CHAPTER 2

EXPLORATION, CONFIRMATION AND EVALUATION OF THE RESOURCE

Work Group

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INTRODUCTION

The techniques of geothermal exploration originated in Italy during the first half of this century and were augmented by New Zealand and Iceland in the 1950's as part of their efforts to develop geothermal resources. No strong consideration was given to developing this discipline in the United States until the late 1960's and early 1970's.

The last ten years have witnessed a strong research effort in the U.S. and the development of a technical foundation is well under way. Great strides have been made in the development of concepts concerning geothermal reservoirs and their unique characteristics. New tools and techniques have resulted in defining an exploration strategy which is now beginning to provide positive results.

Geothermal pioneers in this country have had the marked advantage of a wealth of supporting material (tools, techniques and theory under development for over half a century by the petroleum and mining industries) and the availability of a team of trained and experienced scientists and technicians. In all probability, with this wealth of background data and ever-increasing effort, geothermal exploration will come of age far sooner than if it had developed on its own from the ground up.

GEOLOGIC CONSIDERATIONS

Three important questions at the beginning of any geothermal energy utilization project are: (1) where should a geothermal well be sited, (2) how deep must a well be drilled to obtain the required temperature for the specific need, and (3) how much heat (thermal energy) can be extracted per unit time after drilling a well to the required depth? At most places on the surface of the earth, heat is transferred from deep in the subsurface to the surface by conduction, with temperature increasing regularly along a geothermal gradient of about 14°F/1000 ft (25°C/Km; curve A in Figure 1). However, in some geological provinces, conductive geothermal gradients are as high as 36°F/1000 ft (65°C/Km; curve B in Figure 1).

Abnormally high temperatures at shallow depths are commonly the result of convective flow of hot water that picks up heat deep in the subsurface and transfers it to rock near the surface. Temperature-depth relations that could result from convective transfer of heat are depicted in curves C and D of Figure l. The temperature reversal in the upper part of curve C indicates a component of horizontal flow of hot water. The maximum temperatures that are likely to be maintained for long periods of time in a hydrothermal convection system are shown by the boiling point curve in Figure 1 which separates the fields of steam and hot water. The relative position of the boiling point curve on a temperature-depth profile will vary according to the salinity of the subsurface fluids and the depth of the local water table.

Presently, thermal energy in the shallow crust of the earth is extracted by bringing to the surface the hot water and steam that occurs naturally in the open spaces in rock. Where rock permeability is very low, the rate of thermal energy extraction is low. Therefore, in addition to adequate temperature, a minimum permeability also is required to extract thermal energy economically. In order to extract the heat stored in the solid rock portion of the reservoir, there must be a slow recharge of water into the system as the initial water is extracted.

Research is under way to determine the feasibility (both practical and economic) of creating artificial permeability in hot, relatively impermeable rock (hot "dry" rock) and extracting heat by injecting cold water into the artificial reservoir through one well and removing heated water through a second well. It has been demonstrated that artificial permeability can be created and a water-circulation loop established. The economic feasibility of the system is still uncer-

