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GEOPHYSICAL EXPLORATION FOR GEOTHERMAL RESOURCES

by

Phillip M. Wright
Stanley H. Ward
Howard P. Ross
Richard C. West

Earth Science Laboratory
University of Utah Research Institute
391 Chipeta Way, Suite C
Salt Lake City, Utah 84108

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INTRODUCTION

Development of geothermal resources is being aggressively pursued on a worldwide basis. Approximately 3800 megawatts of electricity are currently being generated from geothermal energy, and about 10,000 thermal megawatts of direct uses are being made worldwide. While this may seem small compared to the estimated human fossil energy use of 8.4×10^6 megawatts (Williams and VanHerzen, 1974), it nevertheless represents a savings in the consumption of about 77 million barrels of oil per year. It is very difficult to estimate the ultimate potential contribution of geothermal energy to mankind's needs for at least three reasons: 1) future energy costs, although generally predicted to be higher than today's levels, are uncertain, and a large number of lower grade geothermal resources could become economic at higher energy prices; 2) only preliminary estimates of the worldwide resource base have been made, and; 3) technology for using energy in magma, hot rock and normal thermal gradient resources, whose potential contribution is very large, is not yet available. Nevertheless, White (1965) estimated that the total heat stored above surface temperature in the earth to a depth of 10 km is about 1.3×10^{27} joules, equivalent to the burning of about 2.3×10^{17} barrels of oil. It is apparent that if even a small part of this heat could be made available, its contribution would be significant.

In the United States, commercial development of geothermal energy is pursued by private industry, and much of the data generated are not available for public inspection and use. In substantially all of the rest of the world, geothermal development is sponsored by federal governments, and there is reasonably good access to data, although not all of it appears in readily available journals. Active programs in geothermal exploration and development are being carried out in China, El Salvador, France, Iceland, Indonesia, Italy, Japan, Kenya, Mexico, New Zealand, the Philippines, the United States, and to a lesser extent in other countries. Expertise arising from first-hand experience in Iceland, Italy, New Zealand, Mexico, Japan, and the U.S., primarily, is being used by the more underdeveloped countries to assist their geothermal efforts. The United Nations sponsors both scientific work and education in underdeveloped countries. Exploration projects using U.N. funding has been carried out in El Salvador, Chile, Nicaragua, Turkey, Ethiopia, and Kenya, and the UN sponsors geothermal training programs at the United Nations Univeristy locations in Iceland, Italy and New Zealand. La Organizacion Latinoamericana de Energía (OLADE), headquartered in Quito, Ecuador, provides coordination and support for geothermal development in Central and South America. In short, an infrastructure for geothermal development is being built throughout the world, and, while it is small compared to the corresponding petroleum or minerals infrastructures, it is making important contributions.

In this paper we seek to review the application of geophysical methods to geothermal exploration and development and to assess the current state of the art. Previous reviews of geophysical applications have been given by Pàlmason (1975), McNitt (1975), Meidav and Tonani (1975), Ward (1983), and Rapolla and Keller (1984), among others. There are many more published accounts of geophysical work in the geothermal environment than can be discussed or referenced in an article of this length. We have cited a few typical references for each of the applications discussed. These are slanted to the U. S. literature, and for this and other omissions in giving credit where it is due we apologize in advance.

NATURE OF GEOTHERMAL RESOURCES

Geothermal resources have three common components: 1) a heat source, 2) permeability, and 3) a fluid to transfer the heat to the surface. In some exploitation schemes, the permeability must be created artificially. One useful classification of geothermal resource types is shown in Table 1. Hydrothermal resources, as the term implies, are those characterized by natural thermal waters, and are divided into those with significant large-scale convection and those without. Hot rock resources have no natural fluid to transport heat to the surface, and are the subject of current research to develop means of extracting their energy. Only the convective hydrothermal resources have been developed to any extent, the other resources being presently uneconomic.

Convective hydrothermal resources are geothermal resources in which the earth's heat is actively carried upward by the circulation of naturally occurring hot water or steam. Underlying some of the higher-temperature resources is presumably a body of molten or recently solidified rock whose temperature may be 400°C to 1,100°C. Other convective resources result simply from circulation of water along faults and fractures or within permeable aquifers to depths where the rock temperature is elevated, with heating of the water and subsequent buoyant transport to the surface or near surface.

Thermal waters can be produced from some basins or from regional aquifers. In the north-central U.S., the Madison and other formations contain thermally anomalous waters, whose origin is not fully understood, over an area of 25,000 sq km. Substantial benefit is being realized in France for space heating by production of warm water contained in the Paris basin (Varet, 1982). Many other areas of occurrence of this resource type are known worldwide.

TABLE 1

GEOTHERMAL RESOURCE CLASSIFICATION
(Modified from White and Williams, 1975)

Resource Type	Temperature Characteristics
Convective Hydrothermal Resources	
a) Vapor dominated	about 240°C
b) Hot-water dominated	about 25°C to 350°C+
Other Hydrothermal Resources	
a) Sedimentary basins/Regional aquifers (hot fluid in sedimentary rocks)	30°C to about 150°C
b) Geopressured (hot fluid under pressure that is greater than hydrostatic)	130°C to about 200°C
c) Radiogenic (heat generated by radioactive decay)	30°C to about 150°C
Hot Rock Resources	
a) Part still molten	higher than 600°C
b) Not molten (hot, dry rock)	90°C to 650°C

Geopressured resources consist of deeply buried fluids contained in permeable sedimentary rocks warmed in a normal or anomalous geothermal gradient by their great depth of burial. These fluids are tightly confined by surrounding impermeable rock and thus bear pressure that is much greater than hydrostatic, that is, the fluid pressure supports a portion of the lithostatic load (Wallace et al., 1978). In the Gulf Coast area of the U. S., these geopressured fluids have temperatures up to 150°C and also contain dissolved methane. Therefore, three sources of energy may be available: 1) heat, 2) mechanical energy due to the great pressure with which these waters exit the borehole, and 3) the recoverable methane. Assessment of the effects of producing these resources is a topic of research by the U. S. Department of Energy.

Radiogenic geothermal resources are postulated to occur, for example, in the eastern U.S. (Costain et al., 1980), where the coastal plain is blanketed by a layer of thermally insulating sediments. Acidic intrusions having enhanced heat production from radioactive delay occur in places beneath these sediments. Gravity and aeromagnetic surveys to locate covered intrusions, followed by heat flow studies to distinguish heat sources have been carried out largely under DOE sponsorship. Only one attempt has been made to drill test an area believed to contain a radiogenic geothermal resource, and this test was moderately encouraging in that temperatures of 80°C were encountered at a depth of about 5000 ft.

Hot rock resources comprise those which have little or no natural hydrothermal convection, and the resource may be molten, partly molten, or solidified. The feasibility and economics of extraction of heat from hot, dry rocks is presently the subject of a cooperative research effort among the U. S., the Federal Republic of Germany and Japan. The research is centered at the U.S. Department of Energy's Los Alamos National Laboratory in New Mexico (Smith et al., 1982). Similiar experiments have been carried out in England (Batcheler, 1982). This work indicates that it is technologically feasible to induce permeability in hot, tight crystalline rocks at depths of about 3 km through hydraulic fracturing from a deep well. Sophisticated seismic techniques have been developed to map the fracture during its formation. A second borehole is used to intersect the fracture system. Water can then be circulated to remove the energy. Fluids at temperatures of 150°C to 200°C have been produced in this way from boreholes at the Fenton Hill site near the Valles Caldera, New Mexico.

Experiments are underway at the U.S. Department of Energy's Sandia National Laboratories in Albuquerque, New Mexico to learn how to extract heat energy directly from molten rock (Carson, 1984). Techniques for locating a shallow, crustal magma body, drilling into it and implanting heat exchangers or possibly direct electrical converters remain to be developed. Neither these experiments nor those to develop hot, dry rock are expected to result in economic energy production in the near future.

As a matter of convenience in further classification, it has been customary to speak of high-temperature resources as those having temperatures above 150°C, of intermediate-temperature resources as those with temperatures in the range 90°C to 150°C, and of low-temperature resources as those with temperatures below 90°C. High-temperature and some moderate-temperature resources are partially amenable to development for electrical power generation, whereas those of lower temperature are usually considered for some direct heat use such as space conditioning or industrial process heat.

