ON THE USE OF GEOPHYSICAL TECHNIQUES IN GEOTHERMAL EXPLORATION

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In the investigation of geothermal reservoirs, geophysical techniques offer co..siderable advantages over conventional drilling techniques although for most people the methods still retain a "black box" image.
The following paper provides a general discussion of these geophysical techniques that proved to be of value to geothermal investigation prospects.

INTRODUCTION

Natural steam and hot water are available for power generation and heating purposes in many regions of the world (McNitt 1965). The recent increase in conventional fuel prices has resulted in an increase in the interest to natural sources of energy such as geothermal energy, and many countries are now involved in large scale exploration work in this field where a great number of geothermal prospects are being evaluated. This evaluation of new prospects has an impact on the science of geophysical exploration.

Although some geothermal reservoirs can be located merely by drilling close to thermal manifestations such as geysers and fumiroles, many geothermal systems may exist without any surface manifestation. The objectives of any geothermal exploration venture are to locate areas underlain by hot rock and to estimate their volume, temperature, and permeability at depth.

Geophysical work has proved eficient in providing answers to these problems, although it should not be regarded in total isolation from other subjects such as geological, hydrological and geochemical investigations.

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In the following a brief review of the technique of geophysical exploration of geothermal prospects is given, and its relative merits are been discussed.

EXPLORATION STRATEGY DURING GEOTHERMAL PROSPECTING

No single method of survey, be it geophysical, geochemical or geological can be expected to yield a unique and unambiguous result, and the overall picture of a geothermal field and reservoir is built up by a continuous process of cooperative data synthesis and cross-checks.

For the initial planning of a geothermal exploration before the execution of any true geophysical work, and for the preliminary selection of localized fields for detailed study, it is extremely useful to have a catalogue of basic preliminary data from all the suspected fields. These data are those that can be collected fairly quickly, at low cost, and without the necessity for setting up an elaborate field establishment for each promissing area.

For the efficient performance of this stage of the work it is very desirable to have available good topographic maps and a set of recent aerial photographs, for survey planning and position control. Normal and infra-red colour photographs can also be useful for outlining possible hot areas in the office

TABLE 1

DATA WHICH HAVE TO BE COLLECTED PRIOR TO ANY GEOTHERMAL SURVEY

THERMAL	*GEOLOGICAL*	*GEOCHE-MICAL*	*HYDRO-LOGICAL*	*CLIMATIC*
Location map of known thermal features Temperatures and mass discharge	Geological reports of the area	Geochemical maps of ionic ratios of dissolved constituents in thermal features Sampling of rivers and lakes for determining total discharge rate	Location of aquifers Drainage pattern	Mean temperature & annual range

before proceeding to the field. Table 1. summarizes all the basic data that is worth to be collected prior to any geothermal survey.

Assuming that a review of the preliminary data has led to the conclusion that a potentially useful geothermal field has apparently been identified, the next object of exploration is to define its location, area and depth. Here is where geophysical prospecting techniques play a very significant role.

THERMAL METHODS

Since temperature constitutes the most important physical characteristic of a geothermal prospect, the thermal methods such as temperature probing in boreholes, thermal gradient maesurements and heat flow mapping at the surface are consequently of primary importance.

a. Shallow surface thermometry

The choise of this method will depend on the type of the surface covere predominant in the area. If it is mainly of loose pumice soil or sediments, this method, using a hand held auger and a thermistor thermometer is both rapid and inexpensive.

The main disadvantage of the method are the varius pertubing effects such as diurnal and annual solar heating variations, soil thermal diffusivity variations, variations in level of groundwater etc., which impinge on temperature measurements. In the interest of eliminating these effects several methodologies have been developed in an effort to obtain the geothermal signal itself (LeSchack and Lewis 1983).

Subject to the topography, it is generally convenient to carry out measurements with station spacings of 50 to 100 m at a depth of up to 2 m. The largere spacing should still be close enough to avoid missing any features of importance, since a geothermal field of minimal economic size is unlikely to cover less than 2 or 3 km (Bodvarson 1966).

b. Deep surface thermometry

The measurement of temperatures in deep boreholes is the only reliable method of providing information on the base temperature of a given geothermal prospect.

c. Thermal gradient drilling

Measurements of thermal gradient in boreholes is the most effective tool for delineating major anomalies. Holes for thermal gradient measurement must be drilled deep enough to penetrate any surface formations liable to be disturbed by ground water movement and other pertubing effects and they should extend far enough into the undisturbed zone below to give reliable gradients.