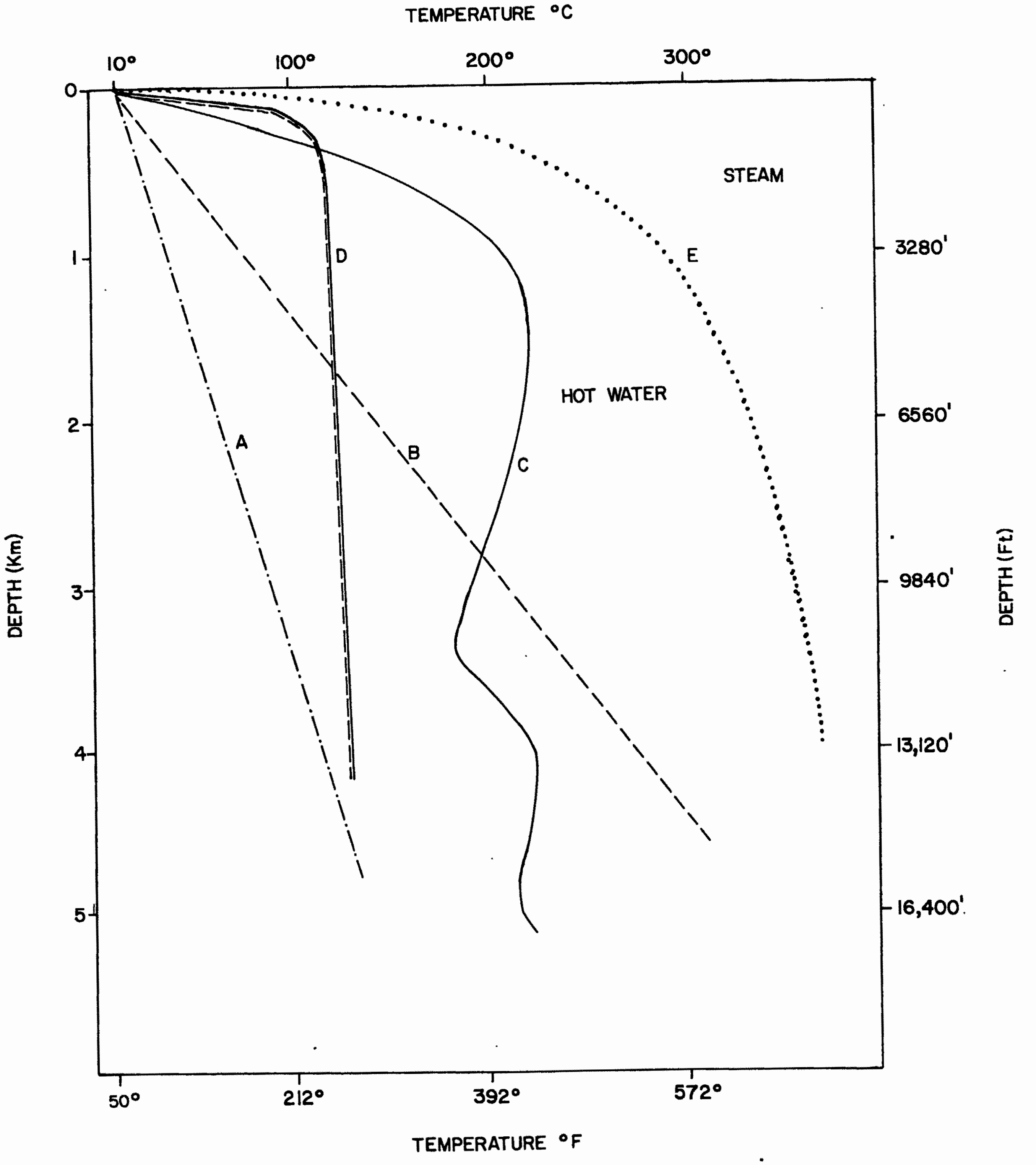

FIGURE 1. Representative depth-temperature relations in the earth's crust. Curve A shows a normal conductive geothermal gradient. Curve B shows a high conductive gradient. Curves C and D show possible temperature-depth relations resulting from convective flow of fluids. Curve E is the boiling point of water vs. depth.

tain. In the remainder of this section, the geothermal exploration target will be assumed to be a conventional hot-water system, although many of the same exploration techniques would be used for any type of geothermal system.

In regions of normal geothermal gradient, it is necessary to drill deeper than four kilometers in order to obtain water above 212°F (100°C). The geological environment in which permeable rocks are most likely to be found at a depth of four kilometers or greater is a deep sedimentary basin such as the basins in Hungary and France that now provide hot water for direct-use geother geothml applications. Highly faulted and folded rocks in regions of normal geothermal gradient may provide conduits for convective upflow of hot water and local shallow reservoirs of water suitable for direct utilization may be present in these types of terrain. Where conductive geothermal gradients are very high, economically useful geothermal reservoirs are likely to be found at relatively shallow depths, particularly where local convection systems are present. The types of geologic environments that have high conductive geothermal gradients and localized hydrothermal-convection systems have been discussed in Chapter 1.

BACKGROUND INFORMATION

Different applications of geothermal energy require different temperatures. Thus, the first step in exploring for the geothermal resource is to define the physical characteristics required for the application. The needed information may vary according to application, but generally include temperature. flow rate and water quality. Proximity of the resource to areas of probable use and the possible conflict with present land uses such as metropolitan areas, highways, industrial or agricultural centers, etc., must also be taken into account.

Once the temperature, quantity and location requirements of the resource are determined, a rational program of exploration can be developed. The first step is a library search to determine what is already known. The library search can be subdivided into two categories: land status and technical information. A good place to start an evaluation of land status is in the local office of the Bureau of Land Management (BLM) where detailed land-status maps are available. These maps show land ownership divided into federal (forest, Indian, military, recreational and BLM), state and private lands. More detailed information, such as leasing procedures, permits required, environmental regulations, etc. (see Chapter 6) can generally be obtained by contacting the agency controlling the lands or the state land office.

