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Exploration Methods for Hot Dry Rock

Report of the Panel Held June 22, 1976

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EXPLORATION METHODS FOR HOT DRY ROCK

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ABSTRACT

The geological and geophysical characteristics of hot dry rock (HDR) necessary for an effective exploration program were discussed June 22, 1976, by 12 members of the Panel on Exploration Methods for Hot Dry Rock. The type of HDR project discussed, that being developed by the Los Alamos Scientific Laboratory (LASL), would utilize hydraulic fracturing to develop a large surface area in rock of low permeability, 10^{-6} darcys, and at temperatures greater than 200°C. Rock that satisfies these conditions is widely distributed at appreciable depths and is also found at shallow depths of 2-5 km in areas of thermal enhancement. The environments characteristic of HDR are generally understood; however, a better definition of the thermal regime in the crust and mantle at reconnaissance (hundreds to tens of kilometers) and exploration (tens of kilometers to 1 km) scales is needed.

Geophysical methods capable of deep investigation would be used with the near-surface geologic information to extrapolate conditions at the depth of interest. Detection of HDR per se may be difficult because the contrast in physical properties of HDR and other rock is not always unambiguous, but boundaries between rock environments can be delineated. When patterns and coincidence of various types of geophysical anomalies and geologic maps are used, the probability of the detection of HDR is greatly increased, especially when a consistent picture is described.

Various geophysical methods are required to detect these anomalies:

(a) electromagnetic techniques can map deep electrically conductive structures, which to some extent can be used to infer isotherms.

(b) Bouguer gravity maps corrected for regional topography are found to correlate with large silicic intrusive bodies, which are often associated with high heat flow.

(c) isotherms and open crack systems at depth can be inferred from seismic wave attenuations, dispersions, and delay times.

(d) heat flow measurements are useful as a primary tool and as a check on the results of other methods.

The individual panel members presented their views and made specific recommendations of needed effort in laboratory, office, and field studies.

I. INTRODUCTION

Exploration for hot dry rock (HDR) as a potential geothermal energy resource presents some novel problems and unusual contradictions not often found in exploration for other natural resources. These problems became apparent at a meeting on Exploration Methods for Hot Dry Rock held June 22, 1976 at the Los Alamos Scientific Laboratory (LASL).

The concept of hot dry rock as an energy resource is based on the thesis that low-permeability rock at a practical drilling depth can be found under large areas of the world. Due to low permeability (of the order of a microdarcy), a hole drilled into hot (greater than 200°C) crystalline basement rock would not produce fluid and thus would be commonly termed "dry," although the rock might be completely water saturated. In a concept being tested by LASL to develop the HDR resource, two deep holes are drilled and connected by a hydraulic fracture. To obtain the large surface area necessary for effective heat transfer, oil field hydraulic fracturing techniques are used to create a large crack.

Hot dry rock is a product of fundamental geologic processes that emplace heat on regional and global scales, for instance, plate tectonics, orogeny, and thermal plumes in the mantle. Regions in which geologic processes have enhanced thermal regimes often coincide with ore districts, volcanism, seismicity, and mountain belts.[1] These associations imply genetic relationships among these manifestations that probably continue to great depths. Hence, understanding of these relationships may provide for a more organized and efficient method of exploring for geothermal resources. As a background to the LASL proposal of geothermal development of hot dry rock, a search of the literature indicated that a low-permeability or dry environment was typical of crystalline basement rock.

A review of these conclusions by an appropriate group of geoscientists appeared to be in order and timely. Support for such a review was received from the Division of Physical Research of the Energy Research and Development Administration (ERDA), and the panel meeting "Exploration Methods for Hot Dry Rock" was held. A list of members is included as Appendix A.

Before the meeting, a summary of the literature addressing the questions: "Is hot dry rock commonplace, and is it feasible to explore for hot dry rock?" was sent to panel members for a critical review. Panel members were asked for their views on the questions, and their comments appear in Appendix B.

The panel meeting began with a discussion of the probable occurrence of hot dry rock. Presentations of the panel members' views followed. The meeting closed with a discussion of possible exploration strategies and a request for an informal written summary of thoughts on hot dry rock exploration. This report is a synthesis of the LASL preliminary summary of the literature and of written comments and informal oral comments of panel members.

II. THE OCCURRENCE OF HOT DRY ROCK: EXOTIC OR COMMONPLACE

Knowledge of the "dryness" or the hydrology of crystalline basement rocks is limited for various reasons and is mainly derived indirectly by geophysical methods. Most of the direct knowledge derives from mining operations with a small part coming from oil ventures.[2] The water produced in mines is generally associated with fracture zones,[3,4] but it is not uncommon for mines, even deep ones, to be dry.[5,6] The relative specific production capacity of most water wells drilled into crystalline rock is low and decreases appreciably with increased depth.[7,8] For instance, studies connected with the Rocky Mountain Arsenal disposal well indicate a logarithmic decrease with depth.[9]

Geophysical information also indicates that crystalline basement rock is usually of low permeability. Geophysical data such as the normal increase of resistivity encountered with increased depth of investigation of electrical soundings[10-12] strongly imply a decrease in the amount of interstitial water present in the first few kilometers[13,14] and are compatible with the observation that increased lithostatic pressure tends to reduce the porosity and to close open cracks.[15] Some consideration has been given to the possible absence of fractures at great depth.[16,17] Increase of seismic velocity [18,19] in the first few kilometers of depth can also be explained by a decrease in porosity and open cracks.[20] The postulated exponential decrease of radioactivity[21,22] with depth can be explained by a similar decrease in the permeability necessary for aqueous deposition of radioactive elements. Maps of heat flow can be interpreted that the principal mechanism of heat transfer in the crust is conduction, again implying low permeability. However, the areas of high heat flow (greater than 5×10^{-6} cal/cm^{2}s) probably indicate convective transport,which requires a permeable media.

Cores of crystalline rock from the 3-km-deep holes of the LASL hot dry rock project do not exhibit an obvious decrease in fracture frequency with depth; however, they show fracture healing does increase with depth.[23] That these healed fractures have not been reopened apparently reflects the low seismic activity of the area. Geophysical logs for these holes indicate an apparent decrease of major fracture zones with depth. Permeabilities measured in the competent sections of the holes are on the order of microdarcys, and of millidarcys in the major fracture zones.

