantes dont il y a peu d'indications en surface.

Diverses institutions gouvernementales, telles que le Service géologique, et diverses entreprises privées, telles que les compagnies d'électricité, ont combiné leurs efforts et ont exécuté des prospections depuis 1947. Des sondages ont été faits, mais, dans la plupart des régions, ils restent peu nombreux et relativement superficiels, avec quelques exceptions. Les températures souterraines qui ont été mesurées ne dépassent pas 200 °C. La vapeur recueillie n'est pas satisfaisante quant au volume et elle est mélangée d'eau chaude, bien que sa composition soit favorable. La prospection géothermique au Japon en est encore au stade préliminaire.

Les prospections géothermiques réalisées au cours de ces dernières années, par exemple celles des régions de Showa-shinzan, Onikobe et Matsukawa, se sont tout particulièrement attachées à l'étude des structures souterraines; les méthodes appliquées aux fins de ces travaux comportaient des relevés géologiques détaillés, divers types de prospection géophysique (mesures sismographiques, gravimétriques, électriques et magnétiques) et, à l'occasion des sondages, des profils électriques en plus de l'examen des carottes et de l'inscription des températures.

Showa-shinzan est un dôme volcanique qui n'a fait son apparition qu'il y a 16 ans. La prospection physique y a révélé l'existence de masses magmatiques dont la température souterraine atteint encore 800 °C. La caractéristique géothermique au contact de cette masse chaude et de l'eau souterraine contenue dans la roche encaissante est encore à déterminer pour les besoins d'applications pratiques.

Dans la région d'Onikobe, les failles de la base de miocène et de granite conduisent les fluides à haute température des profondeurs aux couches supérieures de pliocène, constituées par des roches poreuses, dans lesquelles l'eau souterraine fait apparaître un système géothermique par convection comparable à celui de la région de Wairakei, en Nouvelle-Zélande.

La zone de Matsukawa est constituée par un volcan complexe du quaternaire avec caldeira. Il repose sur la lave d'un autre volcan, constituée par de l'andésite, lequel couvre lui-même une base appartenant au tertiaire. Les fractures associées à la caldeira servent de conduits d'alimentation à la chaleur en provenance du magma profondément situé. Les fluides géothermiques sont conservés dans les couches poreuses du tertiaire le plus superficiel et recouverts d'andésite du quaternaire, constituée essentiellement par des laves compactes et épaisses.

# METHODS USED IN EXPLORING GEOTHERMAL FIELDS IN JAPAN, WITH PARTICULAR REFERENCE TO GEOPHYSICAL METHODS, THEIR ROLE AND RESULTS

*Dr. Konosuke Sato**

In Japan, the volcanic zone extends along and across the islands of the country. There are many active and dormant volcanoes, fumaroles and hot springs.

In 1947, the preliminary prospecting of geothermal fields was started by the staff of the Geological Survey Institute of Japan. In the early days, it was carried out at places near to natural fumaroles mainly by means of geological, geochemical and surface temperature surveys, but also in some areas by means of geophysical prospectings and investigation drillings in a shallow zone under the ground surface. Geophysical surveys of the shallow zone were conducted by the electric and magnetic methods and some indications regarding shallow geothermal alterations of rocks were observed. In these areas, some investigation drillings showed thermal indications. But these methods could prospect only the superficial features of the ground, not the deeper geothermal structures. Consequently when a few deeper wells were drilled in such areas, we could not get steam jets from the deeper levels, but only high temperature water from a relatively shallow level beneath the surface.

Thus the prospection of the deeper structures in geothermal areas became a serious problem to be explored. To solve this problem, it was necessary to make geological mappings to clarify the detailed structural features, some geophysical surveys for the deeper structures, and investigation drillings and well-loggings in the bore holes.

Recently at the Matsukawa geothermal field, detailed geological mappings, geophysical prospectings by means of seismic and electric resistivity methods and geophysical well-loggings were carried out to clarify the underground structure of this geothermal area. From these probes, we were able to obtain some information concerning the stratigraphic successions, faults in the nature of the rocks and hydrothermal alterations. Last year, two new wells were drilled to depths of 325 and 450 metres. Electric loggings were conducted at the time of the drillings and after the end of the drillings. The temperatures in the bore holes are now under observation.

* Geological Survey of Japan.

On the other hand, the volcanic structure has been explored from the standpoint of geothermal structure of some active volcanoes.

Showa-shinzan is a volcanic dome formed in the period from the end of 1943 to September 1945. During these years, as a result of magmatic intrusion at a shallow depth, part of some cultivated hilly land which lies at the north-eastern foot of the Usu volcano was subjected to gradual uplift. The final size of the dome is nearly 150 metres higher than the general elevation of the mountain roof and about 300 metres across the base. This particular volcano gave us a good field for the study of the nature of underground magmatic masses. From this viewpoint, the volcano has been under study since 1952 by the combined means of geological, geophysical (gravity, seismic, magnetic, electric, radioactive and geothermal) and geochemical methods. Besides the interesting results on basic science and research techniques, some underground structural indications that the dome-mass (with a high temperature of more than 800°C) continues downwards inside the roof mountain and extends to the south have been discovered by geophysical methods. But the geothermal condition at the contact of this high temperature mass and the ground water contained in the country rocks is the problem to be solved for practical purposes. Further explorations of the geothermal state are now expected.

Other prospecting was carried out at Oshima volcano, on a solitary island south of Tokyo. Oshima volcano is a composite active volcano with caldera. Mt. Mihara, the central cone, is within the caldera. There have been many volcanic activities of the main craters and this island has been covered with pyroclastic sediments.

Some geophysical research using the gravity and magnetic methods has been conducted in this volcano. From these investigations the situation of the magma reservoir is estimated to be at a depth of about two or three kilometres below the crater. But this volcano is covered by thick pyroclastic sediments and there is little water in the superficial layers, so that surface indications of underground heat, such as fumaroles and hot springs, are poor in this area, except in the crater itself.

The geothermal condition at the point of contact of the underground high temperature mass and the underground water is the problem to be solved in obtaining geothermal fluids. In order to clarify the presence of underground water in the pyroclastic sediments and the underground structures of the volcano, the electric resistivity method was employed in this area. From results of these explorations, the underground water within the caldera was discovered to be at a depth of more than 250 metres below the surface and the structures related with the caldera were clarified. Investigation drillings for underground water showed some thermal indications. This time we were able to get some hot springs from the investigation bore holes. Further progress of the investigations will clear up the geothermal condition in this volcano.

As described above, certain exploration surveys have been carried on in the geothermal areas of Japan. But these are still in a preliminary stage from the viewpoint of exploitation of geothermal energy. Further progress in the prospections is desirable.

## Exploration methods

In order to develop geothermal energy in Japan, the most important problem at present is to explore the underground geothermal conditions. Such a problem can be solved only by complex studies of various factors regarding the geothermal conditions. These factors are (*a*) temperature distribution, (*b*) hydrothermal alteration, (*c*) geological structure and rock features, (*d*) underground water, (*e*) magmatic intrusion or magma reservoirs, (*f*) the flow of fluids obtained by drillings and, (*g*) the chemical character of these fluids. To clarify these factors, exploration methods should be carried out systematically in accordance with

1. Surveys of shallow geothermal indications,
2. Geological mappings,
3. Geophysical methods and
4. Investigation drillings and well-loggings.

Surveys of shallow geothermal indications are the preliminary stage of prospection of geothermal fields. In these surveys, surface temperature, geochemical and simple geological survey are the most common methods. Sometimes simple geophysical surveys and shallow drillings are used to add more information. But results of these surveys reveal only the superficial features of the geothermal fields. In the early days of geothermal prospection of Japan, prospection was limited to surveys of shallow geothermal indications but not followed through with further systematic surveys.

To clarify underground geothermal structure, geological mappings in the geothermal fields and surrounding areas are an important method. Geological mappings are useful in elucidating structural features such as stratigraphic successions, folds, faults, joints and rock characteristics. Geological sheet maps (scale 1:50 000) have been used as geological data in exploring geothermal fields in Japan but, in some areas, detailed geological mappings (scale 1:10 000) were carried out especially for the purpose of geothermal prospection.

Geophysical methods will play an important role in the prospection of underground geothermal conditions. Geophysical methods have been used not only for the prospection of the underground structure, but also to discover geothermal indications and water.

Geophysical methods are useful in clarifying underground structures. These methods are very familiar in the oil fields, but there are some difficulties in the case of the geothermal fields as compared with the oil fields. Ordinarily in Japan, geothermal fields are situated in volcanic regions, so the topography and surface irregularities have restricted the efficiency and the results of these surveys. But if we could use suitable survey methods for the volcanic areas and make minute observations, these handicaps could be overcome.

We have been able to carry out explorations for hydrothermal alterations and magmatic masses as a possible geothermal source by various geophysical methods, and also prospect the distribution of underground water in volcanic areas by the electric resistivity method. Ordinary geophysical surveys are conducted on the surface, except for airborne magnetic survey. The distribution of the observed values has been analysed. But in the case of active volcanoes, variations in the geophysical values may reveal information concerning magma reservoirs.

But we have not been able to explore the underground geothermal conditions adequately by surface surveys alone. It is necessary to drill some investigation wells in the surveyed areas. The temperature measurements in the well, electric and other well loggings and core sample analysis will give us some information concerning the underground geothermal conditions. If we could also obtain data regarding changes in the well conditions, more information would be available.

The results of surface and well surveys will reveal some of the underground geothermal features and will be used together with observation of the fluids obtained from drillings to aid the investigation in the evaluation of resources of geothermal energy.

## Geophysical methods

In the exploration of geothermal fields, geophysical methods are now expected to play a major role together with geophysical well-loggings. Up to now, geophysical methods have not been applied on a large scale, but only on an experimental scale. Some results obtained by geophysical methods have been effective for the exploration of geothermal fields, but on the other hand, there may be some difficulties in the survey techniques. These difficulties will be overcome in the course of technical improvements.

Next, the results obtained by geophysical methods and their role in the exploration of possible sources of geothermal energy will be explained.

### Electric resistivity method

The electric resistivity method has been applied in exploring the distribution of hydrothermal alteration of rocks, underground water and underground structures.

Some hydrothermal alterations of rocks show lower resistivity values when compared with other rocks. At places near natural fumaroles in the Kyushu district and Matsukawa geothermal area, we have measured the apparent resistivity to be less than 10 ohms-m by the resistivity method. The low resistivity zones have been estimated to be equivalent to argilized rocks saturated with hot-spring water.

At Showa-shinzan, we have not been able to find such a high-grade rock alteration area, but the resistivity value on the roof-mountain formed by magmatic intrusion shows about 10 ohms-m, namely, a very low resistivity, while the resistivity value at other places indicates rather high resistivity. This effect may be explained by the temperature and other factors.

In a geothermal area, it is important to elucidate the distribution of underground water. But it is not easy to trace underground water directly. Usually, we prospect the underground structures using the resistivity method, and from these results, presume the distribution of underground water. In an active volcanic area, covered with thick pyroclastic sediments, such as Oshima, it is possible to prospect for underground water directly by means of the resistivity method. The pyroclastic sediments show a very high resistivity value, but a relatively low value when they contain the water. Up to now, the resistivity method has been applied to explore the structure of several hundred metres underground in this volcanic area.

The resistivity method plays the principal role among the exploration methods for geothermal fields. Sometimes the hydrothermal alterations explored by this method correspond to geothermal indications, but this does not always indicate the existence of geothermal fluids. It is necessary to study these features together with other factors related to geothermal conditions.

### Seismic method

The seismic method has been applied in prospecting the underground structure, especially the distribution of underground magmatic masses.

The seismic method applied in the Matsukawa geothermal area is the reflection method using a magnetic tape-recording instrument. We were able to get reflection waves in the recorders from successions of a Neogene series and from the basement rock. But in the fractured zone, close to the caldera, no reflection waves were recorded. Thus, it may be possible to detect the fractured zone in such a volcanic area but, as the surface is covered with volcanic debris and the topography is steep, surveys of such a volcanic region are not so easy as in ordinary cases.

To study the nature and distribution of the underground magmatic mass, the seismic method was applied in the southern part of the dome of Showa-shinzan and the surrounding area. From these results, the velocities at the inner part of the dome were calculated as being nearly 4 km/sec. On the other hand, the velocity of longitudinal wave transmitting in a specimen of the new lava has been determined from the transmission times of ultrasonic impulses sent through them at the ordinary temperature and pressure. From this experiment, a velocity value of 2.5 km/sec. was obtained. We noted this large difference in velocity between the field and experimental data at the dome. From results of laboratory experiments, the value of Young's modulus for this rock at high temperature (about 800-900°C) is about twice that of the value at room temperature. Therefore, the velocity at high temperature becomes 1.4-1.5 times as great compared with room temperature conditions, if the density keeps its value during these stages. In other words, the velocity changes from 2.4 km/sec. (room temperature) to 4 km/sec. (800-900°C). Therefore, the field results may well be explained by supposing that the intruded magma in the dome is still very hot. This supposition is also supported by geothermal and geomagnetic surveys made there at the same time. Working on this assumption, it was discovered by the refraction and reflection methods that this high temperature mass continues downwards and extends to the south.

From these two examples, great hopes have arisen for exploring geothermal structures by the seismic method. But at present there are some difficulties in this method. The complicated features in the volcanic area create some difficulties in observation and interpretation. So it will be necessary to use suitable survey techniques for volcanic areas and to make minute observations.

There are several interesting phenomena concerning the activities of the magma in active volcanoes. Seismological investigations of volcanic earthquakes have been carried out at some active volcanoes in Japan. The distribution of the epicentres of shallow volcanic earthquakes has presented some interesting problems concerning their geothermal structure. These results are not yet widely used in practice, but the seismological observations of active volcanoes will become valuable as a method of exploring geothermal energy resources in future.

### Gravity method

The gravity method has been used for various purposes in exploring underground structures. But this method is apt to be affected by topographic irregularities, so it is not easy to apply in mountain regions. Ordinarily, the geothermal fields of Japan are situated in mountainous districts, so the applications of the gravity method to the geothermal fields have been restricted. But in the case of active volcanoes, such as Showa-shinzan and Oshima, the gravity method was applied to obtain data concerning the volcanic structure, and effective results were obtained once these difficulties had been overcome.

In the case of the gravity survey at Showa-shinzan, it was necessary to ascertain the density distribution for topographic correction and the vertical gradient of gravity for free-air reduction. By careful attention to these two points, we were able to obtain a reasonable evaluation of Bouguer anomalies in this area. From these results, the gravity anomaly at the dome of Showa-shinzan is shown to be the largest one and a clear high gravity zone at the southern part of the roof-mountain has been ascertained. These anomalies were supported by seismic surveys made there at the same time. Another survey, by means of the gravity method, was conducted during the recent activity of the Oshima volcano at four different times between September 1950 and April 1951. Gravity measurements were taken at more than 50 widely distributed stations. Consideration was given to the vertical displacement effected by the eruptions, and levelling surveys using a Wild universal theodolite were conducted three times. These elevation changes, corresponding to 0.07 milligales in gravity effect, are negligible in relation to the observed changes in gravity. Changes in gravity values were observed during the activity of this volcano, and these were correlated with changes in the subterranean mass distribution. Maximum changes in gravity values were about 0.3 mgal within the caldera. The situation of these mass changes was estimated to be at a depth about two kilometres beneath the surface.

### Magnetic method

The magnetic method is possible if there exists a distinct magnetic contrast between various rocks. Actual attempts to learn about the depth of the base of a volcano or to distinguish hidden dykes or craters from other surrounding sediments have been made. The intensity of magnetization in volcanic rocks is not very strong, but it is stronger than that of other kinds of rocks. So, sometimes, these surveys are disturbed by the irregular surface distribution of volcanic rocks, but these handicaps could be overcome by airborne magnetic survey. Some experimental airborne surveys have been carried out in Japan using a flux-gate magnetometer and a proton magnetometer.

The magnetization of volcanic rocks was found to result mainly from the thermo-remnant magnetism and partly from the induced magnetism of ferromagnetic minerals contained in the rock themselves. This magnetization decreases with heating and disappears when the temperature exceeds the Curie point (Ca 600°C). These factors may be used to determine the underground structure of high temperature masses. The possibility that anomalous change in the earth's crust at the time of volcanic eruption might be accompanied by some anomalous change in the geomagnetic field has been considered. Reliable data wete obtained at the Oshima volcano on the occasion of its eruptive activity beginning in 1950. Magnetic dip-surveys were carried out repeatedly over the volcano at various stages of the eruption. In comparing these results, it is assumed that the magnetic change corresponds to the demagnetization of the spherical volume of 2 km radius which is situated 5 km beneath the caldera of the volcano.

A magnetic survey was also carried out at Showa-shinzan, which is thought to be a hot mass with a high temperature of more than 800°C. The value of the vertical magnetic component at the dome of Showa-shinzan is rather small compared with that of the adjacent area, and dip observation also shows a very weak value there. On the contrary, at the Ousu dome which is already cold, we obtained a strong dip value. Judging from these data, we may presume that the northern part of the dome is not magnetized, because it may have a high temperature condition beyond Curie point. This assumption does not contradict the results obtained by gravity and seismic survey. But it is rather difficult to calculate the underground structure in these volcanic regions clearly by surface magnetic survey alone, because of the topographic effect.

Volcanic rocks may be altered by hydrothermal action. In some geothermal fields in Japan, there is some distribution of hydrothermally altered rocks. The magnetization of these rocks decreases with the diminution of the ferromagnetic minerals in the rocks as a result of hydrothermal alterations. When we surveyed at the geothermal fields in Kyushu, the value of the vertical magnetic component was observed to be rather small at the hydrothermally altered area compared with the adjacent area.

## Conclusion

In Japan, there are many volcanoes, fumaroles and hot springs, but we have not yet succeeded in developing the valuable geothermal energy for power generation. It will be not easy to estimate the underground geothermal condition from the superficial geothermal features alone. Therefore, exploration of underground geothermal features will be the most important problem in any geothermal investigation.

It is my opinion that geophysical methods of exploration play the principal role in dealing with this problem, .together with the surveys made through investigation drillings. In this report, I have shown some of the possibilities for the prospection of geothermal fields by geophysical methods, although there may be some difficulties. If we could develop our knowledge regarding underground geothermal features of the thermal state in the upper part of the crust and of techniques of exploration in geothermal fields, it would be possible to obtain more information concerning underground geothermal conditions and then develop the valuable resources of geothermal energy in Japan.


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## *Summary*

In Japan, there are many volcanoes, fumaroles, and hot springs. Some prospecting has already been carried out in the geothermal fields, but we have not yet succeeded in developing the valuable geothermal energy for power generation. So the search for underground geothermal structures is one of the most important problems in Japan. Such a problem can only be solved by complex studies of various factors related to geothermal conditions. To clarify these factors, exploration should be carried out systematically in accordance with surveys indicating superficial geothermal features, geological mappings, geophysical methods and investigation drillings and well-loggings.

Among these methods, geophysical methods are expected to play the principal role, together with geophysical well-loggings. These results will be useful to our investigation to evaluate geothermal energy, together with observation of the fluids obtained from drillings.

Until now, geophysical methods have been conducted on an experimental scale in Japan, but some results have proved useful for the exploration of geothermal fields. The electric resistivity method has been applied to explore the distribution of hydrothermal alternating rock, underground water and other structures and plays the principal role among the methods of exploring geothermal fields in Japan. The seismic method has been applied to prospect underground structures, notably, the distribution of the high temperature magmatic mass in Showa-Shinzan. There were great hopes for exploring geothermal structures by the seismic method, but now there appear to be some difficulties in the method. So it will be necessary to use suitable survey techniques and to make minute observations. The gravity method is apt to be affected by topographic irregularities, so the applications of the gravity method to geothermal fields have been restricted.

But in the case of active volcanoes, the gravity method was applied to obtain data concerning the volcanic structures and effective results were obtained after overcoming some difficulties. The magnetic method is restricted by the surface irregularities of volcanic rocks in the geothermal fields, but these handicaps may be overcome by an airborne survey. The magnetic method has been used to explore underground structures, particularly in the case of underground high temperature masses and hydrothermal alteration of rocks. I have indicated some of the possibilities in prospecting geothermal fields, although there may be some difficulties. If we could develop our knowledge of geothermal structures, research into thermal conditions and techniques of exploration, it would be possible to obtain more information and thus develop the valuable geothermal energy in Japan.


# RÔLE DES MÉTHODES DE PROSPECTION, PARTICULIÈREMENT D'ORDRE GÉOPHYSIQUE, ET RÉSULTATS OBTENUS DANS LES CHAMPS GÉOTHERMIQUES JAPONAIS


## *Résumé*

On trouve, au Japon, beaucoup de volcans, de fumerolles et de sources chaudes. On a procédé à quelques explorations dans les champs géothermiques mais on n'a pas réussi, jusqu'à présent, à mettre en œuvre l'énergie géothermique si précieuse pour la production de force motrice. C'est-à-dire que les recherches visant à trouver les formations géothermiques souterraines représentent l'un des problèmes les plus importants qui se posent au Japon. Ce problème ne peut être résolu que par l'étude complexe des divers éléments qui interviennent dans les situations où se manifeste une activité géothermique. Pour rendre plus clairs ces éléments, on doit procéder à des prospections systématiques conformes aux indications fournies par des enquêtes sur l'activité géothermique superficielle, les cartes géologiques, les techniques géophysiques, les sondages et les carottages.

Dans ce cadre, ce sont les méthodes géophysiques qui semblent devoir jouer le rôle principal, avec les

carottages géophysiques. Les résultats en seront exploités dans nos études en vue d'évaluer l'énergie géothermique en liaison avec les constatations faites sur les fluides prélevés au cours des sondages.

Jusqu'à présent, les travaux géophysiques ont été menés, au Japon, à l'échelle expérimentale, mais certains de leurs résultats présentent de la valeur pour la prospection des champs géothermiques. La méthode de la résistivité électrique a été appliquée pour étudier la répartition des roches altérées par l'activité hydrothermique, les eaux souterraines et autres formations; elle joue le rôle principal dans les techniques de prospection utilisées pour les champs géothermiques du Japon. La méthode séismologique a été appliquée à l'exploration des structures souterraines dans un cas spécial, celui de la répartition de la masse magmatique à haute température de Showa-Shinzan. On compte beaucoup sur les résultats de ces travaux pour l'étude des structures géothermiques, mais on reconnaît maintenant que l'emploi de cette méthode se heurte à quelques difficultés. Il sera donc nécessaire d'avoir recours à des méthodes de prospection convenables et de faire des observations très détaillées. La détermination des variations de la pesanteur est sensible aux irrégularités du relief, si bien que son application aux champs géothermiques est limitée.

On y fait appel toutefois, pour les volcans en activité, pour se procurer des données ayant trait aux structures volcaniques et on a pu obtenir des résultats satisfaisants après avoir surmonté certaines difficultés. La méthode magnétique est limitée par les irrégularités superficielles de roches volcaniques dans les champs géothermiques, mais ces inconvénients peuvent être surmontés à l'aide d'un levé aérien. La méthode magnétique a été utilisée pour l'exploration des structures souterraines, dans un cas spécial, celui des masses souterraines de roches à haute température avec altération hydrothermique. L'auteur indique certaines des possibilités de prospection des champs géothermiques, sans perdre de vue les difficultés. Si l'on réussit à développer les connaissances actuelles sur les formations géothermiques, la recherche sur les états thermiques et la technique de la prospection, il deviendra possible de recueillir des renseignements plus complets et de mettre en œuvre la précieuse énergie géothermique disponible au Japon.

# GEOPHYSICAL PROSPECTING IN NEW ZEALAND'S HYDROTHERMAL FIELDS

*F. E. Studt**

Geophysical prospecting has met with varying success in New Zealand's hydrothermal fields. This is to be expected, considering the varied character of the fields and the wide variety of problems to which geophysics may be applied. The fields range in character from the highly superheated steam vents of White Island to the slightly superheated steam vents of Ketetahi and Karapiti, the boiling water systems of Wairakei and Kawerau, and the warm waters of Helensville and Awakeri. Prospecting may be employed in searching for heat, for steam and gas, for hot and mineralized water, for hydrothermal alteration, for magmatic intrusions, for suitable aquifers and structures, or simply for geological background.

No methods used in this country have yet discovered useful resources far beyond the limits of the visibly active hydrothermal fields. The value of geophysics lies in its contribution to the knowledge and understanding of the known fields and its help in formulating drilling and management policies, but only to a minor extent in locating unseen extensions of the known fields. This is no reflection on the ability of the methods to locate such resources. It is a consequence of permeability of the host rocks, which permits the hot fluids to rise along near-vertical paths, so that adequate deep resources are found beneath the surface exposures.