The preponderant use of geophysics, by a wide margin, has been in exploration for and delineation of moderate- and high-temperature hydrothermal convection resources. For this reason, the remainder of this paper will focus on such applications. The economics of development of low-temperature resources usually preclude anything beyond a simple exploration effort. Discovery of new geopressured resources beyond those known through oil exploration has not received attention because the problems of their development center around economic producibility of known resources, not discovery or delineation. Hot, dry rock resources have not been sought for lack of economic interest, although their exploration would present some interesting problems. Efforts by the U. S. Department of Energy to locate a shallow magma body are just getting started, and only a small overall effort can be expected until and unless these resources someday prove economic.

Models for High-Temperature Hydrothermal Convection Systems

Hydrothermal convection systems are systems of hot, briney circulating fluids that are highly reactive chemically. Models for such systems have been discussed by White et al. (1971) and Mahon et al. (1980), among others. Because geophysical models cannot be separated from geological, geochemical or hydrological models of hydrothermal systems, it is appropriate in this review to comment briefly on general aspects of models that are more or less universally accepted. This will help form a context in which to think about the various geophysical targets that a hydrothermal system may present.

When a pluton intrudes the shallow crust, it begins to cool by conductive heat loss. If vertical permeability is present, hydrothermal convection develops, and may dominate the cooling history (Cathles, 1977; Norton, 1984). Meteoric water penetrating to deep levels (≈ 5 km) is heated by the intrusive body. The heated water rises toward the surface as a result of its lower density and the hydraulic gradient resulting from the cold water on the exterior of the hot column. The water loses heat as it approaches the surface, and the resulting cooler, denser water flows down the side of the hot column. A convection cycle, or a series of cycles, is propagated. To obtain sufficient heat transfer over the long periods of time, that hydrothermal systems appear to last requires penetration of the permeable region into the hot body itself at rates of 0.2 to 20 myr^{-1} (Lister, 1975).

The fluids involved are complex chemically and contain a wide variety and concentration of dissolved constituents. In Table 2 we show some of the chemical parameters of a typical suite of hydrothermal systems. The chemical system becomes more reactive as temperature increases, and in moderate- and high-temperature systems often causes extensive physical property changes through hydrothermal alteration and mineralization of the reservoir rocks. At the low-temperature limit, thermal fluids are much the same as normal groundwater, and may produce only small changes in physical properties.

The bulk of the water and steam in hydrothermal systems is believed to be meteoric (Craig, 1963) and a high proportion of the dissolved constituents are obtained through interaction between the convecting fluid and the reservoir rocks (Ellis and Mahon, 1964; 1967). One general chemical model that appears to be representative of a number of systems has been proposed by Mahon et al. (1980). The following discussion follows theirs closely and refers to Figure 1. A high-temperature chloride water (A) develops at a relatively deep level in the system through interaction of (mainly) meteoric water with rocks close to the heat source. Rapid silicification of rocks occurs where this hot chloride water contacts cold rocks or cold meteoric water. The porosity and permeability of the silicified rocks are considerably reduced, which can effectively seal in the sodium chloride reservoir and prevent its expansion or appearance at the surface. However, steam and gas are able to move through the boundary and to interact with meteoric water above. The product of this

TABLE 2

CHEMICAL CHARACTERISTICS OF HIGH-TEMPERATURE HYDROTHERMAL CONVECTION SYSTEMS

	Salton Sea U.S.A.[1]	Cerro Prieto Mexico[2]	Meager Creek Canada[3]	Broadlands New Zealand[4]
Temp.	340°C	300°C	190°C	265°C
TDS[5]	259,000	16,500	4,500	2,700
pH	5.5	5.7	5.5	6.2
Cl[6]	155,000	9,370	1,740	1,233
Na	53,000	5,004	1,132	772
K	16,500	1,203	84	110
SiO_2		569	266	410
Ca	28,800	284	525	3.3
HCO_3	500	--	2,990	167
SO_4	30	3.6	117	31
Non-Condensable Gases (wt %)	.02-0.2	.3	0.2%	6.7%
CO_2[7]	90	93	99.2	99.7
H_2S[7]	10	7	.8	.3

[1] Helgeson (1968).

[2] Truesdell et al. (unpublished manuscript).

[3] Adams et al. (1985).

[4] Ellis and Mahon (1977).

[5] TDS = total dissolved solids calculated for reservoir (unflashed) composition.

[6] Concentration of aqueous ions in mg/kg, chemical charges are not shown. Analyses are recalculated to the reservoir composition and temperature.

[7] Mole percent of total gas.

interaction is a near-neutral pH sodium bicarbonate-sulfate water (B) that forms a hot, secondary geothermal reservoir. Extensive deposition of calcite, anhydrite, silica, pyrite, illite and montmorillonite occurs as the system develops, and may reduce rock porosity and permeability. Fumaroles may vent CO_2 and H_2S at the surface, which interact further with meteoric water to produce highly acidic waters that cause extensive acid alteration of near-surface rocks and forms such minerals as kaolinite, alunite and anhydrite. Although the bicarbonate-sulfate waters may constitute an exploitable resource, it is the deep chloride water that is the prime geothermal resource. In certain instances such as The Geysers, California, the fluid phase in the upper level rocks may be steam, and a vapor-dominated system results. Beneath such a steam reservoir is presumably a sodium-chloride water resource.

Regarding successful exploitation of hydrothermal systems, the key problem appears to be more in locating permeable zones than in locating high temperatures. Grindly and Browne (1975) state that of 11 hydrothermal fields investigated in New Zealand, all of which have high temperatures (230°C to 300°C), five are non productive chiefly because of low permeability. Three of the eleven fields are in production (Wairakei, Kawerau and Broadlands) and in each of these permeability limits production more than temperature does.

Permeability can be primary or secondary. Primary permeability in clastic rocks originates from intergranular porosity and it decreases with depth due to compaction and cementation. In volcanic sequences, primary intergranular porosity and permeability exists, but open spaces also exist at flow contacts, and within the flows themselves. Secondary permeability occurs in open fault zones, fractures and fracture intersections, contact zones such as those of later dikes, and can also be produced in breccia zones produced by hydraulic fracturing (Brace, 1968; Wadzicki and Weisburg, 1970). Changes in permeability come about through deposition of minerals in sealed zones or by leaching of minerals by the hot fluids. Although none of the geophysical methods maps permeability directly, any geological and geochemical understanding of the controls to permeability can be used to help determine geophysical methods potentially useful for detecting the boundaries and more permeable parts of the hydrothermal system.

GEOPHYSICAL METHODS FOR GEOTHERMAL EXPLORATION

The discussion in this section covers the application and principal problems encountered in using geophysical methods in hydrothermal exploration. Table 3 is a classification of geophysical methods and also shows the common geothermal targets for these methods. In what follows, the emphasis is on application of geophysics to exploration for hydrothermal convective resources.

Thermal Methods

A variety of thermal methods respond directly to high rock or fluid temperature, the most direct indication of a geothermal resource. Among these methods are measurements of thermal gradient and heat flow, shallow-temperature surveys, snow-melt photography and thermal-infrared imagery.

Conventional Thermal Gradient and Heat Flow.

Thermal gradient and heat flow surveys provide basic data about subsurface temperatures and some program of thermal gradient drilling is applied in most systematic geothermal exploration throughout the world. Drill holes must be deep enough to penetrate the near-surface hydrologic regime, which may be dominated by meteoric recharge with vertical and lateral flow of cold water. This requirement provides a basic limitation to the method. In high-rainfall areas, the near-surface hydrologic zone may exceed 1 km in thickness. The other major limitation on the acquisition of thermal gradient data is imposed by the drilling program. The main factor is drilling cost, but environmental restrictions, land control, permitting, and time involved are other considerations.

