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GEOPHYSICAL METHODS IN GEOTHERMAL EXPLORATION

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ABSTRACT

A review is given of geophysical methods used in the exploration of geothermal resources. More recent developments are emphasized, especially in the field of electric and electromagnetic surveys. Other methods discussed include heat flow (thermal gradient), aerial infrared surveys, gravity, seismic and magnetic surveys, microearthquakes and ground noise.

Geophysical surveys should be closely coordinated with geological and geochemical surveys and exploration drilling, and interpretation based on an evaluation of data from all these surveys.

INTRODUCTION

The role of geophysics in the exploration of geothermal resources has been discussed in the past in several review papers (e.g. Banwell, 1970, 1973; Bodvarsson 1970; Combs and Muffler, 1973). A few geophysical methods may be said to be well established in geothermal work, having proved their usefulness in numerous geothermal exploration projects. But improvements are needed, and in recent years there has been a marked effort to test new methods or new variants of older methods. This development is largely associated with the growing interest in geothermal energy following the world wide rise in oil prices.

The strategy of geothermal exploration is often somewhat hampered by a lack of understanding of the geothermal systems, and by the variability of the geological environment (e.g. McNitt, 1970). The hot zones beneath surface thermal fields constitute the outlets of more extensive systems, about which very little is known as regards vertical and horizontal extent. Most exploration work in known geothermal fields is concerned with mapping the geometry of the relatively shallow upflow zone, but it is also possible that the deeper parts may be quite as attractive from an exploitation point of view as the shallower parts. In fact some of the deeper systems may be entirely without an upflow zone; they may be hidden. The most suitable methods of investigating such systems would in part differ from those most suitable for the shallower zones.

A further complication is the thermal state of the fluid ; whether one is dealing with a vapor-dominated system (White et al., 1971) or a hot-water system. Some bulk physical properties of a porous rock, e.g. resistivity and density, would be quite different if steam replaced the hot-water in the pores. Such ambiguities, like many others in the interpretation of geophysical data, have to be resolved by drilling.

In geothermal exploration the geophysical methods used may be classified in various ways (e.g. Bodvarsson, 1970). Direct or thermal methods aim at mapping hot zones thermally and geometrically. Indirect or structural methods have as their objective the investigation of geological structures that may control the movement of the geothermal fluid. Such a classification may be of some help in clarifying the purpose of various kinds of surveys, but it is not very distinct, and many survey methods serve the purpose of thermal and structural investigations at the same time. Methods may also be classified according to the depth range they are particularly suited for, but here again there is a great deal of overlapping and many methods are suitable for a considerable range of depths.

The purpose of this paper is to review the various geophysical methods which are used in geothermal exploration work, and to comment on their usefulness in such work. The thermal and electrical methods are treated first and then the structural methods. Finally some methods which do not fit into this classification, as microearthquakes and ground noise, are discussed. At the end a brief discussion is given on the suitability of the methods for probing to various depths.

HEAT FLOW (THERMAL GRADIENT)

Anomalous surface heat flow by conduction may be caused by water convection at depth. The heat flow can be found by drilling shallow holes and measuring the temperature profile and the thermal conductivity of the core rock. In order to interpret the heat flow values in terms of water convection it is necessary to know the normal regional heat flow pattern as undisturbed by hydrothermal activity. The average heat flow of the Earth is 1.5 HFU (62.7 mW/m^2), but relatively large systematic variations occur between different geological provinces. The highest values occur near diverging plate boundaries as e.g. in Iceland on the Mid-Atlantic Ridge, where "normal" values are considered to be in the range 1.7 to 7.0 HFU depending on distance from the axial zone (Pálmason, 1973, 1974). In New Zealand (Studt and Thompson, 1969) and in Japan (Uyeda, 1972) a different pattern is found with high values on one side of the volcanic zone and low values on the other side. Such a pattern appears to be characteristic of the so-called subduction zones.

Heat flow surveys may be suitable for exploring the boundaries of a hydrothermal area. In a uniform geological environment only gradient measurements are needed, but when the thermal conductivity varies from one hole to another it may be necessary to take this into account (e.g. Sestini, 1970). In some cases variations in thermal conductivity may be estimated from the borehole geological logs (Merkel, 1975).

When geochemical indicators of reservoir temperature are available the gradient measurements may allow an estimate to be made of the minimum hole depth needed to reach the reservoir.

Geothermal gradient or heat flow surveys are useful for detecting weak heat flow anomalies, some 5-10 times the normal heat flow values, as may be associated with convecting water at relatively great depth. When the heat loss through the surface is greater than about 100 times the normal heat flow, as occurs within hydrothermal areas, simpler and less expensive methods may be used to map the shallow temperature field. Mapping of the temperature at a depth of, say, one metre is useful for the purpose of estimating the natural heat flux from a hydrothermal area, as has been done in great detail in New Zealand (Dawson, 1964; Robertson and Dawson, 1964). As an exploration tool for guiding site selection for deep drilling the shallow temperature surveys are of limited value, because of the low effective depth penetration. They are also rather time-consuming.

Thermal gradient surveys have been used in several countries. In Italy a hole depth of about 35 m has been used (Burgassi et al, 1970; Mouton, 1969), but in Iceland a depth of about 100 m is considered necessary. The depth needed will depend on the geological conditions in each area. When the surface rocks are very permeable to a considerable depth as in many (~~[illegible]~~) areas of active volcanism, gradient surveys may not be practicable at all.

There are several examples demonstrating the usefulness of gradient surveys in geothermal exploration. In Iceland in the low temperature area within the capital Reykjavík gradient surveys have markedly guided the selection of sites for deep production drilling. The gradient surveys have outlined four areas (Fig.1) of anomalously high surface gradient, up to 500°C/km. Production drilling in three of these areas has been successful, yielding water at temperatures of 90-140°C, but the fourth area has not been tested yet by deep drilling.

A more recent example is from Marysville, Montana, where a heat flow anomaly was discovered in an area with no known hot spring activity (Blackwell and Baag, 1973). A favored interpretation of the anomaly was that it was due to a cooling intrusion at depth. Subsequent drillings encountered water at 95 °C, showing that the anomaly is due to convecting hot water at depth.

AERIAL INFRARED SURVEYS

At the U.N. Geothermal Symposium in Pisa in 1970 five papers were presented dealing with infrared aerial surveys of thermal areas in several countries (Cassinis et al.; Gomes Valle et al.; Hochstein and Dickinson; Hodder; Pálmason et al.; 1970). The results indicated that the threshold sensitivity of the method to detect abnormal heat flows was in the range 150-700 HFU, i.e. roughly one hundred times the normal heat flow. The main reason for this relatively low sensitivity is the high noise level caused by variations in the thermal properties of surface materials, which affect the thermal radiation sent out. The radiation comes from a very thin surface layer and the method has therefore practically no depth penetration.