The great thickness of more or less permeable rocks through which the hot fluids pass hinders the effective penetration of geophysical prospecting, for it enables these fluids to spread out and displace cold ground water at any slightly impeding layer, and especially at the water table. This interposes a layer of hot water, which in many ways acts as a shield, limiting the power of geophysics to probe deeper in the search for aquifers or feed zones carrying high-enthalpy resources. This is most obvious in electrical prospecting, where hot saline water actually does constitute a shield, but it also affects magnetic prospecting through hydrothermal alteration, gravity prospecting through mineral deposition, and seismic prospecting through the associated high noise level and energy dissipation.

In fields where hot water emerges through well-defined passages in massive rocks, or where the fluid is superheated steam, some of these difficulties would probably not apply, but in New Zealand such fields are of small economic importance. This is one reason why electrical methods which have been used in Iceland and Italy have had limited value in New Zealand.

It is expected that exploitation may ultimately destroy the shielding to some extent at Wairakei, and the later state of the field might permit deeper penetration. This would help in the location of feed zones, but by that time these zones will probably have been found by hydrological studies.

Some examples will be given of successful, as well as unsuccessful, applications in New Zealand. Temperature and heat flow surveys are omitted, however. They are the most frequently used studies, and are described by Thompson and others. All the work has been carried out by the Geophysics Division of the New Zealand Department of Scientific and Industrial Research. Field parties of up to 20 men have been based on Rotorua, Taupo and Te Teko. At present, a party of 6 is based at Wairakei, with laboratory, workshop and office facilities on the project. This party is engaged on heat flow, hydrology and related problems. Other investigations are made by field parties sent out from headquarters in Wellington.

## Structural setting

Gravity and aeromagnetic regional surveys have contributed to the geological background of the hydrothermal fields. The basement rocks are dense but practically non-magnetic, while most of the overlying volcanic rocks have low density and those that are dense have high magnetic polarisation. The two surveys are thus complementary.

Gravity surveys have been made with North American and Worden gravity meters. Elevations were usually measured by altimeter and anomalies computed to the nearest milligal; station spacing was $\frac{1}{2}$ to 2 miles. Bouguer anomalies are corrected for regional anomaly, in order to remove all variations of gravity originating below the basement. The correction is computed from observations made on basement rocks in the surrounding country. The initial interpretation is generally made with a two-layer model, assuming a dense basement and light volcanic cover. This is then examined for consistency with the aero-magnetic map, which indicates areas where dense volcanics should be introduced into the cover. Aeromagnetic instrumentation has been described by Gerard and Lawrie (1). Total force contour maps were drawn from flights at 5 000 ft above sea level, 3 000 to 4 000 ft above

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ground level. A general description of the regional work and its interpretation in the central part of the volcanic belt is given in Modriniak and Studt (2).

A few of the hydrothermal fields are obviously located on important faults, and the geophysical work suggests that many others are so located. This is a more fundamental association than the commonly observed alignment of hot springs and steaming ground along recent minor fault traces, and it might be used as a guide if it is ever necessary to prospect for hot water outside the known fields. At present this does not appear advisable, because almost all measurements in holes drilled for various purposes outside the hydrothermal fields have shown zero thermal gradient. This implies that within the structural basins there is widespread downward percolation of ground water, which returns to the surface in the hot springs. The regional gravity survey gives the depth to the basement, which is probably the depth of such convective circulation. It is usually so great as to make prospecting unattractive at the present stage.

## Formation mapping

Anomalies up to 60 mgal and 1 000 gamma were encountered in the regional surveys described above, and these can be usefully mapped without great precision. Such surveys are not suitable for detailed interpretation, however, and where detail was required more precise methods have been employed.

Seismic refraction and reflection profiles with 24-channel equipment were used to map rhyolite sheets at Wairakei and Kawerau, and ignimbrite in the Reporoa Valley. Good velocity contrast often exists between such rocks and the pumice breccia, but the efficiency of shots fired in the breccia is not great. It has been found that exceptionally high noise levels accompany hydrothermal activity. It is also found that geophones placed in active areas often fail to record refracted and reflected seismic waves. This is thought to be due to the damping or dispersive effect of steam or gas bubbles at the water table.

Gravity surveys have been made with the same instruments as the regional survey, but with closely spaced and accurately levelled stations. Such work has occasionally shown minor positive anomalies, so closely coinciding with the known hot area that the two are probably genetically related. It is not at present certain, however, whether these anomalies are due to buried magmatic bodies, or to the filling of pore spaces in the rocks by minerals carried in solution in the hot water.

## Hydrothermal alteration

Low magnetic field intensity is usually recorded in the New Zealand hydrothermal fields, and for this reason vertical force magnetic balances have been widely used. These are adjusted to a sensitivity of about 30 gamma per scale division. Stations are spaced $\frac{1}{4}$ to $\frac{1}{2}$ mile apart, and repeat observations are made at selected points, in order to adjust for diurnal variation and drift. The surveys are tied to absolute magnetic bases, in order that they may be compared with one another and with aeromagnetic work. Terrain corrections are only applied if the rocks exposed at the surface are highly polarised.

Figure 1 shows a magnetic survey of the Tikitere field, in which hot water rises through pumice sands overlying vesicular rhyolite with a polarisation of $2\,000 \times 10^{-6}$ cgs units. It will be seen that practically all the hot springs are confined to a belt of low magnetic intensity, the anomaly in this instance being about —200 gamma. The Tikitere rhyolite is probably not very thick, and much larger anomalies are recorded in some of the other fields. It has been established that such anomalies are due to the conversion of magnetite ($Fe_3O_4$) to pyrite ($FeS_2$) in place in the rocks, due to the concentration of $H_2S$ carried in solution in the hot water (Foster (3), Studt (4)). Since this gas is not found outside the hydrothermal fields, the magnetic anomaly may be used to indicate the extent of the field. It must, of course, be remembered that low magnetic intensity may be due to absence of magnetite as well as to its conversion to pyrite, also, that the pyrite may be a relic of an old hydrothermal system no longer in operation.

The Wairakei magnetic survey was abnormal because low intensities were recorded in the western half of the field but not in the east. It was therefore predicted that a highly magnetic rock (ignimbrite) was present in the east, below the hot aquifer. This in turn implied that the $H_2S$ concentration and probably also the temperature would be rather lower in the ignimbrite than in the aquifer above. Drilling has confirmed this, and it has therefore been argued that the source of most of the hot water in the aquifer lies to the west of the present production area, where the magnetic intensity is low. According to this theory, the drillholes tap hot water which percolates eastward through the aquifer from this western source.

Hydrothermal alteration has, on the other hand, prevented the use of magnetic methods to discriminate between alternative interpretations of small gravity anomalies in some fields. The replacement of magnetite frequently approaches 100 per cent, so that andesites discovered by drilling at Wairakei, Waiotapu and Kawerau have little magnetic polarisation, and are indistinguishable geophysically from heavily silicified breccias.

## Steam

Although little work has been done on highly superheated steam or gas fumaroles in this country, there are slightly superheated steam vents and underground steam zones in some of the explored fields. Resistivity tests near the Karapiti fumarole showed that there was water at shallow depth despite the superheat in the discharge. Probably all such steam results from the boiling of hot water as it encounters progressively lower pressures on its way toward the surface. There are varying proportions of steam in the different fields, and that at Wairakei is gradually increasing as hydrostatic pressures are reduced by exploitation (5). The steam travels upwards, and tends to accumulate beneath relatively impermeable layers, or in pockets within these. By drilling to tap the formation immediately beneath such a layer, dry steam or a high enthalpy steam-water mixture is often obtained. The geophysical location of such layers may therefore be valuable.

The presence of an extensive steam reservoir beneath rhyolite sheets in the southern extension of the Wairakei field was postulated as a result of early reflection seismic studies. Interval velocity profiles, computed from the reflection data, consistently showed very low velocities at a depth of about 2 500 ft. The velocities were even smaller than the lowest values recorded in uncompacted water-saturated sediments, despite the depth; therefore it was argued that the rocks were not water-saturated, but contained steam. This type of computation is subject to great inaccuracies, but the consistency of the results suggested a steam reservoir. Early drilling gave disappointing results, although temperatures as high as 244°C were recorded, and the hydrothermal alteration found in the drill cores was intense. A more recent hole in this vicinity has tapped a voluminous flow of dry steam from an open fracture in the rhyolite.

## Hot and mineral water

Of all the conventional geophysical tools, resistivity surveying appears the most appropriate for

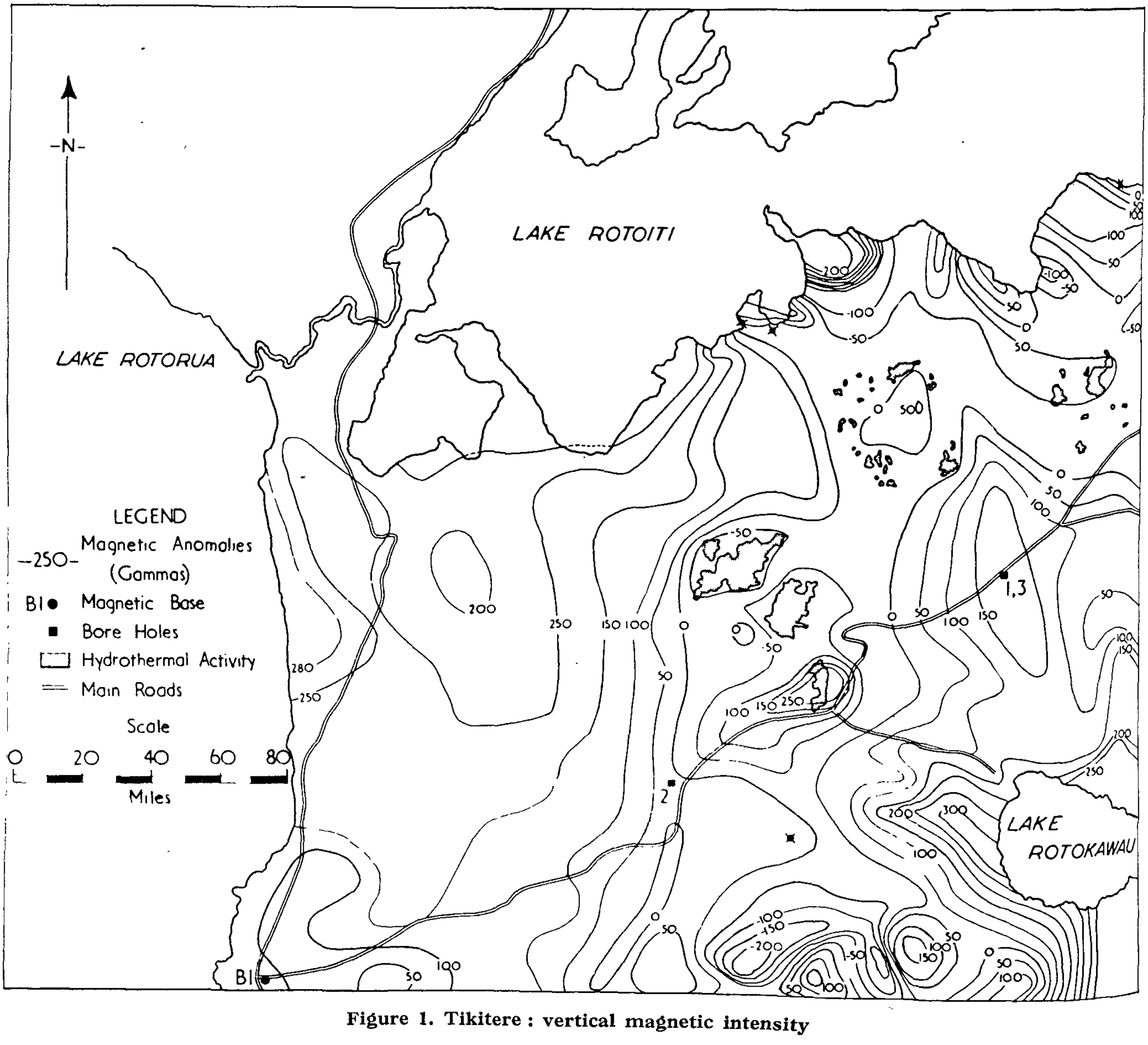


Figure 1. Tikitere : vertical magnetic intensity

hydrothermal work, since formation resistivity is sensitive to the temperature and salinity of the interstitial water. Many of New Zealand's hot waters contain chlorides, but some carry sulphides, which also reduce the resistivity, and others carry bicarbonates, which do not.

The Wenner system has usually been adopted, with a commutated DC supply and equally spaced iron electrodes driven a few inches into the ground. Contact resistance in the pumice soils is frequently very high, and for electrode separations greater than 200 or 300 ft, high applied voltages have been used, with sheet iron electrodes, wetted down with salt solution. Such attempts at deep penetration, however, have yielded little information. The technique has usually been to use expanding spreads only to indicate the electrode spacing which offers the greatest contrast in apparent resistivity between known hot and cold country. The field is then traversed with this fixed spread. This method simply maps hot and saline conditions at the water table. Its only advantage compared with the soil temperature survey is that of speed in easy terrain; the interpretation is less straightforward.

The mapping of an extension to the Kawerau field, which has since been exploited for industrial purposes, has been described (6). Similar results have been obtained at Rotorua and Ohaki, but at Wairakei this method had little success on account of variations in geology, porosity and salinity, all of which complicate the interpretation. At Kawerau, with 100 ft electrode spacing, there was a mean contrast of 10:1 in apparent resistivity of hot and cold country (60 and 600 ohm-metres). The transition from one to the other was gradual, reflecting the gradual drop in temperature and salinity on the margins of the field. For purposes of exploitation, 150 ohm-metres was selected as an arbitrary boundary to the field, but in any other field this would depend on the local salinity and porosity conditions, as well as temperature.

## Electric well logging

Resistivity and natural potential logs were run in one or two drillholes at Wairakei with experimental equipment. Comparison of potential logs made with the hole shut-in and partially discharging showed important differences at certain horizons, probably related to the points of entry of water into the hole (figure 2).

Despite its early promise, this work was later abandoned because the rubber insulated cables were unable to withstand the physical and chemical conditions in the hotter drillholes. The insulation deteriorated rapidly at high temperature; moreover gas, absorbed while in the hole, caused whole lengths of cable to burst on withdrawal. With the exception of the metal sheathed type of cable (which is useless for electric logging since it short-circuits the current

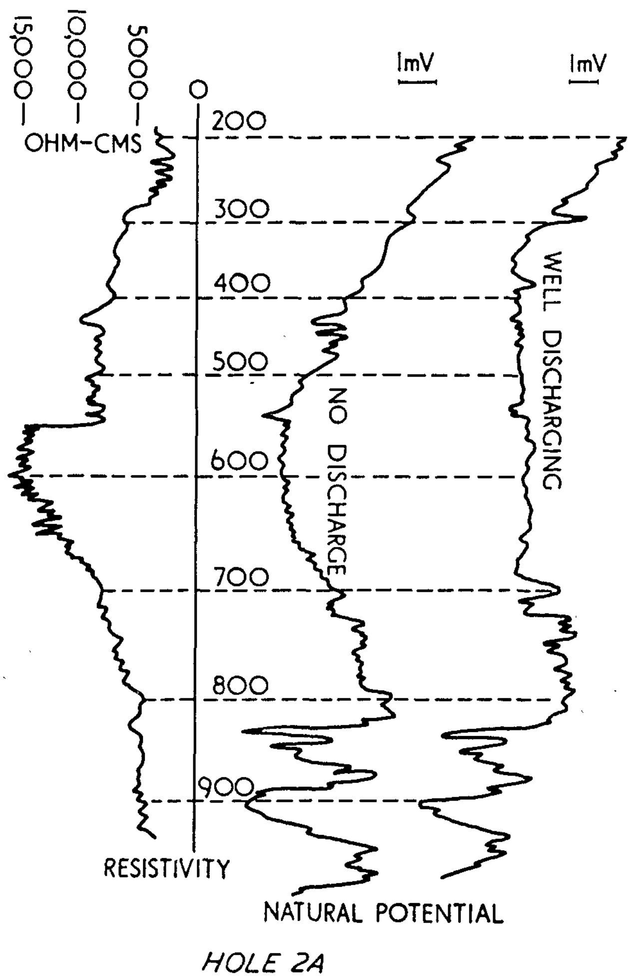


**Figure 2. Electrical logs of a Wairakei drillhole**

paths through the rocks) none has yet been found which is satisfactory for geothermal work. It is, of course, possible to make certain measurements immediately after pumping cold water, while the hole is still cool. But since many holes return to 200°C and above within an hour or so, the time available is very limited. At present the best indication of feed zones comes from bathythermograph data, but the lack of a cable suitable for electric well logging in hydrothermal fields is un undoubted handicap.

## Conclusion

Enough has probably been said to stress the axiom that no two hydrothermal fields are alike, and that a geophysical survey which has proved of value at one may be useless at the next. Each problem must be considered on its merits and any survey which promises to contribute to the understanding of the hydrothermal system should be used. If these serve only to eliminate a small proportion of unproductive drilling, they will have paid their way.

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### *Summary*

Hydrothermal fields differ so greatly in character and environment that geophysical methods meet with varying success in prospecting for steam or hot water. In some cases there is difficulty in applying geophysical techniques and in others there is difficulty in interpretation.

Owing to the permeability of the rocks, most New Zealand fields yield wet steam and little work has been done on dry steam fields. The permeability of the rocks also results in usable hot water being often found by drilling close to the hot springs or fumaroles, so that much small-scale exploitation has been possible without the help of prospecting. Geophysics has been employed in mapping the limits of such fields, but its main uses have been in the study of the geological background, or in the attempt to penetrate beneath the shallow reservoir to locate deeper aquifers or feed channels.

Gravity surveys are primarily used to indicate the basement structure and are not very detailed, but minor positive anomalies have been found, coinciding with some fields, which probably indicate intrusive rocks genetically associated with the hot water.

The basement rocks are only weakly magnetised, and magnetic surveys therefore indicate the distribution of magnetic rocks within the overburden. Detailed surveys are of value, since hydrothermal alteration converts the magnetite in the rocks to pyrite, thus weakening the magnetic field. This has enabled useful deductions to be made about the source of the Wairakei hot water.

Resistivity surveys, designed to map the distribution of hot water at the water table, have been successful in uniform geological conditions, but the interpretation is liable to be complicated by porosity and salinity variations. Deep penetration is hampered by the shielding effect of hot water near the surface.

Seismic refraction surveys have located cap rocks in some fields. Reflection work at Wairakei showed very low seismic velocities, suggesting steam in the rocks in place of water, and dry steam has since been tapped in this area. Seismic work in hydrothermal fields is handicapped by very high natural noise levels and energy dissipation.

Early attempts at well-logging showed promise of locating producing horizons by comparing natural potential logs run under standing and flowing conditions. Similar work on deeper and hotter holes is prevented by the inability of insulated cables to withstand the physical and chemical conditions in geothermal drillholes.

## PROSPECTION GÉOPHYSIQUE DANS LES CHAMPS HYDROTHERMIQUES DE LA NOUVELLE-ZÉLANDE

### *Résumé*

Les champs hydrothermiques présentent de telles différences de caractère et de milieu que le succès des méthodes géophysiques est assez variable en ce qui concerne la prospection de champs hydrothermiques (vapeur ou eau chaude). Dans certains cas, les techniques géophysiques sont difficiles à appliquer, dans d'autres, la difficulté réside dans l'interprétation.

A cause de la perméabilité des roches, la majorité des champs de Nouvelle-Zélande donne de la vapeur humide et il y a eu peu de travail de fait dans les gîtes donnant de la vapeur sèche. La perméabilité des roches donne également pour résultat que l'eau chaude utilisable est souvent trouvée en fonçant un puits près de fumerolles ou des sources chaudes, si bien que beaucoup d'exploitations à petite échelle ont été possibles sans l'aide de prospection. On a eu recours à la géophysique pour le relevé des limites de ces champs, mais ses principales applications ont été l'étude des considérations géologiques de

base, ou des tentatives visant à pénétrer plus bas que le réservoir peu profond, pour trouver des aquifères plus profonds ou des canaux d'alimentation.

Les études sur les variations de la pesanteur sont utilisées au premier chef pour indiquer la nature de la structure de base et elles ne sont pas très détaillées, mais on a découvert certaines anomalies positives peu importantes qui coïncident avec certains champs, ce qui probablement indiquerait l'existence de roches intrusives génétiquement associées avec l'eau chaude.

Les roches de base ne sont que légèrement magnétisées et les recherches d'ordre magnétique indiquent donc la répartition des roches magnétiques à l'intérieur de la roche de couverture. Les relevés détaillés ont de la valeur, car l'altération hydrothermique convertit la magnétite des roches en pyrite, ce qui affaiblit le champ magnétique. Cela a permis de réaliser des déductions utiles sur la source des eaux chaudes de Wairakei.

Les programmes d'étude de la résistivité visant à relever la répartition de l'eau chaude au niveau de la nappe ont réussi dans des conditions géophysiques uniformes, mais l'interprétation en est sujette à des complications dues à la porosité et aux variations de la salinité. Une pénétration profonde est gênée par l'effet de blindage de l'eau chaude près de la surface.

Les études de réfraction sismique ont déterminé la présence de roches de couverture dans certains champs. Les travaux sur la réflexion à Wairakei ont indiqué des vitesses sismiques très faibles, suggérant qu'il y avait de la vapeur dans les roches au lieu et place de l'eau, et depuis lors, on a réussi à extraire de la vapeur sèche de cette région. Les travaux sismiques dans les champs géothermiques sont gênés par les bruits naturels très violents et la dissipation de l'énergie.

Les premières tentatives en vue d'établir des profils de sondage ont permis d'espérer qu'il serait possible de situer les horizons productifs en comparant les profils naturels dans des conditions statiques d'écoulement. Les travaux analogues sur des trous plus profonds et plus chauds ne sont pas possibles car les câbles isolés ne peuvent pas résister aux conditions physiques et chimiques présentes dans les puits géothermiques.

# PROSPECTING OF HYDROTHERMAL AREAS BY SURFACE THERMAL SURVEYS

*G. E. K. Thompson, C. J. Banwell, G. B. Dawson and D. J. Dickinson**

The present paper deals mainly with the methods of thermal mapping and heat flow measurement that have been developed in the New Zealand Thermal Area, and with the results obtained. A discussion of their interpretation and use for the guidance of drilling programmes will be given by one of the authors (C. J. Banwell) in another paper in this series (1).