The interpretation of temperature, thermal gradient, and heat flow data and the evaluation of resource potential from these measurements can be quite complex, as discussed in detail by several authors (Sass et al., 1971; Chapman

TABLE 3

GEOPHYSICAL TARGETS IN GEOTHERMAL EXPLORATION

METHOD	TARGETS
SEISMIC	
Earth Noise	Active hydrothermal processes, distribution of velocity and attenuation.
Microearthquakes	Active faulting, fluid filled fracturing.
Teleseisms	Deep magma chamber.
Refraction	Structure, distribution of velocity and attenuation.
Reflection	Structure, distribution of velocity and attenuation.
GRAVITY	Structure, alteration, densification, intrusions, distribution of density.
MAGNETICS	Structure, hydrothermal alteration, intrusives, extrusives.
ELECTRICAL	
Resistivity	Faulting, brines, hydrothermal alteration.
Induced Polarization	Hydrothermal alteration.
CSEM & Scalar AMT	Faulting, brines, hydrothermal alteration.
MT/AMT	Structure, deep reservoir, magma chamber, partial melt in deep crust or upper mantle.
Self Potential	Fluid and heat flow.
Tellurics	Faulting, brines, hydrothermal alteration.
RADIOMETRIC	Alteration, ^{226}Radon, ^{222}Radium.
HEAT FLOW	Reservoir temperature.

and Pollack, 1977; Lachenbruch, 1978; Sass et al., 1981). Heat flow is often 5 to 500 times the regional average over hydrothermal systems. Smith (1983) showed that the Beowawe, Nevada geothermal area is characterized by a wide range of temperature gradient and thermal conductivity values (65-144°C/km, 1.59-5.95 $Wm^{-1}K^{-1}$) that combine to produce a nearly constant heat flow of 235 mWm^{-2} above a depth of 1600 m. At Roosevelt Hot Springs, Utah, the boundary of anomalous heat flow is considered to be the 100 mWm^{-2} contour, which encompasses an area of more than 175 km^2 (Fig. 2), while the 1000 mWm^{-2} contour encompasses an area of about 15 km^2 (Ward et al., 1978). A maximum value of about 9000 mWm^{-2} occurs over a band 2 km wide parallel to and including the Opal Mount fault. Integration of the heat flux indicates that an estimated 60 megawatts is being continuously supplied by the source at depth. This is obviously a fairly large geothermal system. For comparison, the small, noncommercial resource at Marysvale, Montana has a maximum surface heat flow of about 800 mWm^{-2} and the 100 mWm^{-2} contour encloses an area of about 30 km^2 (Blackwell and Morgan, 1976). At East Mesa, California, the 125 mWm^{-2} contour encloses an area of about 120 km^2 while the maximum heat flow value is somewhat over 300 mWm^{-2} (Swanberg, 1974). At Coso, California, Combs (1980) found that geothermal gradients in 25 holes from 23 to 400 m in depth ranged from 25.3°C/km to 906°C/km while heat flow values ranged from 67 mWm^{-2} to 964 mWm^{-2}. The area encompassed within the mWm^{-2} contour is about 150 km^2 (Fig. __).

Regarding interpretation of heat flow data, early authors recognized that terrain effects must be compensated and several have provided methods to do so (Birch, 1950; Blackwell et al., 1980). Continuation of heat flow data for the purpose of determining subsurface isotherms in geothermal areas has been discussed by Brott et al. (1981), who conclude that the depth and shape of the boundaries of the convection system can be determined by this analysis. A particularly important topic for geothermal exploration is the relationship of measured thermal gradient and heat flow with the local and regional hydrologic regime. Smith and Chapman (1983) give a review of previous work in this topic and report on numerical solutions of the equations of fluid flow and heat transport used to quantify the effects of groundwater flow on the subsurface hydrothermal regime. A great deal more work remains to be done in this topic.

Shallow Temperature Surveys. One relatively low-cost method to determine near-surface temperatures is a shallow-temperature survey. The use of such surveys has been limited apparently because of the uncertainty that the results are related to the temperature distribution at depth. Lovering and Goode (1963), Poley and Van Steveninck (1970), and Kappelmeyer and Haenel (1974) have discussed the perturbing effects. These effects are due to (1) diurnal solar heating variation, (2) annual solar heating variations, (3) aperiodic solar heating variations, (4) variations in surface albedo, which affects amount of energy absorbed, (5) variations in surface roughness, which affect amount of heat convected away due to turbulent flow of the wind, (6) variations of soil thermal diffusivity, (7) slope and exposure of the terrain, (8) variations in elevation, and (9) variations in level of groundwater and groundwater movement. Temperature variations from these effects are generally negligible below a depth of 20-30 m, with the exception of groundwater movement.

An early example of shallow temperature surveying at a geothermal area was presented by Kintzinger (1956) in his survey of hot ground near Lordsburg in New Mexico. Using thermistors emplaced at a depth of 1 m, he observed a temperature anomaly of some 10°C surrounding a hydrothermal area. Noble and Ojiambo (1975), emplacing thermistors at 1-m depth, helped delineate a geothermal area in Kenya. Lee and Cohen (1979) measured shallow, geothermal gradients at various sites at the Salton Sea, California, which ranged from 0.02°C/m to 4.3°C/m. Lachenbruch et al. (1976) provided a temperature map of the Long Valley area at a depth of 10 m. They concluded that as long as synoptic observations are used at the measuring sites, essentially the same temperature pattern emerges for contours at the 6-m depth, and much of it persists at 3 m. LeShack and Lewis (1983) gave a summary of applications of the technique to geothermal exploration along with case histories for Coso Hot Springs, California, Upsal Hogback, Nevada, and Animus Valley, New Mexico. In the absence of near-surface cold-water flow, a shallow temperature survey could form the basis on which to plan a shallow or intermediate-depth thermal-gradient program.

Snow-melt Photography and Thermal-Infrared Imagery. These temperature-sensitive methods have been used in reconnaissance geothermal exploration in some areas. Snow-melt photography has been used at Coso Hot Springs, California (Koenig et al., 1972) and Yellowstone National Park (White, 1969) to indicate surface areas of slightly elevated temperatures at low survey costs. Color aerial photographs of these areas were made hours to days after light to moderate snowfall. The thermally anomalous areas were visible because the snow melted faster over these areas than it did over non-thermal areas.

Airborne thermal infrared surveys have been used to map the occurrence of warm ground and hot springs in Kenya (Noble et al., 1976) and hot springs along the coastline of volcanic islands such as Hawaii (Fischer et al., 1966; Furumoto, 1976). In Kenya the IR survey confirmed several hot springs that were already known and located other areas of hot ground that were previously unknown. Later ground-truth surveys determined that over 90% of the areas indicated as anomalous on IR imagery had actual ground temperatures above ambient.

Dickinson (1975) gives an evaluation of the utility of the method at the Taubora geothermal field near Wairakei in New Zealand. Surveys were flown in the late afternoon and at dusk over areas of surface discharge features as well as over urbanization in the town of Taupo. The instrumentation used was sensitive in the band 4 to 5.5 μm. Thermograms were interpreted into three temperature ranges: $< 1°C$ above ambient temperature, 1° to 3°C above ambient temperature and $> 3°C$ above ambient. Inspection of areal photographs and field checking helped to eliminate the response of cultural features. Field checks consisted of a series of soil temperature measurements at depths ranging from 0.05 m to 1 m. Vegetation over thermally anomalous areas was also found to exhibit elevated temperatures, and so the presence of trees and scrub did not disturb the survey results. The resulting temperature anomaly map was used to indicate areas of thermal discharge and to estimate a total surface heat flow of 111 MW for the area surveyed.

Electrical Methods

Perhaps the most important physical property change due to the presence of a hydrothermal system, other than elevated temperature and heat flow, is the change in electrical resistivity of the rock-fluid volume (Moskowitz and Norton, 1977). Higher temperature increases ionic mobility up to about 300°C, and hence increases conductivity. Ionic conduction in rocks also increases with increasing porosity, increasing salinity, and increasing amounts of certain minerals such as clays and zeolites. Most hydrothermal systems have an associated zone of anomalously low resistivity due to one or more of these factors. At depths exceeding 5 to 15 km, mineral semiconduction dominates aqueous electrolytic conduction and partial melts and magma may become very conductive (Lebedev and Khitarov, 1964; Shankland and Waff, 1977; Rai and Manghnani, 1978). Although magma is conductive due to mineral semiconduction, the amount of contained water substantially affects the conductivity, dry magmas being much less conductive than wet ones. In geothermal exploration, it is possibly the wet magmas that we seek, because they have enough volatile content to produce the fracturing needed for hydrothermal convection.