It is possible that a more refined processing of the infrared data can lower somewhat the threshold limit for detection of geothermal anomalies. Hase (1974) on the basis of a study in Japan gives a limit of "much less than" 800 HFU.

The infrared method has an important application in mapping the surface distribution of hydrothermal activity. The imagery may be of help in relating the configuration of the hot areas to large scale structural features, e.g. faults or calderas, which may control the discharge of hot fluids to the surface. It furthermore provides a record of surface activity which may be compared with similar records at a later date to study the effect of exploitation on the surface thermal manifestations.

ELECTRICAL RESISTIVITY SURVEYS

Electrical resistivity surveys have been used in geothermal exploration for over 25 years (e.g. Bodvarsson, 1950). Initially they were made with the classical Wenner or Schlumberger electrode configuration using DC current. The depth of penetration was small. In recent years there has been a marked effort to test various methods, both DC and electromagnetic, in an attempt to increase the depth penetration under the conditions of low near-surface resistivities which usually occur in hydrothermal areas. There is a very great variety of methods that can theoretically be used and the problem in each case is to select the most suitable method from the point of view of field operations, processing of the field data and interpreting the results.

Geothermal reservoirs are usually characterized by low resistivities. The resistivity depends on a number of parameters, the most important of which are porosity, salinity of the interstitial fluid, and temperature. The effect of a temperature change is greatest at low temperatures, less than 100°C, and becomes small above 200°C. In the deeper parts of a hydrothermal system the resistivity is therefore more affected by porosity and salinity variations than by temperature. An increasing resistivity with depth in a geothermal system may mean that the porosity changes from e.g. intergranular or vesicular porosity to fracture porosity, which is not necessarily adverse from the point of view of fluid production. The effect of temperature is probably greatest in horizontal profiling where lateral variations in resistivity are mapped.

Convenient nomograms showing graphically the relationships between rock resistivity, temperature, porosity, and salinity of the pore fluid, have been given by Meidav (1970).

Controlled-source DC methods.

These methods are the most common ones in geothermal exploration. Electric current is sent into the ground through a pair of electrodes and the resulting potential difference across another pair or pairs of electrodes is measured. Apparent resistivities are calculated directly from relatively simple formulas. Depth soundings are carried out by varying the electrode distances, and interpretation in terms of a vertical resistivity structure is usually made by means of a set of theoretical curves.

For shallow resistivity surveys any one of the electrode arrays may be used. The Schlumberger array is the most convenient one for depth soundings. It has certain operational advantages over the Wenner array in that fewer movements of the electrodes are required. Furthermore it allows the effect of irregular lateral resistivity variations to be detected and corrected for to a certain extent. For horizontal profiling the Wenner array is more convenient because of the regular electrode separations.

The practical limitation on the depth penetration of the Schlumberger array is the long wire needed for the current electrodes. If the resistivity is low a very high current is needed to obtain a measurable voltage between the potential electrodes. Furthermore, in hydrothermal areas, a very long electrode array usually means that lateral resistivity variations are affecting the measurements, thus making interpretation difficult. Often the maximum current arm (AB/2) of the Schlumberger array is limited to 1-2 km in geothermal work.

Dipole arrays avoid some of the difficulties associated with deep Schlumberger soundings in geothermal areas. Very high currents are needed, several tens of amperes, but these are more safely used with short current electrode separations than with long ones. Under favorable conditions a depth penetration of several km is easily achieved.

Experience shows that apparent resistivities calculated from dipole arrays are rather sensitive to shallow lateral resistivity variations. In dipole depth soundings care has to be taken to avoid such effects. On the other hand they may also be used to advantage in mapping in a semiquantitative way lateral resistivity variations, somewhat analogous to resistivity profiling. In this case a source "bipole" is commonly used, i.e. a pair of current electrodes with a separation that is not necessarily small compared to the distance between the centres of the electrode pairs (bipole-dipole arrays). A well-known example of this is from the Broadlands field in New Zealand (Risk et al, 1970). Theoretical calculations (Bibby and Risk, 1973) using a hemispheroidal reservoir model have made possible an estimate of the thickness of the low-resistivity reservoir beneath the Broadlands field from the dipole data.

As a general comment regarding the use of dipole methods for depth soundings, it may be said that shallow resistivity mapping is required to properly interpret the dipole soundings. For horizontal reconnaissance surveys, the dipole methods have certain operational advantages, since a relatively large area can be mapped from a single source dipole. The calculated apparent resistivities, however, do not necessarily correspond to real resistivities in the underlying formations.

Controlled-source electromagnetic methods.

In recent years a considerable effort has been made to test the suitability of various electromagnetic methods in the exploration for geothermal resources (e.g. Keller, 1970, Keller and Rapolla, 1974). These methods have been used in mineral exploration for a long time. In geothermal work the requirement of depth penetration is usually greater than in mineral exploration. This means that lower frequencies have to be used and consequently the equipment becomes somewhat bulkier.

Primary external electromagnetic fields induce eddy currents and secondary fields in a conducting earth. The secondary fields can be detected by a variety of source-receiver arrangements (see e.g. Keller and Frischknecht, 1966; Vanyan, 1967). Depth soundings are made by varying either the source-receiver distance or the frequency. Interpretation is usually carried out by a comparison with calculated models, often consisting of horizontal layers. The depth penetration may be expressed by the "skin depth"

$$d = 0.5 \sqrt{\frac{\rho}{\nu}} \text{ km.}$$

A plane electromagnetic wave of frequency ν Hz in a medium of resistivity ρ ohmmeters is attenuated to 37% of its original amplitude in a distance equal to the skin depth. The expression for the skin depth shows that the electromagnetic methods are particularly suitable for probing through high-resistivity surface materials, but have lower penetration in conductive surface materials.

A two-coil moving source-receiver arrangement ("electromagnetic gun") has been used in New Zealand and in Chile to map resistivity variations to a depth of the order of 30 meters (Lumb and Macdonald, 1970). This method appears to be an attractive alternative to a shallow temperature survey or conventional shallow resistivity profiling, because of its low cost and high speed. The field procedure is straightforward, and apparent resistivities are obtained from calculated curves. The resistivities obtained in the Broadlands field agree reasonably well with those obtained from a Wenner survey.