The general purposes of these surveys are threefold:

1. To provide, rapidly and inexpensively, a map showing the size and distribution of areas of surface heat flow associated with the hydrothermal system under investigation. Maps of this kind have proved

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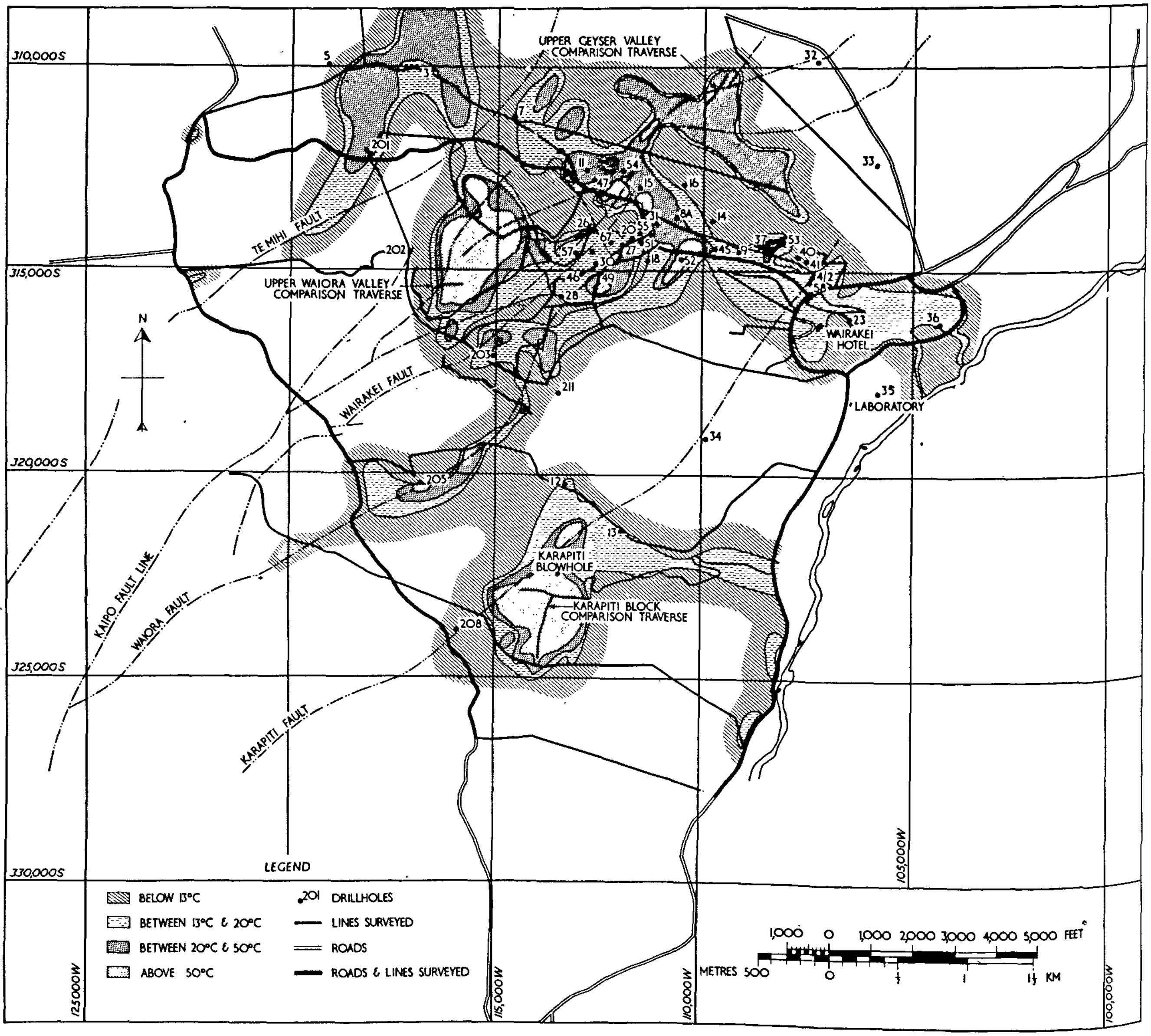



**Figure 1. Isotherms at one-metre depth, Wairakei, 1958**

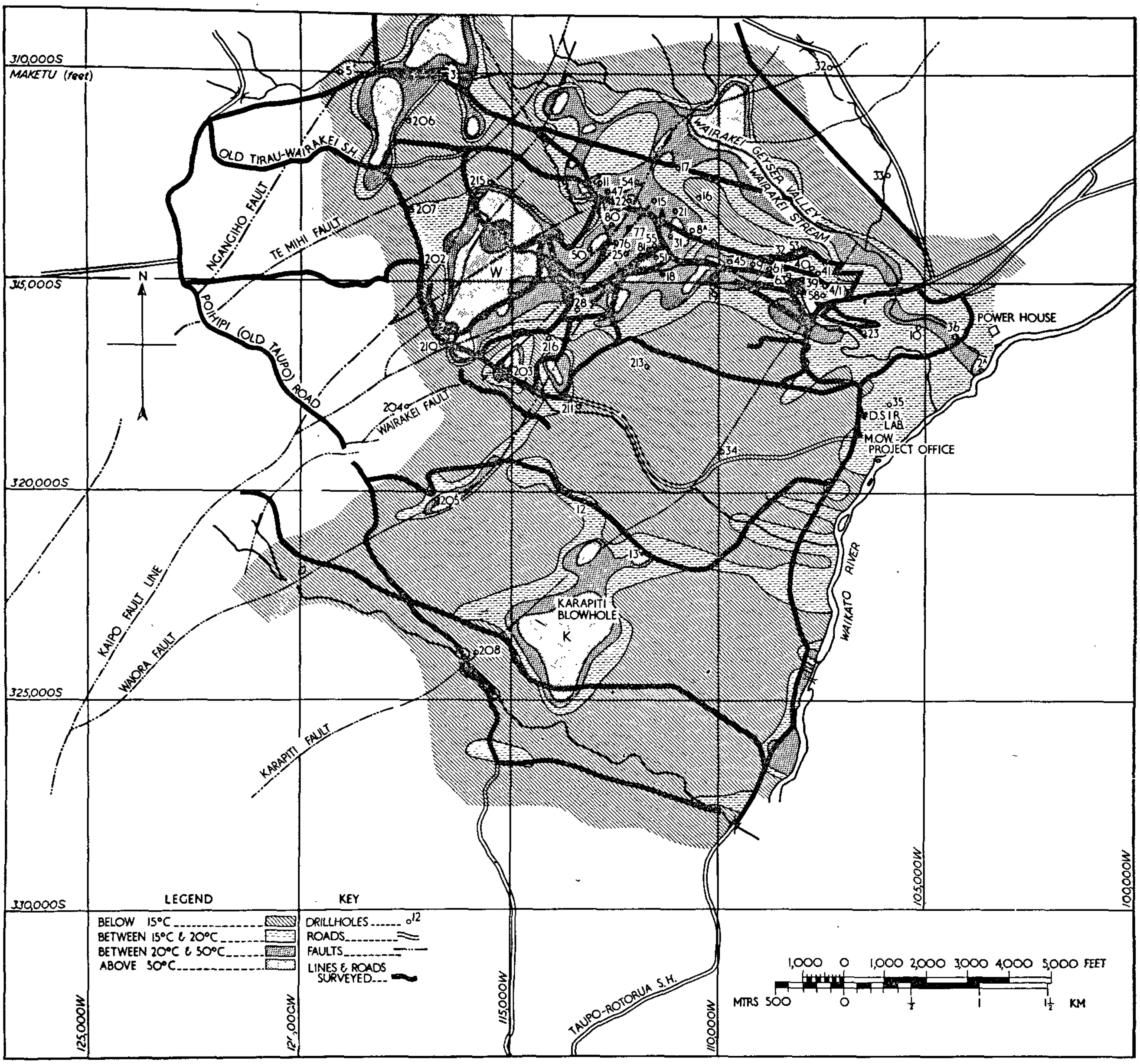



**Figure 2. Isotherms at one-metre depth, Wairakei, 1960**

of value for providing an initial indication of the effective limits of the system to be explored by drilling, and of the areas to be covered by the more detailed heat flow surveys. Taken in conjunction with the results of the heat flow survey, a knowledge of the area of hot ground also gives a useful preliminary indication of the power potential that may be available.

2. To provide as accurate determinations as possible of the total natural heat and mass discharge from the area, if possible before the commencement of exploitation, and of the variations in these quantities during the course of exploitation.

3. To provide a record of variations with time of surface thermal activity as exploitation for power production proceeds, by means of surveys repeated at suitable intervals.

## Surface temperature mapping—one-metre probe survey

Temperature observations at shallow depths will be subject to disturbances which will tend to obscure the desired pattern, especially near the boundaries of the hydrothermal system where the temperatures are little higher than those outside the system. These disturbances are caused by seasonal and diurnal climatic variations, rainfall, etc., and they vary with soil type. Since the amplitude of temperature disturbances of surface origin diminishes exponen-

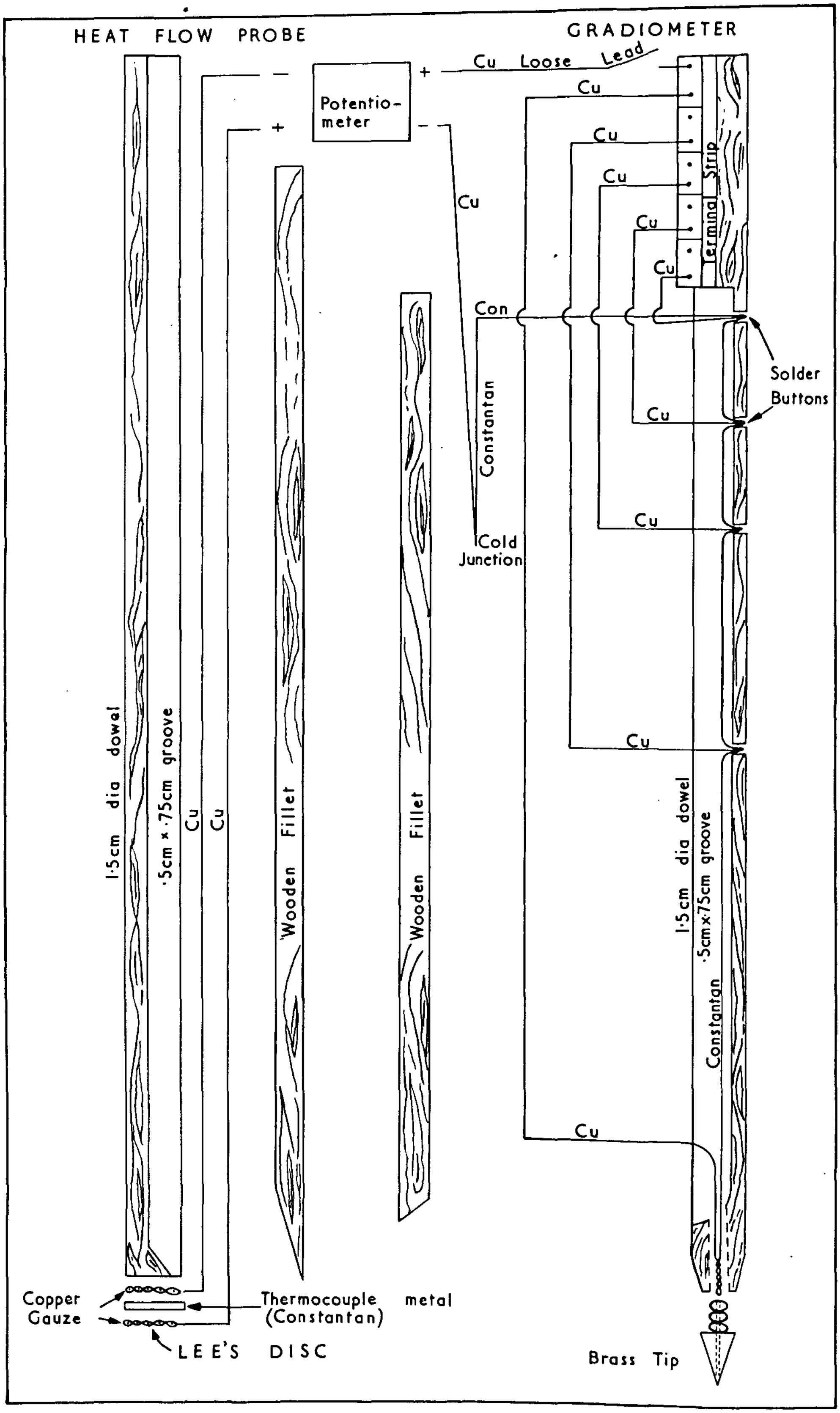



Figure 3. Heat flow and gradiometer probes

tially with depth, these effects can be reduced to any desired level by choosing a great enough depth for the measurements, but with the disadvantage that the need for deeper holes will reduce the speed and increase the cost of the survey. In the New Zealand pumice soils which cover most of the New Zealand Thermal Area, a depth of one metre for the measurements represents a satisfactory compromise. The amplitude of diurnal temperature variations is negligible, while the amplitude of variations with periods from a week to a month seldom exceeds 0.3°C at any site. The range of seasonal variation at one metre may reach 9°C at exposed sites. It is discussed below.

## Planning and conduct of one-metre survey

Experience from extensive surveys in the Wairakei and Waiotapu thermal areas shows that the scatter in temperatures recorded at one metre depth is such that 1°C above normal is the smallest rise that can be regarded as significant, and this has been chosen as defining the area to be mapped. Within this boundary there may be fumaroles and steaming ground and there is little advantage in carrying the one metre survey into the vicinity of these, where temperatures at one metre are generally close to the boiling point. Such areas are in any case more readily mapped in the course of the heat flow survey to be dealt with below. A convenient common boundary for these two surveys is marked by a temperature of 50°C at one metre, so that the one metre survey is only required to examine the areas where the temperature lies between an upper limit of 50°C and a lower limit of 1°C above ambient. The upper limit has not been referred to ambient temperature because it is found that seasonal variations of tem-

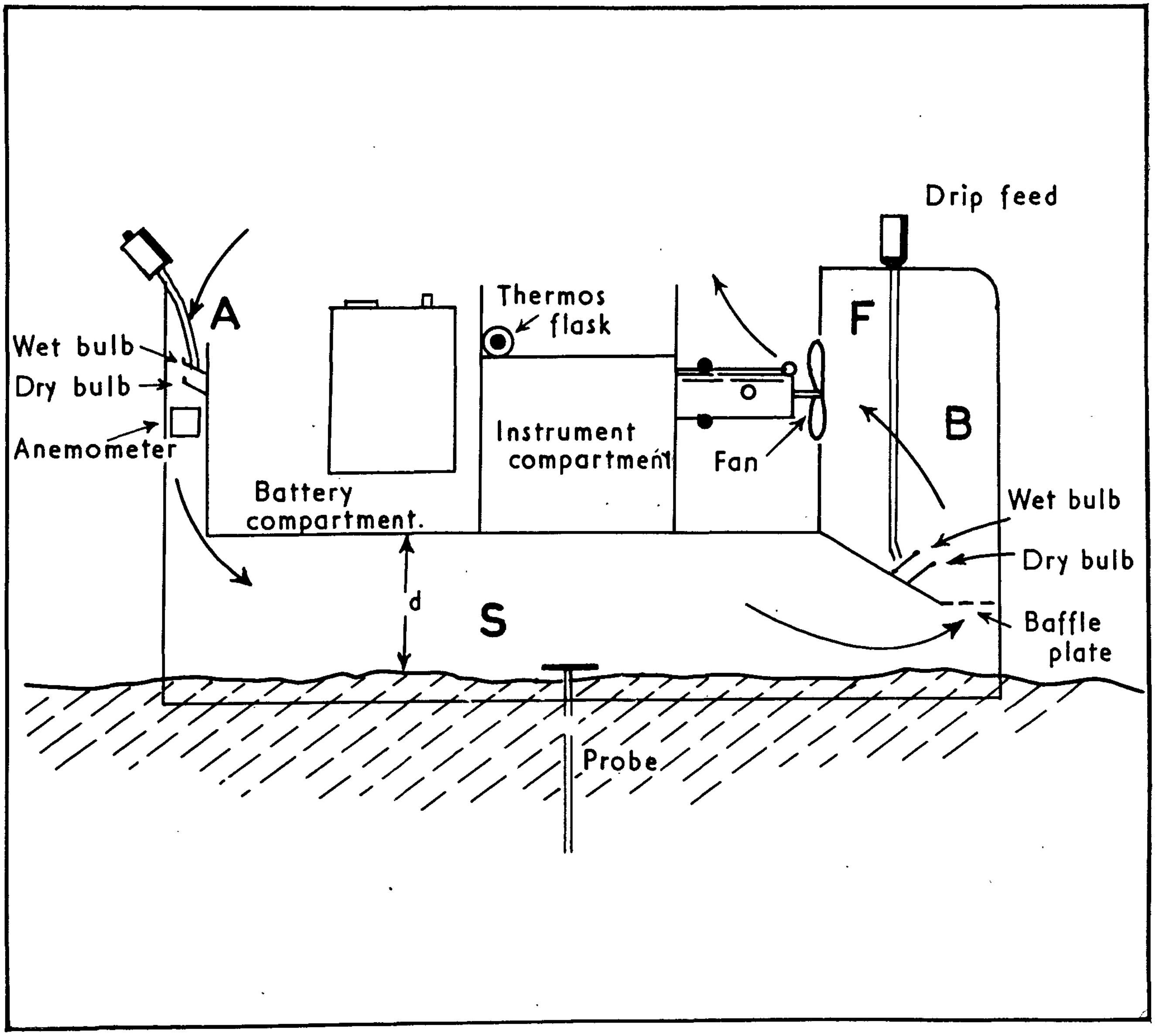



Figure 4. Total heat calorimeter

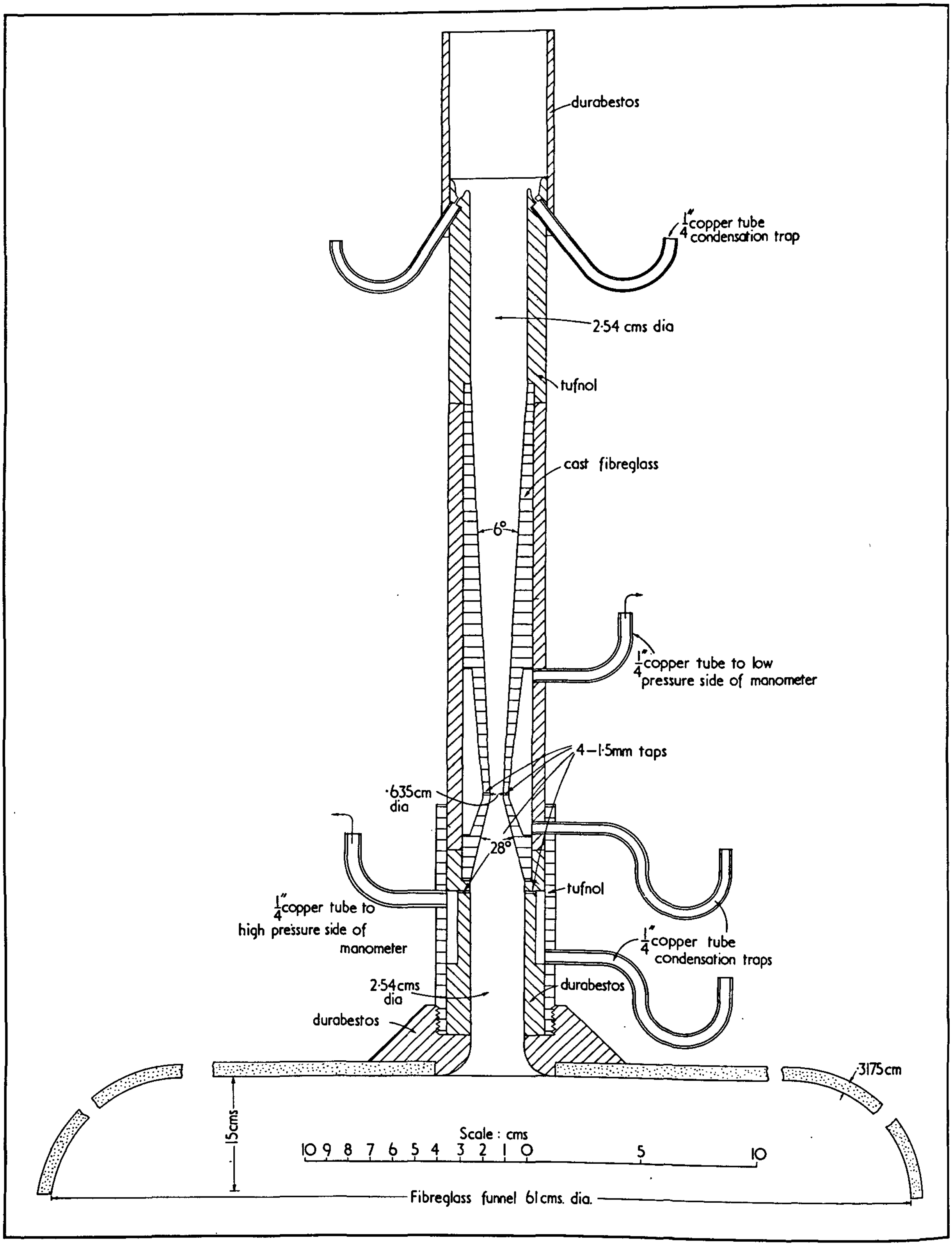



**Figure 5. A collector and venturi meter for measuring small steam flows**

perature are negligibly small at one metre in the hotter areas.

## Station densities

Experience in the larger New Zealand areas shows that a density of approximately 50 stations/km$^2$ will provide sufficient coverage to allow satisfactory maps to be drawn, while not involving too much work. At Wairakei, the total area to be investigated is about 23 km$^2$, and this has been covered with slightly more than 1 000 stations at an average spacing along survey lines of 60 m. This is only about 40 per cent of the spacing for a uniform grid coverage with this number of stations, but it is found more economical to space stations more closely along fewer lines. Loss of detail in the maps is usually not serious, and special traverses are readily run where they prove to be necessary. For the most part, the stations have been located along existing roads and fence-lines, thus avoiding many access difficulties, line cutting and surveying.

## Survey equipment and procedure

The measuring probe is a single copper-constantan thermocouple mounted in a brass tip at the end of a length of 1.5 cm dia. wooden dowelling. It is inserted into a hole punched one metre into the ground by a 1.6 cm dia. pointed rod of high tensile steel. A hand-operated weight moving between two collars on the upper part of the rod supplies the motive power for both the insertion and extraction of the tool. The reference junction of the thermocouple is kept in melting ice contained in a vacuum flask, and after a period of stabilizing which varies from one to four minutes according to the ground temperature at each location, the thermo-emf is measured with the aid of a portable potentiometer. Of the equipment required, only the portable potentiometer involves any substantial cost; the price of the type of instrument used is approximately £100.

A field party of three is required. While one member is taking the measurement at the first station, the probe already installed at the second station is stabilizing, and the remaining two members are locating and installing a probe at the third station. Where access is not difficult, a daily average of forty to fifty stations at 60 metre spacing can be maintained without difficulty. The latest complete survey of the Wairakei area was completed in twenty-eight working days.

The potentiometer readings for each station are converted to C° and corrected for seasonal change if necessary to some selected epoch (e.g., the middle of the survey period). Isothermal contours are then drawn at the outer boundary (1°C above local ambient), and at 20°C and 50°C. To define local ambient temperature it is desirable to carry a few of the earlier traverses in different parts of the area far enough out to ensure that normal temperatures have been reached, and there install fixed thermocouple stations at one metre depth, which are read at regular intervals throughout the survey and used to provide any corrections required.

Figure 1 is an example of the detail obtained, and shows the temperatures existing at Wairakei in 1958, while figure 2 is the result of a repeat survey in the same area in 1960 after a period of high draw-off by drillholes.