In general, crystalline rock at appreciable depth is probably commonplace, of low permeability (microdarcys), and in terms of total water can be considered dry even though the sparse crack structure is completely saturated. Areas with permeable crystalline rock at depth are by comparison exotic and are usually associated with recent volcanism,[24] earthquakes, or recent faulting.

III. HOW CAN HOT DRY ROCK BE CHARACTERIZED FOR USE IN EXPLORATION?

A. Geologically

The tectonic history of an area influences or controls local hydraulic permeability and heat flow. Elevated stress levels or cyclical stresses[25] tend to develop cracks and increase permeability.[26,27] Further, the heat flow in a region has been shown to be correlative with the age of tectonism.[28] This may imply that heat-generating elements were emplaced in the fracture permeability generated at the time of the tectonism. In young tectonic areas much of the heat is introduced by convective transport, hydraulic and volcanic. Most active geothermal areas are in an environment of present tectonic activity, in part because the permeability necessary to maintain convective heat transport is continually rejuvenated by tectonic stresses.[29] Undisturbed convective systems tend to self-seal with hydrothermal alteration products and thus have limited lifetimes.[30]

The *in situ* stress level and its orientation are of particular interest wherever the LASL hot dry rock development technique is used because hydraulic fracturing is the method for developing effective heat transfer area. The orientation of a hydraulic fracture will be dominated by the existing stress field in the rock, hence the *in situ* stress and its orientation are of basic interest to the LASL technique for developing an effective heat transfer area. The depth necessary for containing a pressured hydraulic fracture is probably a minimum of 3-4 fracture radii, based on engineering experience in analogous situations. It has been observed[31] and recently demonstrated[32] that in certain areas fluid injection raises pore fluid pressure to levels such that significant amounts of tectonic energy can be released as earthquakes.

Known active seismic or recent volcanic areas have two main drawbacks to HDR development. First, the rocks more likely have unhealed fractures[33] and therefore a permeability unacceptable to LASL's present project development technique. Second, the probability of inducing a damaging earthquake may increase in proportion to the relative seismicity of the area, with the potential earthquake magnitude being equal to the largest event experienced along the source.[34] The advantage of an active area is that many high-grade thermal resource areas occur in association with such an environment. It may be possible to locate a competent stable block in a high-grade thermal resource area. Although the core of these areas may be a permeable convective system, bounding it will be a low-permeability environment. The normal range of characteristics of the transition zone, high to low permeability, is not known at this time, but its definition by exploration methods is one object of an HDR prospecting program.

Hot dry rock is generally pervasive at appreciable depths and can occur close to hydrothermal convective systems at relatively shallow depths. The relatively shallow (2 to 5 km) drilling depth to a desired temperature that is found near convective systems must be balanced against the relative abundance of low-permeability rock and more effective containment of a hydraulic fracture in dry crystalline rock at equal or greater depth.

B. Geophysically

1. Gravity. Studies of gravity maps give insight as to the distribution with depth of rock type and structure;[35] in fact, a map of relatively low-density silicic rocks shows a striking resemblance to the Bouguer gravity map.[36] Major faults or flexures are expressed as trends in the maximum gravity gradient.[37] In some cases, the gravity lows associated with silicic rocks cut obliquely across structural trends.[38] Emplacement at depth of low-density silicic rocks having a relatively high thermal conductivity and a high thermal generation rate due to high content of natural radioactive elements should enhance heat flow. Correlations have been made between high terrestrial heat flow and negative Bouguer gravity anomalies,[39] other geophysical parameters,[40,41] and tectonics.[42] Long-wavelength residual Bouguer anomalies with regional topographic bias removed enhance these correlations.[43]

Table I is an overview of gravity applications to the problem of finding thermal concentrations on a broad, reconnaissance scale and on a scale for which geothermal exploration is possible.

TABLE I

GRAVITY EXPLORATION METHOD

Method	Parameter Detected	Limitations	Present State of Knowledge	Further Observations Needed
Reconnaissance Scale (hundreds to tens of kilometers)				
Trends or lineations in anomalies	Rock type or structure	Nonuniqueness of solutions	Reports from various areas in the U.S.	Correlation studies with EM, seismic, and heat flow methods and drilling data
Maximum gravity gradients	Deep-seated faults	Same	Same	Same as above
Gravity lows	Silicic rock	Same	Same; also some correlation with aeromagnetic lows	Same as above
Gravity highs	Shallow mafic rock	Same	Same; also some correlation with aeromagnetic highs	Same as above
Exploration Scale (tens of kilometers to 1 km)				
Same as above	Same as above	Increased data density reduces the degree of nonuniqueness by giving a better depth estimate	Same as above	Same as above

2. Geoelectromagnetic. The electrical properties of rocks, especially the resistivity, vary over a larger dynamic range than any of the other physical properties characterizing the geologic system. Crustal rocks at depths of 2 - 5 km, the region of interest in geothermal exploration, commonly have compressional seismic velocities in the range of 3 - 6 km/s, densities in the range 2.5 - 3.3 g/cm^3, magnetic susceptibilities in the range 10^{-5} - 10^{-2} cgs, but electrical resistivity commonly may range from 10^{-1} - 10^5 $\Omega \cdot m$, or by 6 orders of magnitude. Numerous authors have discussed the possible use of transients in electric and/or magnetic fields to map electrically conductive structures to great depths.[44-51] In a number of studies these electrically conductive structures correlate with high terrestrial heat flow,[52-71] which suggests that the mapping of lateral variations in crustal electrical conductivity is a feasible method for determining the temperature pattern at depth. The physical basis for such a map is a general dependence of electrical conductivity on the temperature of the electrical conductor.[72-74] Figure 1 shows a correlation between maps of heat flow and magnetic variations.