Thermal brine and alteration may occur predominantly along faults, so electrical methods may map faults controlling a fractured reservoir. Alternatively, they may map a stratigraphic unit that contains thermal brines and/or alteration. By virtue of resistivity contrasts among rock units, each of these methods can map faults, stratigraphy, intrusions, and geologic structure in general, independent of the presence of brine or alteration. Hohmann and Ward (1981) have recently reviewed the applications of electrical methods in mining exploration, and many of the points made in this article apply also to geothermal exploration.

Galvanic Resistivity. The uses of the Schlumberger and Wenner arrays have been referenced in Hatherton et al. (1966), Zohdy et al. (1973), Arnorsson et al. (1975), Stanley et al. (1976), Tripp et al. (1978) and Razo et al. (1980). The Schlumberger array is the most convenient one for depth sounding, i.e. estimation of the thicknesses and resistivities of the layers of a horizontally layered earth (Palmason, 1975). Successful use of the head-on Schlumberger method has been reported by Lezana (1984), among others working in Iceland. A significant problem with the Schlumberger array, and with galvanic resistivity sounding techniques, in general, is the effect of lateral resistivity variations on the measurements. Many, if not most, geothermal areas are characterized by three-dimensional resistivity structure at the scale of the electrode separations required for soundings to 1 to 2 km. Although lateral resistivity variations can sometimes be recognized on secondary curves and correctly interpreted for using two- or three-dimensional modeling techniques, there is often not enough data to do this. One must be very careful when using sounding techniques in areas of complex structure.

The bipole-dipole array was first used in geothermal exploration by Risk et al. (1970) and subsequently studied by Beyer et al. (1975), Williams et al. (1975), Jiracek and Smith (1976), Stanley et al. (1976), and Souto (1978). Keller et al. (1977) used this method effectively in the reconnaissance exploration for geothermal resources on the East Rift Zone of Kilauea Volcano, Hawaii Island. The bipole-dipole array achieved early success over broad areas of resistivity lows caused by hydrothermal alteration, but it has subsequently fallen into disfavor because of its failure to produce distinctive anomalies over some geothermal systems (Dey and Morrison, 1977). Also, the reduced resistivity values are strongly dependent on the local resistivity distribution in the vicinity of the transmitting dipole (Frangos and Ward, 1980).

Dipole-dipole arrays were used in surveys reported by Beyer (1977), Fox (1978b), Ward et al. (1978), Baudu et al. (1980), Patella et al. (1980), Wilt et al. (1980), and Mackelprang (1982) among many others. This array is widely used in geothermal, mineral and petroleum exploration because it is an efficient means of collecting a large number of data points which are influenced by both the lateral position and depth characteristics of the resistivity distribution. Numerical modeling programs are widely available to determine the resistivity distribution and intrinsic resistivity values (Dey and Morrison, 1976; Rijo, 1977; Killpack and Hohmann, 1979). McNitt (1975) recognized the great advantage of the dipole-dipole technique in discriminating between vertical and horizontal resistivity boundaries and commented that resistivity surveys were by far the most effective of all the geophysical surveys used in the United Nations exploration programs between 1965 and 1975.

Induced Polarization. The induced polarization method is theoretically capable of mapping the distribution of pyrite and clays, common alteration products in convective hydrothermal systems. Ward and Sill (1984) recently reviewed the principals and measurement techniques for this method as applied to geothermal exploration. Few induced polarization measurements are reported for hydrothermal areas, and those we have examined show low-amplitude anomalies and no definite relationship to the hydrothermal system (Zohdy et al., 1973; Chu et al., 1983).

Controlled Source Electromagnetics (CSEM). Keller (1970) made a baseline review of the applications of active and passive electromagnetic methods in geothermal exploration. Subsequently, a number of articles have appeared which illustrate the success and failure of these methods. Included are the articles by Lumb and MacDonald (1970), Keller and Rapolla (1974), Morrison et al. (1978), Wilt et al. (1981), Goldstein et al. (1982), and Keller et al. (1982). These methods have been used as an alternative to resistivity methods in some geothermal environments. Time domain and pulse EM methods (TDEM) have been used in volcanic areas of high surface impedance such as Hawaii (Kauahikaua, 1981) where grounded resistivity surveys are slow and costly. Wilt et al. (1981) describe a high-power system developed primarily for geothermal exploration. The primary limitation to these methods is that interpretation techniques have been commonly available for only for the layered-earth, one-dimensional case. If the subsurface has a resistivity distribution that is two-dimensional or three-dimensional in nature, as it usually does in geothermal environments, interpretations using one-dimensional techniques can produce misleading results.

CSAMT is a subset of CSEM, and a subset of AMT, in which the transmitter is a grounded bipole. It is the only CSEM method that does not utilize a loop source. Two orthogonal, horizontal components of electric and magnetic field are measured (as in magnetotellurics). Samberg and Hohmann (1982) have evaluated its use in the Roosevelt Hot Springs, Utah geothermal system. It offers advantages over galvanic resistivity methods in that it is faster and suffers less from the effects of lateral resistivity variations when providing sounding information (Ward, 1983).

Scalar Audiomagnetotellurics (AMT). The AMT method utilizes either natural or artificial electromagnetic fields in the 10 Hz to 20 kHz band. Hoover and Long (1976), Hoover et al. (1978), Keller (1970), and Jackson and O'Donnell (1980), among others, have reported on its use in geothermal exploration. The method suffers from two particular problems. First, the natural fields occasionally are too weak to obtain useful information. Second, and far more important, the scalar data are totally inadequate for interpretation in two- and three-dimensional terrains, in which the tensor AMT method should be used. The CSAMT method is a substantial improvement over scalar AMT insofar as the direction of the inducing fields can be controlled, thus simplifying interpretation in two- and three-dimensional environments. In spite of the interpretational difficulties with scalar AMT data, the technique has been used to produce anomalies that apparently reflect low subsurface resistivity due to hydrothermal systems. An example at Coso Hot Springs, California, is given in a subsequent section.

Tensor Magnetotellurics and Audiofrequency Magnetotellurics (MT, AMT). Papers describing application of the tensor MT/AMT method in geothermal areas include Hermance et al. (1975), Stanley et al. (1977), Dupis et al.

(1980), Gamble et al. (1980), Musmann et al. (1980), Wannamaker et al. (1980), Berktold (1982), Martinez et al. (1982), Stanley (1981, 1982) and Wannamaker et al. (1983). A comprehensive review of data acquisition, processing, and interpretation for the method, plus a full discussion of the problems it encounters in geothermal exploration, has been prepared by Ward and Wannamaker (1983).

The tensor magnetotelluric/audiofrequency magnetotelluric method is usually too expensive to be used for mapping the resistivity distribution in the shallow parts of a geothermal system. Hence, it is more logically used to map regional structure, to map the deeper parts of convective hydrothermal systems, to attempt to map magma chambers, and to detect and delineate zones of partial melt in the deep crust and upper mantle (Ward and Wannamaker, 1983). MT has been used in most of the high-temperature resource exploration programs in the western United States. We attribute this to its advertised great depth of exploration and to a common assumption that it is able to detect the molten or partially molten source of heat. Neither of these attributes is necessarily correct. The conductivity of magma at elevated temperatures is strongly dependent upon the partial pressure of water (Lebedev and Khitarov, 1964) and so a dry partial melt will be more difficult to detect by MT than a wet partial melt. Only if a carefully performed two- or three-dimensional modeling of the data is used in interpreting the survey results may one predict accurately the distribution of resistivities in the subsurface. We attribute the rather poor success rate of MT to inadequate interpretation, poor data quality in some instances and misapplication of the method, as discussed by Ward (1983). Perhaps the most important application of MT in regional geothermal exploration will lie in detecting regions of partial melt in the deep crust or upper mantle (Wannamaker et al., 1980).