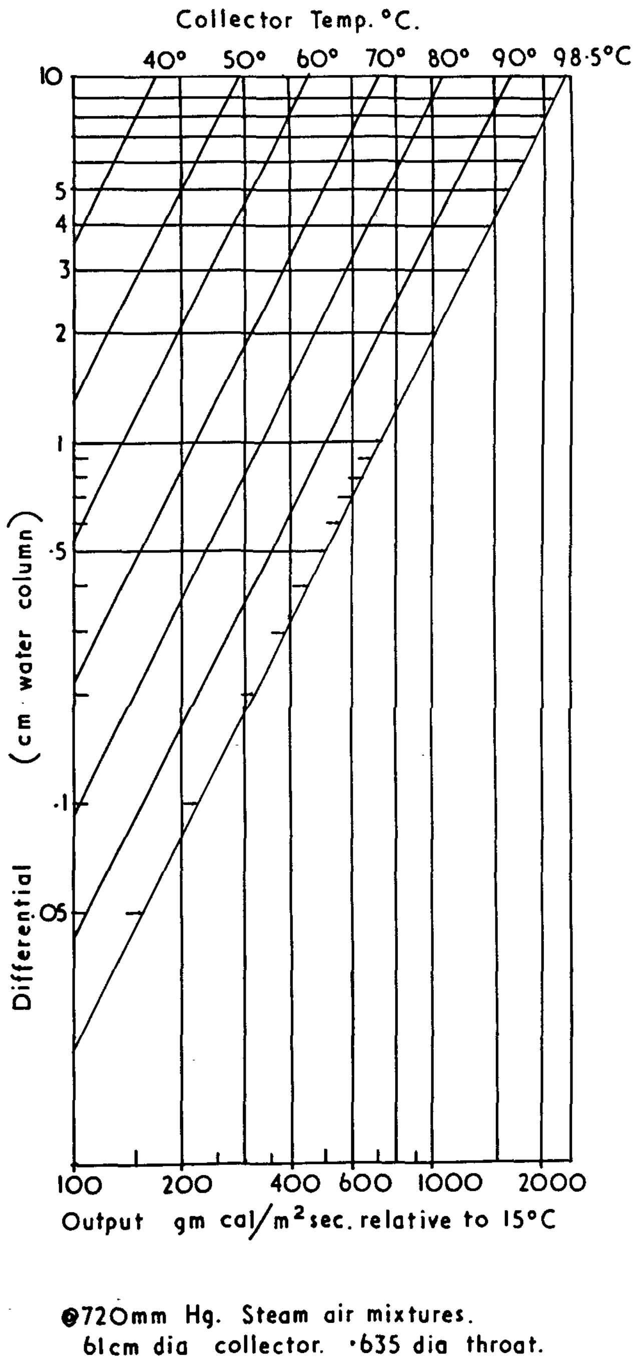



**Figure 6. Venturi meter calibration**

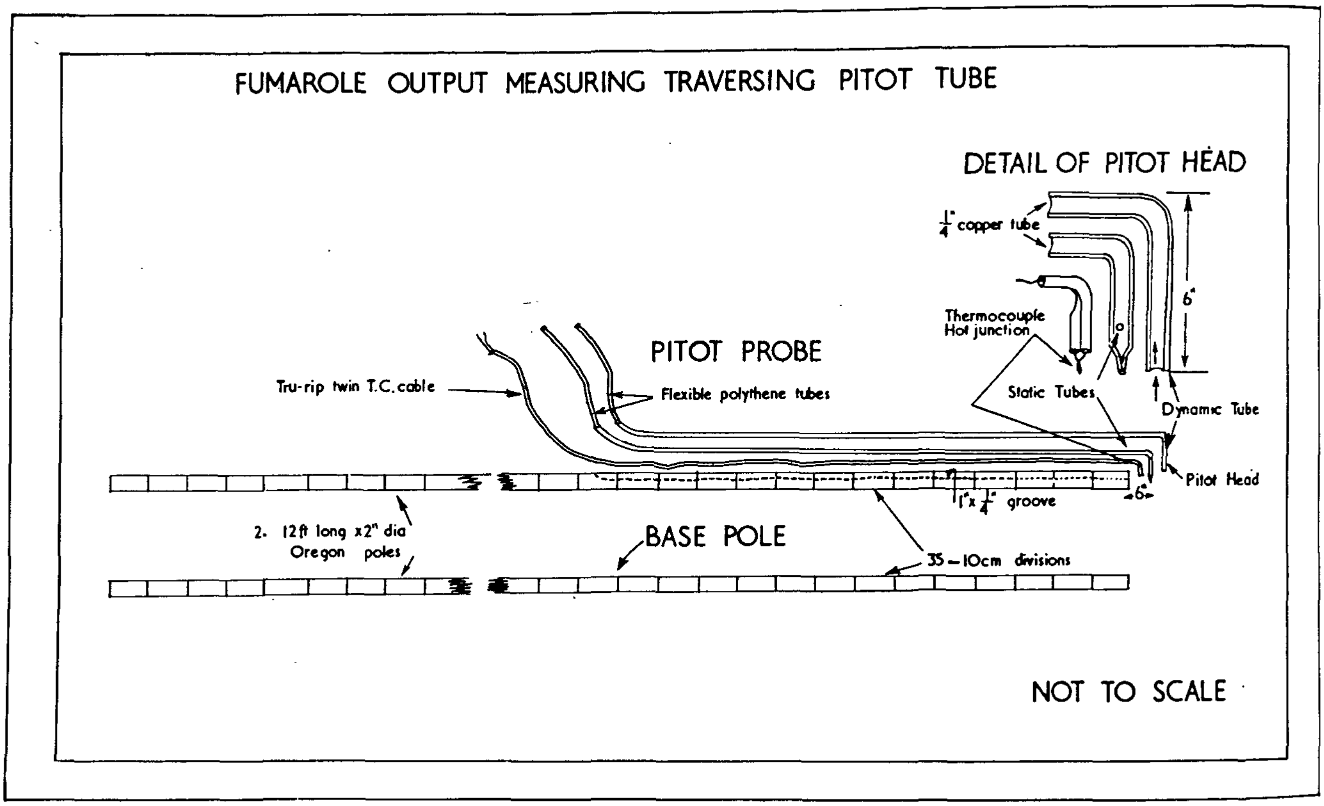



Figure 7

## Heat and mass flow surveys

The surface heat discharge from a thermal area may take one or more of the following forms:

1. Conductive flow due to an abnormally high temperature gradient in the surface layers and not accompanied by any important convective flows of water vapour. Heat flow ranges from less than 1 to about 20 gm cal/m$^2$ sec.

2. Combined conductive and convective flow. Ranges from 4 to 200 gm cal/m$^2$ sec. In the upper part of the range, convective flow predominates, and there is an appreciable discharge of water vapour.

3. Convective flow. Ranges from 200 to 2 000 gm cal/m$^2$ sec; the conductive contribution is only a few per cent of the total. There is an important discharge of water vapour and towards the top of the range these areas are characterised by visible steam, especially at times of high atmospheric humidity. The greatest flow comes from bare and thermally altered ground, small fumaroles, and occasional mud pots.

4. Larger fumaroles with throat diameters ranging from 15 cm up to a metre or so, often discharging slightly superheated steam. Range from about $10^6$ up to $2 \times 10^7$ gm cal/cm$^2$ sec depending mainly on steam velocity.

5. Steam discharge from hot pools and mud pots. Rates range from about $10^3$ to $1.5 \times 10^4$ gm cal/cm$^2$ sec for still water up to an estimated $1.5 \times 10^6$ gm cal/m$^2$ sec for violently boiling pools. Pools of this type generally have little or no overflow and the mass discharge is in the form of water vapour. They are usually perched and acid and are not classified as true hot springs.

6. Steam and water discharge from hot springs and geysers. These features may also be quiescent or in states of active or intermittent ebullition. They have a considerable discharge of clear, near neutral or slightly acid water which may deposit sinter. The water appears to come direct from the main hydrothermal system, as its mineral content is very similar to that tapped by bores. In certain areas, the discharge of hot water represents a major contribution to the total mass flow. Heat flows due to evaporation will be of the same order as for 5.

### Direct measurement methods

The object of these is to measure the absolute value of each form of heat and mass flow within the limits set by instrumental and other factors. Since the methods are, in general, fairly slow and require relatively complex equipment and skilled operation, they are to be regarded primarily as a means for calibrating the quicker indirect methods by which it becomes possible to sample large areas.

Direct measurement methods used are as follows:

1. Conductive heat flow is measured at a number of sites by means of a Lee's disc inserted into the

soil on the end of a wooden probe (figure 3). By measuring thermal gradient as well as heat flow, the thermal conductivity of the soil can be calculated, and average values determined for different parts of the area. Conductivities range from 0.0005 to 0.0025 cgs units as the moisture content rises to saturation. The average conductivity values, together with the one-metre probe data, enable the total conductive heat flow to be computed.

2. In areas of mixed flow, the total heat calorimeter (figure 4) described by Benseman (2) is used. This instrument operates satisfactorily over a range of heat flows from 10 to 500 gm cal/m$^2$ sec.

3. Flows in the range above 500 gm cal/m$^2$ sec are measured with the collector and venturi arrangement shown in figure 5. The main features of the instrument are a 61 cm diameter collecting funnel which discharges through a venturi flowmeter with a mouth diameter of 2.54 cm and a throat diameter of 0.635 cm. The collector and venturi meter are constructed of cast epoxy resin reinforced with fibre glass. All other parts except the copper tube connections are machined from hard polymerised resin rod reinforced with asbestos. With the dimensions given, measurements are possible down to flows as low as 200 gm cal/m$^2$ sec, giving a useful overlap with the total heat calorimeter. Provided care is taken with the measurements, agreement between the two instruments is good. The upper limit to the range of this model (about 2 000 gm cal/m$^2$ sec) is readily increased by increasing the venturi throat area or reducing the collector diameter. However, at these higher intensities, the flow is beginning to take the form of fumaroles of such size that they are more readily measured individually. Calibration curves giving the heat flow as a function of venturi inlet temperature and pressure differential appear in figure 6. For measuring the lower pressure differentials it has been found convenient to use an inclined water manometer.

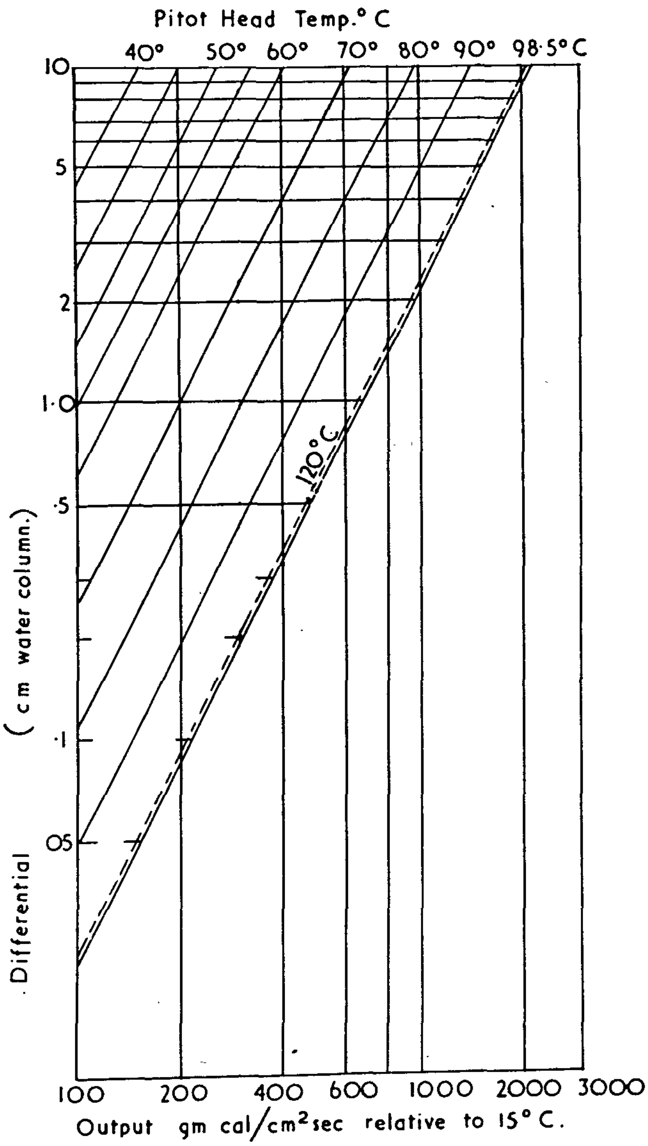



**Figure 8. Fumarole pitot probe calibration**

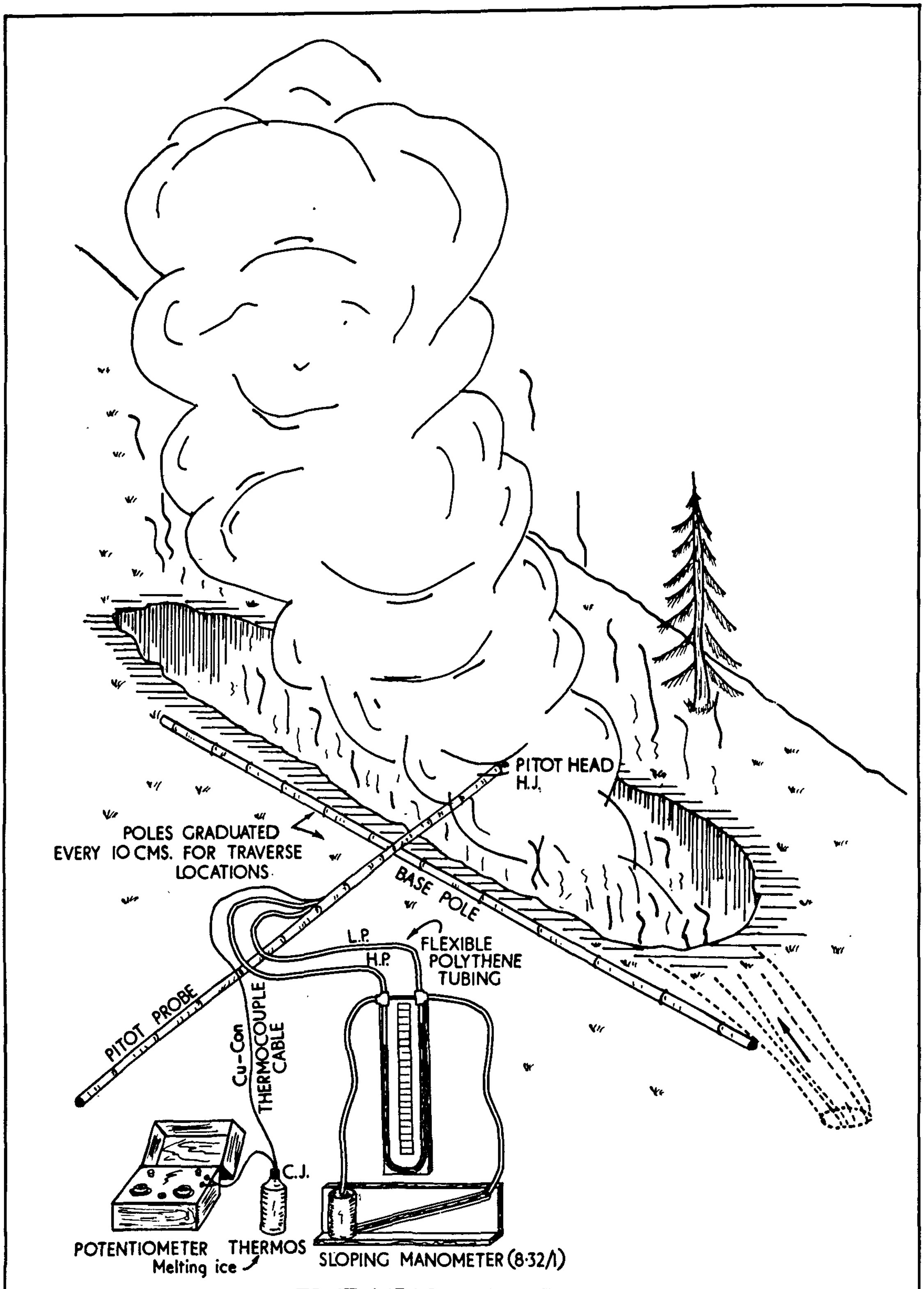
4. For fumaroles with diameters of 15 cm upwards, the pitot-static assembly and thermocouple shown in figure 7 are used to measure the steam velocity and temperature. Calibration curves are given in figure 8. The larger fumaroles are measured by traversing the whole jet area, and heat flow contour diagrams are then prepared from which the total heat flow is calculated. Figures 9 and 10 show the traversing arrangements and an example of a contour diagram.

5. Evaporative heat loss from quiet hot pools is determined from the water temperature and pool area by reference to the graph given in figure 11. Steam discharge from actively boiling pools is more difficult to determine, but work by Robson and Willmore (3) in West Indian soufrieres shows that the heat discharge from a strongly boiling pool may be more than ten times the quiet discharge. Measurements made at Wairakei with a collecting funnel and pitot assembly over a small pool with perhaps 15 cm height of fountaining showed a heat discharge of twice that of the quiet pool.

6. Apart from the heat discharge included under 5 above, the heat output carried by the water from flowing hot pools can be determined by measuring the hot water discharge by any of the conventional methods : V-notch, flumes, floats, etc. At Wairakei, heat and water discharges in the main streams flowing through the area have been measured regularly by Ministry of Works, and reference should be made to papers submitted in section II.A.2 for an account of methods and results.

## Heat and mass flow surveys. Field methods and procedure

The methods of field observations that have been developed from the direct measurements described above all aim at maximum simplicity of equipment




FUMAROLE HEAT OUTPUT MEASUREMENT TRAVERSING PITOT SETUP AS ON F714

Figure 9

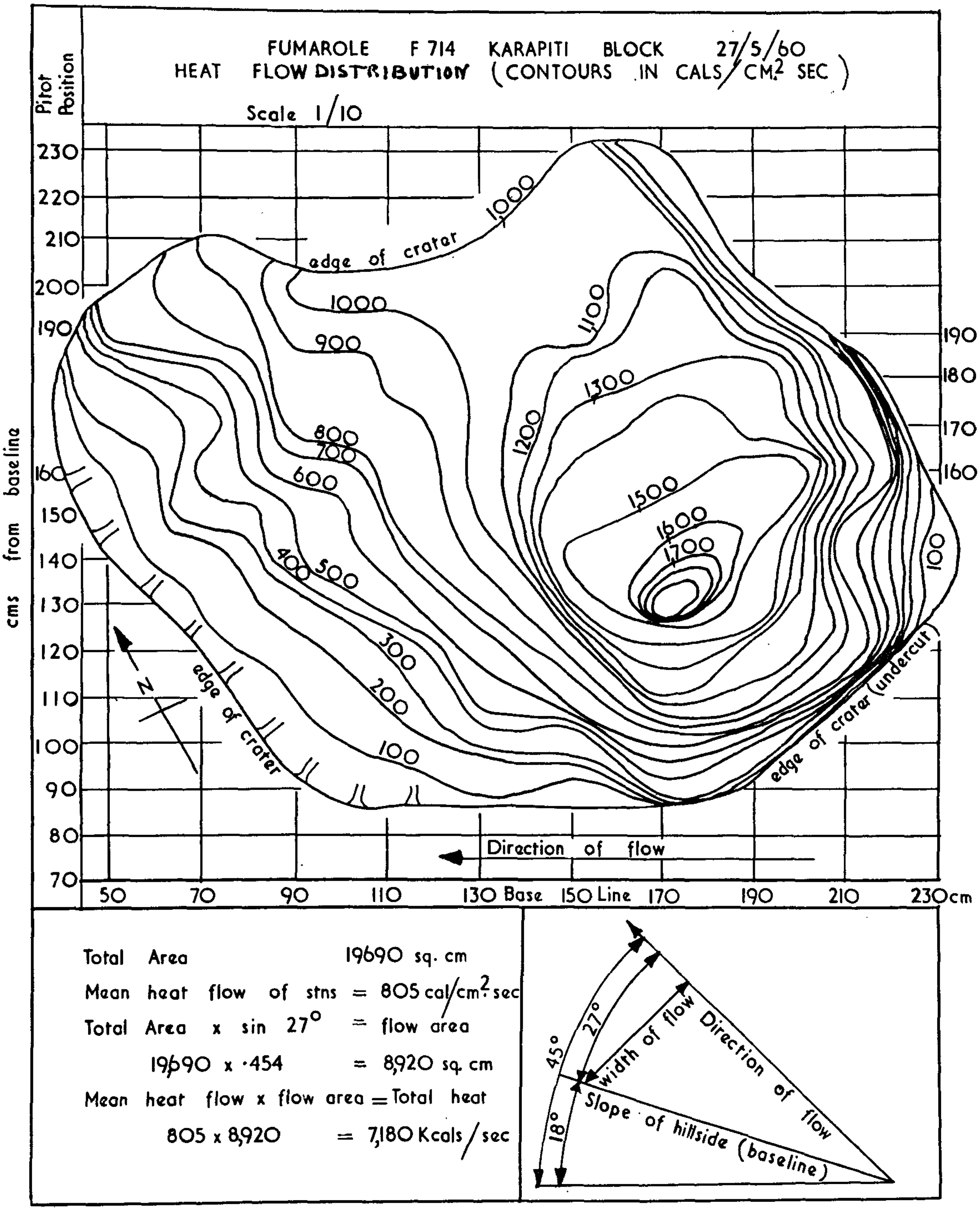



Figure 10. Survey of a typical fumarole

and speed of operation. Since they involve, in steaming ground areas, the measurement of quantities (e.g., depth and temperature) which can be related only empirically to heat and mass flow, it must be recognised that the calibration graphs below refer to a particular soil type and set of surface conditions. In new areas it will be advisable to check them against the absolute methods if these factors appear likely to be different and, if necessary, compute new graphs.

## Equipment

Equipment for the field surveys consists of a dial thermometer or other temperature probe capable of being inserted into the soil to a depth of 15 cm, a graduated ruler and a 25-metre measuring tape. For hot stream and pool discharges a stopwatch, supply of floats, (e.g., corks), suitably sized metal V-notch weirs, digging tools, etc., according to circumstances, are required. A set of recent aerial photographs will also be found of great value for most surveys. By their use, the size and location of hot areas to be investigated can be determined, the areas of larger hot pools and lakes measured, and information obtained about features where access is difficult or dangerous. In open country, the photographs can be used for direct mapping of traverse lines.

### Conductive and fumarole flows

The determination of conductive heat output by use of the one-metre probe results and measurement of the larger fumaroles have already been discussed above. Where fumarole vents are too inaccessible or too numerous to make direct measurement practicable, an approximate comparison with measured vents can often be made by measuring the relative diameters and rates of rise of the steam columns under similar weather conditions, using a simple transparent grid which can be held at a fixed distance from the eye, or by photography.

### Steaming ground

In the more active thermal areas of the Wairakei type, a large fraction of the total heat discharge is accounted for by steaming ground, which covers very extensive areas, and which has proved the most difficult to measure with precision. The field methods illustrated in the graphs of figures 12, 13 and 14, which relate temperatures in the top 15 cm of the soil to heat flow, are based on large numbers of observations of temperature distribution and heat flow. From these observations, the family of curves of figure 12 has been prepared, showing the form of typical temperature-depth curves at different heat flow rates. Figure 13 covers the range of heat flows from 1 to 100 gm cal/m$^2$ sec. For measurements in this range, it is necessary merely to observe