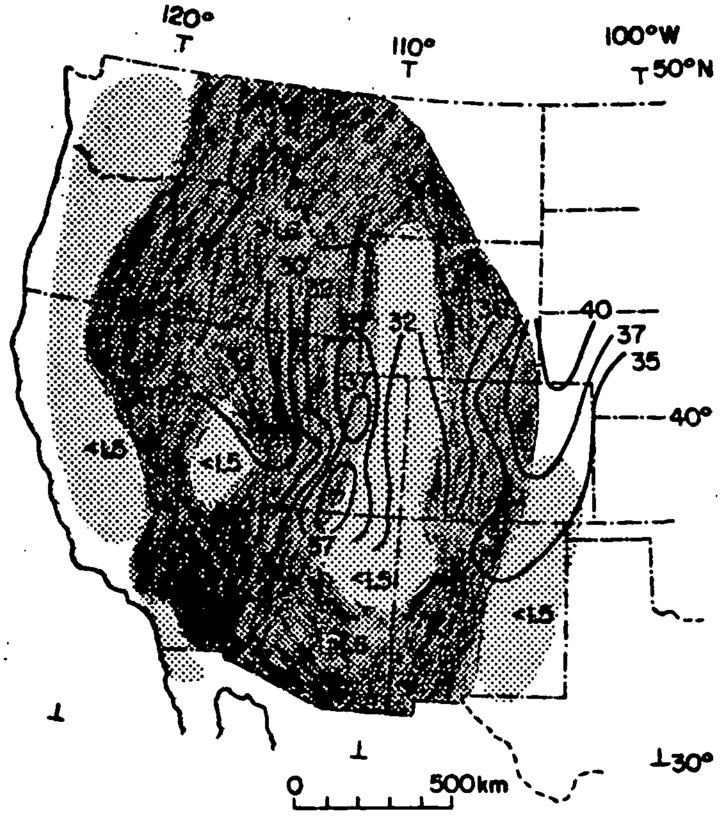

Fig. 1.

Stippled areas show average regional heat flow values (in HFUs) (modified from Sass et al., 1971). Contours show vertical magnetic component ranges (in gammas) for a daily variation (modified from Reitzel et al., 1970).

The depth of origin (greater than 10 km) and scale of these electrically conductive zones imply that the thermal energy is being transported through the crust by thermal conduction rather than by hydraulic convection. The configuration of these electrically conductive zones can be determined at various depths by utilizing a natural or induced transient of a particular period.[75] If the electrical conductivity rapidly increases at sounding depths near the surface, in all likelihood the thermal transport mechanism is hydraulic convection. In this case, a development technique other than the hot dry rock concept must be employed. Hot dry rock itself, however, because of its low total porosity and permeability and only moderate temperature is likely to be electrically elusive because it is easier to induce currents in nearby or surface conductive structures. Thus, the pattern of conductivity variations may be more revealing of the presence of HDR than attempts to locate it directly.

In the western United States, rather featureless aeromagnetic maps reflect the relative youth of a predominately silicic crust, whereas maps east of the Rockies are characterized by large-amplitude anomalies indicative of a mature mafic crust.[76] Regional patterns of magnetic anomalies in the western United States trend northeast. They have been interpreted as deep-seated fracture zones which may be a continuance of the Pacific transcurrent fracture zones.[77, 78] Intersections of transcurrent fracture zones may act as a focus of hot spots,[79] with the spacing of these fracture zones being a function of crustal thickness.[80] Long-wavelength magnetic anomalies may reflect upper crustal rock type or isothermal surfaces of Curie point distributions.[81,82] Correlations between heat flow and magnetic anomalies may be the result of increased viscous magnetization at elevated temperatures.[83]

Table II is an overview of geoelectromagnetic applications on a broad scale and on a scale for which geothermal exploration is possible.

3. Heat Flow. Because it is the measurable quantity from a thermal concentration, heat flow can afford a relatively direct indication of geothermal resources, including hot dry rock. For the same reason heat flow measurements are useful on every scale of exploration from regional to local. In recent years, several hundred measurements of heat flow on land have been made,[84-89] and heat flow province maps drawn from these data grossly resemble maps of geomorphological provinces,[90] suggesting a genetic relationship. Geologic processes, especially orogeny, strongly influence the geomorphology as well as the distribution of rocks containing above-average concentrations of heat-generating radioactive elements.[91,92] In the outer 5-10 km of the Earth's surface the heat transfer mechanisms are twofold: conduction and convection. Modern studies have indicated that convection is a much more common mechanism and circulation exists to greater depths than previously recognized. Convective heat transfer plays a dominant part in the heat transfer in most geothermal areas. Permeable fracture zones created by tectonism provide a medium capable of convective heat transport. These fracture zones may be extended by natural hydraulic fracturing,[93] particularly if temperatures are high.[94] Fracture zones, which often extend laterally for large distances, tend to remain as zones of

TABLE II

GEOELECTROMAGNETIC EXPLORATION METHODS

Method	Parameter Detected	Limitations	Present State of Knowledge	Further Observations Needed
		Reconnaissance Scale (hundreds to tens of kilometers)		
Magnetotellurics	Resistivity tensor impedance	Interpretational methods available. Inability to uniquely discriminate between temperature-related conductivities and those related to other causes. Lateral delineation of conductive bodies limited only by station spacing.	Correlations of a number of deep conductive structures with other geophysical parameters including heat flow, seismic wave velocity retardation, and attenuation.	Dependence of resistivity on temperature and pressure. Field data from case study of a geothermal area underlain by a deep conductive anomaly.
Time domain electrical method.	Resistivity	Same as above.	Same as above.	Same as above.
Geomagnetic depth sounding.	Same as above.	Resolving power decreases with decreasing depth.	Same as above.	Same as above.
Aeromagnetic	Magnetic field	Non unique interpretation.	Data on correlations with rock type, structure, and heat flow.	Field data on case studies. Dependence of viscous magnetization on temperature.
		Exploratory Scale (tens of kilometers to 1 km)		
Magnetotellurics	Resistivity tensor impedance.	Same as above.	Same as above.	Dependence of resistivity on temperature and pressure. Field data from case study of a geothermal area underlain by a deep conductive anomaly.
Time domain electrical method.	Resistivity	Nonunique interpretation.	Data on correlations with rock type, structure, and heat flow.	Field data on case studies, Dependence of viscous magnetization on temperature.
Geomagnetic depth sounding.	Same as above.	Resolving power decreases with decreasing depth.	Same as above.	Same as above.
Aeromagnetic	Same as above.	Resolving power of the depth of the anomaly increases with increased density of data.	Same as above.	Same as above.
Induced electrical soundings.	Resistivity	Resolving power decreases with increasing depth.	Large body of field studies and interpretational methods.	Dependence of resistivity on temperature.

structural weakness;[95] typically they are also high heat-flow areas. Heat flow measurements often cannot be used to discriminate whether the flow is conductive or convective. However, if a critical Raleigh number of 40 is used for the onset of convective heat flow in porous media,[96] a measured permeability of microdarcys, a reasonable geothermal gradient, and representative thermal conductivity for silicic rock, then upper limits can be placed on the values of total heat flow that can be expected, although unusual conditions may exist that violate this guideline. The hot dry rock program, however, seeks mainly to utilize the general case of thermal conduction.