Technical information includes both specific geothermal data and general geological information that may bear indirectly on the nature and occurrence of geothermal resources. Specific geothermal information with references, such as locations of hot springs and hot wells, has been published by the U.S. Geological Survey in two circulars, 726 and 790 (White and Williams, 1975; Muffler, 1979). A nationwide geothermal gradient map has been published by the American Association of Petroleum Geologists (AAPG-USGS 1976 a, b) and several researchers have published national heat-flow maps (e.g., Sass, et al., 1976). In addition, the National Oceanographic and Atmospheric Administration has published a geothermal-resource map of the Western United States (See Muffler, 1979, Map No. 1). In addition, detailed state-by-state geothermal-resource maps have either been published or are in preparation (Wright, et al., 1978). A rather complete bibliography of geothermal publications has been published by the U.S. Energy Research and Development Administration, now the U.S. Department of Energy (ERDA, 1976), and is updated quarterly.

There may also be a wealth of site-specific geological information available which can be very important in designing an exploration program. This type of information is scattered throughout the geological literature and may, therefore, be difficult to locate. The most useful sources are reports of the U.S. Geological Survey, state geologic surveys and the major geological publications, such as those listed in the Bibliography of North American Geology. The types of general geological information most useful in the early stages of geothermal exploration are the location and distribution of young volcanics and recent faults, chemical analyses of thermal and non-thermal waters upon which the standard techniques of chemical geothermometry can be applied, and the presence of deep sedimentary basins.

EXPLORATION TECHNIQUES

After a thorough review of the pertinent literature has been completed and access to the land has been established, a decision should be made as to whether or not a given prospect area shows sufficient potential to warrant detailed site-specific exploration. The various geological, geochemical and geophysical tools available to the geothermal explorationist are briefly described in the following sections. These methods are designed to produce specific information. Because each geothermal prospect is in many ways unique, there is no one method or series of methods which will work in all circumstances. The costs of various methods must be considered in terms of the benefits received and the value of the particular resource. Nevertheless, the final verification of a geothermal resource must be based on drilling.

GEOLOGICAL EXPLORATION

Geological exploration techniques are concerned with the identification and interpretation of the surface manifestations of geothermal activity and the identification of structures that channel the geothermal fluids in the shallow subsurface. The principal methods of data collection are geologic mapping and air-photo interpretation. Hot-spring deposits and associated hydrothermal alteration are often clearly shown on air photos. In addition, faults or intersections of faults which control hot springs commonly can be delineated on air photos. The documentation of the orientations of these structures allows prediction of the subsurface geometry of the structures which may control or communicate with the reservoir. From this information, coupled with other geochemical and geophysical data, drill sites can be located to intersect desired structures at depth.

Hot thermal waters alter the minerals of the rocks with which they come in contact (Browne, 1978). In addition, these waters commonly form hot-spring deposits consisting of calcium carbonate (travertine) or opaline silica (sinter). Extensive travertine deposits usually indicate that the temperature of the aquifer feeding the spring is less than 248-284°F (120-140°C). Sinter deposits are considered prime facie evidence of geothermal reservoir temperatures exceeding 356°F (180°C; Renner, et al., 1975). These higher temperature systems tend to self seal through the precipitation of silica and the alteration of wall rocks. This often results in the termination of hot-spring activity. Thus, even though activity has ceased at the surface, the geothermal resource may exist at depth.

Radiometric dating of rocks is a valuable tool for the identification of young volcanic rocks. The presence of rhyolites one million years old or less and basaltic activity within a few thousand years before present are both excellent evidence for the existence of anomalously high thermal gradients. Although the age dating of rocks is not a site-specific exploration technique, it does provide identification of regions of geothermal exploration interest.

Characterization of the geology either through existing geologic maps or new mapping provides a data base for the modeling and evaluation of many of the geophysical and geochemical techniques which will be discussed in subsequent sections. This is particularly true for the modeling of gravity and magnetic surveys as well as the interpretation of physical-parameter contrast identified using other geophysical techniques.