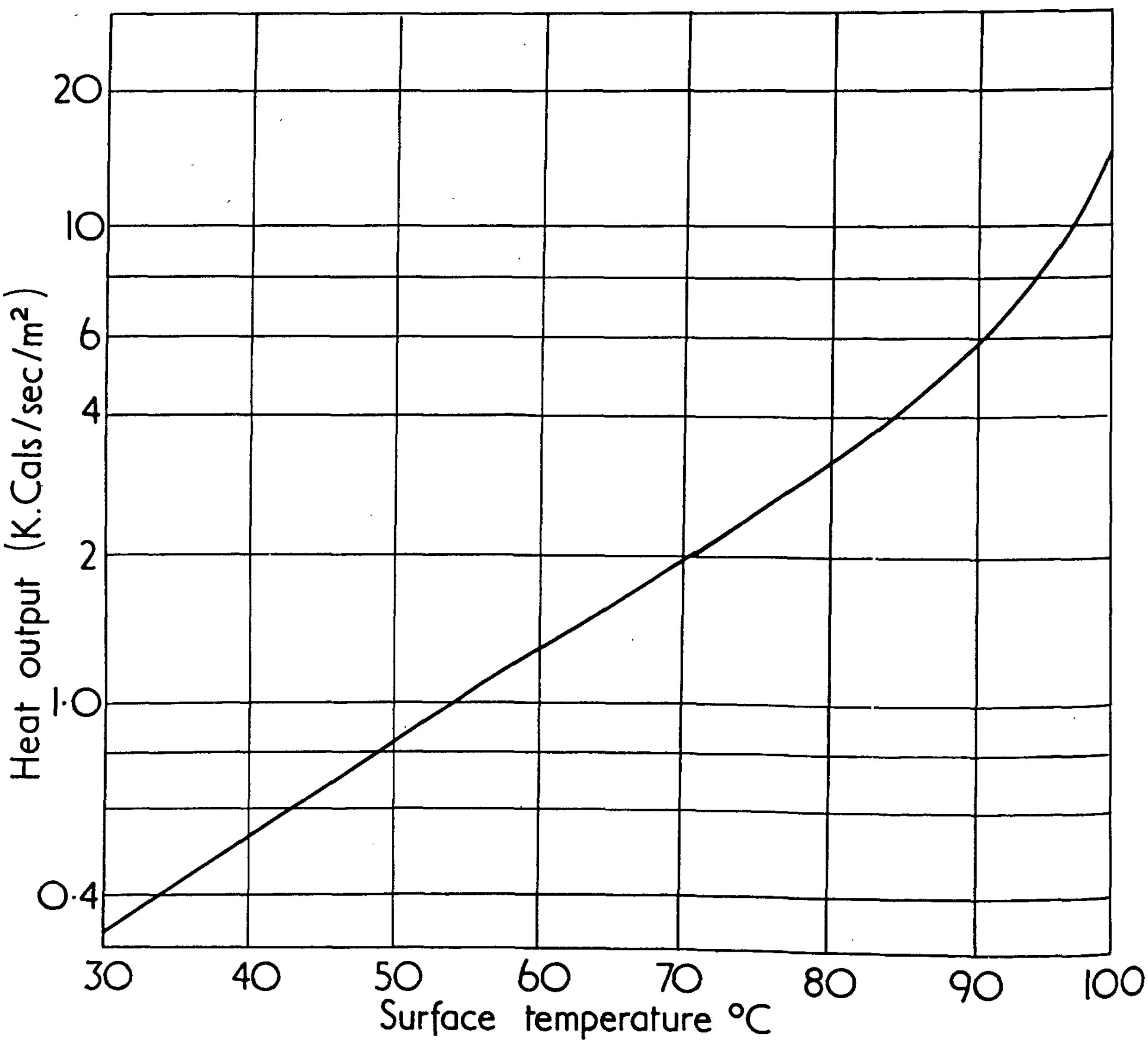



**Figure 11. Heat lost as evaporation from quiet water surfaces**

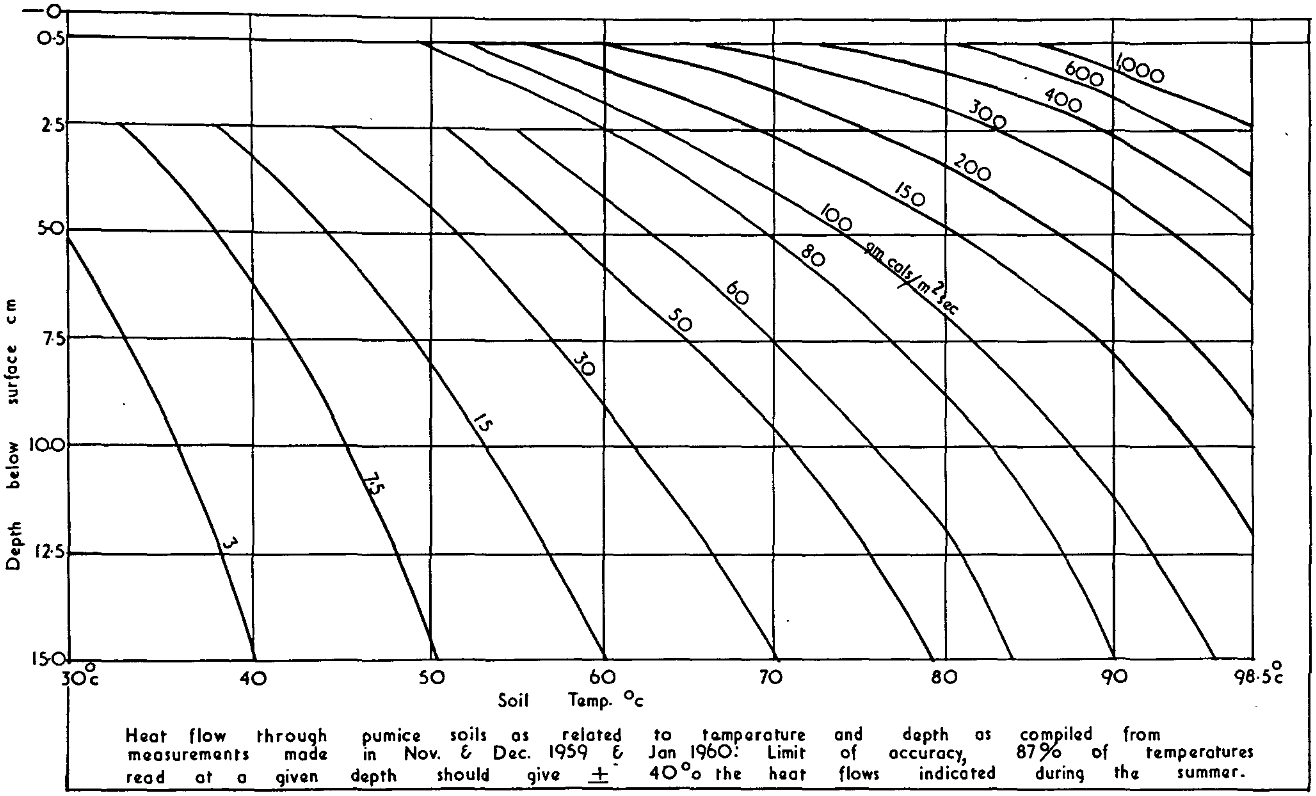



Figure 12

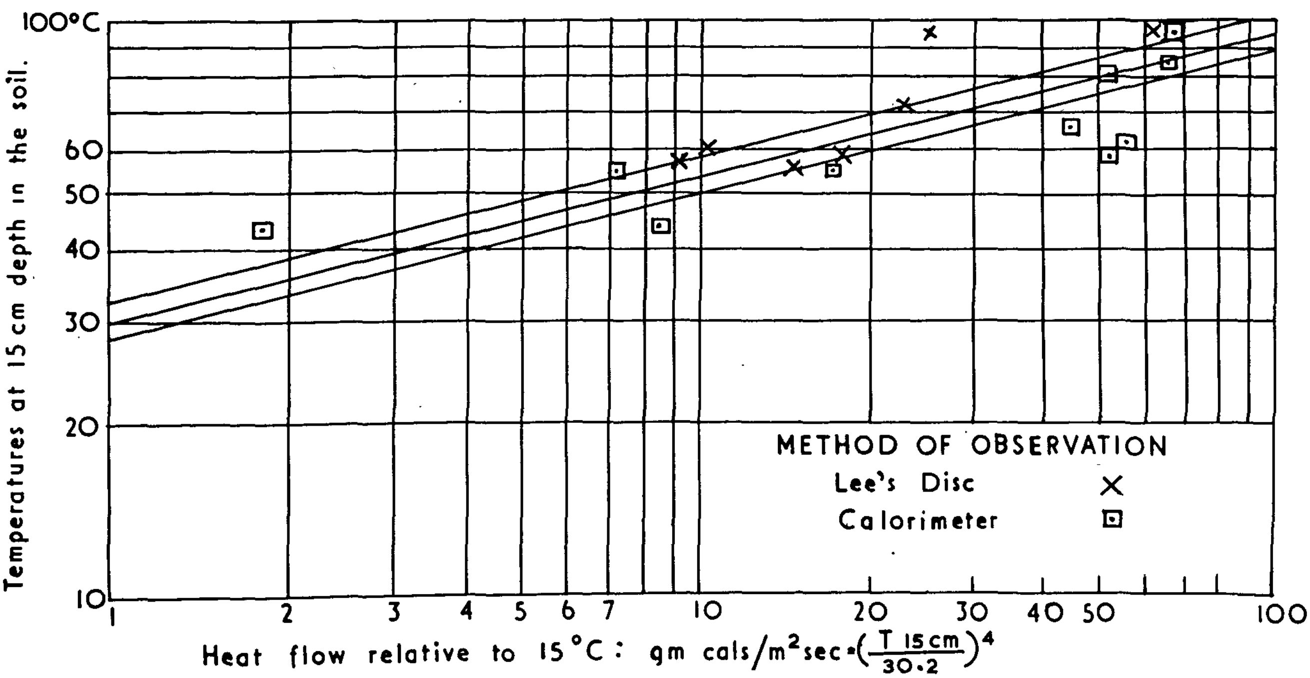



Figure 13. The relationship of the heat flow from Wairakei soil to the temperature at 15 cm

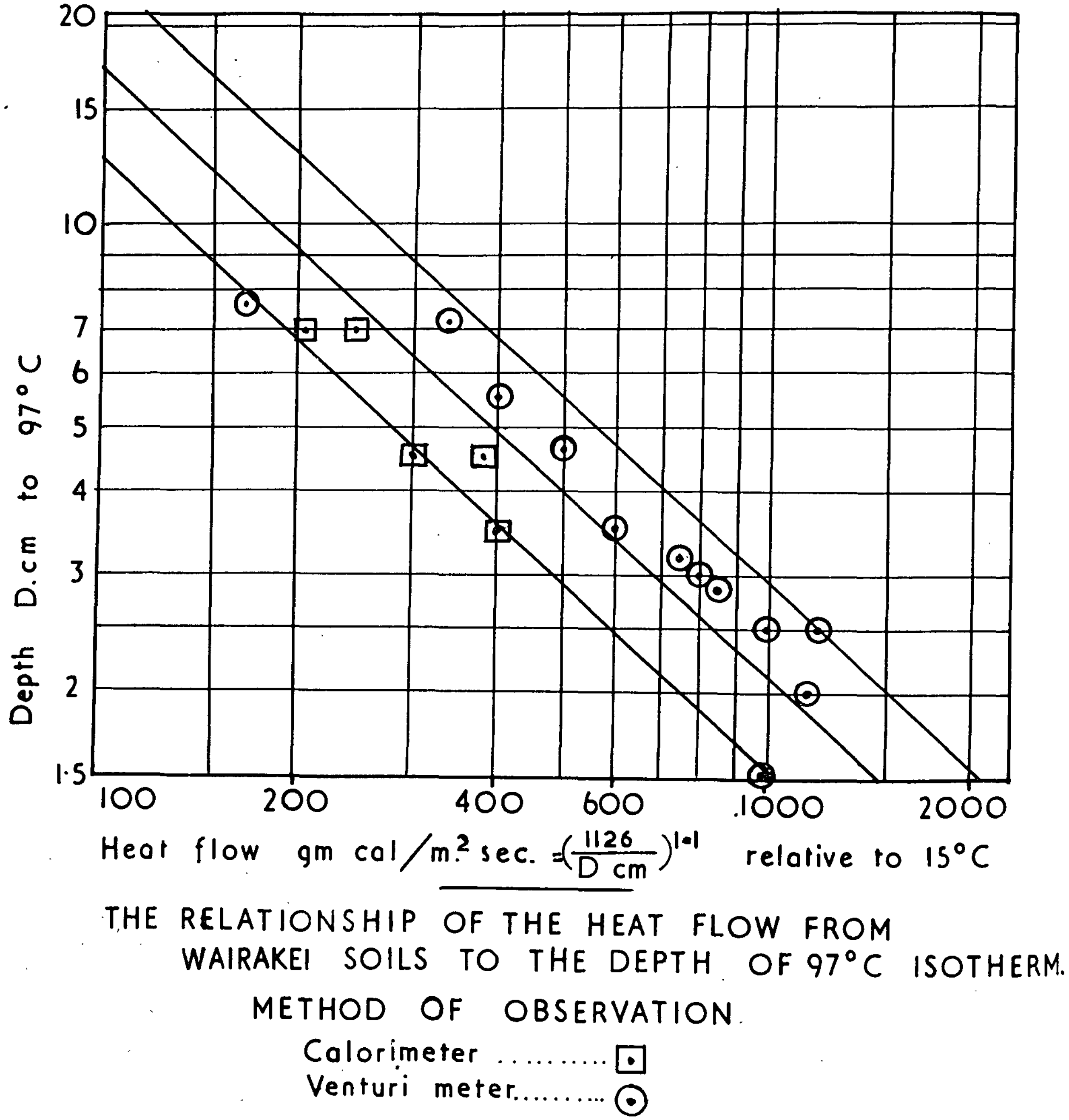



Figure 14

the soil temperature at a fixed depth of 15 cm by means of a suitable probe or thermometer. At higher heat flows, the soil temperature at 15 cm approaches boiling point and increases only slowly with increasing heat flow, so the method becomes too insensitive, and is used instead.

To make measurements in this range (100 to 2 000 gm cal/m² sec) the thermometer or probe is pushed gradually into the soil until a temperature of 97°C is read, when the depth of insertion (D) is measured. The results of direct heat flow measurements by various methods have been plotted on figures 13 and 14 to show the errors to be expected from the indirect measurements. It will be seen that most of the points fall within the ±40 per cent lines, so that this is about the precision to be expected from single measurements. The errors in total heat flows based on a large number of measurements can be expected to be somewhat smaller than this, provided soil types and conditions are constant over the areas covered. For these surveys, a station spacing along traverse lines of five to ten metres, depending on the type of ground traversed, has been found suitable. Line spacing may be several times greater.

### Vegetation on hot ground

In the New Zealand thermal areas, growth and type of vegetation are characteristically modified on ground at different temperatures, and this has proved to be of value for rapid preliminary surveys, especially since it is possible, with practice, to recognise and classify these modifications from aerial photographs. Table 1 relates to the Wairakei area; it may, *mutatis mutandis*, be of value elsewhere.

**Table 1**

| *Temperature at 15 cm (degrees C)* | *Type of growth* |
|---|---|
| Up to 30 | Pines and large manuka scrub, nearly normal. |
| 30 to 45 | Thin tall growing manuka scrub. |
| 45 to 60 | Large bushy manuka shrubs with trailing and hanging branches. |
| 60 to 85 | Stunted, low-lying manuka shrubs. |
| 85 to 92 | Low-lying mosses. |
| Above 92 | Mostly bare, visibly steaming ground, thermally altered and coloured red or white. |

### Measurement of hot water discharge by chemical means

The water from hot springs often has a high mineral content which is characteristic for a given area and, under favourable circumstances, use may be made of this for estimating the total water discharge from the system by measuring the increase in mineral content of streams or rivers draining or passing through the area. This has been done for Wairakei by Ellis and Wilson (4) and it is possible to deduce from their results that the total discharge of chloride water from pools, springs, etc. (but excluding bores) in the Wairakei system in 1954 was close to 200 kg/sec. This method has the great merit that it will include water from concealed sources which may be missed in a survey, or which it may not be possible to measure directly.

## Results for Wairakei area

**Table 2**

*Heat discharge* (exclusive of drillholes) relative to 15°C, for 1958-59.
*Mass discharge* (exclusive of drillholes) total steam and water.

| *Type of area* | *Heat kg cal/sec.* | *Mass kg/sec.* |
|---|---|---|
| Steaming ground | 91 000 | 146* |
| Hot springs and geysers | 17 000 | —** |
| Evaporation from hot water surfaces | 43 000 | 69* |
| Seepage to Waikato River | 3 000 | —** |
| Conduction | 9 000 | 14* |
| Total chloride water to river | — | 200 |
| TOTALS | 163 000 | 429 |

* Calculated as steam at 100°C.
** Included in total chloride water to river.

**Table 3**

*Areas of hot ground. Changes between 1958 and 1960*

A = area included between outer boundary (1°C above ambient at 1 metre) and 50°C isotherm at 1 metre.
B = area within 50°C isotherm (i.e., steaming ground and fumarole areas).

| | *April 1958* | *April 1960* | *Per cent increase* |
|---|---|---|---|
| A | 5.128 km$^2$ | 7.188 km$^2$ | 40 |
| B | 1.152 km$^2$ | 1.332 km$^2$ | 16 |
| (A + B) | 6.280 km$^2$ | 8.520 km$^2$ | 36 |

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3. Robson, G. R., Willmore, P. L., Some Heat Measurements in West Indian Soufrieres, *Bull. Volcanol. Ser. II*, 17: 13-39, 1955.
4. Ellis, A. J., Wilson, S. H., The Heat from the Wairakei-Taupo Thermal Region Calculated from the Chloride Output, *N.Z.J. Sci. Tech. B36, 6*: 622-631, 1955.


### *Summary*


Surface surveys of various kinds represent an important preliminary step in the development of a thermal area. The present paper deals with the temperature and heat flow surveys which have been carried out in the course of the exploration and development of certain thermal areas in New Zealand, with special reference to Wairakei. The results obtained from these surveys have proved to be of value for the assessment of power potential, for the planning of an efficient siting programme for prospecting bores, and for the study and interpretation of the response of the hydrothermal system to large-scale exploitation.

Mapping of the form and distribution of surface hot areas by means of a one-metre thermocouple probe can be carried out rapidly and inexpensively in the light pumice soil which covers much of the New Zealand thermal area. These surveys have shown that measurably hot areas extend well beyond the directly observable surface activity, and indicate further regions from some parts of which steam may be obtainable. Repeat surveys at intervals, as bore draw-off has increased, have shown appreciable changes in the size and intensity of the hot areas at Wairakei, most of the changes being increases. Surface temperature maps are given showing these changes, and a further map of underground temperatures derived from borehole measurements is presented in a companion paper for comparison.

Methods for measuring the natural heat flow from hot springs, geysers, steaming ground and fumaroles have been improved considerably in recent years, and the latest measurements in the Wairakei area give considerably higher values for both the heat flow and enthalpy than the estimates made in 1950. The new results lead to an appreciably different and generally more optimistic conception of the hydrothermal system than would have been justified by the original observations. There is some evidence for a moderate increase in the true surface heat flow (exclusive of bore draw-off) between the start of exploitation in 1950 and the present stage of heavy bore draw-off in 1960.

The paper gives details of the methods used in the foregoing surveys, and includes an account of the use of a Pitot tube for the measurement of the steam output of fumaroles, which now represents a significant contribution to the total heat flow at Wairakei.


## PROSPECTION DES CHAMPS HYDROTHERMIQUES PAR ÉTUDE DE L'ACTIVITÉ THERMALE EN SURFACE

### *Résumé*


Les relevés de divers types faits en surface représentent un préliminaire important dans la mise en œuvre d'une région géothermique. Dans le présent mémoire, on s'intéresse à la question des observations ayant trait à la température et au débit de chaleur exécutées au cours de l'exploration et de la mise en œuvre de certaines régions géothermiques de la Nouvelle-Zélande, plus particulièrement de celle de Wairakei. Les résultats de ces travaux ont démontré leur valeur pour l'évaluation des réserves de force motrice, le planning d'un programme bien compris de choix des emplacements pour les puits de prospection et l'étude et l'interprétation de la manière dont un gîte hydrothermique réagit à son exploitation sur une grande échelle.

Les tracés indiquant la forme et la répartition des régions chaudes de la surface, au moyen d'une sonde à thermocouple d'un mètre, peuvent être faits rapidement et à bon marché dans le terrain constitué par une pierre ponce fine qui couvre une grande partie de la région thermique de la Nouvelle-Zélande. Ces travaux ont démontré que des aires dont la température peut être mesurée s'étendent bien au-delà de la zone d'activité superficielle observable directement et indiquent l'existence d'autres régions de certaines parties desquelles on peut extraire de la vapeur. Des revisions périodiques de ces tracés, au fur et à mesure de la consommation des produits des puits, révèlent des changements appréciables dans les dimensions et l'intensité des régions chaudes

à Wairakei, la plupart des changements se faisant dans le sens de l'augmentation. On donne des cartes indiquant la température de la surface. Elles montrent ces modifications, et on présente une autre carte des températures souterraines prises à l'occasion des mesures faites dans les puits dans un autre mémoire, aux fins de comparaison.

Les méthodes servant à la mesure du débit de la chaleur naturelle des sources chaudes, des geysers, des vapeurs sortant des évents et des fumerolles, ont reçu des améliorations considérables au cours de ces récentes années et les dernières mesures faites dans la région de Wairakei donnent des chiffres beaucoup plus élevés pour le régime d'écoulement de la chaleur et l'enthalpie que les évaluations faites en 1950. Ces nouveaux résultats mènent à des points de vues notablement différents et généralement plus optimistes quant au système hydrothermique en cause que ne l'auraient justifié les observations originales. Selon toutes indications, il semble y avoir eu une augmentation modérée de l'écoulement réel de chaleur en surface (exclusion faite de celle des puits), entre le début de l'exploitation, en 1950, et l'état actuel en 1960, caractérisé par les gros prélèvements des puits.

On donne, dans le mémoire, les détails des méthodes utilisées pour les recherches mentionnées ci-dessus, notamment une description de l'emploi d'un tube de Pitot pour la mesure du débit de la vapeur des fumerolles, qui représentent maintenant une fraction importante du régime total d'écoulement de la chaleur à Wairakei.

# PRELIMINARY EVALUATION OF GEOTHERMAL AREAS BY GEOCHEMISTRY, GEOLOGY, AND SHALLOW DRILLING

*Donald E. White**

Much information on the heat potential of a geothermal area can be obtained at relatively low cost by well-planned exploratory surveys. Deep drilling of large diameter holes for combined exploration and production purposes in a little-known area is very expensive. The high overhead costs discourage the gaining of critical information on distribution of temperatures and structural control of migrating fluids.

Thermal areas may be classified by the magnitude of their thermal anomalies, or deviations from the normal. Important aspects are : (1) size of the thermal area; (2) natural heat flow; and (3) excess heat above normal that is stored within given depths of the thermal area. Natural heat flow as used hereafter is the quantity of heat flowing from a thermal area in water and steam and by rock conduction prior to appreciable disturbance by exploration. The heat flow from an area of normal geothermal gradient and thermal conductivity is about 12 000 cal per sec per sq km (Birch, 1954, p. 646). This figure is a useful yardstick for gauging the abnormality of heat flows of thermal areas.

Most thermal areas are classed as low-temperature or low-intensity, and relatively few are classed as high-temperature or high-intensity, with heat flows at least fifty times greater than normal. The latter group is naturally of greater interest in the early development of geothermal resources of a country.

## General principles

### Sources of heat

Localized heat anomalies of low intensity are produced in many ways, including exothermic chemical reactions, radioactivity, friction of fault movement, and migration of waters of different origin in areas of nearly normal geothermal gradient in over-all aspect. Heat flows caused by such phenomena may be much above normal in restricted areas or for short periods of time. The high-intensity areas, however, demand transfer of heat on such a scale that magmatic temperatures and magma reservoirs must be present nearby. For example, Steamboat Springs, Nevada, is a relatively small area that qualifies as high-intensity, with a heat flow of about 120 times the normal rate for an area of 5 sq km (White, 1957, p. 1639, 1642). The yearly requirement of magma or its heat equivalent to supply this heat flow is 1/2 000 of a cubic kilometre per year. This quantity may seem small until one realizes that the system has been active on the order of 100 000 years, requiring a minimum of about 50 cubic kilometres of magma. The same rate of heat flow from uranium would require 300 million tons of metal. Many high-intensity areas are not known to have a geologic history as long as that of Steamboat's, but the yearly requirement of heat may be much higher.

In some areas that produce dry steam from heat reservoirs at depth, insulated by thick impermeable rocks, the flow of heat at the surface in springs and fumaroles may be relatively unimpressive, but the total amount of heat lost in steam conducted through rocks with abnormally high gradients is probably at least 50 times that of a normal area.

### Sources of water

If all of the required heat of a high-intensity area is supplied by steam from a magmatic source and none by rock conduction, more than 20 per cent of the total water or steam of the system must be magmatic (White, 1957, p. 1643). Isotope studies (Craig, Boato, and White, 1956), however, have shown that the quantity of magmatic steam in all thermal areas studied to date, including Larderello, Wairakei, "The Geysers" in California, Yellowstone Park, and Icelandic thermal areas, is not large enough to be clearly recognizable by isotopes and is unlikely to exceed more than 5 to 10 per cent of total water. The greatly dominant component is water of meteoric origin. Most of the heat at depth must therefore flow from magma by rock conduction, with only a relatively small proportion of the total heat being transferred in magmatic steam.

### Importance of heat supply relative to water supply

The fundamental difference between those few areas yielding dry steam at depth and the more numerous areas of hot water that yield some steam from water upon release of pressure is the prevailing balance deep in the system between heat supply and water supply. Isotopic evidence, as mentioned, indicates that most of the water in *all* the studied

* U.S. Geological Survey, Menlo Park, California, U.S.A. — publication of this paper has been authorized by the Director, U.S. Geological Survey.

systems is meteoric. Mass rock permeability seems to be more important than climate as a factor in limiting the quantity of water that can migrate to great depth. In a dry steam area mass permeability of the rocks is so low, and upward flow of heat by rock conduction and in magmatic steam is so high, that all meteoric water penetrating deep into the system is vapourized. Where rock permeability is greater or total heat flow is correspondingly lower, meteoric water penetrating the system condenses the volcanic steam, thereby creating a hot water area.

## Characteristics of hot water areas

Hot water areas are usually found in permeable sedimentary or volcanic rocks, or in competent rocks such as granite that can maintain open channels along faults or fractures. The hot springs of such an area are typically slightly acid to alkaline at the surface and characteristically contain chlorides, sulfates, and some bicarbonates. Total discharge from springs of a typical system is commonly in the order of hundreds of gallons per minute. However, where near-surface rocks are permeable and the surrounding water table is relatively low, much or all of the circulating hot water escapes from the system below the surface, and little or none is discharged from local surface springs. About 90 per cent of the water at Steamboat Springs escapes in this way. The proportion is probably about the same at Bradys Hot Springs and Beowawe Geysers in Nevada, and is nearly 100 per cent at Casa Diablo Hot Springs in California. Where spring outlets are at or near the level of surrounding ground and surface waters, probably most of all hot water of a system is discharged from the local springs.

The temperatures of many near-boiling spring systems increase with depth to a "levelling-off" temperature that differs for each system, with little additional increase in temperature above the normal geothermal increment at greater explored depths. At Steamboat Springs, Nevada, for example, the temperatures in six drill holes were near 170°C at depths of 300 to 350 feet, but deeper drilling found no higher temperatures even though major channels were intersected at depths of more than 500 feet. GS-5 drill hole at Steamboat is an example (figure 1). Temperatures at Wairakei, New Zealand, rise to about 250°C near 1 500 ft of depth but increase little if any more at further explored depths (Banwell *et al.*, 1957, pp. 52-56). In such areas, meteoric water probably penetrates to considerable depths along available permeable channels, and is heated first by rock conduction and then by volcanic steam, attaining a temperature that is hereafter called the mixing temperature. The water, commonly above 100°C but far below its boiling temperature at this depth and high pressure, rises in the core of the spring system, losing only a little heat by conduction because of its high rate of flow and the insulating effects of rock walls with low thermal conductivities. As the hot water rises the hydrostatic pressure decreases, and eventually a level is attained where boiling can begin. This depth is about 300 ft. at Steamboat Springs and 1 500 ft. at Wairakei.