Self-potential. Spontaneous-potential anomalies over convective hydrothermal systems arise from the electrokinetic and thermoelectric effects, which couple the generation of natural voltages with the flow of fluids and the flow of heat, respectively (Sill, 1983). SP measurements in geothermal areas have shown anomalous regions associated with the near-surface thermal zones and faults thought to be fluid conduits (Zohdy et al., 1973; Corwin, 1975; Anderson and Johnson, 1976; Zablocki, 1976; Mabey et al., 1978; Corwin and Hoover, 1979). The signs of these anomalies have been both positive and negative. Pronounced SP anomalies, often dipolar in shape, have been documented for several geothermal systems which occur along basin and range faults in the western United States. Noise in self-potential surveys arises in telluric currents, electrode drift, topographic effects, variations in soil moisture, cultural noise, vegetation potentials, and electrokinetic potentials due to running surface water. Although SP surveys are relatively easy to perform, they are difficult to interpret in terms of the nature and location of the source. Sill (1983) has developed interpretation techniques that have potential for solving some of these problems.

Tellurics. The telluric method is mainly suitable for reconnaissance of horizontal resistivity variations. It is based on the assumption that telluric currents flowing in extensive sheets are affected by lateral variations in the resistivity structure, which can be caused, for example, by variations in geological structure or by hydrothermal systems. The method requires the simultaneous measurement of the telluric electric field at two stations. 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 the base station fixed and moving a field station about, one can thus map resistivity variations in a qualitative way

(Palmason, 1975).

The method has been used in geothermal exploration by Beyer (1977), Isherwood and Mabey (1978), Jackson and O'Donnell (1980), and others. It appears to be a convenient method for regional surveys in order to detect areas worthy of more detailed exploration by resistivity methods (Palmason, 1975). The method suffers from a number of problems which include random noise, geological noise due to overburden, lack of resolution, and effects of topography, but the worst problem is that it is a semi-quantitative method at best.

Gravity Method

Density contrasts among rock units permit use of the gravity method to map intrusions, faulting, deep valley fill, and geologic structure in general. Gravity surveys are used in the Basin and Range and similar settings as a relatively inexpensive means of obtaining structure and thickness of alluvium. Geothermal-related anomalies in the basins are most commonly residual gravity highs that are interpreted to reflect densification of porous sediments, structural highs, or anomalous geometry of fault zones (Isherwood and Mabey, 1978).

Gravity has proven to be highly useful in the location of positive anomalies due to densification of sediments and metamorphism in the Imperial Valley of California (Biehler, 1971). At the Broadlands field in New Zealand, the major cause of a positive gravity anomaly is attributed to an increase in density of rocks through alteration and deposition by ascending hot waters (Hochstein and Hunt, 1970). In other areas, gravity highs are expected due to rhyolite domes and hydrothermal alteration (Macdonald and Muffler, 1972). Association of negative gravity anomalies with acidic intrusion is well known to mixing geophysicists (Wright, 1981). Isherwood (1976) concluded that the large gravity low over the Mt. Hannah area at The Geysers field in California is most likely due to a hot silicic magma under this area. This interpretation has been supported by teleseismic studies as described below. Goldstein and Paulsson (1979), Berkman and Lange (1980), and Edquist (1981) found gravity particularly useful in mapping range-front normal faults in the Basin and Range province. Detailed gravity data have delineated major faults that probably control the geothermal fluid flow at Cove Fort-Sulphurdale, Utah (Ross et al., 1982).

Regional gravity studies and their interpretation may play a major role in understanding the tectonic framework of geothermal systems in the Cascade Range and in other similar volcanic environments. Bacon (1981) reports a contiguous zone of gravity lows west of the High Cascades in central Oregon and notes that these define major structural trends and delineate fault zones which may localize the movement of geothermal fluids. The zone of gravity lows coincides with (1) an abrupt east-to-west decrease in heat flow from High Cascades value of 100 to 40 mW/m^2, and (2) a substantial east-to-west increase in depth to the lower crustal conductor defined by magnetotelluric soundings. Couch et al. (1981) report similar interpretations. Williams and Finn (1982) report that large silicic volcanoes with calderas exceeding 10 km diameter produce gravity lows when proper densities of 2.15 to 2.35 g/cm^3 are used for the Bouguer reduction whereas other volcanoes produce gravity highs as a result of higher-density subvolcanic intrusive complexes.

Magnetic Method

Magnetic surveys, either airborne or ground, have been conducted at many geothermal prospects. Their use can be either for structural or lithologic mapping or for mapping decreases in the magnetization of rocks caused by hydrothermal alteration. Magnetic anomalies in New Zealand geothermal fields have been interpreted as being due to a conversion of magnetite to pyrite (Studt, 1964). A magnetic low occurs over a part of the hot spring area at Long Valley (Plouff and Isherwood, 1980), and is interpreted by Kane et al. (1976) as due to magnetite destruction. Such an effect would, of course, remain in extinct hydrothermal systems.

The locations of faults, fracture zones, intrusives, silicic domes and major alteration areas are apparent on data we have examined from the Coso Hot Springs KGRA in California, from Baltzaor, Tuscarora, McCoy, and Beowawe in Nevada, from Cove Fort-Sulphurdale and Roosevelt Hot Springs, in Utah. The Monroe Hot Springs, Chief Joseph, Cove Fort-Sulphurdale, and Roosevelt Hot Springs KGRAs are all located in close proximity to a major magnetic discontinuity which trends east-west for a distance exceeding 150 km. This trend reflects the northern margin of the Pioche-Beaver-Tushar mineral trend with many intrusive and volcanic rocks to the south, and thin volcanics overlying thick Paleozoic through Tertiary sediments and few intrusions to the north. The magnetic trend clearly indicates a major tectonic-geologic feature important to geothermal resource localization. Bacon (1981) interprets major structural trends and fault zones from aeromagnetic data in the Cascades. Magnetics are routinely used in Iceland to delineate dikes, some of which are bordered by zones of high permeability (Palmason, 1976; Flovenz and Georgeson, 1982).

Magnetic data can also be used to determine the depth to the Curie isotherm (Isherwood and Mabey, 1978; Bhattacharyya and Leu (1975); Shuey et al. (1977) and many others. These interpretations are dependent on many assumptions and have serious limitations. It is assumed that long-wavelength negative anomalies due to lithologic changes do not significantly perturb the interpretation, and that the decreasd magnetization of crustal rocks at depth is due to temperatures above the Curie point rather than to deep-seated lithologic changes. In addition, because the bottom of a magnetized prism is not accurately determined, accuracy of Curie-point depth can be poor.

Seismic Methods

Microseisms. Two methods have been proposed to utilize microseisms for delineating geothermal reservoirs. The first is based on the speculation that hydrothermal processes radiate seismic energy in the frequency band 1 to 100 Hz. If this phenomenon exists, the exploration method becomes a rather straightforward "listening" survey, using stations on a 0.5- to 2-km grid. Contours of noise power on the surface should delineate noise sources. This is the standard noise survey used widely in geothermal exploration. Noise in the 1 to 10 Hz band sometimes arises in nearby cultural sources such as traffic, trains, rivers, wind, etc. It is also known that seismic noise amplitudes are usually higher over alluvium and soft sedimentary basins than over hard rock. Thus, noise power anomalies may merely reflect a local increase in sediment cover. Ground noise surveys have yielded high levels of noise over Taupo, New Zealand (Clacy, 1968), The Geysers (Lange and Westphal, 1969), and in the Imperial Valley (Douze and Sorrells, 1972).

A second approach intpreted the noise field as propagating elastic waves of appropriate type and uses the propagation characteristics to make inferences about the source. Iyer and Hitchcock (1976) postulated that seismic waves radiating from a hydrothermal source a few kilometers deep may propagate as body waves and thus can, in principle, be distinguished from cultural microseisms, which generally propagate as surface waves. Seismic arrays can determine the phase velocity of microseisms and can thus distinguish body waves emanating from deep sources and exhibiting high phase velocities (typically exceeding 3 km/sec) from surface waves. There is limited evidence that body waves do exist in association with geothermal occurrences.