A somewhat similar shallow test survey was recently carried out by Ward et al (1975) in a geothermal area in Utah. It was concluded from a comparison of Schlumberger soundings with electromagnetic soundings that the latter are less affected by lateral inhomogeneities than the Schlumberger soundings. A better definition of a shallow low resistivity area may thus be possible with the electromagnetic method. Deeper soundings to a depth of 1-3 km are also discussed in the paper and it is concluded that here also much smaller transmitter-receiver distances are required than the corresponding current electrode separations in the Schlumberger array.

An interesting possibility in electromagnetic soundings is the use of a transient method (time-domain technique). The method, which is based on theoretical work by Vanyan (1967), has been developed further at the Colorado School of Mines, and tested mainly around the Kilauea Volcano in Hawaii (Jackson and Keller, 1972; Keller and Rapolla, 1974). A step-current is introduced into the ground through a pair of electrodes, and the voltage induced in a coil by the time-varying magnetic field is measured as a function of time. Apparent resistivity is obtained as a function of time. It may be shown that early time resistivity is characteristic of shallow depth and the late time resistivity of deeper layers. The method thus has a certain appeal in that information on resistivity variation with depth is obtained in a single measurement. This advantage, however, may be more than offset by the rather complicated processing that is needed to obtain the resistivities, involving synchronous stacking, deconvolution, and smoothing of the recorded signal. Furthermore the interpretation in terms of resistivity variation with depth is not as straightforward as in the DC methods. It appears that the transient method needs to be further tested in geothermal areas by a comparison with more conventional methods before its merits in geothermal exploration can be judged.

Natural field methods.

Natural electromagnetic fields caused by thunderstorm activity (frequency >1 Hz) and micropulsations in the Earth's magnetic field (frequency <1 Hz) are affected near the surface by the resistivity distribution in the underlying rocks. The depth effect depends on the frequency. Where and when these fields are sufficiently strong in the frequency range of interest they can be used to explore the resistivity distribution in the depth range of importance in geothermal exploration.

There are essentially three variants of the natural field methods which have been used and appear to be promising in geothermal exploration. They are a) the ordinary low-frequency magneto-telluric method, utilizing frequencies below about 1 Hz, b) the audio-frequency magneto-telluric (AMT) method, which utilizes frequencies above 1 Hz, mainly in the range 8Hz-20kHz, and c) the telluric method. The first two are depth sounding methods. They might perhaps be classified together but because of the different frequency ranges the measuring techniques are different. The third method is a horizontal profiling method primarily.

In the magneto-telluric methods one measures the two perpendicular horizontal components of the electric and magnetic fields in the incoming radiation. After spectral analysis or narrow-band filtering an apparent resistivity is calculated from the formula

$$\rho_a = \frac{0.2}{\nu} \left(\frac{E}{B}\right)^2$$

where E (mV/km) and B (gammas) are the two perpendicular components of the electric and the magnetic field, and ν is frequency (Hz). This relationship is based on the assumption that the resistivity varies only in a vertical direction. Where there are significant lateral resistivity variations, a more complicated relationship is obtained, involving the so-called impedance tensor.

The ordinary or low-frequency <u>magneto-telluric method</u> is useful for probing to very great depths, from a few km to one hundred km or more. Its place is therefore mainly in regional work where information is sought on deep crustal resistivity which may be related to temperature and possible heat sources. The method has been used for this purpose e.g. in Iceland (Hermance and Grillot, 1970, 1974; Hermance 1973; Björnsson, 1975; Thayer and Hermance, 1975) and gives results in good agreement with those predicted from regional heat flow studies and model calculations (Pálmason, 1973).

A good description of the experimental, analytical and interpretative techniques used in magneto-telluric surveys was given by Vozoff (1972).

In geothermal exploration the direct usefulness of the low-frequency magneto-telluric method is limited because of the large probing depth and a consequent insensitivity to shallower resistivity variations. A much more promising method appears to be the audio-frequency magneto-telluric method which employs frequencies mainly in the range 8Hz-20kHz (Keller, 1970; Keller and Rapolla, 1974). The lower part of this range appears to be especially suitable under the conditions commonly found in geothermal areas. Surveys with this method have been reported from geothermal areas in New Zealand, Hawaii and Nicaragua.

The instrumentation for an AMT survey is relatively simple, consisting of two narrow-band tuned voltmeters of high sensitivity, measuring the output from a pair of electrodes and from an induction coil (Fig.2). By varying the tuning frequency, a set of apparent resistivity values are obtained, which can be interpreted by a comparison with theoretical curves. Where the electromagnetic noise in the audio-frequency range is sufficiently strong and continuous, the AMT method appears to be a rapid and inexpensive tool for reconnaissance surveys of geothermal areas.

The third natural field method, the telluric method, may be used for reconnaissance of horizontal resistivity variations. It is based on the notion that telluric currents flowing in extensive sheets are affected by lateral variations in the resistivity structure, which can be caused e.g. by variations in geological structure or by hydrothermal systems. The method requires the simultaneous measurement of the telluric electric field at two stations, and from the ratio of the amplitudes of the electric field at the two stations inferences may be drawn about variations in the underlying resistivity structure. By keeping one base station fixed and moving a field station about, one can thus map resistivity variations in a qualitative way.

The method has been used in geothermal exploration in Nevada (Beyer et al, 1975) and in Iceland (Thayer and Hermance, 1975). It appears to be a convenient method for regional surveys in order to detect areas worthy of more detailed exploration by dipole methods.

The three natural field methods that have been mentioned,i.e. the low-frequency magneto-telluric method, the audio-frequency magneto-telluric method, and the telluric method all depend on the presence of natural electromagnetic fields that may be of variable intensity in space and time. This dependence is a disadvantage in practical exploration work. On the other hand nature provides the source equipment for these fields so that the field instrumentation required in an exploration program is simpler than with some other methods. Present experience indicates that the telluric profiling method may be useful in regional surveys, and that the audio-frequency magneto-telluric method may be very convenient in more detailed work.

The Schlumberger, dipole and magneto-telluric methods may be combined to obtain a continuous section from shallow to relatively great depths. An example from a survey across the volcanic zone in northern Iceland through the Námafjall high-temperature field is shown in Fig. 3.