Other hot water areas may show step-like increases in temperature with depth, as a result of different depths of penetration of meteoric water.

Springs of the hot water areas characteristically contain higher concentrations of chloride than do surrounding waters. The evidence suggests that sodium chloride and other alkali chlorides are transported continuously from the magma, first in solution in high-density steam and then in water that has circulated deeply and condensed the volcanic steam at high pressure. This theory was supported by White (1957, p. 1646) and has recently been strengthened greatly by new evidence from Ellis and Wilson (1960, p. 611-614). Steam under high pressure is so dense that it has the solvent properties of water rather than of low pressure steam (see review by Morey, 1957, especially pages 233-237).

The practical consequence of this theory, if correct, is that dry steam cannot be expected normally in hot water areas at depths of less than about 10 000 ft. Meteoric water must circulate to such depths in order to maintain a pressure near or above the critical pressure of pure water

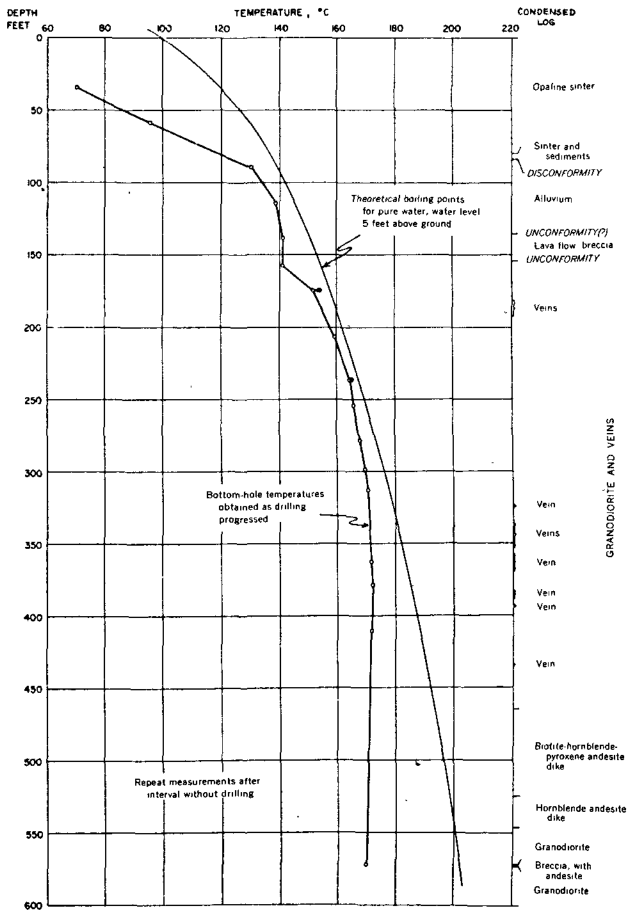


**Figure 1. Data from GS-5 diamond drill hole, 150 feet east of crest of the Main Terrace, Steamboat Springs, Nevada**

through the zone of condensation and mixing. If pressure is not maintained and the steam is permitted to expand before condensation, the sodium chloride in solution in the steam will precipitate. The critical pressure of a column of pure water everywhere just at its boiling point is attained at a depth of about 11 700 feet. Conceivably, volcanic steam could be contained under high pressure in tight conduits up to somewhat shallower depths, " jetting " the steam with its dissolved sodium chloride up into meteoric water. It is unlikely that uncondensed vapour at a pressure of more than 200 atmospheres can occur above 5 000 feet of depth where the lithostatic pressure may be exceeded.

### Characteristics of dry steam areas

Larderello, Italy, and "The Geysers", California, are the outstanding dry steam areas described in the literature. The rocks of both areas are characteristically tight and incompetent, and presumably do not permit penetration of large quantities of meteoric water deep into their systems. Even in these areas, isotopic compositions of the waters indicate that most of the water must be meteoric. The total heat supply is so large in relation to the total water supply that the meteoric water is vaporized and volcanic steam is not condensed. Extensive flow of heat by rock conduction is therefore required.

Surface springs at " The Geysers " are typically very low in discharge, totalling only a few gallons per minute. Most of these waters are strongly acid, with pHs in the order of 2 or 3. Their chloride contents are very low, similar to that of local rain water, and none of the chloride is of volcanic origin. A careful search of Big Sulphur Creek, which flows through " The Geysers " area, was made on the chance that volcanic chloride might be escaping somewhere from nearby springs. However, throughout an area of at least 30 sq miles surrounding the springs, chloride content is no higher than that of normal streams. I have not found chloride contents mentioned in studies of natural springs of Larderello, but available physical descriptions of spring activity, dominated by mud pots and fumaroles, suggest acid sulfate waters low in cloride (White, 1957, p. 1651-1952).

The apparent absence of chloride waters in the areas of superheated steam suggests that meteoric water does not penetrate as deeply or in as great a quantity as in the hot water areas. In the areas of superheated steam, chloride is presumably retained in the magma or is precipitated at depth upon sufficient expansion of the steam.

## Methods available for preliminary evaluation of an area

### Geochemical surveys

A rapid geochemical survey can tell much at low cost about the potential of a geothermal area.

1. Possibilities for dry steam *vs.* hot water and wet steam : Dry steam is unlikely in an area where springs contain appreciable chloride (over 20 ppm). An abundance of acid sulfate springs near boiling in temperature but low in discharge favours the possibility for dry steam at depth. However, chloride waters in the surrounding area are an unfavourable indication because local acid sulfate springs may also result from boiling of chloride waters at depth (White, 1957, p. 1652).

An area containing boiling springs with appreciable sodium chloride and relatively high ratios of K/Na and Li/Na is likely to have a notable temperature increase with depth, at least within a hundred feet or so of the surface. I am not aware of any chemical indicators for those areas with extremely high temperature at depth.

2. Significance of dilute spring waters : Dilute neutral or alkaline spring waters, even if moderately high in temperature at the surface, are not likely to have notably higher temperatures at depth. Springs with chemical compositions similar to ordinary meteoric water almost certainly do not have a volcanic component. Temperatures near those of magma are highly unlikely in the vicinity, and thermal gradients cannot then be high for long periods of time adjacent to conduits carrying such waters.

3. Potential problems of deposition and corrosion : Some thermal waters precipitate large quantities of $CaCO_3$ when discharged naturally at the surface (see table 1, anal. 5, and Allen and Day, 1935, pp. 375-378). Other thermal waters precipitate little or no $CaCO_3$ during natural discharge, but when erupted rapidly from high temperature and pressure, much $CO_2$ is selectively lost to the vapour, carbonate equilibria is shifted and the $HCO_3$ dissolved in the water is converted to $CO_3$, which in turn results in deposition of $CaCO_3$ in the wells. These processes have been discussed briefly by White, Sandberg, and Brannock (1953, pp. 496-499), and are illustrated by analyses 1 and 2 of table 1. At Steamboat Springs, continuously erupting wells may fill with $CaCO_3$ within 4 days to 4 months or more. The wells are then shut down and cleaned by drilling out the deposits.

Thermal areas characterized by natural carbonate deposits are likely to have particularly serious problems in erupting wells. An occasional shut-down for removal of deposit is not necessarily serious, but frequent shut-downs with resultant low average production cannot be tolerated in many areas. Carbonate-depositing waters can probably be utilized by producing the water under pressure and removing the heat by heat exchangers.

A few thermal spring waters are exceptionally high in $SiO_2$. Eruption with vaporization of some of the water results in an increase in concentration of $SiO_2$ in the remaining water, as indicated by analyses from Beowawe, Nevada (3 and 4 of table 1). The solubility of amorphous silica in spring waters is about 350 ppm at 100°C (White, Brannock, and Murata, 1956, p. 30) and is probably about 500 ppm

**Table 1. Partial chemical analyses of thermal waters in parts per million, illustrating relation of composition to chemical problems. Most significant components underlined**

| | | | | | | |
|---|---|---|---|---|---|---|
| Locality | Steamboat Springs, Nevada | | Beowawe Geysers, Nevada | | Yellowstone Park, Wyoming | |
| Description | Geyser well | Geyser well | Spring | Well | Spring, main terrace, mammoth | Acid spring, Norris Basin |
| Analysis No. | 1 | 2 | 3 | 4 | 5 | 6 |
| Condition when sampled | Non-erupting | Erupting | Flowing | Erupting | Flowing | Seeping discharge |
| $SiO_2$ | 245 | 245 | *444* | *534* | 60 | 184 |
| Ca | *15* | *11* | *< 1* | *.8* | *272* | 2.4 |
| Mg | 1.0 | 1.4 | < 1 | .2 | 68 | 0 |
| Na | 667 | 728 | 241 | 232 | 129 | 10 |
| K | 63 | 66 | 29 | 30 | 69 | 12 |
| $HCO_3$ | *340* | *143* | *148* | *39* | *667* | 0 |
| $CO_3$ | 0 | *100* | *161* | *224* | 0 | 0 |
| $SO_4$ | 122 | 128 | 78 | 90 | 501 | *471* |
| Cl | 885 | 986 | 44 | 49 | 170 | 7 |
| B | 52 | 58 | 2.2 | 2.4 | 4.3 | .6 |
| Evaporated solids, 180°C | 2 322 | 2 505 | 1 110 | 1 200 | 1 630 | |
| Temperature, °C | 92.1 | 95+ | 96 | 96+ | 72 | 65 |
| pH | *7.4* | *8.7* | *9.5* | *9.7* | *6.6* | *2.4* |
| Chemical problems: | | | | | | |
| Carbonate deposition | Occurs when water erupted | | Slight—little available Ca | | Occurs naturally | None |
| Silica deposition | None? | | Possible | | None | None |
| Chemical corrosion | None? | | None | | None? | Strongly acid |

at 150°C. Waters that are very high in silica when erupted may precipitate silica in pipes. Such a deposit would be considerably more difficult to remove by drilling than is carbonate.

Some thermal spring areas are strongly acid near the surface (see anal. 6, table 1) and condensates of gases that are high in free $CO_2$ and $H_2S$ are corrosive. Problems of external and internal corrosion of pipes have already been encountered in explored thermal regions of Italy, New Zealand, and elsewhere, and apparently have been solved without great difficulty.

### Geologic mapping

Geologic mapping of rocks exposed at the surface provides three types of information of practical use in exploring a thermal area :

1. The kinds and physical properties of rocks that may be encountered at depth.

2. The recognition of the structural control of migrating thermal fluids. In tight rocks such as granite, impure sandstone and shale, the channels of migration of thermal water are faults, fractures, or any relatively more permeable strata.

3. Geologic mapping unravels the history of an area and gives some key to the length of time a system has been active, as well as some information on the probable magnitude of the heat source.

### Geophysical surveys

The first reconnaissance of a thermal area is commonly a type of geophysical survey, the measurement of surface temperatures of springs and fumaroles, and the estimation or measurement of discharge from hot springs.

More elaborate geophysical surveys, such as measurement of total heat flow at the surface in fumaroles and springs and by rock conduction, and magnetometer, gravity, and resistivity surveys, are appropriate parts of an intensive study of a promising area (White, Sandberg, and Brannock, 1953, pp. 495-496). These surveys are best made after geologic mapping and prior to exploratory drilling.

### Exploratory drilling

A common approach to development of a thermal area is to drill large-diameter holes to considerable depths without prior exploration, in the immediate hope of obtaining impressive erupting wells capable of high rates of production of steam or hot water. A thermal area can be evaluated at lower cost if first priority is given to obtaining useful information with attention focused on temperature distribution. Holes drilled by large rotary equipment progress so rapidly, especially if operated twenty-four hours per day, that the original ground temperatures are greatly disturbed and little reliable data can be obtained. Some disturbance of original temperatures must be expected from any drilling method, but the best temperature data are obtained from holes drilled by cable tools in which bottom-hole measurements are taken as drilling progresses. In a well that "makes" its own water, fairly reliable bottom-hole temperatures can be measured at any time, but the best are obtained after a shut-down of several hours or more.

Graphs of data obtained from two wells drilled by cable tools at Steamboat Springs are shown in figures 2 and 3. The south Steamboat well was drilled on the southern extremity of the thermal area, where all temperatures were considerably below 100°C. Note the close relation between changes in temperature and structure, with confirming evidence from the chloride curve. The low salinity and low temperature of the bottom water indicate that this water is entirely meteoric in origin, is migrating into the spring system, and has already been considerably heated by rock conduction.

The Rodeo well yielded similarly useful information in its upper 164 feet drilled by cable tools. The highest temperatures and most saline water occurred at about 145 feet of depth. Flow of cooler, less saline, water near 160 feet in depth was found in porous sands lying on the granodiorite bedrock. Deeper drilling by light rotary equipment also provided good temperature data in this well because only a single shift was drilled per day, permitting rather closely spaced and relatively reliable temperature measurements.

The GS-5 drill hole (figure 1) and seven other holes of the same series were drilled by diamond bits. Core was recovered, and provided very useful geologic data on rock types and structural control at depth. Average cost for more than 3 000 feet of hole with average depth of about 400 feet per hole was a little more than $6 per foot (1950 prices).

Dry steam cannot be expected in a spring system where temperatures are entirely below the boiling-point curve. Day-to-day plotting of measured temperatures relative to the boiling-point curve gives a continuing evaluation of the possibilities for dry steam at reasonable depths.

If a characteristic mixing temperature exists in a spring system, it is probably recognizable from a few holes drilled primarily to obtain knowledge of geologic structure and temperature data. If, for example, several holes show a levelling-off of temperatures, regardless of the depth of intersection of the principal structures, a mixing temperature has probably been defined. Deep drilling of hot water areas probably will not encounter any major increase in temperature until the base of circulation of meteoric water is approached, perhaps at depths as great as 10 000 feet. Much costly drilling can then be avoided.

Maximum temperatures obtained in shallow drilling can be used to provide a fairly reliable estimate

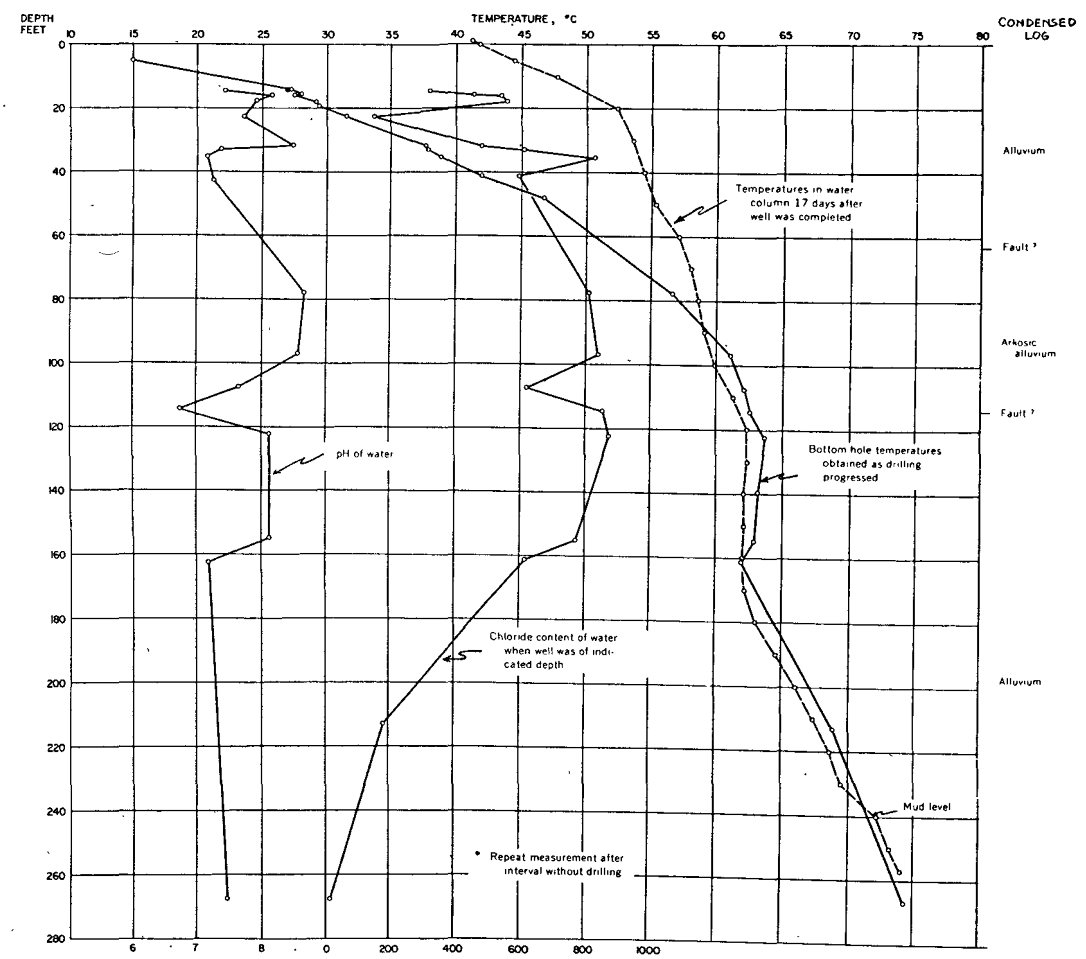


**Figure 2. Data from South Steamboat near the south end of the Steamboat Springs thermal area. Drilled by cable-tool equipment; cased to 175 feet**

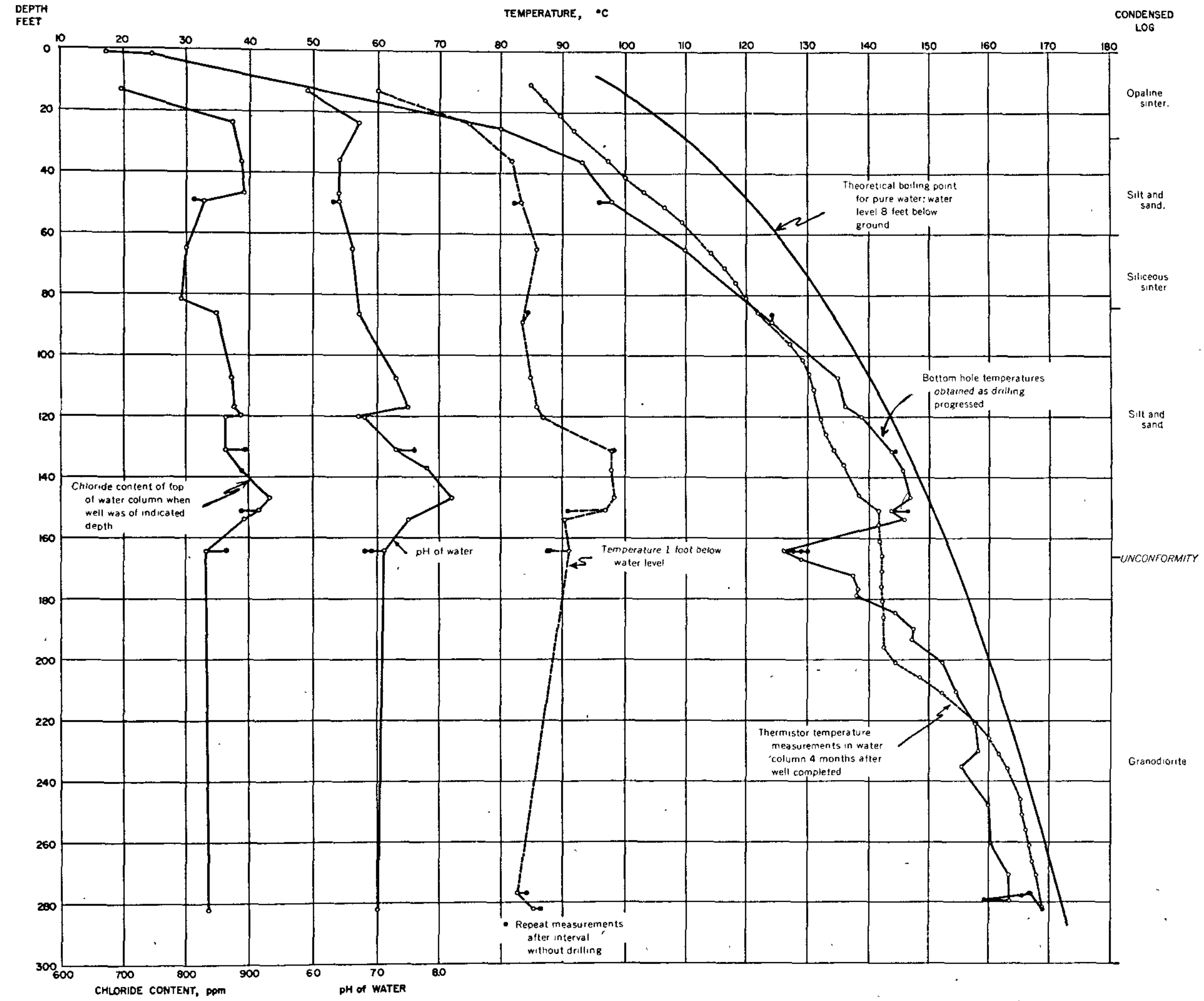


**Figure 3. Data from Rodeo well immediately west of the crest of the Main Terrace, Steamboat Springs, Nevada. Drilled by cable-tool rig to depth of 164 feet, then completed by rotary equipment; cased to bottom of hole**

of the steady-state flow of heat in a hot water system prior to its development, if total surface and subsurface discharges of water can also be determined directly or by chloride inventory. This method was first used by Ellis and Wilson (1955, pp. 627-630) at Wairakei, New Zealand, and was later extended by White (1957, p. 1642) to some other areas. Steady-state heat flows determined by this method for the following spring systems are in millions of calories per second: Steamboat Springs, 7; Norris Basin, Yellowstone, 8; Upper Basin, Yellowstone, 90; Wairakei, New Zealand, 82.

If average temperatures below the surface at Steamboat Springs are 160°C above normal, the quantity of excess stored heat in an area of 5 sq km and 3 km deep is approximately $1.6 \times 10^{18}$ cal. This is equivalent to the natural flow of heat at the present rate for 7 000 years. This is a minimum figure because much excess heat is also stored at greater depth and below the surface of the surrounding area.

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## *Summary*

High-temperature geothermal areas are caused by volcanic heat, but chemical and isotopic evidence indicates that most of the water is meteoric. This relationship demands extensive transfer of heat by conduction from magma through rock to deeply circulating meteoric water.

The prevailing balance of heat supply and water supply determines whether an area contains dry steam or hot water and wet steam. Where heat supply is great but mass rock permeability is low, dry steam occurs because relatively little meteoric water penetrates down into the zone of mixing. Such areas are characterized by fumaroles and acid-sulfate springs, with no significant chloride.

Where permeable channels extend to great depth, meteoric water migrates in a huge convection system and is heated, at first by rock conduction and then by some condensing volcanic steam, resulting in a hot water system. A mixing temperature characteristic for each area may be attained at depth. Little loss in temperature occurs as the heated water rises, until pressures decrease sufficiently to permit boiling. The volcanic hot water-wet steam areas can generally be recognized at the surface by abundant chlorides. Evidence suggests that alkali chlorides are transported continuously from magma. The chlorides were at first in solution in high-density steam and then in water that circulated deeply and condensed the steam at high pressure. The pressure that is necessary to provide continuous transport of alkali chlorides from magma requires a depth on the order of 10 000 feet at the zone of condensing steam.

Exploratory drilling as contrasted to development drilling should aim for maximum data essential for evaluation. Results at Steamboat Springs, Nevada, indicate that cable-tool drilling provides best bottom-hole temperatures, obtained as the hole progresses. Diamond drilling provides best geologic control, with satisfactory temperatures. Rotary drilling with large rigs is so expensive, holes progress so rapidly, and original ground temperatures are disturbed so much that few reliable data can be obtained. On the other hand where preliminary evaluation of a thermal area is favourable, deep large-diameter holes may demand large rotary drills for production wells.

Important applications of reliable temperature data during preliminary exploration are:

1. Dry steam cannot be expected wherever bottom-hole temperatures are below the boiling-point curve for water under hydrostatic pressure; current evaluation of outlook is possible.

2. If a characteristic mixing temperature does exist, it is probably recognizable from a few holes drilled primarily for geologic structure and good temperature data. If a tendency for levelling-off in temperature exists at depth, large increases in temperature probably will not be encountered until the base of circulation of the meteoric water is approached, perhaps at depths on the order of 10 000 feet; thus much costly drilling can be avoided.