Thus, one of the main problems in the identification of the hot dry rock geothermal resource is a better understanding of the patterns and mechanisms of circulation in crystalline rocks below depths of 1 to 2 km because hot dry rock technology demands that a distinction be made between conductive and convective heat flow regimes. Somewhat surprisingly, the highest heat-flow regions are often unsuitable. Experience indicates that heat flow values greater than about 5 $\mu cal/cm^2s$ are found only in association with hydrothermal convection in the crust. This maximum heat flow value implies that conductive gradients in crystalline rock (with a thermal conductivity on the order of 6-8 m·cal/cm·s°C) will not exceed 50-80°C/km. Thus, hot dry rock geothermal resources at temperatures above 200°C will not occur at depths less than 3 km, except in very rare instances. If exploration techniques for hot dry rock can be improved to the extent that pertinent rock properties can be determined below complicated surface features, then the areas included as part of the hot dry rock resource base can be increased several times. For example, by drilling through low thermal conductivity sedimentary basins, hot crystalline rocks may be found at relatively shallow depths because of the enhancement of the geothermal gradient in the basins (gradients of 100°C/km may be common even for typical heat flow values in the thermally anomalous areas of the western United States). Similarly, coastal plain sediments of the eastern United States are good thermal insulators despite their large water content,and the underlying basement is a potential hot dry rock resource. These areas are often of particular interest because of their high population density and large energy demands.

Conductive heat flow values greater than the regional average (about 2 $\mu cal/cm^2s$) and unrelated to local hydrothermal systems are known to occur in large areas as rings around large hydrothermal convection systems associated with active magma chambers and/or associated with large regional heat flow anomalies. Such anomalies are associated with the Long Valley, Yellowstone, and Valles Calderas, and possibly others. Large regional heat flow anomalies exist along the Rio Grande Rift, the Wasatch Front, and the Snake River Plain. Obviously these areas are attractive for initial studies of hot dry rock exploration. In fact, the Los Alamos project test is proceeding in the thermal conduction ring around the magma chamber underlying the Valles Caldera. Of secondary interest will be lower grade anomalies due to thermal refraction, regional concentration of radioactive heat production, or special structural situations such as crystalline rocks beneath thick sections of low-conductivity sedimentary rocks.

Studies of natural radioactive heat generation in crustal rocks are a logical part of heat flow exploration methods. In the presence of an insulating sedimentary blanket, a temperature of 200°C can be attained at 6-km depth with a heat production of 10-20 x 10^{-13} cal/cm^3s. Even without the sediment cover the temperature at 6 km would be about 150°C. The northeastern Appalachians is a region where characterization of heat production would be particularly useful in an exploration program.

Thus, target areas for hot dry rock geothermal exploitation will generally be near major structural or volcanic features. For this reason geological investigations, which are relatively inexpensive, should be conducted before heat flow studies on a local scale.

Table III is an overview of heat flow applications to the problem of finding thermal concentrations on a broad reconnaissance scale and on a scale for which geothermal exploration is possible.

4. Seismic Methods. Various parameters affecting the transmission of seismic waves have been correlated with temperature.[97] For example, travel time differences of P and S waves in certain areas have been explained by differences in mantle temperatures.[98,99] Also, the P_n velocity of waves traveling in the upper mantle tends to reflect the thickness of the crust; it is low where the crust is thin and high where it is thick.[100] Regions with low amplitudes of P_n and P waves usually exhibit considerable tectonic activity.[101] Attenuation of seismic waves suggests that large parts of the upper mantle are partially melted,[102] and the anelasticity of the partially melted zone is used to account for the low seismic velocity of the zone.[103] An accurate velocity attenuation map would help provide a delineation of isotherms at depth.[104] Figure 2 shows a correlation between maps of heat flow and seismic wave amplitudes.

Deep zones of geologic disturbance, inactive or active, that may be related to magmatic intrusions and heat flow, have been detected by seismic reflections as well as by observation of the refracted waves.[105] Some evidence exists for a correlation of low-velocity zones with electrically conductive zones.[106,107] Anomalous zones of elastic wave propagation have been related to the presence of active hydrothermal alteration in geothermal areas,[108] and zones of tectonic or hydrothermal activity can be mapped by monitoring microearthquakes.[109] Precise continuous measurements of the seismic velocity may provide a method of monitoring the *in situ* stress.[110]

TABLE III

HEAT FLOW EXPLORATION METHODS

Scale	Parameter Detection	Present State of Knowledge	Future Observations Needed		Most Effective Procedure	Relevant Mag. of Indicators
			Field	Lab		
10^3 to 1 km	Good for heat concentration; relatively poor indicator of permeability, except when deep cores are recovered.	Adequate methods, improved rate of accumulation of data and maps on regional and local scales. Regional heat flow is fairly well mapped, but much work is needed on scale 1-10 km within regions.	Detailed studies of type areas, e.g., San Francisco Peaks, Jemez, Rio Grande, Long Valley.	Automated methods to measure heat conduction of samples.	Within a region of high heat flow, select areas for study on basis of geol. information, e.g., location of faults, young volcanics, before doing heat flow.	2-5 x 10^{-6} cal/cm^2·s (80-200 in W/m^2)