SELF-POTENTIAL SURVEYS

A natural field method which may be useful in the study of hydrothermal areas is the self-potential method. Recent surveys in several hydrothermal areas (Zohdy et al., 1973; Anderson & Johnson, 1973; Rapolla, 1974) have established that electrical DC field anomalies are commonly found associated with hydrothermal activity. One explanation of such electric fields is that they are associated with the movement of conducting geothermal fluids (streaming potentials), when cation enrichment of the water takes place by preferential adsorption of the anions by the rock, leading to a positive self-potential anomaly over a zone of upward-moving water. Although the electric potentials may also be affected by other factors, such as variations in the electrical properties of altered rocks, it appears that further studies of self-potential anomalies associated with hydrothermal areas would be worthwhile in order to evaluate their usefulness in geothermal exploration.

STRUCTURAL METHODS

In geothermal exploration the gravity, seismic and magnetic survey methods are often classified together as structural methods in contrast to the thermal and electrical methods whose main purpose is to outline the geometrical and thermal parameters of a hydrothermal system. In this sense the structural methods are primarily an extension of geological mapping. But there is also considerable evidence showing that some of the anomalies mapped by the structural methods in geothermal areas may be directly caused by the effect of the hydrothermal system on the host rock. On the other hand the electrical methods may also be called structural, to the extent that the resistivity variations are caused by variations in porosity. This shows that there is no sharp distinction possible between methods which map the thermal and the structural parameters of a hydrothermal system.

<u>Gravity surveys</u> are relatively easy to make in the field, but they are dependent on good elevation control and this may be the main cost item in the collection of the data. In areas of rugged topography the terrain corrections may be large and time-consuming to make. Therefore the gravity survey method is most suitable in areas of smoothly varying relief. One of the more useful properties of gravity anomalies is that they allow an estimate to be made of the total anomalous mass causing the anomaly, even though absolute density contrasts are not known.

Gravity surveys in geothermal areas in different geological environments appear to indicate that the sources of gravity anomalies may be 1) hydrothermal alteration of reservoir rocks, 2) a high proportion of intrusives, 3) structural, e.g. faults, calderas, basement structure.

In the New Zealand geothermal areas positive gravity anomalies are considered to be due to rhyolithic domes and to hydrothermal alteration of the reservoir rocks (Hochstein and Hunt, 1970; MacDonald and Muffler, 1972). In the Imperial Valley of California a correlation has been noted between positive gravity anomalies and high heat flow (Meidav, 1970), and the gravity effect is considered to be due to metamorphism of the sedimentary reservoir rocks. In Iceland the high-temperature areas are often associated with major volcanic centres, and positive gravity anomalies commonly found in such areas have been interpreted to be due to either a high proportion of intrusives or to metamorphism, or both.

There appear to be sound arguments for including a gravity survey in any major geothermal exploration program, in particular in areas of smooth relief and poor geological exposures.

One other important use of gravity measurements in geothermal work is connected with exploitation. Withdrawal of fluid from a hydrothermal system may lead to net mass transfers that affect the gravity values measured in the area. Such changes can be very conveniently monitored by measuring the gravity values at a set of fixed bench marks in the area under exploitation, as has been done at Wairakei (Hunt, 1970). The method is cheap and rapid, and is likely to become a standard procedure in any major exploitation of geothermal fields.

The seismic reflection method, which is a major geophysical method in oil exploration, has found relatively little use in geothermal work. This is mainly due to the different geological environments of these two energy resources. Most of the geothermal fields that have been explored so far, are in volcanic areas where smooth sedimentary series are absent, or highly disturbed by intrusions. The only case known to me where the reflection method appears to have been used with some success, is in the Mazukawa field in Japan (Hayakawa, 1970).

The seismic refraction method on the other hand appears to be quite useful in volcanic areas, especially for structural studies in conjunction with gravity surveys, since the two physical properties density and seismic velocity are empirically related. If a gravity survey shows an anomalous mass distribution, it can not be unambiguously interpreted in terms of structure without further information. A seismic refraction survey is likely to provide such an information, e.g. on the depth to the anomalous mass.

Refraction profiles have been measured across some of the high-temperature areas in Iceland, as a part of a regional survey of seismic crustal structure (Pálmason, 1971). A seismic boundary at a depth of about 1 km has been correlated with a geological section in a drillhole in the Reykjanes thermal field. It is of some interest that aquifers appear to be more abundant in a deeper higher-velocity ($v_p \approx 4.2$ km/sec), material than in a shallower lower-velocity material ($v_p \approx 3.0$ km/sec), which is more porous (Björnsson et al., 1970, 1972). A similar result, that the highest porosity rocks are not always the most productive ones, has been reported from the Kawerau geothermal field in New Zealand (MacDonald and Muffler, 1972).

A disadvantage of the seismic refraction method is that explosives or equivalent sources of seismic waves are needed in the field. It is advisable that refraction surveys be preceded by gravity surveys, which may indicate anomalous structures as well as help in planning the refraction survey.

Magnetic surveys have been carried out in many geothermal fields. Their use can be either as a structural method or as a method of mapping changes in the magnetization of rocks caused by the hydrothermal fluids. Magnetic anomalies in New Zealand geothermal fields have been interpreted as being due to a conversion of magnetite to pyrite (Studt, 1964). Such an effect would remain in extinct hydrothermal systems.

Opinion has been divided on the usefulness of magnetic surveys in geothermal exploration (e.g. Cheng, 1970; Banwell, 1970). The magnetization of different rock units may be quite variable, especially in volcanic areas. Alteration effects in a hydrothermal system would affect a large volume of rock, and the best way to detect such effects is by an aeromagnetic survey, which is less affected by near surface rocks than a ground survey would be.

There is no doubt that distinct magnetic anomalies are associated with many high-temperature geothermal fields. As examples of this may be mentioned the Námafjall and Krafla fields in Northern Iceland (Fig. 4). But it is also known from other areas that such anomalies are not always present. Test profiles on the ground should therefore be made before one decides on an extensive aeromagnetic survey in a geothermal exploration program.

Magnetic ground surveys have been used extensively in low-temperature fields in Iceland for tracing hidden dikes and faults that often control the flow of thermal water to the surface. Drillholes are then sited so as to cut the dyke at a certain depth. In some cases the dikes or faults act as barriers to horizontal flow and may then form a boundary of the hydrothermal system in one direction.

MICROEARTHQUAKE SURVEYS

Surveys of microearthquake activity (magnitude -1 to 3) in some tectonically active and volcanic areas have shown that geothermal fields are often characterized by a relatively high level of such activity (Ward et al., 1969; Lange and Westphal, 1969; Ward and Björnsson, 1971; Ward, 1972; Hamilton and Muffler, 1972). A very extensive study of this kind has been made in the Reykjanes peninsula in southwest Iceland (Björnsson and Einarsson, 1974).