3. Total natural heat flow of an area can be estimated from the mixing temperature and from total discharge of saline water, either measured or computed from chloride inventories. Estimates in $10^6$ cal/sec are : Steamboat Springs, 7; Norris Basin, Yellowstone, 8; Upper Basin, Yellowstone, 90, and Wairakei, New Zealand, 82. Stored heat in the upper 3 km of the Steamboat thermal area is at least equivalent to present natural heat flow for 7 000 years.

Potential chemical problems can be recognized during reconnaissance studies. In particular, much is known about deposition of $CaCO_3$, which occurs most commonly where spring waters range in pH from 6 to 8 and dissolved calcium exceeds a few parts per million. Eruption of such water results in loss of $CO_2$ to the vapour phase; the pH rises, bicarbonate is converted to carbonate, and $CaCO_3$ is then precipitated. Production of water under pressure can prevent precipitation of carbonate. Deposition of silica may be a hazard in waters containing more than 350 parts per million of $SiO_2$.

# ÉVALUATION PRÉLIMINAIRE DES CHAMPS GÉOTHERMIQUES PAR LA GÉOCHIMIE ET LA GÉOLOGIE, COMPLÉTÉES PAR LE FORAGE DE PUITS PEU PROFONDS

## *Résumé*

Les champs géothermiques où règnent des températures élevées doivent leur existence à la chaleur volcanique, mais les indications chimiques et nucléaires (activité de certains isotopes) révèlent que la majeure partie de l'eau en cause est d'origine atmosphérique. Cette situation impose une transmission massive de la chaleur du magma aux roches avoisinantes par conduction et, de celles-ci, aux eaux météoriques qui circulent en profondeur.

Le bilan existant à un moment donné entre la chaleur et le volume d'eau disponibles détermine si un gîte donné recèle de la vapeur sèche ou encore de l'eau chaude et de la vapeur humide. Là où les disponibilités de chaleur sont fortes et la perméabilité des roches peu marquée, on trouve de la vapeur sèche, parce que la masse d'eau météorique qui pénètre jusqu'à la zone de mélange est relativement réduite. Ces régions se caractérisent par la présence de fumerolles et de sources sulfatées acides, tandis que la teneur des eaux en chlorures y est insignifiante.

En présence de passages perméables s'étendant jusqu'à une grande profondeur, l'eau météorique accède à un gigantesque système de convection et elle est donc chauffée, tout d'abord, par la conduction des roches, puis par une partie de la vapeur volcanique qui se condense, ce qui fait apparaître un système d'eau chaude. On peut déterminer une température de mélange caractéristique pour chaque gîte. Les pertes de température pendant la montée de l'eau chaude sont faibles et, une fois que les pressions tombent à une valeur suffisamment faible, l'ébullition devient possible. Les régions où l'on trouve de l'eau chaude et de la vapeur humide sont généralement identifiables en surface par la présence d'une abondance de chlorures. Les indications dont on dispose donnent à penser que des chlorures alcalins s'échappent constamment du magma. Tout d'abord en solution dans une vapeur à forte densité, ces chlorures passent à l'eau qui a circulé à de grandes profondeurs pour condenser cette vapeur à haute pression. Celle qui est nécessaire pour assurer un exode continu des chlorures alcalins du magma exige une profondeur de l'ordre de 10 000 pieds (3 000 m) à la zone de condensation de la vapeur.

Les forages destinés aux sondages et aux expériences, à l'inverse des puits d'exploitation, doivent viser à l'obtention d'un maximum possible de données aux fins d'évaluation. Les résultats obtenus dans l'État du Nevada, à Steamboat Springs, indiquent que le forage au câble donne les meilleures lectures de la température en fond de puits au fur et à mesure de son fonçage, tandis que le foret au diamant assure le meilleur contrôle géologique compatible avec la récolte de données satisfaisantes sur la température. Le forage à la perforatrice rotative, avec ses grandes installations, est si coûteux, le fonçage progresse si vite et les températures initiales du sous-sol s'en trouvent tellement modifiées qu'il est rare de pouvoir s'y remettre pour recueillir des données dignes de foi. Là, en revanche, où l'évaluation préliminaire d'un champ géothermique se solde par des indications favorables, la réalisation de puits profonds et de gros diamètre peut exiger l'emploi de forets rotatifs de fort calibre quand on veut passer à l'exploitation.

Voici d'importantes applications que l'on peut donner aux profils de température dignes de foi, tels qu'ils se dégagent de l'exploration préliminaire :

1. On ne saurait s'attendre à trouver de la vapeur sèche là où les températures de fond de sondage sont inférieures à ce qu'indique la courbe des points d'ébullition pour l'eau soumise à une pression hydrostatique. On peut toutefois procéder à une évaluation des perspectives telles qu'elles se présentent au moment considéré.

2. S'il existe une température caractéristique de mélange, ce fait sera probablement révélé par quelques puits forés au premier chef dans le but de se renseigner sur la structure géologique de la région en cause et de recueillir de bonnes valeurs de la température. Si cette température a tendance à se stabiliser à une profondeur appréciable, elle ne présentera probablement plus d'accroissements marqués jusqu'à ce que la base du système de circulation de l'eau météorique soit proche, peut-être à des profondeurs de l'ordre de 10 000 pieds ou 3 000 m, ce qui permettra, le cas échéant, d'éviter beaucoup de travaux de forage dispendieux.

3. Le débit total de chaleur naturelle, dans un champ donné, peut être évalué à partir de la température de mélange et le débit total d'eau salée, soit mesuré directement soit calculé à partir des réserves de chlorures. Les évaluations, en millions de calories par seconde, sont les suivantes : Steamboat Springs, 7; bassin de Norris, Yellowstone, 8; Bassin supérieur, Yellowstone, 90; et Wairakei, Nouvelle-Zélande, 82. Les réserves de chaleur trouvées dans les 3 km supérieurs de la région thermique de Steamboat sont équivalentes à un minimum de 7 000 années de fourniture de chaleur naturelle au débit actuel.

On peut se faire une idée, lors des reconnaissances, des problèmes d'ordre chimique susceptibles de se présenter. On sait beaucoup, en particulier, sur les dépôts de $CO_3Ca$, très communs là où le pH des eaux de source s'échelonne entre 6 et 8 et où il y a un peu plus de quelques parties de calcium par million. Les éruptions d'eau de ce genre s'accompagnent d'une perte de $CO^2$ au profit de la phase aqueuse, le pH monte, le bicarbonate se transforme en carbonate et le $CO_3Ca$ est précipité. La production d'eau sous pression peut empêcher cette précipitation du carbonate. Les dépôts de silice sont un risque à envisager avec les eaux qui contiennent plus de 350 parties de $SiO_2$ par million.

# CHEMICAL PROSPECTING OF HOT SPRING AREAS FOR UTILIZATION OF GEOTHERMAL STEAM

*S. H. Wilson**

1. Prior to the drilling at Wairakei from 1950, there were available some chemical analyses of the waters and gases of the hot spring activity in the locality. This activity consisted of the boiling springs and geysers of clear chloride water at Geyser Valley, and an area of muddy acid sulphate springs with one geyser of mixed chloride-sulphate water in Waiora Valley. Further, there were some fumaroles, of which the largest was Karapiti Blowhole. For the locations, reference may be made to figure 5 in the paper by Banwell (1).

2. This earlier chemical work was of little use in interpreting the results of drilling, as it was not realised that the hot chloride water of Geyser Valley was the important type of water, and further, many constituents later found of importance had not been determined.

3. The chemical investigation of the discharges of the drillholes at Wairakei gave a better understanding of the relation between the water tapped at the drillholes, and the waters and gases of Geyser Valley, Waiora, and Karapiti. When it was proposed in 1956 to drill prospecting holes at Waiotapu, advice in the drilling programme, from the chemical aspect, was given on the basis of the knowledge of Wairakei, and of fairly full analyses from four springs. Drilling at Waiotapu did not tap the type of water expected, and has turned up unforeseen difficulties in comparing the area with Wairakei.

4. Fuller analyses of the waters of all the active areas of the Rotorua/Taupo region are becoming available, and there is progress to a clearer understanding of the chemical evidence. In the light of this work, it is suggested in this paper how chemical investigation of natural activity could be used to choose localities for prospecting in other thermal regions.

## Sampling of hot springs

1. Development and improvement of methods of sampling the outputs of drillholes and natural hot springs have proceeded together since 1950. In sampling hot springs, the emphasis should be on simplicity of the methods, and the robustness of the apparatus. Fragile glassware must be replaced as far as possible by the equivalent article in plastic material.

2. The methods of sampling gas and steam from fumaroles differ, depending on whether the gas content of the steam is high or low. The high content will be found in volcanic craters where it will be desirable to sample in order to make comparisons with hot spring areas. The method used is that described by Rafter, Wilson, Shilton (1a). In hot spring areas the method used is similar to that illustrated by a figure given by Wilson (2, p. 30).

For collecting gas from bubbling pools, the method given by Wilson (3) has been improved in detail, such as the use of butyl rubber (impervious to carbon dioxide) for closing the bottles.

For complete analyses of water samples, four 500 ml bottles should be collected. Two closed with wide-bore butyl rubber tubing should be used, with precautions taken against contact with air. One of these is to be analysed when cool for hydrogen sulphide, and the other kept for other volatile constituents. A polythene bottle of filtered water should be used, and a glass bottle of water acidified with nitric acid.

## Areas heated by magmatic steam

1. There has been no experience in this country of drilling for unsaturated steam such as is found at Larderello, or "The Geysers", California. Such steam of deep origin, "plutonic steam", may be steam coming from a deep magma source. On the other hand, if the steam is not from juvenile water, it may come from chloride water at or near the critical temperature, and the occurrence of such steam may be associated with the high gas content. Steam of high gas content is found in this country in fumaroles in or near volcanic craters, and is mainly magmatic steam. Steam vents are also found in hot spring areas, but in these cases the steam rises from the hot chloride water below.

2. It may be of importance to determine whether steam in a hot spring area can be of magmatic origin. The gas content of the steam gives the best distinction. The gas content of magmatic steam is high, 2-3 per cent (by volume), whereas steam from chloride water is generally of low gas content. When a small amount of steam separates from water, the gas content of the steam will be high, whereas if the amount separating is great, the gas content will be low. Steam of direct magmatic origin will be high and fairly constant in gas content,

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but the content in steam from chloride water will be low and variable. For example, the large Karapiti Blowhole near Wairakei had a gas content of 0.03 per cent, whereas smaller fumaroles had contents of 0.2 and 0.4 per cent. Further, the contents of gases of different solubility will vary according to the amount of steam lost from chloride water. This effect has been found at Wairakei in the ratios $CO_2/H_2S$ and $CO_2/NH_3$. Gas in steam of magmatic origin is more likely to be constant in composition.

3. Good flows of hot chloride water coming to the surface without much dilution lose, with the steam that comes off, nearly all the gas content (mainly carbon dioxide and hydrogen sulphide). Any gas collected is mainly nitrogen. This is probably from air picked up in solution in the small admixture of surface water.

Hence, good samples of gas are best obtained from acid sulphate pools. Ratios of carbon dioxide to the constituents, $H_2S$, $H_2$, $CH_4$ and $N_2$ can be determined, but so far have not been useful. Determinations of the inert gases, though difficult, could probably be more useful. The content of carbon monoxide, in relation to that of hydrogen and carbon dioxide, should give information as to the temperature at which these gases are in equilibrium in the underground water.

4. Volcanic craters are regarded as undesirable sites for drilling. In cases where it is not possible to distinguish easily areas of recent volcanic activity from acid hot spring areas, it will be desirable to examine the steam for sulphur dioxide, and the waters of acid sulphate springs for their polythionate content. Otherwise, the analyses of waters of such springs are useless.

## Chloride waters

### Constituent ratios

An important discovery at Wairakei was that the output of the bores comes from an underground supply of hot chloride water of which the composition is remarkably constant, especially if allowance is made for small differences in the enthalpy of the discharges. In comparing waters from bores and hot springs with waters from different areas, there is the difficulty that the former, or shallow bores, are diluted with varying amounts of surface water. To eliminate this effect, it is best to compare mole ratios, generally of chloride to anionic constituents, and sodium to cationic constituents.

If differences in concentrations of chloride or sodium are great, it is not to be expected that the mole ratios will agree well. In order to indicate this, the author uses what is called the "chemical index". For example, the "chemical index, chloride to boric acid" is a fraction of which the numerator is the chloride content in moles per million grammes, while the numerator is the mole ratio, chloride to boric acid (Cl/B). The fraction expressed as a decimal is the content of boric acid. In the tables, to avoid repetition of figures, both chemical indices and mole ratios are used.

### Comparison of natural and drillhole waters

Table 1 presents a comparison of spring and bore waters at Wairakei. Although the natural waters are diluted with about 20 per cent of surface water, certain of the mole ratios are much the same as those of the waters of both eastern and western bores. The ratios which show good agreement are Cl/B, Cl/F, Cl/As, Cl/Br, Na/Li, Na/Cs.

The ratio $Cl/SO_4$ is another which in general is constant but which can be low owing to oxidation of hydrogen sulphide at the surface.

As steam is lost from natural water before it reaches the surface, ratios of certain constituents in the underground water cannot be determined for natural springs, although they can be obtained for bore discharges by analyses of both steam and water. These ratios are $Cl/CO_2$, Cl/(total sulphur) and Cl/(total ammonia). The ratio $Cl/NH_4$ can be determined for the water, but the value may not be the same as for bore waters because the separation of steam does not occur in the same way as in bore discharges.

There is another group of ratios in which there are considerable differences. These are the ratios Na/K, Na/Rb, Na/Ca, Na/Mg. These differences are due to the interaction of some of the cations with the country rock. The effect is particularly shown by the ratio Na/K, as potassium tends to replace sodium in the country. Rubidium is similar to potassium. Lithium may be somewhat absorbed near the surface, so that Na/Li may be higher in spring waters.

### Hot spring areas at Wairakei

Champagne Cauldron has by far the largest outflow of the springs at Geyser Valley, Wairakei. The ratios for this spring could be taken as those of the underground chloride water. From the high Na/K ratio it appears that Geyser Valley spring waters have been for some time in the permeable breccia and do not come, like waters of the western bores, direct from fissures in the ignimbrite. However, it cannot be decided whether the waters are from the same fault as that feeding the eastern bores.

The values for springs in Waiora Valley differ considerably from those of the Wairakei bores. The high sulphate will be due to surface oxidation of hydrogen sulphide in steam. The low chloride/ammonium ratio is a good indication that the water has been partly heated by steam. Low values of the ratio Cl/B are probably also associated with transport of boric acid in steam. The figures for Waiora Valley illustrate the conclusion that ratios from acid sulphate areas are of little value.

### Comparison with other thermal areas

Evidence for constant ratios in other thermal areas was found. For example, at Orakei Korako,

**Table 1. Comparison of waters of springs and bores at Wairakei, New Zealand**

1A (ANIONS)

| *Spring name, etc.* | *Outflow litre/sec.* | *Chemical index* [b] *Cl to B* [a] | *Mole ratio Cl/F* [a] | *Id. Cl/As* [a] $\times 10^{-3}$ | *Id. As/Sb* [a] |
|---|---|---|---|---|---|
| *Geyser Valley* | | | | | |
| Dragon's Mouth | 0-10 | 51.9/24.2 | 161 | 1.02 | — |
| Haematite Geyser | 0.75 | 40.0/24.4 | 141 | 1.00 | — |
| Champagne Cauldron | 120 | 49.9/24.5 | 164 | 1.01 | 34 |
| Eagle's Nest | 0-7 | 39.4/24.3 | 148 | 0.92 | 34 |
| Devil's Inkpot | 0 | 35.8/24.7 | 140 | 1.03 | — |
| *Waiora Valley* | | | | | |
| Heavenly Twins | 7 | 3.2/19.1 | high | 1.10 | — |
| Devil's Eyeglass | ? | 18.5/20.7 | high | 1.40 | — |
| *Bores* | | | | | |
| Shallow bore (No. 9) | 2.7 | 33.0/22.3 | 265 | 0.90 | — |
| *Eastern bores* | | | | | |
| Weighted mean | 30 | 60.3/24.2 | 162 | 0.96 | 67 |
| Standard deviation | — | ±0.2/±0.2 | ±3 | ±0.04 | ±4 |
| *Western bores* | | | | | |
| Weighted mean | 64 | 63.0/24.0 | 165 | 1.00 | 65 |
| Standard deviation | — | ±0.2/±0.2 | ±4 | ±0.04 | ±3 |

[a] Cl to P: chloride to boric acid.
Cl/F: chloride/fluoride.
Cl/As: chloride/arsenious acid.
As/Sb: arsenic/antimony.

[b] For explanation of term, see 4 (*a*) (ii).

**Table 1.** (continued)

1B (MAINLY ANIONS)

| *Spring name, etc.* | *Mole ratio Cl/Br* [a] | *Mole ratio Br/I* [a] | *Id. Cl/SO₄* [a] | *Id. Cl/NH₄* [a] | *SiO₂* [a] *p.p.m.* |
|---|---|---|---|---|---|
| *Geyser Valley* | | | | | |
| Dragon's Mouth | — | — | 185 | 1,250 | — |
| Haematite Geyser | 780 | 10.0 | 100 | 3,800 | — |
| Champagne Cauldron | 1,000 | 9.0 | 188 | 1,200 | 294 |
| Eagle's Nest | 820 | — | 150 | 1,720 | — |
| Devil's Inkpot | 800 | 9.5 | 130 | 3,450 | 254 |
| *Waiora Valley* | | | | | |
| Heavenly Twins | 80 | 2.5 | 0.7 | 15 | — |
| Devil's Eyeglass | 440 | 4.5 | 6.9 | 84 | 318 |
| *Bores* | | | | | |
| Shallow bore (No. 9) | 890 | — | 147 | 31 | 350 |
| *Eastern bores* | | | | | |
| Weighted mean | 870 | 19 | 178 | 4,100 | 402 |
| Standard deviation | ± 20 | ± 6 | ± 5 | ± 300 | ±18 |
| *Western bores* | | | | | |
| Weighted Mean | 905 | 15 | 172 | 4,800 | 521 |
| Standard deviation | ± 20 | ± 3 | ± 7 | ± 300 | ±11 |

[a] Cl/Br: chloride/bromide.
Br/I: bromide/iodide.
$Cl/SO_4$: chloride/sulphate.
$Cl/NH_4$: chloride/ammonium.
$SiO_2$ p.p.m.: silica, parts per million.

**Table 1.** (continued)

1C (CATIONS)

| *Spring name, etc.* | *Chemical index*[b] *Na to K*[a] | *Mole ratio Na/Li*[a] | *Id. Na/Rb*[a] $\times 10^{-3}$ | *Id. Na/Cs*[a] $\times 10^{-3}$ | *Id. Na/Ca*[a] | *Id. Na/Mg*[a] |
|---|---|---|---|---|---|---|
| *Geyser Valley* | | | | | | |
| Dragon's Mouth . . . . | 49.6/22.9 | 28.6 | 2.3 | 3.6 | 79 | — |
| Haematite Geyser . . . . | 41.2/22.4 | 26.7 | — | — | 78 | 460 |
| Champagne Cauldron . . | 46.5/17.8 | 29.8 | 3.6 | 2.5 | 56 | 1,400 |
| Eagle's Nest . . . . . . | 40.0/29.2 | 29.6 | 2.5 | 2.4 | 79 | 320 |
| Devil's Inkpot . . . . . | 36.6/23.0 | 27.2 | — | — | 94 | 460 |
| *Waiora Valley* | | | | | | |
| Heavenly Twins. . . . . | 4.1/10.8 | 36.5 | 4.0 | 20 | — | — |
| Devil's Eyeglass. . . . . | 17.8/15.5 | 32.4 | 2.0 | 20 | 20 | 102 |
| *Bores* | | | | | | |
| Shallow Bore (No. 9). . . | 46.9/24.8 | 43.2 | — | — | 78 | 370 |
| *Eastern bores* | | | | | | |
| Weighted mean . . . . . | 55.8/12.7 | 29.1 | 1.85 | 3.4 | 117 | 520 |
| Standard deviation . . . | ±0.2/±0.4 | ±0.6 | ±0.1 | ±0.2 | ±7 | ±20 |
| *Western bores* | | | | | | |
| Weighted mean . . . . . | 57.1/ 9.8 | 27.0 | 1.60 | 2.9 | 180 | 520 |
| Standard deviation . . . | ±0.3/±0.2 | ±0.1 | ±0.04 | ±0.1 | ±10 | ± 25 |

[a] Na to K: sodium to potassium.
Na/Li: sodium/lithium.
Na/Rb: sodium/rubidium.
Na/Cs: sodium/caesium.
Na/Ca: sodium/calcium.
Na/Mg: sodium/magnesium.

[b] For explanation of term, see 4 *(a) (ii)*.

the waters of eight springs with flows from 0.5 to 5 litre/sec had chemical indices, chloride to boric acid (8-11)/(28.0-29.4), and mole ratios Cl/F: 16-20; $Cl/SO_4$: 5-10; $Cl/NH_4$: about 400. From this and further work, it was concluded that each area has its characteristic constituent ratios, and that many of these differ considerably from area to area.

In areas such as Geyser Valley, the values for the characteristic ratios are taken as those of the largest spring, and at areas such as Orakei Korako, the averages for springs of good flow. Conditions are not always so favourable. At Ohaki, for example, there is only one large pool of good flow, and other springs are acid sulphate, so that there is no confirmatory evidence for the value taken.

Initially, the useful characteristic ratios were Cl/B, Cl/F, Cl/As, $Cl/SO_4$ and Na/Li. The ratio $Cl/NH_4$ should be included although it is hard to decide a characteristic ratio for an area. Low values are a good indication of admixture of steam.

Work by Ritchie (4) and Golding and Speer (5), have shown that As/Sb and Na/Cs respectively are useful ratios. Work by Ellis and Anderson (6) shows that Cl/Br is to be considered and possibly, but less certainly, Cl/I or Br/I.

## CHARACTERISTIC RATIOS FOR THE THERMAL AREAS OF THE ROTORUA TAUPO REGION

From the results available, the ratios most likely to be close to those for the underground water are brought together in Table 4 for most of the thermal areas in the thermal region. The location of the springs referred to in Table 4 and 5 may be found in figure 1. The values used for the ratios Na/K and Na/Rb are the lowest so far found in each area for chloride springs of good flow. Figures for the bicarbonate content, or the ratio $Na/HCO_3$, could not be included. Reference to bicarbonate content is made above.

Values for silica content are included, as the maximum silica content is an indication of the minimum temperature of the water. The solubility of quartz is 490 ppm at 250°C (Kennedy, 7). However, natural waters have been concentrated by loss of steam, and then diluted by surface water.

From the tables it will be seen that there are large differences in the ratios Cl/B, Cl/F, $Cl/SO_4$, $Cl/NH_4$. The differences in the ratios Cl/As, Cl/Br, Na/Li, Na/Cs are generally not great. This agreement points to the similarity of the magma under the whole region, and values in other magmatic provinces may be considerably different. The high values for the ratios Cl/As, Na/Cs for the three Rotorua areas may be related to the conclusion drawn by Grindley (8) that this is an old hydrothermal field established before a general shift of activity to the east.