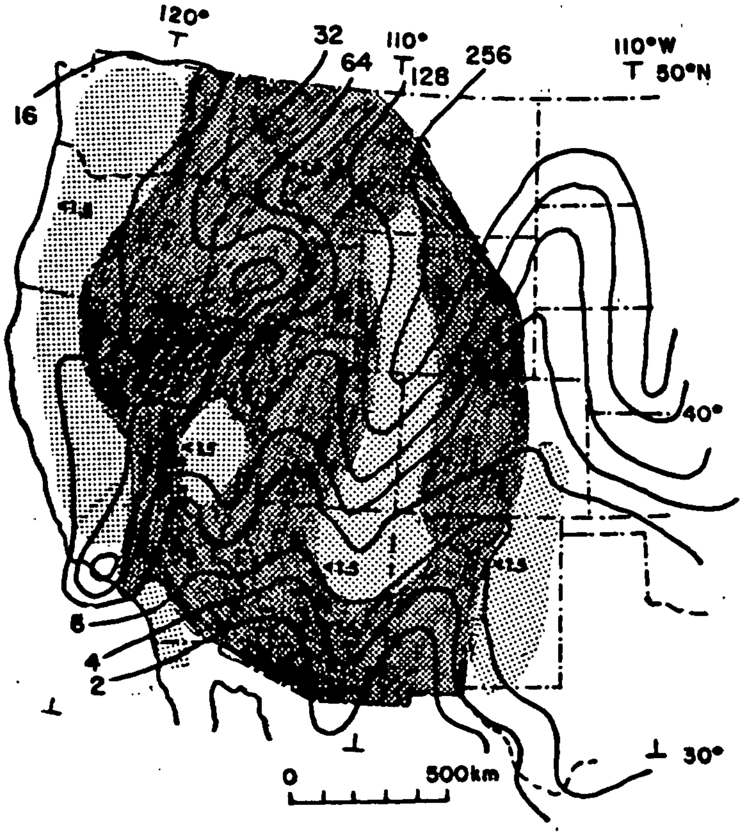

Fig. 2.

Stippled areas show average regional heat flow values (in HFU) (modified from Sass et al., 1971). Contours show longitudinal wave A/T values (in 10^{-9}m/s) from the Kazakh Event (modified from Jordan et al., 1965).

Table IV is an overview of seismic applications to the problem of finding thermal concentrations on a broad scale and on a scale for which geothermal exploration is possible.

TABLE IV

SEISMIC EXPLORATION METHODS

Method	Parameter Detection	Limitation	Present State of Knowledge	Further Observations Needed
Reconnaissance Scale (hundreds to tens of kilometers)				
Surface wave dispersion, attenuation ($T > 10$ s).	V_s, Q_s^{-1} esp. partial melting.	Long paths needed (~1000 km), natural sources, LP seismic stations. Assumes horizontal layering.	Data from several long paths in W. U. S.	Additional field data, esp. shorter paths and periods Lab data on V_s, Q_s^{-1} at seismic f's as f'ns of T, P, esp. near melting conditions.
Travel time delays, relative attenuation of teleseismic P & S.	Vertically integrated V_p, V_s, Q_p^{-1}, Q_s^{-1}.	No vertical resolution at this horizontal scale.	Data from standard permanent observatories.	Same as above.
Refraction: crustal P; velocities of P_n, S_n.	Ave. vert. V_p structure. Upper mantle V_p, V_s.	Poor lateral resolution. Poor vertical control.	Many profiles Data for many paths in W. U.S.	Same as above.
Exploration Scale (tens of kilometers to 1 km)				
Surface wave dispersion, attenuation ($T \approx 1$-10 s period).	Shallow V_s, Q_s^{-1}. Applicable to low Q medium.	Need portable, broad-band sensors; natural sources. Assumes horizontal layering.	Sparse data.	Field data from 'standard' geothermal areas.
Travel time delays of teleseismic P & S (Aki technique).	Three-dim. V_p and V_s structure.	Need large seismic array, teleseismic sources from many azimuths. Need initial model from refraction. Assumes ray paths known. Vertical resolution is comparable with horizontal spacing.	Data from several arrays (inc. Yellowstone and Island of Hawaii).	Field data from additional geothermal areas.
Propagation direction anomalies of P & S.	Lateral gradients in V_p, V_s (esp. associated w/ melting).	Need dense seismic array. Need ray tracing calculations to compare model w/observations.	Applied to mid-ocean ridge and subduction zone structures, but not yet to any geothermal areas.	Field data from one or more geothermal areas w/magma chamber.
Relative attenuation of S waves (teleseismic or local).	Low Q_s bodies, esp. magma chambers.	Need broadband seismic data, many paths crossing area of interest.	Applied to magma bodies in several volcanic fields (Kuriles, Alaska, Yellowstone).	Same as above.
Particle motion of teleseismic P waves (diffraction effect of inhomogeneous body).	Lateral discontinuity such as the edge of magma lens.	Need 3-component seismograph array.	Applied to magma lens under Kilauea Iki.	Same as above.
Location of seismic events due to thermal cracks.	Lateral extent of heat source.	Sufficient thermal stress to cause cracks, unlikely in DHR region.	Applied to locate the lateral extent of magma lens under Kilauea Iki.	Same as above.
Deep crustal sounding by active sources.	Strong impedance contrast.	Expensive.	Deep-seated inhomogeneity detected under Rio Grande rift that may be associated with geothermal source.	Same as above.
Active seismic profiling.	Substantial velocity contrast.	Insensitive to grading, continuous velocity changes as from thermal gradient.	Very well developed.	Same as above.

The seismological methods used to help identify possible geothermal areas are divided and discussed according to the stage of the investigation — reconnaissance, exploration, and site selection. In a reconnaissance stage, lateral distributions of temperature at depth can be inferred by definition of seismic velocities and Q of the upper mantle by using phase and group velocities, attenuation of long-period surface waves over regional paths, travel time delays and relative attenuation of teleseismic body waves, and amplitudes and velocities of P_n and S_n waves from natural or artificial sources. Such studies have already been carried out for large portions of western North America.

Until recently, maps of gravity anomalies provided the best geophysical basis for identifying underground bodies on a regional scale in terms of large-scale trends. However, in the past few years, researchers have shown that a seismic array covering an area of about 100 x 100 km can give three-dimensional velocity anomalies with resolution roughly equal to station spacing to a depth comparable to the linear dimension of the area covered by the array. The data are the time residuals of P waves from teleseismic events that penetrate the region under the array. The method has been applied to the data from many arrays around the world, including several new and old geothermal areas, such as Yellowstone, Hawaii, Oslo-graben, Coso, and the Geysers. Unlike the gravity map, the seismic velocity anomaly map can be constructed at various depths without a loss of resolution with depth.