This area is a part of the axial zone of the Mid-Atlantic Ridge, and includes three high-temperature geothermal fields. Continuous recordings for more than three years have confirmed the earlier indications that the geothermal fields have a fairly consistent microearthquake activity of 3-30 events/day, with a focal depth range of 2-6 km. The intermediate parts of the axial zone also have a high microearthquake activity, but here the events are more distributed in swarms, with quieter periods in between. Fig. 5 shows the distribution of foci beneath the Krísuvík high-temperature field in southwest Iceland (Ward and Björnsson, 1971).

The value of microearthquake surveys for geothermal studies is at present somewhat limited by a lack of understanding of the mechanism causing these events. The microearthquakes may be tectonic in origin, and their depth distribution controlled by the temperature distribution. It is also conceivable that they are somehow related to a penetration of water into hot rock (Lister, 1974). At the present time it appears that the main use of microearthquake surveys may be to try to predict the depth of water circulation in hydrothermal systems, something which can not easily be done with other methods.

GROUND NOISE SURVEYS

Since the pioneering work of Clacy (1968) on ground noise in a geothermal area in New Zealand, a number of similar studies have been undertaken by others (Whiteford, 1970; Douze and Sorrells, 1972; Goforth et al, 1972; Luongo and Rapolla, 1973; Cappello et al, 1974; Iyer and Hitchcock, 1974). A high noise level is invariably found in geothermal fields, decreasing with distance from the surface activity. Spectral analysis of the noise shows that surface activity produces noise with frequencies above about 10 Hz. As an example may be mentioned Old Faithful with a spectral range of 8-24Hz. Lower frequencies, down to about 1 Hz, are also usually found and are postulated to be due to deeper water convection. In high heat-flow areas in the Imperial Valley, which are without surface thermal activity, most of the noise energy is in the frequency range 0.5-5 Hz.

All the above mentioned ground noise surveys have been made in areas where hydrothermal activity is known from surface manifestations or other geophysical aurveys. If ground noise surveys are to be useful as an exploration tool the source of the noise must be understood. Douze and Sorrells (1972) have developed a model to explain the spatial distribution of noise in the Mesa area of the Imperial Valley. It involves pressure variations (3 Hz) of about 1 millibar at 1500 m depth. Perhaps such models could be further tested by measurements of the ground noise at various depths in deep boreholes.

APPLICABILITY OF METHODS TO DIFFERENT DEPTH RANGES

The geophysical methods which have been and are used in geothermal exploration can be discussed and compared on the basis of various criteria such as rapidity, cost, and simplicity of field operations, data processing, interpretation and so on. It appears to be useful also to discuss them in relation to the depth range that each one is suitable for probing. Such a division will of course not be distinct, but may still be of some use. The depth ranges will be denoted, shallow (0-200), intermediate (200-2000 m) and deep (more than 2000 m).

For *shallow investigations* the greatest variety of methods is available. Such investigations aim to define the area of hot ground associated with surface thermal activity. They have no place in the search for hidden reservoirs.

An aerial infrared survey is the most convenient and rapid method of mapping surface activity, especially in areas that are little known and are not masked by vegetation. The shallow temperature field is best explored with conventional Schlumberger resistivity profiling. A rapid, low-cost reconnaissance may also be provided by the electromagnetic (EM gun) and the audio-frequency magnetotelluric method, although at the present time there is less experience available with these methods in geothermal work than with the conventional DC resistivity methods.

At *intermediate depths* the Schlumberger and dipole DC methods appear to be the most suitable ones for outlining low resistivity zones. The dipole methods can be used either as depth sounding or profiling methods. Considerable experience has been gained in using them and interpreting the measurements. Electromagnetic controlled-source methods may prove to be suitable also, but much less experience has been gathered so far with them. Of the natural field methods the telluric profiling appears to be an effective reconnaissance tool. Aeromagnetic surveys may be feasible if test profiles on the ground indicate variations in the magnetic field that may be associated with a thermal zone at depth.

Heat flow or gradient surveys are particularly suitable in the search for hidden reservoirs or for exploring the boundaries of a thermal field. They are expensive because drillholes are needed, but they give unambiguous indications of thermal anomalies. They are effective only where the surface rocks are of low permeability.

All of the structural methods may be useful for mapping anomalies whose sources are at intermediate depth. Their usefulness depends on the particular geological environment under consideration.

For deep investigations of hydrothermal reservoirs several methods can be used, but their resolution is smaller than at shallower levels. Gradient surveys for predicting temperature at depth are suitable in impervious surface rocks, and dipole DC methods are suitable for probing the resistivity to a depth of a few km if the shallower resistivities are laterally not very inhomogeneous. The low-frequency magnetotelluric method permits probing resistivity variations from a few km to very great depths.

Of the structural methods the gravity and seismic refraction methods are particularly suitable for studying deep structures, which may be of importance for controlling the flow of water, or as heat sources. A gravity survey would normally come first because it is cheaper. If major structural anomalies are indicated they can be studied further by seismic methods. An interpretation based on both gravity and seismic measurements is much more reliable than if based on only one of these methods.

In connection with deep investigations the microearthquake survey should be mentioned. As mentioned earlier focal depths of microearthquakes may give an indication of the depth of circulation of hot-water, although this needs to be confirmed by independent methods. It appears that in order to have a reliable estimate of the average behaviour of microearthquake activity, a recording time of several months may be needed.

REGIONAL SURVEYS

Geophysical surveys of geothermal resources are often restricted to the immediate neighbourhood of surface thermal activity, as this is the most likely area for the siting of drillholes. It is a fairly common knowledge, however, that geothermal systems are more extensive at depth than near the surface. When deep investigations are conducted, they should therefore cover a considerably larger area than would be indicated by the near-surface hot zones. Such regional surveys are also very useful when interpreting data from a more detailed survey near the thermal manifestations. A geological map of a thermal field is more useful when viewed in its regional setting than by itself. The same reasoning applies to geophysical surveys. The added cost of collecting some regional data may well be returned in a more reliable interpretation of the main bulk of the data.