Although it may sometimes be possible to estimate the thickness of the disturbed layer from geological or other evidence, it is very desirable to check whether a hole is deep enough by measuring temperatures at multiple points spaced about 2.5 m apart over the bottom 20 m of the hole. If the measured temperatures fall on straight line when plotted against depth, the deduced gradient is probably reliable, otherwise the hole must be deepened or the area avoided.

It is also desirable to be able to combine these gradients with reliable estimates of thermal conductivity, to provide data on the energy flux and to constrain models of the heat sources responsible for the anomalies.

SEISMIC METHODS

Both active and passive techniques have found application primarily in the exploration and assessment phases of geothermal projects.

Although active seismic methods (reflection and refraction) have been highly developed and utilized in hydrocarbon exploration, they have not been widely used in geothermal exploration (Ball et al., 1979). These methods are potentially capable of delineating hydrothermal zones from velocity anomalies (refraction) or from structural assessment (reflection) and maping the depths of high temperature source regions.

Passive methods including microearthquakes and ground noise are less expensive than active methods and are used in early reconnaissance and exploration phases to define possible drilling targets. These methods, because of their importance will be discussed in a greater detail in the following section.

a. Seismic activity in geothermal fields

The fact that microearthquake seismicity of a ermal area is often different from that of the rounding region is well established (Ward et. al., 969; Evison et al., 1982), and its potential as a prospecting tool was quickly pointed out (Lange and Westphall 1969; Ward 1972; Rotstein 1975; Foulger 1982).

Although certain aspects of the seismicity of some seismically active geothermal areas can be related to the regional (Bjornsson and Einarsson, 1974), it has been pointed out by many investigators (Bolt et al., 1968; Majer and McEvilly, 1979) that in several geothermal areas the direction of failure may be controlled by regional stress, whilst the rate of failure is controlled by local stress levels.

Variations in the pressure and temperature conditions in the crust can cause variations in seismicity. Laboratory experiments have shown that fault motion may occure as a series of discrete, rapid slips (stick-slip mechanism) most readily at high pressures and low temperatures. This is supported by many field investigations (Majer and McEvilly 1979) which have shown that earthquake activity increases towards the edges of the geothermal reservoirs where relatively high pore pressure gradients occure.

From all these, it may be concluded that in many cases the location of a geothermal area coincides with an area where regional stress is being released at a different rate to the surrounding areas.

b. Seismic parameters of geothermal fields

Many imvestigators (Marks et al., 1978; Majer and McEvilly 1979; Walter and Weaver 1980) have pointed out that the b-constant of the Guttenberg - Richter frequency magnitude relation tends to have relatively high values when geothermal areas are considered. This is due to the fact that usually geothermal fields are in a low stress state and small magnitude shocks dominate. This implies (Foulger 1982) that the microearthquake activity probably results from crack closing and sliding rather than the propagation of new fractures.

Another characteristic of geothermal areas is that they usually display low Poisson's ratio values (Combs and Rotstein 1975; Majer and McEvilly 1979). Laboratory experiments show (Somerton 1978; Dobereiner 1982 personal communication) that dry rocks display a lower Poisson's ratio than the saturated ones. From this it can be suggested that the low Poisson values of geothermal fields, probably reflect the presence of steam vapor.

Variation in the degree of water saturation, temperature, pressure and compositional heterogeneity may be in many situations indicated by variations in the quality factor-Q (Kjartansson and Nur 1981), which can be obtained from the analysis of microearthquake data.

The presence of geothermal reservoirs is associated also, with high levels of noise at the surface. This is due to the fact that the htdrothermal processes such as phase change which occur within reservoirs radiate seismic energy.

c. Seismic survey strategy

In order to be able to examine in detail the seismic features of a probable geothermal area, a seismograph network has to be installed in such a way, to allow local earthquakes to be accurately located. A few weeks operation of the network is usually enough to find out the following:

a) Spatial and vertical distribution of epicenters and relation with known tectonic features.

b) Magnitude frequency relationship and estimation of b-values.

c) Calculation of Q-values and Poisson's ratios.