Previously obtained regional and site-specific geological information is available to a limited extent from publications and personnel of state geological surveys, the Division of Geothermal Energy of the Department of Energy and the U.S. Geological Survey. Furthermore, ongoing geological and geothermal programs of the organizations continue to provide new as well as reinterpreted geological data. Professional geological services are available from consulting geologists who specialize in the evaluation of geothermal prospects. These consultants may be found through listings with state surveys, registration boards or advertisements in professional journals.

GEOCHEMICAL EXPLORATION

Geochemical investigations provide information about subsurface temperatures, locations of faults which act as conduits for upward movement of hot waters and gases, sources of potential scaling or corrosion during production and possible waste-disposal problems and environmental concerns. Summary information about geochemical-exploration methods pertaining to geothermal resources is contained in Ellis and Mahon (1977), Truesdell (1976), Fournier (1977; 1979) and Brook, et al. (1979).

The compositions of spring and well waters can be used to estimate geothermal reservoir temperatures provided that various implicit assumptions are valid. The most important of these assumptions are: (1) that chemical (or isotopic) equilibria have been established in the reservoir between wall rock and the geothermal fluid with respect to the specific indicator reaction, (2) that there is insignificant re-equilibration at lower temperature after the water leaves the reservoir and (3) that either there is no mixing with different waters during movement move to the surface or estimation of the results of the mixing is possible. At present, the most commonly used chemical and isotopic geothermometers are silica, Na/K, Na-K-Ca, Na-K-Ca-Mg, and $\Delta^{18}O$ (H_2O-HSO_4^-). Each of these geothermometers has its limitations and each requires considerable interpretation in its use. Application of chemical and isotopic geothermometers also requires proper collection, preservation and chemical analyses of the samples.

The following factors should be considered when using the silica geothermometer to explore for low-temperature resources. Most groundwaters which have not attained temperatures greater than 175-195°F (80-90°C) have silica concentrations greater than those predicted by the solubility of quartz. Many of these waters have equilibrated with chalcedony (sometimes up to 355°F, 180°C), but some silica concentrations result from non-equilibrium situations in which silica is released to solution during acid attack upon silicate minerals. The acid may come from decay of organic material, oxidation of sulfides or influx of H_2S or CO_2 from depth. High concentrations of dissolved silica in cold waters are particularly common where CO_2 reacts with serpentine at low temperatures. The pH of the spring water also must be considered. At 77°F (25°C) the solubilities of silica minerals are significantly increased at pH > 9. At temperatures above 212°F (100°C), significant increases occur at pH values as low as 7.5. However, in most geothermal reservoirs rockwater reactions buffer the pH of the water at values below 7.5. As those waters rise to the surface, dissolved CO_2 escapes from solution and the pH increases. Whether or not a correction should be applied to adjust the silica content of an alkaline hot-spring water for pH effects depends upon where and when the solution attained its aqueous silica. If a solution attained a high silica content because of high underground temperature and then became alkaline after cooling and loss of CO_2, no pH correction should be applied.

The Na/K geothermometer has been used for several years, but has been found to be very unreliable at temperatures below 302-392°F (150-200°C). Therefore, the Na/K geothermometer should not be used in evaluating low-temperature resources. The Na-K-Ca method is reasonably good at low temperatures, but will give temperatures that are too high if $CaCO_3$ precipitated because of the loss of CO_2 after the water left the reservoir. The Na-K-Ca geothermometer may require correction for the Mg content of the water for certain types of waters.

The ^{18}O (H_2O-HSO_4^-) geothermometer has recently been investigated, but it cannot be used in cases where some of the sulfate in the water results from low-temperature, near surface oxidation of H_2S or sulfide minerals such as pyrite. Mixing of hot and cold waters also results in incorrect $\Delta^{18}O$ (H_2O-HSO_4^-) temperatures even if the low-temperature component of the mixture contains no sulfate.

When using chemical geothermometers to estimate reservoir temperatures in geothermal systems, the hydrologic complexities which are commonly present must be examined. Water may move relatively quickly and directly to the surface from a deep reservoir with little heat loss on the way, or it may flow through a series of intermediate reservoirs where new water-rock equilibria are attained at lower temperatures. In particular, geothermometers applied to water emerging at the surface give information about the temperature of the last water-rock equilibria. Hot water ascending to the surface from a geothermal reservoir may cool by conduction of heat to the surrounding rock, by boiling, by mixing with cooler shallow water or by a combination of these processes, depending on the depth of the aquifer, the geometric configuration and path of the channel way, the rate of mass flow, the coefficient of thermal diffusion through the surrounding rock, and the initial temperature of the water. The effects of these different cooling mechanisms should be considered when estimating reservoir temperatures from hot spring compositions. However, in those places where emerging thermal waters appear to be mixtures of hot water and cold, dilute, shallow groundwater, the composition and temperature of the high-temperature component may be calculated using mixing models, provided various favorable conditions are met.