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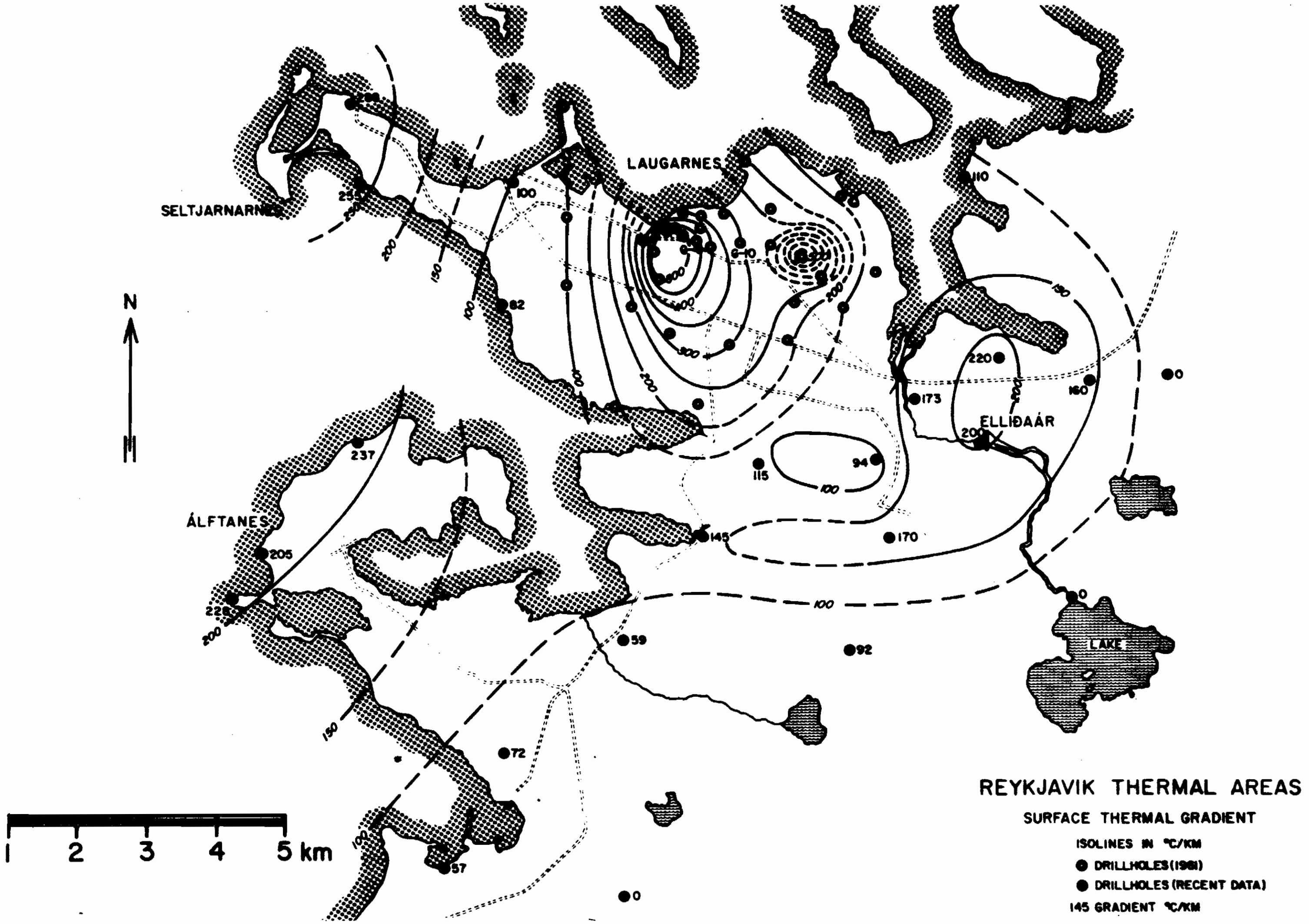
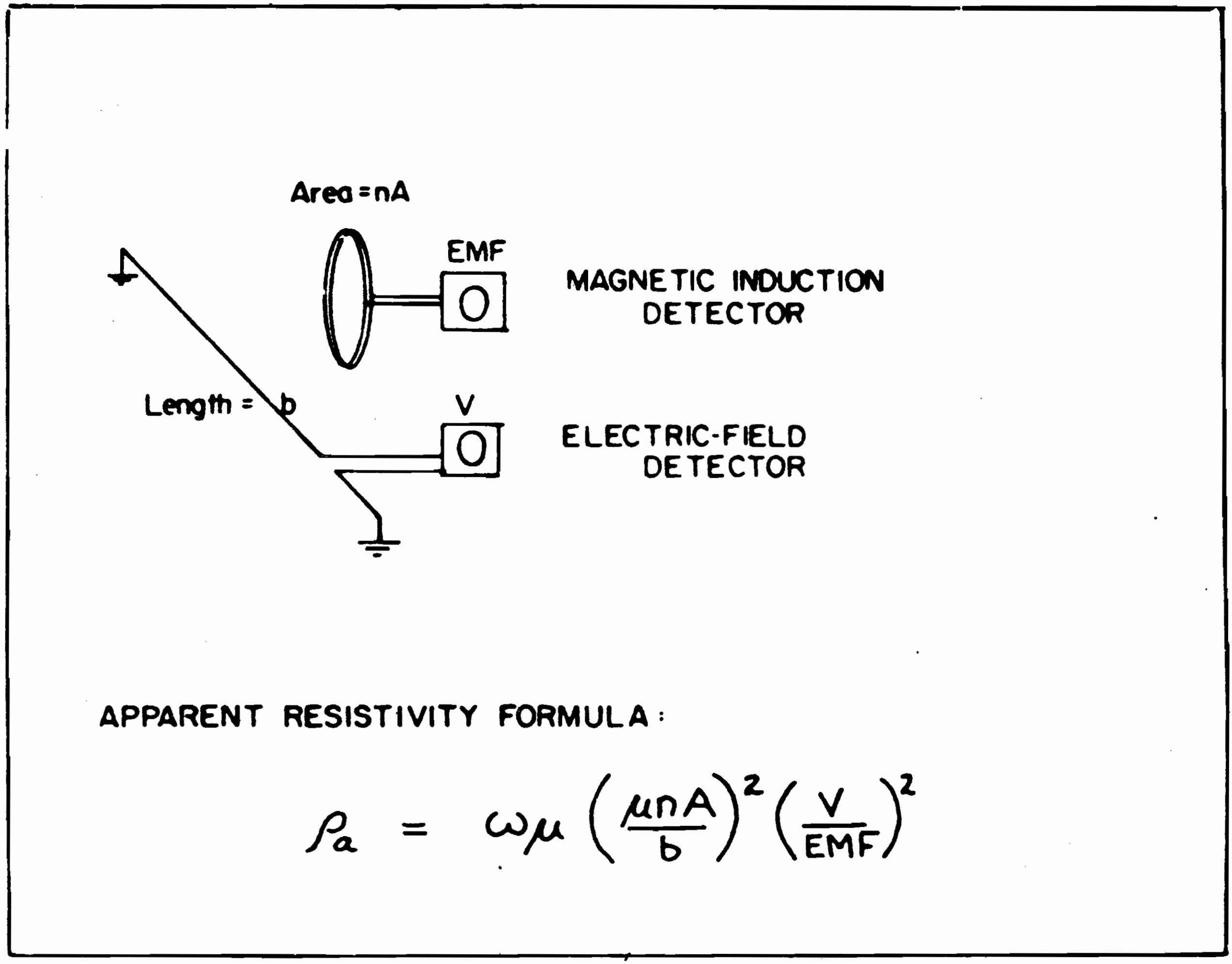


Figure 1. Thermal gradient map of the Reykjavik low-temperature areas, southwest Iceland, showing the anomalies associated with the Laugarnes, Seltjarnarnes, Ellidaár and Álftanes fields. Based on Bodvarsson and Pálmason (1961) and later additional data.