In addition to the above, ambient ground noise measurements is worth to be carried out. Basically the method is very simple since it consists of measuring the power spectrum of the vertical background noise in the survey area. New portable equipment permit direct on-site spectral analysis of the registered signals (Tselentis and Thanassoulas 1985).

ELECTRICAL AND ELECTROMAGNETIC METHODS

Electrical and electromagnetic methods of geophysical prospecting have found many applications in geothermal exploration and are being used routinely by the industry today. They consist a large variety of different techniques and the most important of these are listed in Table 2.

TABLE 2

ELECTRICAL AND ELECTROMAGNETIC METHODS OF GEOPHYSICAL PROSPECTING

NATURAL FIELD	
ELECTRICAL	ELECTROMAGNETIC
Self Potential (SP)	Telluric (T) Magnetotelluric (MT) Audio frequency Magnetotelluric (AMT)
CONTROLLED FIELD	
Electrical resistivity (ER) Induced Polarization (I)	Magnetometric resistivity (MMR) Electromagnetic induction (EM)

Natural field methods have the pricipal advantage that they need no controlled source instrumentation, although there is some uncertainty concerning the nature of the natural fields being recorded. These passive methods have also the potential of rapid reconnaissance (T,AMT) and both shallow and deep-resistivity profiling (AMT,MT).

Controlled-source methods can be applied to reconnaissance mapping or profiling, vertical soundings, pseudosections, and delineating reservoir boundaries and depth.

Although the application of electromagnetic methods in geothermal exploration is relatively recent when compared with electrical methods and although the instrumentation is very complex they have some theoretical advantages over the electrical methods. Electromagnetic techniques, because of the fact that they tend to detect conductors preferentially (signal size increases with decreasing resistivity), they are particularly useful in geothermal exploration. This is true whether one is searching for a hydrothermal system or the conducting zone that surrounds a vapor-dominated or hot-rock reservoir. On the other hand, they are not adversely affected by near surface high resistivity zones.

a. Telluric (T) and Magnetotelluric (MT) method

The primary requirements of the method is that measurements of natural electric field (telluric method) or both electric and magnetic field (magnetotelluric method) fluctuations (the surface impedance of the earth for natural electromagnetic waves) must be recorded over a frequency range and the apparent resistivity calculated as a function of frequency. The theoretical basis of the method has been described by Cagniard (1953); Strangway et al., (1973) and Kaufman and Keller (1981). The field equipment must have adequate dynamic range and sensitivity to permit the recording of satisfactory data even though signal levels may vary widely from day to day, or even from hour to hour at a given recording site. During geothermal investigations T and MT surveys are carried out in an attempt to locate and identify shallow masses of rock with sufficiently high temperature to be electrically conductive. The principal information obtained when using T and MT methods during geothermal prospecting is the total thickness and conductance of the sedimentary sequence and the recognition of major faults in the survey area.

When natural field at high frequency must be observed relatively shallow investigation depths are being encountered and the application has been termed audio frequency magnetotellurics (AMT).

b. Electromagnetic induction methods

From these, the two loop method (EM gun) is the most commonly used. The system is designed to measure the tilt angle and ellipticity of the polarization ellipse of the magnetic field scattered by any conductive region of the under investigation geothermal field. It composes of a transmitting coil and two tunable orthogonal receiver coils which enable the operator to make the axes of the coils coplanar with the oscillating dipoles and then align the coils with the major and minor axes of the polarization ellipse. A detailed description of the method can be found in Ward et al., (1974).

c. Self potential method (SP)

The method consists of measuring natural electric potentials throughout the survey area. The rising termal waters, if moving through a heterogeneous medium, (Nourbehecht 1963) could be expected to give self potentials due to electrokinetic, thermal, and chemical effects. Positive potential values appear to define zones along faults in which thermal waters are rising to, or near, the surface. The method thus, offers promise of providing a direct indication of the presence of thermal waters, although the encountered anomalies are usually small and can be easily masked or confused with other effects.

d. Electrical resistivity methods

Investigation of geothermal areas via direct current resistivity surveys has been extensive and worldwide (Cheng 1970; Zohdy et al., 1973; Tripp et al., 1978). The application of electrical methods in such surveys is based on the fact that the electrical conductivity of rocks increases rapidly with increasing temperatures. More over, the conductivity of geothermal areas is usually enhanced by the high degree of metamorphism in these areas, and the high degree of mineralization of the thermal waters of the reservoir.