Another use of geochemistry in a geothermal-exploration program involves determination of the isotopic composition of both the thermal and nonthermal groundwater in a given region. The isotopic information is useful for determining where the recharge water entered the system and the amount of water-rock reaction that occurred at high temperature as that water moved through the system. The tritium content of emerging hot-spring water gives an indication of how long that water has been underground. No tritium indicates that the water has been underground for many years and probably comes from a deep reservoir. Increasing amounts of tritium in hot-spring waters is a sure sign of near surface mixing with cold, meteoric water.

Analyses of soil gases for mercury, carbon dioxide and helium and groundwaters for volatile components in general (particularly boron and ammonia) have been found to be useful in some places for detecting where anomalously high temperatures exist at shallow levels. Larger than average amounts of helium, radon and mercury in soil gas also have been used to outline the presence of otherwise hidden faults. The above methods are most useful where boiling waters exist at depth. Unfortunately, they tend to outline areas of fossil geothermal activity and places where faults allow gases to escape from very deep in the crust. Soil geochemistry has also been shown to be useful in outlining geothermal resources on the basis of anomalous trace element zoning. Arsenic and mercury anomalies seem to be particularly successful in delineating the upper levels of hydrothermal systems. Analysis of drill cuttings for trace elements shows promise of being able to predict the approach to hot water entries in exploration holes (Bamford, 1978).

GEOPHYSICAL EXPLORATION

A geophysical survey consists of a set of measurements made over the surface of the earth, in the air above and parallel to the earth and in boreholes within the earth. The measurements are of the variations in the physical properties of the subsurface rocks including thermal conductivity, electrical resistivity, propagation velocity of elastic waves, density and magnetic susceptibility. Geothermal systems commonly give distinctive and fairly easily measured discontinuities in the above-mentioned physical properties, e.g., high heat flow, low electrical resistivity and attenuation of high-frequency elastic waves. Therefore, the existence of geothermal resources can be inferred from the indirect measurement of these various physical parameters at depth. The most useful geophysical techniques for geothermal exploration are temperature or geothermal-gradient surveys, heat-flow determinations, electrical-resistivity surveys, and passive seismic surveys, such as microearthquake measurements. These geophysical methods can aid in the delineation of geothermal reservoirs and furnish data on subsurface thermal processes.

The accuracy with which geothermal systems can be detected by geophysical means depends on the degree of contrast in the physical properties between the rocks comprising the geothermal system and the surrounding subsurface. Geothermal reservoirs usually have irregular shapes and occur in rocks of complex structure and varying type, i.e., geothermal systems are three dimensional. The emphasis in geothermal exploration is therefore upon detection of geothermal systems and their lateral extents. Geophysical surveys are conducted in order to provide data for the location of geothermal systems and to aid in locating geothermal drillholes.

The direct applications of geothermal resources require lower temperature resources than do electrical applications; therefore, the extent of assessment may be significantly reduced in order to obtain a sufficient level of confidence for acquiring a suitable geothermal resource for direct applications. However, because a lower temperature subsurface environment is sought in most direct-use applications of geothermal resources, the discontinuities in the physical properties of the rocks are not as distinctive and therefore geophysical techniques that are quite useful for detecting high-temperature geothermal resources may not provide definitive data when exploring for low-temperature geothermal resources. Geophysical techniques or surveys can be grouped into four separate categories when considering their use for geothermal exploration. These four groups include structural methods, electrical and electromagnetic methods, passive seismic methods and thermal methods.

Structural methods

Active seismic methods (reflection and refraction), gravity surveys and magnetic surveys all fall under the category of structural methods as applied to geothermal exploration. In contrast to thermal and electrical methods, for example, these structural methods do not determine the physical properties of the warm and hot geothermal fluids sought, but instead investigate the attitude and nature of the host rocks. Structural methods may prove justifiable for geothermal exploration in refining a regional or local geological subsurface model, but they generally provide little useful information for defining geothermal reservoirs. However, these methods can be useful in defining faults or fault zones which may control the geothermal resource.