Liaw and Suyenaga (1982) detected high-velocity body waves at Beowawe, but did not detect body waves at Roosevelt Hot Springs. Liaw and McEvilly (1979) failed to find body waves at Leach Hot Springs, Nevada, but did find microseismic energy propagating as fundamental mode Rayleigh waves from the vicinity of the thermal manifestations. Their paper, additionally, presents the foundations for proper survey design, and data analysis. Oppenheimer and Iyer (1980), using appropriate techniques, found microseisms at two recording sites near Norris Geyser basin, Yellowstone National Park that were propagating from near-surface sources in the geyser basin as both surface and body waves in the frequency range 1.4 to 6.3 Hz. The low phase velocities, 1.0 to 4.0 km/sec, appear to preclude body waves originating from deep hydrothermal sources in the basin. It is apparent that careful data collection and analysis must be done to produce valid results using microseismic techniques.

Microearthquakes. Microearthquakes frequently are closely related spatially to major geothermal systems. Accurate locations of these earthquakes can provide data on the locations of active faults that may channel hot water toward the surface (Ward et al., 1969; Lange and Westphal, 1969; Hamilton and Muffler, 1972). Microearthquake surveys have been completed in several geothermal areas including East Mesa (Combs and Hadly, 1977), Coso (Combs and Rotstein, 1976), and Wairakei (Hunt and Lattan, 1982).

P- and S-wave velocities may be retrievable from microearthquake data. Gupta et al. (1982) used microearthquake data to obtain regional P- and S-wave velocities for The Geysers. Ideally, detailed velocity models, obtained from refraction surveys, are used to control the hypocenter determinations of the microearthquakes. Majer and McEvilly (1979) report locally high P-wave velocities in the production zone at The Geysers as determined from refraction surveys.

Measurement of either the absorption coefficient or a differential attenuation number called "Q" may reveal the presence of exceptionally lossy materials in a reservoir due to fluid-filled fractures, or it may reveal the presence of low-loss materials due to steam-filled fractures or to silica- or carbonate-filled fractures. Majer and McEvilly (1979) found a shallow, high Q in the production zone at The Geysers from refraction and microearthquake surveys while they found a deeper, lower Q from the refraction survey. Majer (1978) reported that a refraction survey yielded high Q at Leach Hot Spring due to silica densification of sediments. Gertson and Smith (1979) found high Q over the geothermal system at Roosevelt Hot Springs, using refraction data.

Nur and Simmons (1969) observed, experimentally, that fluid saturation in rocks leads to high values of Poisson's ratio ($\sigma \geq 0.25$) while dry rocks exhibit low values of Poisson's ratio ($\sigma < 0.20$) . The ratio, K, of P-wave to S-wave velocity may be estimated using a Wadati diagram in which S-P arrival times are plotted versus the P-wave arrival time at many different stations for a single event. From such a plot, a value for Poisson's ratio may be found. Thus, determination of Poisson's ratio in MEQ surveys can conceivably result in determining whether a geothermal reservoir is vapor or water dominated. Majer and McEvilly (1979) and Gupta et al. (1982) noted Poisson's ratios of 0.13 to 0.16 over the production zone at The Geysers, California, and values 0.25 and higher outside of it. The low Poisson's ratio in part corresponds to a decrease in P-wave velocity.

For any of the above analyses of microearthquake data, a good model of the subsurface velocity distribution is required. Lack of good velocity control is a principal problem in analysis of MEQ data. Some geothermal systems, such as Roosevelt Hot Springs, have a generally low, episodic occurrence of microearthquakes (Zandt et al., 1982). Swarms of earthquakes occur, but in the intervals between them, insufficient activity may preclude any of the foregoing analyses. Indeed, one can record passive seismic data for a two- or three-week period or longer and erroneously conclude that the geothermal system is unimportant since it is not seismically active during the time of recording.

Teleseisms. If a sufficiently distant earthquake is observed with a closely spaced array of seismographs, changes in P-wave travel-time from station to station can be taken to be due to velocity variations near the array. A magma chamber beneath the geothermal system would give rise to low P-wave velocities and hence to late observed travel times (Iyer et al., 1979; Reasenberg et al., 1980; Robinson and Iyer, 1981).

Steeples and Iyer (1976b) found relative P-wave delays of 0.3 sec at stations in the west central part of the Long Valley caldera. Reasenberg et al. (1980) recorded relative P-wave delays of 0.2 sec at Coso. Iyer et al. (1979) found relative P-wave delays as large as 0.9 sec at The Geysers. Robinson and Iyer (1981) reported relative P-wave delays up to 0.3 sec at Roosevelt Hot Springs. While one can speculate that relative P-wave delays are caused by partial melts or magmas, as may be the case at Coso, Long Valley, and The Geysers, they can also be caused by alluvium, alteration, compositional differences, lateral variations in temperature or locally fractured rock (Iyer and Stewart, 1977). Wechsler and Smith (1979) suggest that the P-wave delays found by Robinson and Iyer (1981) at Roosevelt Hot Springs may well be due to fluid-filled fractures or to a compositional change.

Refraction. The seismic refraction and reflection methods can be used to map the depth to the water table, stratigraphy, faulting, intrusions, and geologic structure in general. They may also yield the subsurface distribution of seismic P-wave and S-wave velocities, attenuations and Poisson's ratio. Detection of a characteristic attenuation or a "bright" spot, as found over reservoirs in petroleum exploration, would be a useful feature (Ward, R.W. et al., 1979; Applegate et al., 1981), but this has not been reported.

The seismic refraction method has been used mainly as a geophysical reconnaissance method for mapping velocity distributions and, hence, faults, fracture zones, stratigraphy, and intrusions (Williams et al., 1975; Hill, 1976; Combs and Jarzabek, 1977; Majer, 1978; Ackerman, 1979; Gertson and Smith, 1979). Hill et al. (1972) recently reported on a 270-km profile from Mount Hood to Crater Lake in the Cascades and presented reuslts in terms of crustal velocity structure. These data contribute to a better understanding of regional geology and are indirectly used in geothermal exploration.

The seismic refraction method does not give resolution of structure as well as does the seismic reflection method. Sentiment today calls for performing seismic refraction at the same time as seismic reflection, with little added cost. Some attempts have been made to map velocity and amplitude attenuation anomalies, of both P- and S-waves, coinciding with a geothermal system (Goldstein et al., 1978b). Beyer et al. (1976), Combs and Jarzabek (1977), Majer (1978), and Gertson and Smith (1979) found anomalous velocities and amplitudes of refracted waves passing through the reservoir region.

Reflection. The seismic reflection method provides better resolution of horizontal or shallow-dipping layered structures than any other method and, hence, is invaluable in mapping stratigraphic geothermal reservoirs of the Imperial Valley type. However, where the structure becomes highly faulted or folded, diffraction of seismic waves occurs at sharp corners and makes the task of interpreting structure difficult.

Conventional [reflection] seismic surveys appear to give good definition of Basin and Range border faulting and depths to the base of alluvial fill at Roosevelt Hot Springs, UT, Soda Lake, NV, San Emidio, NV and Grass Valley, NV. One seismic line which crosses the Mineral Mountains at Roosevelt Hot Springs shows little obvious lithologic or structural information within the range itself, or within the reservoir, but substantial structural information along the range front (Ward et al., 1981). At Beowawe, extensive and varied digital processing was ineffective in eliminating the ringing due to a complex near-surface intercalated volcanic-sediment section. Majer (1978) found reflection data extremely useful in delineating structure in Grass Valley, NV. At Soda Lake, in 1977, Chevron obtained modern, 1200% CDP seismic reflection coverage (12 line miles, 48 channel, explosion). The seismic data yielded a complex NE-SW trending graben from the shore of Soda Lake passing south of Upsal Hogback. The reflectors dip to the southwest, consistent with a small basin over the gravity low. The maximum depths of reliable seismic data are governed by a thin basalt unit and vary from 2,400-4,000 ft (Swift, 1979).