APPARENT RESISTIVITY FORMULA:

$$\rho_a = \omega\mu\left(\frac{\mu n A}{b}\right)^2\left(\frac{V}{EMF}\right)^2$$

Figure 2. The audio-frequency magneto-telluric method of resistivity mapping (from Keller and Rapolla, 1974).

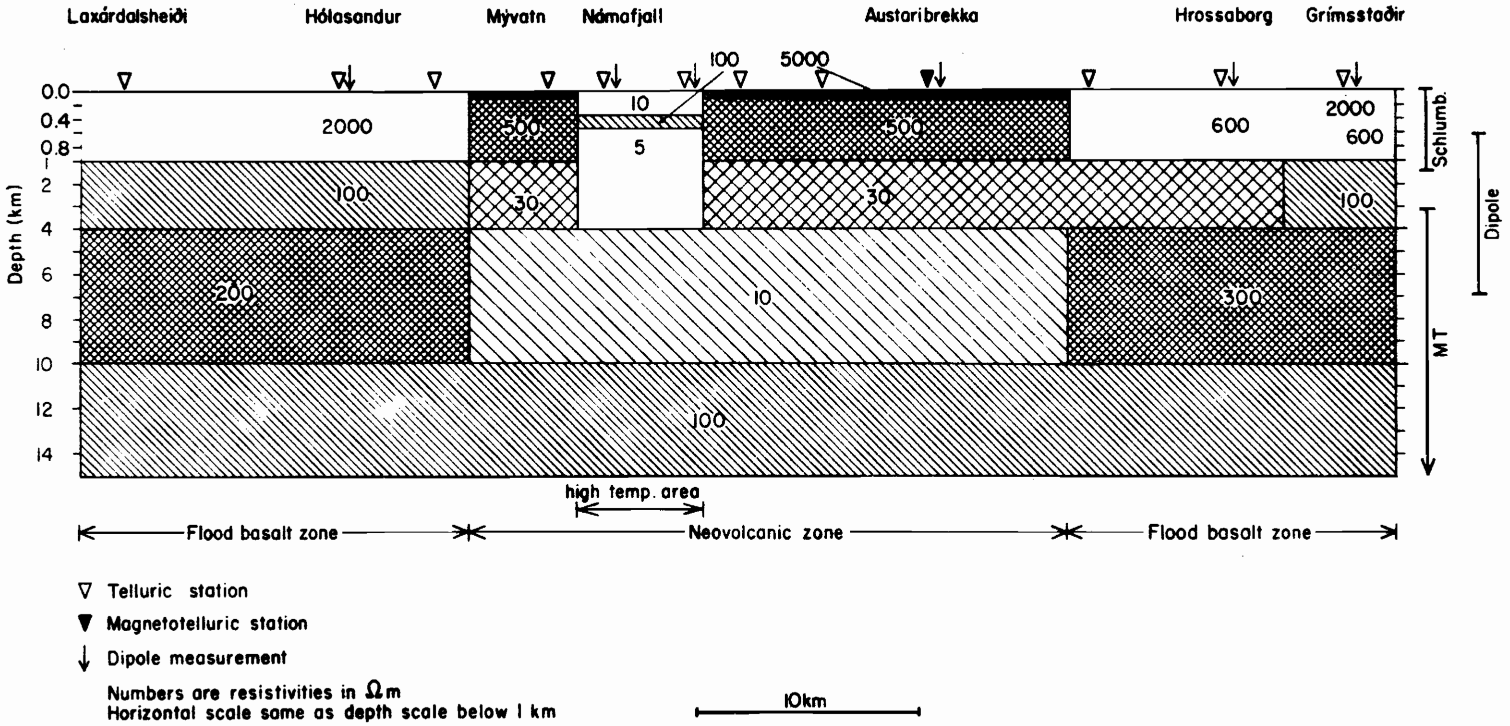


Figure 3. A schematic resistivity section across the volcanic zone in northern Iceland through the Námafjall high-temperature field. Based on Schlumberger, dipole and magneto-telluric measurements from a joint survey by Brown University, R.I., and National Energy Authority, Reykjavik, (A. Björnsson).