Active seismic methods (Dobrin, 1976) involve the use of man-made explosions or surface vibrations to generate elastic waves. The reflection method utilizes energy reflected back to the surface from subsurface interfaces between rocks of different physical properties. The refraction method utilizes seismic waves refracted horizontally along an interface and thence back to the surface. Both methods are used to determine subsurface structure and the configuration and depth to basement rocks.

Gravity surveys (Dobrin, 1976), which determine density contrasts of subsurface rocks, have been used both to outline major structural features and to delineate local positive and negative anomalies that may be related to geothermal systems. Local gravity anomalies may be caused by local structural highs, buried volcanic rocks, intrusive rocks, or hydrothermally altered rocks. However, because these gravity anomalies can be produced by factors other than active geothermal systems, gravity surveys in geothermal exploration are open to gross misinterpretation unless used in conjunction with other exploration techniques.

In general, magnetic surveys, which detect differences in magnetic susceptibility of subsurface rocks, are the geophysical method least useful in defining geothermal drilling targets. In some areas, negative magnetic anomalies appear to be caused by hydrothermal alteration, and in other areas, positive magnetic anomalies can be related to very young intrusive and volcanic rocks associated with geothermal systems. In most areas, however, so many factors influence the character of a magnetic survey and the resulting magnetic map, that the results are difficult to interpret in terms of geothermal resources.

Electrical and electromagnetic methods

Electrical and electromagnetic methods (Keller and Frischknecht, 1966) in geothermal exploration measure the electrical resistivity of rocks at depth. Temperature, porosity, salinity of interstitial fluids and/or content of clays and zeolites tend to be higher within geothermal reservoirs than in the surrounding subsurface. Consequently, the electrical resistivity in geothermal reservoirs is relatively low compared to the host rocks.

Many different electrical and electromagnetic methods are used to measure electrical resistivity at depth. The telluric, audiofrequency magnetotelluric (AMT) and magnetotelluric (MT) techniques depend on measuring variations in the natural electrical and magnetic fields of the earth. Each of the several different electrical techniques utilized in geothermal exploration involve the use of man-made electrical generators putting current into the ground at two electrodes and measuring the resultant potential at two other electrodes. Electromagnetic methods involve the generation of a magnetic field that varies with time and the detection of either the electrical or the magnetic field arising from currents induced in the earth.

Published data on the application of electrical techniques in geothermal areas indicate that the most useful technique is DC-resistivity profiling or sounding using linear arrays, primarily the Wenner or Schlumberger array. DC-resistivity methods are preferred to AC methods because of skin effects present at large spacings with the AC methods. However, with linear arrays, the effective probing depth is controlled by electrode spacing so that in order to effectively evaluate deeper prospects, it may be necessary to lay cables over considerable distances and thus rugged topography may result in severe logistical problems. An electrical prospecting technique that has been increasingly utilized in geothermal exploration is the dipole-dipole array. Although the method is logistically simple and is essentially insensitive to rugged topography, effective dipole-dipole investigations require complicated data analysis and are subject to ambiguous interpretation.

Electromagnetic methods have been applied in geothermal exploration only during the past few years. Although instrumentation and interpretation are complex, electromagnetic (inductive) methods have two theoretical advantages over electrical methods: (1) with an inductive method, signal size increases with decreasing resistivity, making measurements easier and more accurate in geothermal areas; and (2) inductive methods are not adversely affected by near surface high-resistivity zones.

The major problem associated with all electrical and electromagnetic methods is the interpretation of the electrical-resistivity anomalies that are measured. Because the electrical resistivity of subsurface rocks is a complicated function of temperature, porosity, salinity and content of clays and zeolites, if and when a relatively low electrical-resistivity anomaly is observed, the causal relationship must be determined by utilizing some other type of data, e.g., direct temperature or geothermal-gradient measurements. More specifically, a low-temperature, highly saline, groundwater in the subsurface can provide the same low electrical resistivity anomaly that is exhibited over a high-temperature, moderate salinity, geothermal system.

Passive seismic methods

Geothermal areas are characterized by an enhanced level of microearthquake activity (Majer and McEvilly, 1979). The measurement or detection of these microearthquakes and determination of their precise hypocentral locations provide the data necessary to locate active fault zones in a geothermal area which may be functioning as subsurface conduits for the geothermal fluids. In addition, the results of microearthquake surveys can be used to estimate the subsurface physical characteristics of geothermal systems because the temperature of the subsurface and the type and amount of interstitial fluids significantly affect the velocity and attenuation of elastic waves of both compressional (P) and shear (S) type. For example, the attenuation of shear waves may indicate high-temperature zones of low rigidity. Similarly, low values of Poisson's ratio found from the ratio of the velocity of compressional to shear waves may indicate rock voids that are not saturated with liquid and could therefore be steam-filled. However, passive seismic methods are just beginning to be used in geothermal exploration and are not completely understood. They may, however, provide many new and quite useful geothermal exploration techniques in the future.