Zoback (1983) has nicely demonstrated the use of seismic reflection data in mapping the style of initial faulting, infill and subsequent slumping and faulting in some basins in the province. Denlinger and Kovach (1981) showed that seismic-reflection techniques applied to the steam system at Castle Rock Springs (The Geysers area) was potentially useful for detecting fracture systems within the steam reservoir, as well as for obtaining other structural-stratigraphic information. Beyer et al. (1976) reported on the value of seismic-reflection profiling for mapping concealed normal faults associated with the Leach Hot Springs geothermal system, Grass Valley, Nevada. Blakeslee

(1984) processed seismic-reflection data obtained by the Comisiòn Federal de Electricidad over the Cerro Prieto geothermal field, was able to define subtle fault features and other important velocity features related to hydrothermal effects.

Radiometric Methods

Gamma-ray spectrometry may be used to map the areal distributions of ^{40}K, ^{238}U, and ^{232}Th. If ^{226}Rn or ^{222}Ra are present in a geothermal system, they will be detected in the ^{214}Bi peak, since they also are daughter products of ^{238}U decay. An examination of hot-spring waters in Nevada indicates the presence of ^{226}Rn and ^{222}Ra, in varying abundances, in spring systems where $CaCO_3$ is the predominant material being deposited. Systems where silica predominates are relatively low in radioactivity (Wollenburg, 1975). The use of alpha-cup detectors for radon emanating from hydrothermal systems has been reported by Wollenburg (1975) and Nielson (1978). Surface randon emission surveys appear to be capable of detecting open channels that may conduct geothermal fluids.

Geophysical Well Logging

Much research remains to be done in order to understand fully the responses of various well logs in geothermal reservoirs and their typically fractured, altered, commonly igneous and metamorphic host rocks. In spite of the relative lack of knowledge of well log response in geothermal reservoirs, several logs or log combinations have been used successfully to investigate such properties as lithology, alteration, fracturing, density, porosity, fluid flow and sulfide content, all of which may be critical in deciding how and in what intervals to complete, case, cement or stimulate the well.

Many of the logging techniques used by petroleum and mining industries have been adopted or modified for use in geothermal exploration and development programs. The major differences in usage are the requirements of high temperature tools and the different interpretation required for hard rock (volcanic, igneous) lithologies. Other differences include a strong emphasis on fracture identification and the effects of hydrothermal alteration upon certain log responses. Several papers have discussed these items (Glenn et al., 1981). The interpretation of well log suites from various geothermal areas are numerous (Glenn and Hulen, 1979; Glenn and Ross, 1982; Huffman, 1982).

Borehole Geophysics

The class of techniques which we call borehole geophysics require a combination of surface and in-hole sources and/or receivers or sources and receivers in separate boreholes.

VSP. The least experimental of the borehole geophysical techniques is vertical seismic profiling (VSP) using both P- and S-wave surface sources (usually mechanical vibrators) arranged circumferentially around the well. Direct and reflected waves are detected by means of strings of down-hole geophones clamped to the well wall or hydrophones. VSP has been used mainly to trace seismic events observed at surface to their point of origin in the earth and to obtain better estimates for the acoustic properties of a stratigraphic sequence (Balch et al., 1982). Gal'perin (1973) presented a review of VSP research in the USSR including recent results of three-component VSP (P- and S-wave sources with 3-component detectors) to estimate compressional-shear velocity ratios and Poisson's ratio. An S-wave shadow zone was detected following one hydrofrac operation at 2300 feet (Fehler et al., 1982). On the basis of data from three shot points, a finite-difference model showed that the shadow data fitted other information about the hydrofac. However, due to the low frequency S-wave source and the long wavelength of the S-wave (200 feet) in the medium, it is apparent that the fractured region must have large dimensions (a few wavelengths) for this shadow effect to occur. There has been some interest in developing methodologies to derive fracture permeability information from the tube waves (Paillet, 1980). Crampin (1978 and 1984) and others have argued that VSP conducted with 3-component geophones might prove extremely useful for mapping the fractured conditions of rocks if one were to extract seismic anisotropy information from the shear-wave splitting effect.

Electrical Techniques. Surface-to-borehole EM in which a large transmitter is coaxial with the well and a downhole detector is run in the well may provide useful information on the location of conductive fractures intersecting the wellbore. Whether this technique will work in cased wells and whether a "crack" anomaly can be distinguished from a stratigraphic conductor are topics under study.

Borehole-to-borehole and borehole-to-surface resistivity methods also appear to be applicable to geothermal exploration. Yang and Ward (1985) presented theoretical results relating to detection of thin oblate spheroids and ellipsoids of arbitrary attitude. The theoretical model results indicate that cross-borehole resistivity measurements are a more effective technique than single-borehole measurements for delineating resistivity anomalies in the vicinity of a borehole.

Beasley and Ward (1985) obtained the representative results in their mise-à-la-masse studies. The dip of the body and the location of the energizing electrode within it were both varied. The maximum depth at which a body can be located and still produce a detectable surface anomaly is dependent upon the position of the buried electrode and upon the contrast in resistivity between the body and the host. It was found that locating the buried electrode just outside the body does not significantly alter the results from those when the electrode is embedded in the inhomogeneity.

From the above studies we tentatively conclude the following: the cross-borehole method produces larger anomalies than does a single-borehole method; the cross-borehole anomalies using a pole-pole array are smaller than those for a cross-borehole dipole-dipole array; the cross-borehole mise-à-la-masse method produces larger anomalies than for the other cross-borehole methods, and the anomalies due to a thin sheet were generally much smaller than those for a sphere as is to be expected (e.g. Dobecki, 1980).

ANALYSIS OF WORLDWIDE APPLICATION

In conjunction with on-going research work, we have conducted a computer-aided bibliographic search of worldwide applications of geophysics in geothermal exploration and development using the GEOREF data base. A total of 554 references was selected, and these were supplemented by approximately 200 additional references obtained through specific literature search. A total of 47 countries or regions and 88 geothermal resource areas are represented. Geothermal exploration in the USA comprised 59 percent of the reference list, introducing significant bias in the data set. Italy is next with 5 percent, and five other countries, the USSR, Japan, Mexico, Iceland and New Zealand, each provide somewhat less than 5 percent. References for these seven countries comprise 80 percent of the list.

Considering all resource areas and temperatures, ten methods saw significant utilization: galvanic resistivity sounding or VES (59%), gravimetric (52%), temperature gradient (50%), heat flow (48%), magnetic (39%), MT (35%), dipole-dipole resistivity (33%), reflection seismology (33%), MEQ (32%), remote sensing (28%), and bipole-dipole resistivity (26%). The least used methods include CSAMT, IP, pole-dipole, resistivity, earth noise, and geomagnetic soundings. The greatest utilization of geophysics is in exploration for moderate- and high-temperature resources. An average of 6 different geophysical methods were utilized in each of the 88 resource areas. On the basis of geologic setting, the results can be summarized as given in Table 4.

One obvious criticism of this compilation is that the level of use of a method does not necessarily indicate its value as an exploration tool. Too often a technique that has been successfully employed in one environment is tried in other geologic settings for which it is not appropriate. Ward (1983)

TABLE 4

UTILIZATION OF GEOPHYSICAL METHODS IN GEOTHERMAL EXPLORATION

rift valley: significant - VES method
moderate - MEQ, gravimetric, magnetic, MT, dipole-dipole, bipole-dipole and heat flow and TG methods

basin and range: significant and moderate - all of the methods with the exception of geomagnetic soundings, CSAMT, HEP, SP and BG (borehole geophysical) methods

intrusive: significant - gravimetric, magnetic, VES, and temperature gradient methods
moderate - reflection seismology, AMT, MT, dipole-dipole and heat flow methods

extensive: significant - gravimetric and VES methods
moderate - MEQ, reflection seismology, magnetic MT, dipole-dipole, bipole-dipole, SP, heat flow, TG, and remote sensing methods

basin: significant - gravimetric, VES, heat flow and TG methods
moderate - reflection seismology, MT and telluric methods

provides an excellent evaluation of the geophysical methods in the exploration of geothermal resources in the Basin and Range Province of the western US. He evaluated 14 methods in 13 high temperature sites (including Long Valley, Coso Hot Springs, Roosevelt Hot Springs and Raft River) and concluded that: a) none of the various geophysical methods were uniformly consistent in performance; b) none of the methods could be ranked in the "good" category and only five methods were ranked in the good-to-fair category (MEQ, gravimetric, electrical resistivity, SP and heat flow/TG); c) the least effective methods were earth noise, magnetic and MT; and d) no combination of any four methods was ranked as "good to fair" in success at more than one site.