An example of velocity anomalies that show some correlation with the geothermal anomalies is the USGS central California seismic array, where heat flow was studied.[79] The highest heat flow (greater than 2 heat flow units (HFU)) was found in the Franciscan Formation on the east side of the San Andreas fault. A seismic velocity anomaly map for the crust (0- to 25-km depth) was obtained from 3500 residuals (115 teleseismic events) recorded at 91 stations. The low-velocity anomalies show a good correlation with the Franciscan Formation, suggesting a correlation between the low-velocity anomalies and areas of high heat flow. The teleseismic method uses the seismic waves transmitted through the body under study. Because the waves arrive at incidence angles closer to vertical than to horizontal, resolution about the lateral extent of the body is good. The method is more robust than the reflection method, because it relies on direct waves rather than reflected waves.

At the exploration stage, a number of related seismic studies can be accomplished using a large, perhaps several tens of kilometers in aperture, movable array of relatively broadband seismometers (0.1 to 10 Hz). The recordings of natural events from such an array can be used to: (1) model crustal shear velocity from the dispersion of short-period Love and Rayleigh waves; (2) construct three-dimensional block models of crustal velocity using body wave travel times and the inversion techniques of Aki, Husebye, and Christoffersson;[111] (3) measure anomalies in the propagation direction of short-period teleseismic body waves such as those that might be produced by a lens of low-velocity material in the crust; (4) measure variations in apparent Q for body waves, including possible screening of high-frequency P and S waves by magma bodies.

When the attenuation is severe, which seems to be the rule in a geothermal area, relatively long-period waves must be used. In this case, the dispersion, diffraction, and scattering effects due to the body may be used to infer the presence of the body. In fact, one of the most important data sources for defining the magma lens under a frozen lava lake in Hawaii was the dispersion of Love waves. The loci of particle motion observed at an array of two-component stations were also useful in locating the tip of the magma lens.

At the site-selection stage, detailed active-seismic surveys may be desirable. Shallow reflection surveys and short refraction lines, including fan shooting about an expected low-velocity intrusion, are two possibilities. The reflection method can give excellent results on the details of the underground body when it is bounded by a strong impedance contrast and the boundary surface is smooth and not too far from horizontal. The refraction method will give a reliable estimate of average seismic velocity over a profile.

The real usefulness of seismic methods is not mainly in the direct detection of hot dry rock -- it has already been said that this would likely present a low-velocity contrast as a result of thermal gradients on a local scale. Rather, much of the utility of seismic methods, particularly active profiling on a scale of a few kilometers, is in delineating subsurface structure when used in conjunction with other field work. For examples, seismic methods are useful for locating and identifying basement rock under volcanic overburden, finding the downward boundary between a caldera or intrusive region and the native rock, or distinguishing between the competent rock suitable for hot dry rock technology and a strongly fractured region, wet or dry, that would more appropriately be developed by a different technology.

Finally, it is necessary to examine the patterns of seismicity in a region because the relatively high seismicity that maintains an open crack system in most water-dominated geothermal systems is undesirable where low natural permeability is a requirement.

It should again be emphasized that even a combination of seismic measurements should be regarded only as complementary to a thoroughly integrated geological and geophysical program.

IV. PANEL RECOMMENDATIONS

A. Laboratory Investigations

Considerable need was expressed for rock resistivity data at elevated temperature and pressure. Some data exist for the effects of pressure and temperature on seismic velocities, but do not include needed data on the effects of frequency and partial saturation to water or steam. The apparent genetic relationship between some deep electrical conductive anomalies and low seismic velocity zones as interpreted from field studies should be investigated in the laboratory to help improve interpretations of field data.

B. Office Studies

Appreciable progress has been made in the interpretive techniques available for geoelectromagnetic surveys; however, with support and interest further advances are feasible. The same can be said for interpretive techniques of gravity data.

Geomagnetic depth sounding data exist for much of the western United States. Compilation and interpretation of these data could produce a regional-scale electrical conductivity map. Unfortunately these data may be difficult to synthesize if sufficient overlap of data sets is not available. In all likelihood only one person can resolve this question, Ian Gough of the University of Alberta, Canada, who made the surveys and has the necessary files of data.

Considerable seismic data exist which, when compiled and interpreted, would provide regional maps of delay times, attenuation, low-velocity zones, and crustal velocities, which would be very useful to the geophysical community. The compilation and interpretation of the data would be relatively straightforward, if funding is given to support this work.

By modeling studies of plutons and various tectonic situations, in particular, their heat budgets, hydrologies,stress fields, and fracture systems, a feeling for the probable sharpness of the transition from a "wet" environment to a "dry" one might be gained.

The formation of a small working panel of experts from each of the major fields of geophysics to evaluate and interpret all available data was proposed. This panel would prepare preliminary regional scaled maps that could be used to delineate more efficiently areas of primary interest.

C. Field Studies

The panel consensus was that a field application of the geological and geophysical methods discussed was necessary for a complete evaluation of the real potential of these methods in hot dry rock exploration. This application could be tested at a proven site, such as the Valles Caldera site, or at new sites selected as type locations for particular geologic environments.

Field application would also provide a test program for new instrumentation and interpretive methods. New instrumentation methods could conceivably lower costs. New as well as old interpretive techniques can be tested only by a direct field application, which has rarely been done to date, and when done industrially, often remains in the province of trade secrets.

Because most or all geophysical studies have been specifically directed toward the investigation of convective hydrothermal systems, little is known about the gradation from a wet to a dry system. Definition of the sharpness of this transition would be helpful in understanding the formative processes.

V. CONCLUSIONS

Certain patterns of geologic conditions and geophysical parameters that are characteristic of occurrences of hot dry rock may be useful in detecting promising areas. These patterns are also consistent with the geologic processes that tend to create an environment conducive to hot dry rock. Hydrothermal or wet system patterns are distinctly different, especially when all the data are analyzed. Possibly hot dry rock can be located by using one element of the pattern, though the probability for success is enhanced by using the complete suite of available methods. Unambiguous direct detection of a hot dry rock resource is difficult at the present state of sophistication.