Thermal methods

The temperature within the reservoir is the most important physical characteristic of a geothermal system. The physical and chemical processes within the geothermal reservoir depend critically on this quantity, and the techniques of heat and fluid extraction have to be selected with regard to these temperature conditions. Because the temperature constitutes the most important physical characteristic of a geothermal system, thermal exploration methods, such as geothermal-gradient measurements in boreholes and heat-flow determinations, are of primary importance. Thermal-exploration techniques provide the most direct method for making a first estimate of the size and potential of a geothermal system with surface geophysical exploration.

Temperature and gradient measurements at depths on the order of 3 ft (1 m) are fast and inexpensive, and can be used to detect anomalously hot areas. These shallow temperature measurements are strongly influenced, however, by near-surface effects, including insolation, topography, precipitation and movement of groundwater. The last of these effects is particularly important, for a relatively slow movement of groundwater across even a strong thermal anomaly can carry away the conductive heat flow, displacing surface-temperature patterns and grossly distorting gradient measurements.

Temperatures measured as a function of depth in boreholes 50-2000 ft (15-600 m) deep have been used as the primary thermal method in geothermal exploration. At these depths most near-surface thermal disturbances are avoided, and gradient measurements can be made with considerable precision and reliability. Nevertheless, the data must always be evaluated for the effects of lateral and vertical movement of ground water. Over most economically attractive geothermal areas, the gradients at shallow to intermediate depths are equal to or greater than 36°F per 1000 ft (65°C per km), compared to a normal geothermal gradient of about 14°F per 1000 ft (25°C per km).

Although gradient measurements do define the areal extent of geothermal anomalies, one must be very cautious in extrapolation of these gradients to depth. Two factors combine to ensure that a linear extrapolation will be in error on the high side. The first is the variation in thermal conductivity of the subsurface rock with depth. The second factor, thermal convection, will have an even greater effect in reducing gradients at depth (see Figure 1). In an area where thermal convection of water within the pore space of rocks is possible, the extrapolation of measured high, near-surface gradients is clearly unjustified and likely to suggest erroneously high temperatures at shallow depths.

When the mean thermal conductivity of the rocks is essentially constant throughout the subsurface through which boreholes are drilled, the geothermal gradients measured are obviously proportional to the heat-flow values, because heat flow is the product of geothermal gradient and thermal conductivity. Geothermal gradient must decrease with depth as the thermal conductivity of the rocks increases. The advantage of heat-flow determinations, as opposed to purely geothermal-gradient measurements, is that heat flow is independent of the thermal conductivity of each rock type. Therefore, in nonhomogeneous terrains, only heat-flow measurements enable one to obtain accurate data on the potentially productive geothermal zones.

Remote sensing (infrared) techniques

Infrared techniques have been used for geothermal exploration with limited success. Under ideal conditions (flat homogeneous terrain), they can detect regions that are as little as 1°F (0.5°C) warmer than the ambient temperature and have duplicated results of shallow thermal gradient surveys measuring heat flows greater than 0.07 heat flow units ($3w/m^2$). However, emissivity effects due to natural terrain variances can obscure 1-10°F (0.5-5°C) temperature differences. Infrared scanners normally operate in the 3-5 or 8-14 micron ($3-5 \times 10^{-6}m$) or ($8-14 \times 10^{-6}m$) transmission ranges. To minimize solar heating effects, areas are usually flown between midnigh and one hour before dawn.

Infrared methods are best suited for mapping surface manifestations, especially large areas of remote regions. For this reason, it has been used successfully by the United Nations in Ethiopia and Kenya (McNitt, U.N. proceedings, 1975). In general, this method has not been used as an exploration tool in the United States since most surface manifestations (hot springs, etc.) have already been mapped.