STATE OF THE ART

In this section we give a brief evaluation of the state of the art in application of geophysics to exploration for and within moderate- and high-temperature geothermal systems. Many of these comments are summarized in Table 5.

Thermal Methods

Instrumentation for measuring thermal conductivity seems to be basically adequate, although a better understanding of the variation of this parameter with temperature, pressure, porosity and the effects of hydrothermal alteration is needed. Instrumentation for precise measuring of temperature downhole is adequate for temperatures below about 250°C, but above this temperature several components of usual borehole systems begin to fail in the corrosive hydrothermal environment. Logging equipment rated for higher temperature is needed for study of the higher temperature parts of hydrothermal systems. Referring to interpretation techniques, it seems to us that continued work on the understanding of regional and local hydrologic effects on temperature measurements is needed in order to understand observed thermal gradient and heat flow patterns. Continued development of two- and three-dimensional algorithms to model complex geologic situations including uplift, deposition, erosion, faulting, extension, and intrusion is also needed.

We believe that available equipment and interpretation techniques for shallow temperature surveys are adequate and that experience reported in the literature is sufficient to facilitate decisions on whether or not to apply this technique in specific exploration problems. The thermal IR technique has seen only limited use in hydrothermal exploration, and this will continue to

TABLE 5

STATE OF THE ART IN GEOPHYSICAL METHODS

METHOD	INSTRUMENTATION	INTERPRETATION	EXPERIENCE
Thermal Methods			
Heat Flow/Gradient	Need temp logging for T > 225°C	Needs models for hydrologic effects	
Shallow Temperature	Adequate	Adequate	Adequate
Thermal IR			
Electrical Methods			
Resistivity/IP	Adequate	Need broader use of 2-D, 3-D techniques available	Adequate
CSEM	Need portable equipment	Need 2-D, 3-D interpretation techniques	Need better evaluation
Scalar AMT	Adequate	Adequate	Adequate
Tensor MT/AMT	Need portable equipment	Need broader use 2-D, 3-D techniques available	Need better evaluation
SP	Adequate	Need better interpretation techniques	Need better evaluation
Telluric Current	Adequate	Adequate	Adequate
Gravity Method	Adequate	Adequate	Adequate
Magnetic Method	Adequate	Adequate	Adequate
Seismic Methods			
Microseisms	Adequate	Need continued development of techniques	Need better evaluation
Microearthquakes	Adequate	Less expensive equipment	Need more experience w/ high precision surveys
Teleseisms	Adequate	Adequate	Adequate
Refraction	Adequate	Adequate	Adequate

TABLE 5 (cont.)

METHOD	INSTRUMENTATION	INTERPRETATION	EXPERIENCE
Reflection	Need portable high resolution equipment	Need continued development	Need better evaluation
Radioactive Method	Adequate	Adequate	Adequate
Well Logging	Need logging tools for T > 225°C	Need interpretation in hard-rock environ.	
Borehole Geophysics			
VSP	Adequate	Adequate	Need evaluation
Electrical	Need equipment	Need to develop techniques	Need to acquire experience
Seismic Geotomag	Need equipment	Need to develop techniques	Need experience
Electrical Geotomag	Need equipment	Need to develop techniques	Need experience

be the case as exploration proceeds toward increasing search for concealed resources.

Electrical Methods

There is no wholly satisfactory electrical method for exploration for concealed resources in rugged volcanic terrains. Galvanic resistivity surveys, while relatively easy to run and for which interpretation methods are reasonably well worked out, lack depth penetration. Scalar AMT, which is easy to run and for which highly portable equipment is available, does not provide enough data to resolve the subsurface resistivity structure adequately. The MT method is able to resolve complex structure better, but uses very sophisticated, marginally portable equipment and requires a highly trained crew and complex, sophisticated interpretation. The CSEM methods are relatively easy to run but equipment is only marginally portable and adequate two- and three-dimensional interpretation is only now becoming available. SP surveys are easy and cheap but interpretation is difficult and ambiguous. In view of the relevance of electrical methods to geothermal exploration, development of electrical equipment and techniques specifically for the geothermal environment would seem like a wise research investment.

Resistivity methods appear to be adequately developed. Two-dimensional and three-dimensional interpretation algorithms are available but are still not in universal use. CSEM methods have a great deal of potential to contribute much more to hydrothermal exploration than they have so far. There is need for development of state of the art portable equipment and for continued development of two-dimensional and three-dimensional interpretation techniques. These geophysical techniques also need further field evaluation. Much of the data collected in the past has been interpreted using layered-earth models, and we consider these to be inadequate in most geothermal environments. The scalar AMT technique is well enough developed and tested that we can conclude that it has only limited use in geothermal exploration. Tensor MT and AMT are still classed as largely untested techniques. Adequate equipment has not been available for very long, and many of the first geothermal applications suffered from poor data quality. In addition, the majority of the interpretation has been done using layered-earth models, which are, as we have stated before, totally inadequate for the geothermal environment, especially when the scale of the measurement is considered.

The spontaneous-potential method has long suffered from lack of interpretation techniques to facilitate the level of information needed in order to make a decision about whether or not to drill test an anomaly. Provided that the technique can be understood better, more field evaluation might be warranted. We consider the telluric current method to have limited application because of its semi-quantitative naure and to be adequately developed and understood.

Gravity and Magnetic Methods

These methods both seem to be well enough developed for routine application to geothermal exploration problems. Advances in instrumentation and interpretation will continue to be made and will be adapted as appropriate for geothermal use.

Seismic Methods

The microseismic methods lack adequate field testing, largely because of the poor level of understanding of survey design and data analyses prior to about five years ago. Continued work on data processing and interpretation as well as further testing in geothermal environments appears to be warranted.

Microearthquake surveys have potential to contribute to defining drill targets in hydrothermal systems. Less expensive equipment is needed for field deployment for sufficient times to mitigate to some extent the episodic nature of the phenomenon. Equipment, interpretation and field testing of the teleseismic and refraction techniques are deemed to be adequate for routine application where appropriate, although we recognize that advances will continue to be made.

The seismic reflection method has potential for greater contributions to geothermal work than it has made to date. The method will always be expensive per unit of coverage, but if information derived could be increased, adequate payout may result. Portable, high resolution gear is needed for shallow reflection work in the hard rock environment. Better techniques of data acquisition and processing are needed for use in volcanic terrains. Interpretation of steep structures and supression of diffraction effects are needed in the geothermal environment. Much of the required research and development will probably be provided by the petroleum industry, as it has in the past.

Radioactive Method

It is unlikely that conventional radioactive methods will play a significant role in geothermal exploration. We deem them to be adequately developed.

Well Logging

There are significant needs for both new equipment development and for new interpretation techniques in well logging, and these needs have been summarized in Sanyal et al. (1980) and Lawrence Berkeley Laboratory (1984). The main instrumentation problem is lack of downhole tools for logging in slim holes at geothermal temperatures. Most tools are limited to temperatures below 175°C to 200°C, although a few have capability to 260°C. Neither tools nor cable exist for temperatures above 300°C. This lack of high-temperature downhole instrumentation seriously compromises the quantity of data that can be obtained in many of the hydrothermal systems currently under production or development, and will also compromise information on some of the deep research drill holes currently being planned under the Continental Scientific Drilling Program. Regarding interpretation, few of the available tools are calibrated for the hard-rock environment, and interpretation techniques remain to be worked out for many of the measurements.

Borehole Geophysics

As a general statement, borehole geophysics has not undergone the development required even to assess its potential contribution to geothermal development. The VSP techniques have begun to emerge as being important in petroleum exploration, and development for these purposes will have important spin-off for geothermal application. Electrical borehole techniques have neither been developed nor seriously applied, although some numerical modeling capability exists to assess their contribution. Seismic geotomography is in the research and development stage, and its analog electrical geotomography has received virtually no effort. We believe that the borehole techniques are fertile ground for research and development.

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