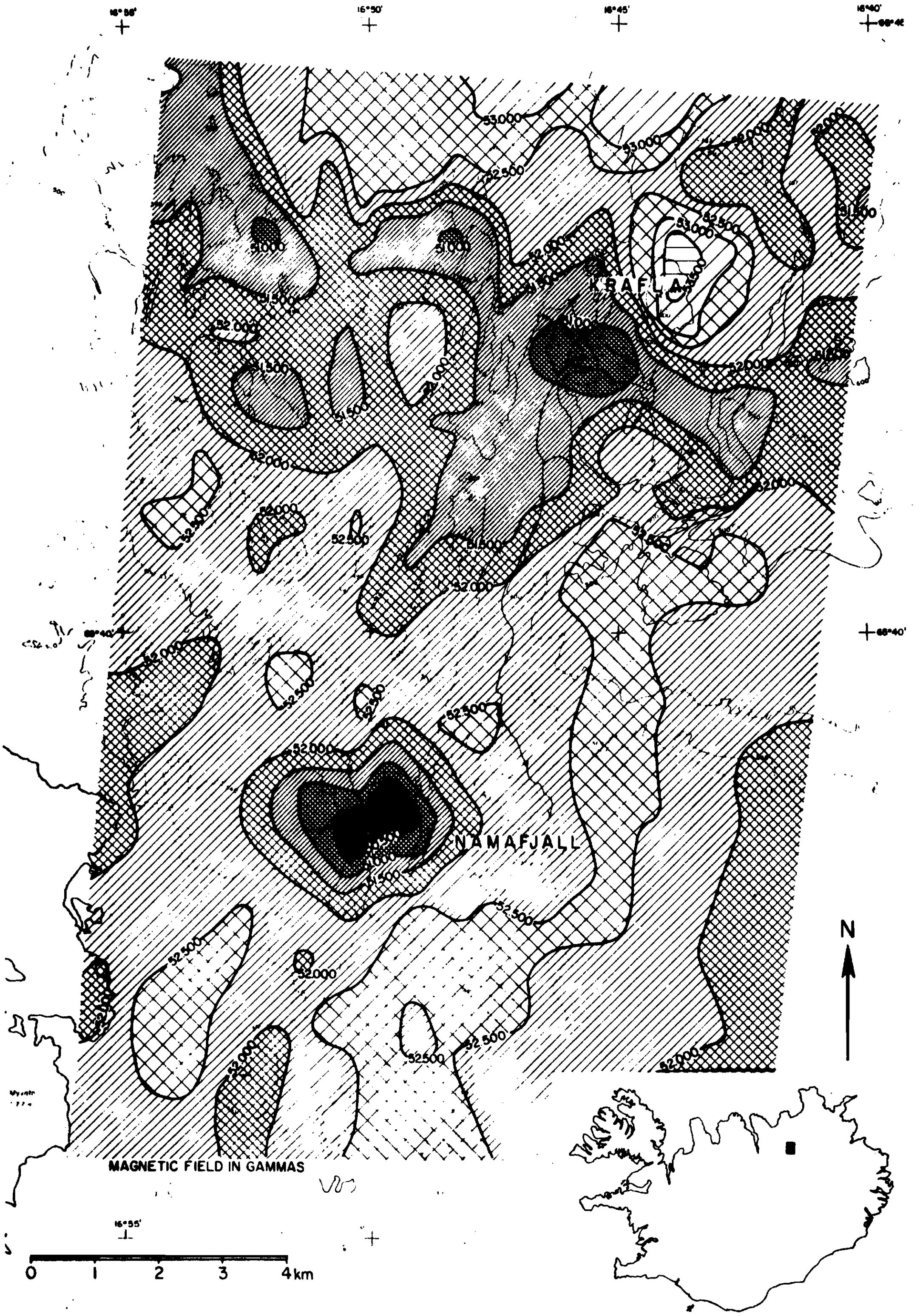


Figure 4. An aeromagnetic map of the Námafjall and Krafla high-temperature fields in northern Iceland, showing negative anomalies associated with the hyddrothermal fields (survey by Th. Sigurgeirsson).

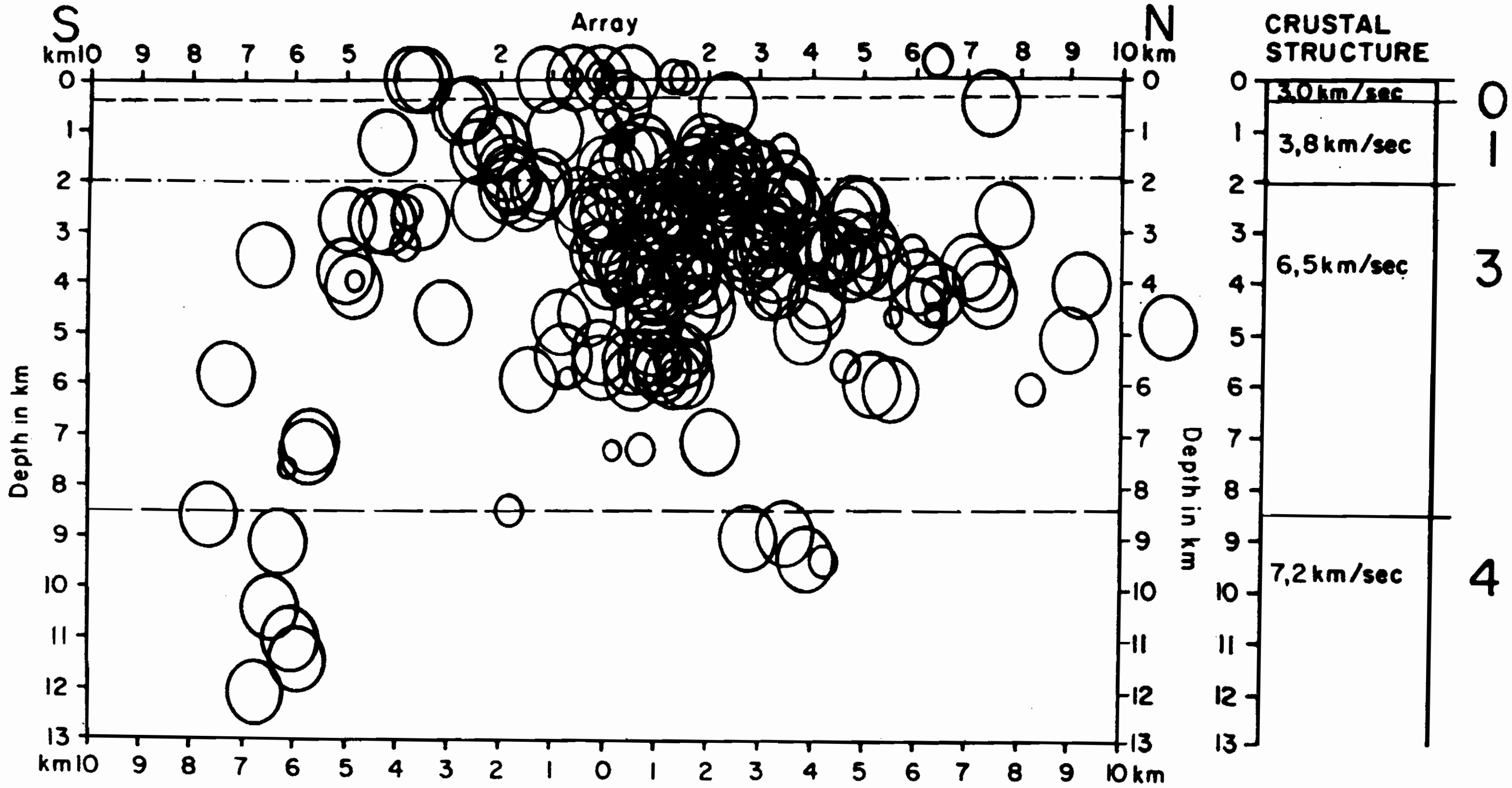


Figure 5. Distribution of microearthquake foci beneath the Krísuvík high-temperature field in southwest Iceland (Ward and Björnsson, 1971).