The exploration program will vary to some extent with the emphasis based on the potential of the thermal resource, placed on the apparent potential or grade of the thermal resource and its nearness to users. If a remote high-grade, shallow resource is developed, some efficiency may be lost by transmission to a user population center. If a lower grade, deep resource is used, some of the advantage of proximity to the user may be partly offset by increased drilling costs.

In either case the exploration program must begin at a reconnaissance scale using techniques with a horizontal resolution of several tens to hundreds of kilometers to adequately define regional geological and geophysical characteristics. Regional studies provide the basis for increasingly site-specific surveys by establishing the mode of occurrence and verifying a large-scale, deep-seated genesis for the thermal resource. The exploration methods for a particular region would be selected on the basis of available geological and geophysical knowledge of the area. Ideally, some real-time interaction or feedback will occur between the users of various tools for a more efficient program.

At all stages of hot dry rock exploration, the strategy is to look for favorable patterns of parameters, rather than directly for hot dry rock. The geological and geophysical methods to implement this strategy are within the capabilities of current technology if it is applied intensively to the problems of temperature distribution in the crust.

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APPENDIX A
EXPLORATION METHODS FOR HOT DRY ROCK
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APPENDIX B

INDIVIDUAL ABSTRACTS

RESIDUAL BOUGUER GRAVITY ANOMALY ANALYSIS OF ARIZONA AND HOT DRY ROCK EXPLORATION

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A long-wavelength Bouguer gravity anomaly in Arizona with a 200-mgal amplitude has been found to correlate with the regional elevation of the topography (Figs. B-1 and -2). Long-wavelength anomalies usually reflect deep or widespread density heterogeneities and often tend to overshadow smaller wavelength anomalies related to shallower sources.

The removal of the gravitational effect of those elements of the terrain that are in isostatic equilibrium by a Bouguer correction will generate long-wavelength anomalies that will correlate with regional elevations (Fig. B-3). Such a long-wavelength correlation is especially prevalent in areas with significant regional variations in the elevations of the topography, such as western North America.

If a regional trend of the elevations of topography is used as the reduction datum in the Bouguer correction, the resultant anomalies will no longer correlate with regional elevations (Fig. B-3). The anomalies will have wavelengths smaller than the wavelength of the regional elevation datum and can be considered residual Bouguer gravity anomalies.

Residual Bouguer gravity anomaly values have been computed for Arizona. Elevation values from topographic maps were Fourier analyzed in order to determine the regional elevation datum (Fig. B-4). Gravity station elevations were not used since their distribution was not considered adequate in depicting the regional elevation of the topography (compare Figs. B-2 and -4).

Some preliminary conclusions have been reached by an analysis of the residual anomalies with regard to areas that may be favorable for hot dry rock.

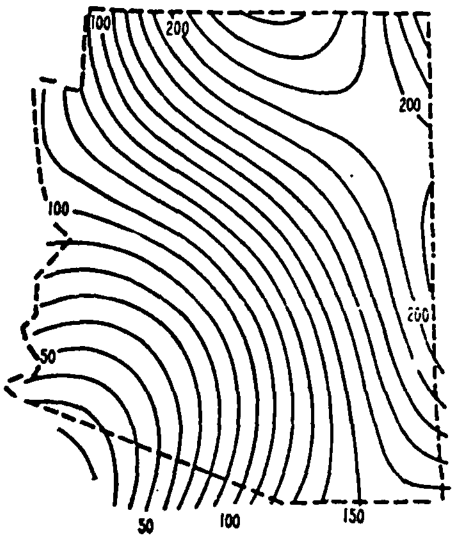

Fig. B-1.

First harmonic trend surface of Bouguer gravity anomalies (sea-level datum) of Arizona; 10-mgal contour interval.

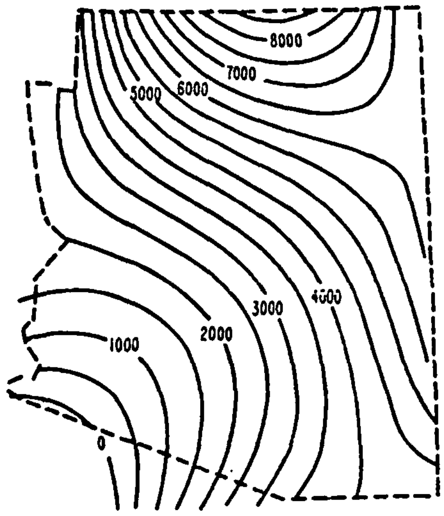

Fig. B-2.

First harmonic trend surface of the elevations of gravity stations of Arizona; 500-ft contour interval.

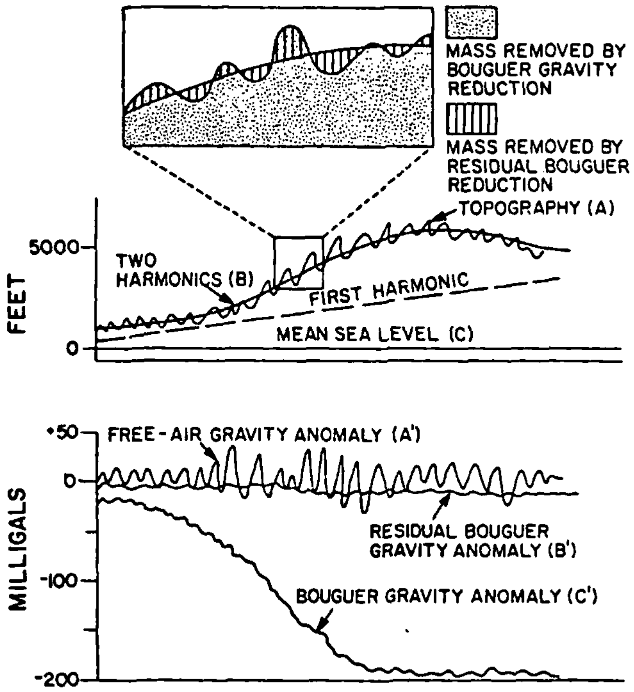

Fig. B-3.

Relation between elevations of topography, reduction datums, and resulting anomalies. Upper figure shows resulting free-air anomalies (A), smoothed topography (B), and mean sea level (C). Lower figure shows various free-air anomalies (A') from using Bouguer datum A, residual Bouguer gravity anomalies (B') from Bouguer datum B, and Bouguer gravity anomalies (C') from using a Bouguer reduction datum of mean sea level C.