For the case of hot water reservoirs, the apparent resistivity pattern takes the form of a central "low", representing the porous reservoir filled with hot mineralized water, surrounded by a region of rapidly increasing resistivity outside the hot area.

In steam field reservoirs, there would probable be a central resistivity "high", because the reservoir rocks are now filled with steam which has low electrical conductivity, surrounded or overlain by lower resistivity zones containing steam-heat ground water.

It must be noted out that, in practice things are seldom so simple and resistivity along will seldom give a complete answer. The presence of clay formations, for example, can behave deceptively like hot water reservoirs.

e. Electrical exploration strategy

The recommended method will generally be a series of Schlumberger traverses over the survey area and as far as outside as may be necessary to find apparently normal resistivity values.

In addition to the traverses, a number of soundings uld be made at selected points to determine the vertical resistivity distribution and possible layering of different formations. From the soundings it should be possible to deduce whether the reservoir is filled principally with steam or with hot water.

An apparent hot water reservoir can be readily mapped by means of. traverses, using a current electrode spacing of 500-2000 m. giving an effective penetration of some 250-1000 m. With a steam reservoir it is possible that overlying confining formations will have a lower resistivity than the reservoir rocks, which may therefore be identified by a resistivity rise in the soundings.

A lot of care is needed during the interpretation stage, since most of the existing interpretation procedures assume a horizontally stratified earth, and usually encountered geothermal fields rarely exhibit this pattern. Considerable advantages during such applications has a new finite-difference intepretation method (Dey 1976; Dey and Morrison 1976), which is capable of modelling arbitary resistivity variations in two dimensions.

OTHER GEOPHYSICAL METHODS

The following geophysical techniques have also been used from time to time for geothermal exploration:

Gravity
Magnetic
Radon-222 measurements

The choise of technique, and the justification for using it at all, must arise and be defined by, the progress of the basic survey. Thus, gravity surveys are some times useful in determining details about the tectonic structure of the under survey area and in particular faults. Small variations also in the Bouguer gravity map may reflect local density changes related to induration of the rocks by thermal water. Magnetic negative anomalies can correlate sometimes with the hydrothermal conversion of magnetite to pyrite, while in other areas, positive magnetic anomalies can be related to very young instrusive and volcanic rocks associated with a geothermal system. Radon-222 measurements are based on the fact that this gas exists in geothermal steam and may well diffuse to the surface of the ground as an indirect indicator of favourable sites for drilling.

CONCLUSIONS

Numerous geophysical techniques of exploration can furnish data on the subsurface thermal processes and are therefore, of importance in geothermal prospectin.

Although no one method has been capable of providing each time unequivocal targets for drilling, when combined with other geophysical methods and with geologic and geochemical data can assist in limiting the drilling target.

Microearthquakes, gravity and magnetic surveys have routinely been used to define the regional setting of the survey area while electric, electromagnetic and thermal surveys have been used to localize the convective hydrothermal system, and locate the source of heat.

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ΠΕΡΙΛΗΨΗ

Η Εφαρμογή της Γεωφυσικής στην Γεωθερμική Έρευνα

από
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Στην εργασία αυτή γίνεται μιά εξέταση των διαφόρων γεωφυσικών μεθόδων που έχουν αποδειχθεί χρήσιμες στον εντοπισμό γεωθερμικών πεδίων.

Μολονότι η χρήση μιάς και μόνο μεθόδου τις περισσότερες φορές φέρνει περιορισμένα αποτελέσματα, όταν συνδυασθεί με άλλες γεωφυσικές μεθόδους και με γεωλογικά και γεωχημικά δεδομένα μπορεί να οδηγήσει στον ακριβή εντοπισμό των ορίων του γεωθερμικού πεδίου.

Από τις βρισκόμενες σε χρήση σήμερα γεωφυσικές μεθόδους, οι βαρυτικές, οι μαγνητικές, η μέτρηση σεισμικού θορύβου και η κατανομή μικροσεισμών χρησιμοποιούνται για τον καθορισμό των γενικών ορίων του γεωθερμικού πεδίου και των τεκτονικών του χαρακτηριστικών, ενώ η ηλεκτρική, η ηλεκτρομαγνητική και η θερμική μέθοδος, χρησιμοποιούνται για τον ακριβή εντοπισμό των θερμικών πηγών.