## ANOMALOUS AREAS

*Waiotapu.* Care must be taken in rejecting apparently anomalous values in some springs as due to accidental surface effects. At Waiotapu, in 1955,

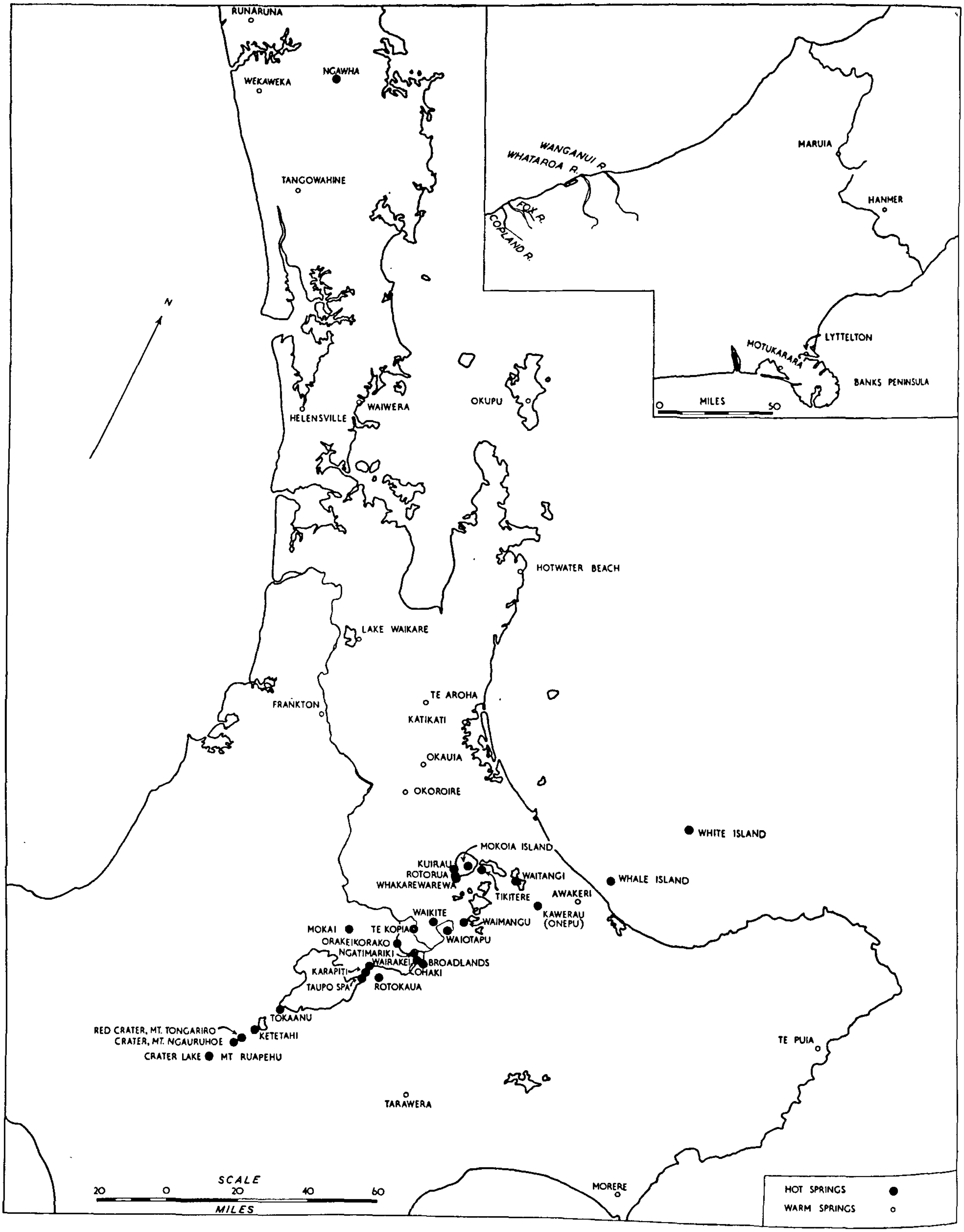


Figure 1. Hot springs of New Zealand

**Table 2. Waiotapu thermal area**

2A (MAINLY ANIONS)

| *Spring or bore* | *Location* | *Chemical index Cl to B* | *Mole ratio Cl/F* | *Id. Cl/As* | *Id. Cl/Br* |
|---|---|---|---|---|---|
| Champagne Pool | (C.P.) | 53/21 | 226 | 720 | 620 |
| Spring by Lake Ngakoro | 0.4 miles S. of C.P. | 50/22 | 176 | 480 | 670 |
| Postmistress Spring | 0.6 miles N.W. of C.P. | 19/29 | — | 1,260 | 770 |
| Lady Knox Geyser | 0.7 miles N.E. of C.P. | 23/24 | 84 | — | — |
| Waikite Spring | 4.0 miles N.W. of C.P. | 3/24 | 24 | 920 | 6 000 |
| *Prospecting bores* | | | | | |
| Bore 1 | 2.0 miles N.N.W. of C.P. | 8/24 | 50 | — | — |
| Bore 3 | 1.1 miles N. of C.P. | 19/29 | 65 | — | — |
| Bore 4 | 0.7 miles N. of C.P. | 56/31 | 190 | — | 740 |
| Bore 5 | 0.5 miles N.W. of C.P. | 27/27 | 130 | — | — |
| Bore 6 | 0.1 miles W. of C.P. | 31/37 | 87 | 980 | 700 |
| Bore 7 | 0.3 miles S.W. of C.P. | 36/26 | 92 | — | 380 |

the values for the spring of large outflow, Champagne Pool, were taken as characteristic of the area, and the values for a hot spring to the north, Postmistress Spring, were disregarded. When prospecting drilling was carried out, it was found, as will be seen from Table 2, that the bores have not yet tapped water like that of Champagne Pool, but the water of bore 3, at any rate, is more like that of Postmistress Spring. It appears now that there may be four types of water in the area. It is possible that there is no large uniform body of hot chloride water, but different water comes up each fault. Possibly there may be a disturbance in an older hydrothermal system, due to more recent volcanism.

*Rotokawa.* Table 3 of the ratios for the Lake Rotokawa area indicates that evidence from acid waters of mixed chloride-sulphate type should receive consideration. Surface oxidation of hydrogen sulphide to sulphate should give a random distribution of $Cl/SO_4$ ratios. The occurrence of two sets of these ratios is too clear for this to be likely. The sulphate seems to be a constituent of the underground water, of which there are two types associated with different fault systems. The high sulphate content is probably the cause of the acidity of the waters, for the second dissociation constant of sulphuric acid alters rapidly with temperature. The underground water is probably nearly neutral, but as the temperature falls bisulphate ions will dissociate to $H^+$ and $SO_4^{2-}$ ions, so that the pH will fall. Corrosion difficulties would be great in such an area.

## A theory of hot springs

It would be useful to have a theory of the origin of hot springs that would give a fuller understanding of the varying types of spring and afford a guide to the information to look for in assessing a thermal area. Any theory of hot springs must account for the following findings:

The heat in the chloride water cannot all be due to magmatic steam, for then the content of juvenile

**Table 2.** (continued)

2B (MAINLY CATIONS)

| *Spring or bore* | *Mole ratio $Cl/SO_4$* | *Id. $Cl/NH_4$* | *Chemical index Na to K* | *Mole ratio Na/Li* | *Id. Na/Ca* | *Id. Na/Mg* |
|---|---|---|---|---|---|---|
| Champagne Pool | 51 | 70 | 50/12 | 37 | 67 | 470 |
| Spring by Lake Ngakoro | 82 | 320 | 48/54 | 57 | 59 | 620 |
| Postmistress Spring | 26 | 290 | 21/36 | 33 | 94 | 740 |
| Lady Knox Geyser | — | 59 | 19/38 | 22 | — | — |
| Waikite Spring | 3 | 45 | 8/33 | 26 | 62 | 74 |
| *Prospecting bores* | | | | | | |
| Bore 1 | — | — | 20/29 | 61 | — | — |
| Bore 3 | 22 | — | 23/24 | 40 | 930 | 560 |
| Bore 4 | — | 1 010 | 51/9 | 38 | — | — |
| Bore 5 | — | 820 | 34/22 | 73 | — | — |
| Bore 6 | 36 | 270 | 28/10 | 38 | 122 | 250 |
| Bore 7 | — | — | 26/15 | 38 | 360 | 220 |

**Table 3. Rotokawa thermal area**

3A (MAINLY ANIONS)

| *Spring No. or name* | *Outflow litre/sec.* | *Chemical index Cl to B* | *Mole ratio $Cl/SO_4$* | *Id. $Cl/NH_4$* |
|---|---|---|---|---|
| 9 | 0-0.05 | 43/9.3 | 10 | 405 |
| 6 | 7 | 38/9.6 | 7 | 430 |
| 163-168 | 3-5 | 5/16.8 | 6.5 | 470 |
| Lake | 20 | 11/10.5 | 2.7 | 216 |
| 82 | 5 | 14/8.8 | 1.1 | 200 |
| On Parariki Stream | 2.5 | 12/11.8 | 1.3 | 179 |
| Do. average of four | 0-0.05 | 20/12 | 2.6 | 240 |

water would have to be about 35 per cent. From the chloride content, the author Wilson (2) deduced a content of 8 per cent, and the evidence from oxygen isotopes (Craig *et al.*, 9) indicates a content generally in hot spring waters of possibly 5 per cent.

The conductivity of the crustal rocks is so low that the heat unaccounted for cannot be supplied by conduction from a magma, or hot rock (Day, 10 or Banwell, 11).

The high content of lithium and caesium in the water at Wairakei (Ellis and Wilson, 12) or water of the thermal areas (Golding and Speer, 5) cannot be supplied by leaching or carried in magmatic steam, but must come from the residual aqueous phase of a crystallising magma (Ellis and Wilson, 12).

The author (work not yet published) surmounts these difficulties by the simple suggestion that there is a long preliminary period of soaking out of heat from a magmatic intrusion, followed by a much shorter period of hot spring activity. The equations given by Jaeger (13) for conduction of heat from an intrusion have been used by the author to make some calculations on a possible model for Wairakei. An intrusion 7 km × 7 km × 1 km is proposed at a depth of 3 km. The intrusion solidified in a period of 40 000 years, and in this time ground water took up the heat by conduction, together with the chemicals in the separated magmatic fluid. A reservoir 20 km × 10 km × 1 km was then formed in strata of 5 per cent porosity under a layer of ignimbrite at a depth of 3 km. The heat in the water and rock would supply the natural activity at Wairakei for 4 000 years.

2. This theory suggests a reason for the differing chemical characteristics of hot spring waters. There will be differences in the ratios of the constituents at different times in the life of the reservoir. These may be caused by separations due to differences in volatility or absorption in rock. The real situation will be much more complicated than the simple model. The time suggested for the cooling of one intrusion is short compared with the total period of volcanism proposed by Grindley (8). Hence there may be rejuvenation of a cooling reservoir by another intrusion, and owing to the size of the reservoirs there may be mixing of separate reservoirs.

Much more work needs to be done before the effect on chemical characteristics of leaching, absorption and time can be understood in the light of the theory. From Table 3, it does not seem that low chloride, low Cl/B ratio, or high Cl/F ratios can be, as expected, simply related to age of the activity. Nevertheless, there may be progress on these lines that will lead to more assistance from theory in prospecting other thermal regions.

**Table 3.** (continued)

3B (MAINLY CATIONS)

| *Spring No. or name* | *Chemical index Na to K* | *Mole ratio Na/Li* | *Id. Na/Ca* | *Id. Na/Mg* | *Silica p.p.m.* |
|---|---|---|---|---|---|
| 9 | 42/16 | 38 | 81 | 150 | 355 |
| 6 | 43/16 | 38 | 154 | 90 | 340 |
| 163-168 | 12/18 | 36 | 77 | 100 | 280 |
| Lake | 12/15 | 42 | 31 | 100 | 195 |
| 82 | 17/14 | 48 | 45 | 40 | 330 |
| On Parariki Stream | 15/14 | 47 | 28 | 35 | 330 |
| Do. average of four | 23/15 | 45 | 39 | 87 | 304 |

**Table 4.** Characteristic ratios for hot spring areas of the Rotorua-Taupo region

4A (MAINLY ANIONS)

| *Area* | *Chemical index Cl to B* | *Mole ratio Cl/F* | *Id. Cl/As* $\times 10^{-3}$ | *Id. As/Sb* | *Id. Cl/Br* $\times 10^{-3}$ | *Id. $Cl/SO_4$* | *Id. Cl/NH* $\times 10^{-3}$ |
|---|---|---|---|---|---|---|---|
| Tokaanu | 87/10 | 1 000 | 0.74 | 15 | 0.8 | 100 | 1.0 |
| Taupo Spa | 45/18 | 220 | 1.05 | — | 0.85 | 1.7 | 0.4 |
| Wairakei (western bores) | 63/24 | 165 | 1.00 | 65 | 0.90 | 172 | 4.8 |
| Rotokawa | 40/9 | high | 0.97 | — | 1.0 | 2 | 0.43 |
| Ohaki | 30/10 | 145 | 1.4 | 2 | 0.8 | 54 | 0.11 |
| Ngatimariki | 12/23 | — | — | — | 0.5 | 0.5 | 0.22 |
| Onakei Korako | 12/28 | 25 | 1.4 | 25 | 0.75 | 0.75 | 0.40 |
| Waiotapu | 53/21 | 230 | 0.7 | 7 | 0.6 | 44 | 0.075 |
| Waikite | 3/25 | 84 | 0.9 | — | 0.9 | 3 | 0.024 |
| Waimangu | 27/34 | 140 | 1.4 | 21 | 0.71 | 3.5 | 0.070 |
| *Rotorua* | | | | | | | |
| Whakarewarewa | 16/34 | 57 | 3 | 3 | 0.6 | 13 | 0.80 |
| Rotorua town | 21/24 | 54 | 4 | — | 0.9 | 16 | 0.40 |
| Kuirau | 9/16 | 21 | 6.5 | — | 4.0 | 11 | 1.10 |
| Tikitere | 9/5 | — | — | — | 0.6 | 12 | 0.035 |
| Waitangi | 10/39 | 250 | 2 | — | — | 20 | 0.50 |
| Kawerau (Onepu) | 31/7 | 250 | 0.95 | — | 0.7 | 210 | 0.09 |

## Warm springs

1. Springs of warm water may be due to heat of tectonic origin—i.e., the energy is released by crustal movement. It seems improbable that there will be a great store of geothermal energy of tectonic origin. It is desirable to have methods to distinguish such springs from warm springs of volcanic origin. There may be useful reserves of heat associated with warm volcanic springs, even if the temperature is low. There does not seem to be any one definite way of distinguishing such springs. One reason for the similarity may be that the heat is transferred underground to the water, not by conduction, but by volatile matter, mainly steam, from heated rock. The constituents in this steam could be much the same as those in magmatic steam.

2. Table 5 gives some comparisons of the two types of spring. The main distinction is that in "volcanic" springs, the ratio Ca/Mg is about 1 : 4, whereas the values for "tectonic" springs can be either very much higher or lower. This is probably associated with another difference in gas composition. In areas of tectonic heat, the gas contains large amounts of methane, whereas at Te Aroha, for example, the gas is nearly pure carbon dioxide.

**Table 4.** (continued)

4B (MAINLY CATIONS)

| *Area* | *Chemical index Na to K* | *Mole ratio Na/Li* | *Id. Na/Rb* $\times 10^{-3}$ | *Id. Na/Cs* $\times 10^{-3}$ | *Id. Na/Ca* | *Id. Ca/Mg* | *$SiO_2$ p.p.m.* |
|---|---|---|---|---|---|---|---|
| Tokaanu | 79/18 | 23 | 5.5 | 2.4 | 62 | 5 | 300 |
| Taupo Spa | 44/24 | 27 | 4.7 | 2.6 | 80 | 1.6 | 120 |
| Wairakei (western hores) | 57/9.8 | 27 | 1.6 | 2.9 | 180 | 2.9 | 520 |
| Rotokawa | 43/16 | 38 | 6.0 | 3.3 | 150 | 2.8 | 400 |
| Ohaki | 39/19 | 28 | 7.0 | 4.8 | 130 | — | 305 |
| Ngatimariki | 18/42 | 54 | 50 | — | 105 | 4.7 | 250 |
| Orakei Korako | 14/19 | 28 | 7.0 | 7.5 | 280 | 1.0 | 430 |
| Waiotapu | 50/12 | 38 | 2.0 | 4.1 | 65 | 6.6 | 450 |
| Waikite | 8/33 | 26 | 0.5 | 1.6 | 62 | 1.2 | — |
| Waimangu | 24/26 | 40 | 2.1 | 35 | 130 | 1.6 | 740 |
| *Rotorua* | | | | | | | |
| Whakarewarewa | 20/13 | 38 | 3.8 | 7.9 | 230 | 4.2 | 440 |
| Rotorua town | 26/33 | 60 | 3.3 | 1.6 | 80 | 1.5 | 225 |
| Kuirau | 15/19 | 41 | 4.3 | — | 130 | 3.5 | 320 |
| Tikitere | 26/40 | 30 | — | — | 130 | 2.3 | 250 |
| Waitangi | 13/32 | 47 | 8.0 | 5.0 | 25 | 1.2 | 220 |
| Kawerau (Onepu) | 30/11 | 28 | 4.9 | 7.0 | 70 | 4.0 | 330 |

**Table 5. Some warm springs of New Zealand**

5A (MAINLY ANIONS)

| Area | Chemical index Cl to B | Mole ratio Cl/F | Id. Cl/As $\times 10^{-3}$ | Id. Cl/Br $\times 10^{-3}$ | Id. Cl/I $\times 10^{-3}$ | Id. $Cl/SO_4$ | Id. $Cl/NH_4$ |
|---|---|---|---|---|---|---|---|
| *Probably of volcanic origin* | | | | | | | |
| Te Aroha . . . . . . | 16/1.1 | 1 000 | 3.1 | 0.73 | 3 | 1.6 | 86 |
| Ngawha . . . . . . . | 26/0.5 | 280 | 9.8 | 0.87 | 2 | 5 | 0.2 |
| Banks Peninsula . . . | 8/110 | 70 | > 5 | 0.86 | > 5 | 19 | 2 500 |
| *Probably of tectonic origin* | | | | | | | |
| Morere . . . . . . . | 436/100 | 22 000 | 10 000 | 0.45 | 2.3 | 1 600 | 5 000 |
| Tarawera . . . . . . | 20/2.7 | 28 | 50 | 0.78 | 0.9 | 23 | 150 |
| Hanmer . . . . . . . | 14/2.8 | 55 | > 400 | 0.80 | 1.4 | 18 | 58 |
| Maruia . . . . . . . | 3.8/11 | 21 | > 100 | 0.32 | 2.5 | 11 | 29 |

## Conclusions

### 1. The field for chemical investigations

In prospecting areas of hot spring activity for the possibility of developing the power or heat resources, the first work to be undertaken should be chemical investigations. Samples are easily taken, and the analytical work should not be costly. It will be desirable to sample first the waters of springs of clear water and good flow, in the areas under consideration for drilling. In addition, the main springs should be sampled in areas in the whole region of activity, even if, for various practical reasons, many of the areas are not available for drilling.

The constituents determined should include those in the following ratios: $Cl/HBO_2$, Cl/F, Cl/As, $Cl/SO_4$, $Cl/NH_4$, Na/K, Na/Li, Na/Ca, Ca/Mg. In addition the contents of silica and bicarbonate ion should be determined. For the significance of the bicarbonate content, particularly in regard to deposits of calcite in drill holes, reference should be made to the paper by Ellis (14) in this series. If further work is possible, the ratios Cl/Br, Br/I, As/Sb, Na/Rb, Na/Cs should also be determined. From these ratios it should be possible to determine whether there is one set of ratios characteristic of each area.

At the same time, the gas content of the steam of any fumaroles in the area should be determined, as well as the ratios $CO_2/H_2S$ and $CO_2/NH_3$ in the gas. The value of this information has already been discussed. A survey of the composition of gases from bubbling pools may be left till it is required to amplify the information from the water analyses.

### 2. The utility of characteristic ratios

Comparison of the ratios Cl/As, Cl/Br, Na/Li, Na/Cs for all the areas in a region may indicate whether any of the activity is of a distinct or older type.

From the constancy of the ratios Cl/B, Cl/F, Cl/As, $Cl/SO_4$, $Cl/NH_4$, Na/Li in the various areas, one can judge where there is likely to be a uniform body of hot chloride water. By comparison of the values, and the chloride content with those for areas where there has been successful drilling such as Wairakei, it may be possible to select an area for prospecting drill holes.

**Table 5.** (continued)

5B (CATIONS)

| | Chemical index Na to K | Mole ratio Na/Li | Id. Na/Ca | Chemical index Ca to Mg | $SiO_2$ p.p.m. |
|---|---|---|---|---|---|
| *Probably of volcanic origin* | | | | | |
| Te Aroha . . . . . . . . . . | 136/67 | 142 | 100 | 0.2/1.3 | 120 |
| Ngawha . . . . . . . . . . . | 30/20 | 42 | 34 | 0.6/1.5 | 112 |
| Banks Peninsula . . . . . . . | 10/34 | 44 | 6.3 | 0.8/0.7 | — |
| *Probably of tectonic origin* | | | | | |
| Morere . . . . . . . . . . . | 318/130 | 330 | 5.1 | 7.3/12 | 25 |
| Tarawera . . . . . . . . . . | 22/94 | 81 | 75 | 0.3/71 | 42 |
| Hanmer . . . . . . . . . . . | 16/16 | 66 | 96 | 0.2/18 | 49 |
| Maruia . . . . . . . . . . . | 6/38 | 28 | 52 | 0.14/20 | 65 |

Initially, areas should be avoided where the chemical evidence indicates that different types of water are coming to the surface, or where the underground water seems to be high in sulphate.

If the thermal area favoured consists of several centres of activity, the lowest Na/K ratio would indicate the centre fed most directly from the underground supply, and this locality should be chosen for drilling.

Finally, when drilling commences, it will be necessary to compare the values for the first bores with those for the hot springs till it is confirmed by good agreement that prospecting is successful in locating that body of uniform chloride water which so far seems to be required for a successful power development like Wairakei.

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## *Summary*

The first investigation to be made in prospecting for possible utilization of hydrothermal heat resources should be chemical analysis of the larger springs of clear chloride water, in most of the hot spring areas of a thermal region.

Sampling of gas from fumaroles and pools can also be useful. Low gas content of the steam in large fumaroles, and large variations in the gas content, and in the ratios $CO_2/H_2S$ and $CO_2/NH_3$, are an indication that steam is boiling off from underlying chloride water.

Experience at Wairakei indicates that the values of the constituent ratios Cl/B, Cl/F, Cl/As, Cl/Br, $Cl/SO_4$, Na/Li are the same in the spring waters as in the underground source of chloride water. From the study of other active areas, it is concluded that a thermal area often has characteristic ratios, constant in that area, but very different from those of other areas. The values of the ratios Cl/As, Na/Li, Na/Cs for all the areas of a region are useful in judging the uniformity of the magma, in detecting areas belonging to an older period of activity, and in comparing the region with others in the world. In choosing any one area for the first prospecting by drilling, the most favourable chemical indication for a large uniform supply of hot water would be a general similarity to Wairakei in chloride content, and in the ratios Cl/B, Cl/F, $Cl/SO_4$. Areas with more than one set of constituent ratios should initially be avoided, also areas with low $Cl/SO_4$ ratios. Low Na/K ratios should be a favourable indication for locating bores near feeding fissures. Progress in prospecting drilling is followed at first by comparison of the values for the bore waters with those for the natural waters.

# PROSPECTION CHIMIQUE DES RÉGIONS DE SOURCES CHAUDES POUR L'UTILISATION DE LA VAPEUR GÉOTHERMIQUE


## *Résumé*

La première recherche ayant trait à la prospection en vue de l'utilisation possible de sources de chaleur hydrothermique doit être dans la majorité des zones d'une région thermique, possédant des sources chaudes, une analyse chimique des sources principales d'eau claire.

L'échantillonnage des gaz provenant des fumerolles et des accumulations d'eau peut également avoir sa valeur. La faible teneur en gaz de la vapeur dans les grosses fumerolles et les variations importantes de la teneur en gaz, ainsi que des rapports $CO_2/H_2S$ et $CO_2/NH_3$ signalent que de la vapeur s'échappe de l'eau chlorurée souterraine.

L'expérience acquise à Wairakei indique que les valeurs dans les proportions des composants Cl/B, Cl/F, Cl/As, Cl/Br, $Cl/SO_4$, Na/Li, sont les mêmes dans les eaux de sources que dans les sources souterraines d'eaux chlorurées. A la suite d'une étude des autres régions actives on en a conclu qu'une zone thermique présente souvent des rapports caractéristiques constants dans cette région mais bien différents de ceux des autres régions. Les valeurs des rapports Cl/As, Na/Li, Na/Cs pour toutes les zones d'une région, servent à juger de l'uniformité du magma quand il s'agit de trouver les régions qui appartiennent à une période d'activité plus ancienne et par comparaison entre celle-ci et d'autres dans le monde. Lors d'une première prospection par sondage, dans une région donnée, l'indication chimique la plus favorable indiquant des ressources uniformes d'eau chaude, serait une teneur en chlorure analogue à celle de Warakei, dans les proportions Cl/B, Cl/F et $Cl/SO_4$. Au début, il faut éviter les zones où il existe plus d'un jeu de combinaisons de composants, ainsi que celles où le rapport $Cl/SO_4$ est faible. Les rapports Na/K faibles devraient être une indication favorable pour situer des puits près des fissures qui alimentent ce système. Le progrès, dans les forages de prospection est suivi tout d'abord d'une comparaison des valeurs des eaux de forage avec celles des eaux naturelles.