DRILLING

The exploration methods previously described are extremely important in the selection of a drilling site. However, drilling is the only way to confirm the presence of a geothermal resource. Exploration drilling can be very helpful in assessing the geological and hydrological controls of the geothermal system. Therefore, care and consideration should be taken in the planning of the drilling program so that one obtains all of the information that will be useful in the later development of the resource, in addition to the initial delineation and evaluation of the resource. Factors to consider in the drilling plan include basic well design (see Chapter 3), sample recovery (including collection of cutting and cores), geophysical logging and flow testing (including fluid sampling). The proper acquisition of this data will allow a reassessment of the previously acquired geological, geophysical and geochemical data. The result will be a better understanding of the nature and extent of the geothermal resource.

GEOPHYSICAL LOGGING

Geophysical logging is the application to the borehole environment of the physical principles used for surface geophysics. In the borehole environment, these techniques provide more resolution than is normally obtained from surface geophysics. Geophysical logging has been the primary tool used by the petroleum industry in assessing the properties of rocks in petroleum reservoirs. Much of this technology is directly transferable to the geothermal industry, and hence is useful in evaluating the properties of rocks in geothermal reservoirs. However, most of the rocks encountered in geothermal exploration are significantly different from the rocks commonly found in petroleum exploration. Hence, care must be taken not to run the basic petroleum logging suite blindly, attempting to interpret the data as if it were encountered in a petroleum reservoir.

Parameters extremely valuable in assessing the potential of a geothermal reservoir are temperature, flow rate, porosity (which can then empirically relate to permeability), elastic-wave velocity, electrical resistivity, density and natural radioactivity. Many of these parameters are very useful in defining geological units and rock types for correlation with rocks in nearby boreholes. These help also to define potentially productive zones that dictate how to complete the well, and reinterpret exploration data for the siting of additional wells.

The nature and character of the logging suite will vary with the type of geothermal resource. The obvious parameters to be measured are temperature and flow rate, which are obtained with temperature logs and flow meters. However, for most direct applications of geothermal resources, the effective porosity (permeability) is a very important parameter. The effective porosity may be either intergranular or fracture-controlled (possible fault related). The porosity is best obtained via the gamma-gamma log (density), the neutron log or the sonic log. Lithology information can be gained from many logs, but the fundamental tools are SP (spontaneous potential) and natural gamma.

The acquisition of a complete suite of geophysical logs utilizing major petroleum logging firms is quite expensive. Some of these firms do, however, have equipment capable of logging very hot holes. However, there are other, less expensive firms that can run logs, especially in the relatively shallow and moderately hot holes drilled for direct-application uses. These firms include geothermal and mineral exploration firms. Some of this equipment is extremely portable. Thus, adequate logging services are available at a variety of costs, and hence the acquisition of this data is possible and essential to the orderly development of the resource.

EXPLORATION COSTS

The following table (Table I) shows many of the exploration methods discussed in the previous sections. Approximate times for completion of the surveys and order-of-magnitude costs for the methods are also indicated. It should be stressed that the costs shown are approximate and will vary as a function of many factors including survey detail, accessibility, terrain and weather. Geothermal-gradient/heat-flow borehole costs include cost of drilling and completing holes as well as logging. The geochemical procedures include sample collection as well as analytical costs. The methods are also characterized as being principally of use in regional and/or detailed evaluations.

TABLE I

Summary of costs, time frames and area covered with various geothermal exploration methods

Method	Time	Expense	Area
Consulting geologist	< month	\$200-\$400/day	Regional/detailed
Airphoto interpretation	< month	\$5/mi^2 (\$2/km^2)	Regional/detailed
Water analyses	month	\$100-\$200/sample	Regional/detailed
Surface geochemistry	month	\$30/sample	Detailed
Volatile geochemistry	month	\$20/sample	Detailed
Temperature gradient/heat flow boreholes	> month	\$10-\$100/ft (\$30-\$300/m)	Regional/detailed
Electromagnetic methods	month	\$200-\$1500/line mi (\$125-\$930/line km)	Detailed
Resistivity	month	\$200-\$1500/line mi (\$125-\$930/line km)	Detailed
Magnetics - airborne	< month	\$25/line mi (\$15/km)	Regional
- ground	< month	\$200/line mi (\$125/km)	Detailed
Seismic - refraction	< month	\$5000/line mi (\$3000/km)	Detailed
- reflection	< month	\$5000-\$10,000/line mi (\$3000-\$6000/km)	Detailed
- microearthquakes	3-6 months	\$1200/day	Regional/detailed
Gravity	month	\$30-\$70 station	Regional/detailed
Magnetotellurics	month	\$1200-\$2000/line mi (\$750-\$1250/km)	
Geophysical logging	< week	\$2000-\$20,000/hole	Detailed

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