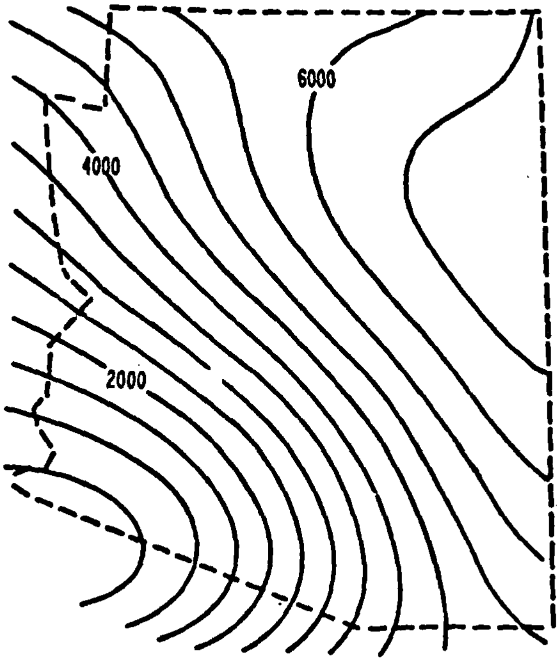

Fig. B-4.

First two harmonic trend surfaces of elevations of the topography of Arizona: 500-ft contour interval. Note: the fundamental wavelength of the data distribution is twice that of Figs. B-1 and B-2.

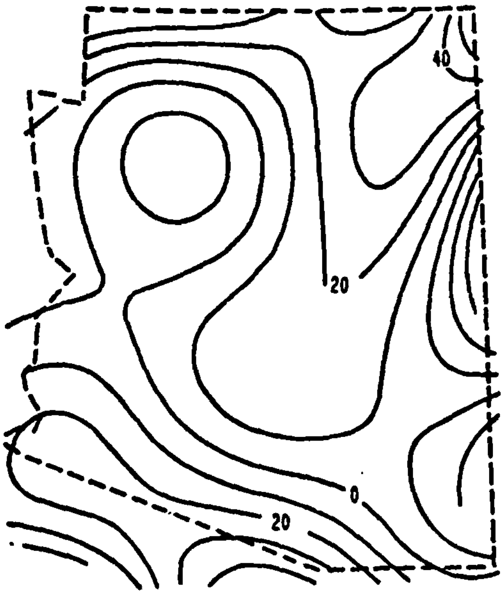

Fig. B-5.

First two harmonic trend surfaces of residual Bouguer gravity anomalies of Arizona; 10-mgal contour interval.

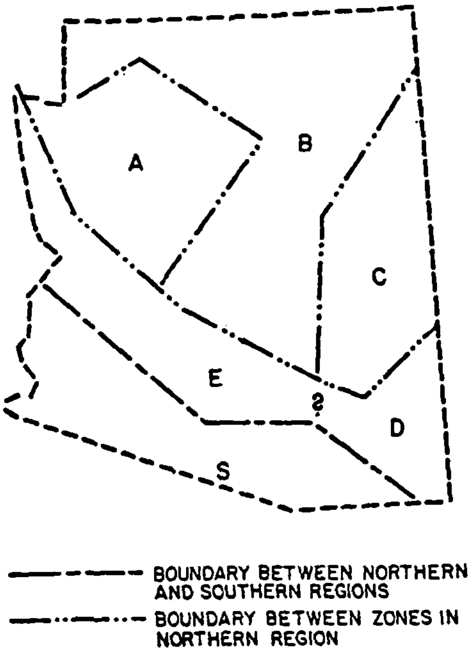

Fig. B-6.

Regions and zones with particular geological and geophysical signatures.

The correlation of the long-wavelength anomalies of the residual Bouguer values (Fig. B-5) with other geological and geophysical information indicates that the anomalies reflect density variations in the crust and mantle that may be ultimately related to temperature variations. Specific residual anomalies and anomaly trends are clearer on the residual map than in previous gravity studies. Arizona has been divided into several zones with consistent geological and geophysical characteristics (Fig. B-6). Zones A and C are considered most favorable for hot dry rock.

SEISMIC METHODS

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(1) The map of seismic velocity anomalies at a regional scale.

Until recently, the map of gravity anomalies provided the best geophysical basis for identifying the underground bodies at a regional scale in terms of large-scale trends. A seismic array covering an area of about 100 x 100 km can give the three-dimensional velocity anomalies with the resolution roughly equal to station spacing to the depth comparable to the linear dimension of the area covered by the array. The data are the time residuals of P waves coming from teleseismic events which penetrate through the region under the array. The method has been applied to the data from many arrays around the world, including several new and old geothermal areas such as Yellowstone, Hawaii, and Oslo-graben. Unlike the gravity map, the seismic velocity anomaly map can be constructed at various depths without a loss of resolution with depth.

An example of velocity anomalies that show some correlation with the geothermal anomalies is found under the USGS central California seismic array. The heat flow in this area was studied by Sass et al. (1971). The highest heat flow (greater than 2 HFU) was found in the Franciscan Formation on the east side of the San Andreas fault. The low-velocity anomalies on the seismic velocity anomaly map for the crust (0-to 25-km depth) obtained from 3500 residuals (115 teleseismic events) recorded at 91 stations show a good correlation with the

Franciscan Formation, suggesting a correlation between the low-velocity anomalies and areas of high heat flow.

(2) Importance of multiple approaches.

It is well recognized that the exploration of geothermal energy sources requires combined use of various methods. Even in the seismic method alone, it is important to use a diversified approach. The teleseismic method described above used the seismic waves transmitted through the body under study. Because the waves arrive at incidence angles closer to vertical than to horizontal, this method gives a good resolution about the lateral extent of the body.

The method is more robust than the reflection method, because it relies on the direct waves rather than reflected waves.

The reflection method can give excellent results on the details of the underground body when it is bounded by a strong impedance contrast and the boundary surface is smooth and not too far from horizontal. The refraction method will give a reliable estimate of average seismic velocity over a profile.

When the attenuation is severe, which seems to be a rule in geothermal areas, one has to use relatively long-period waves. In that case, the dispersion diffraction and scattering effects due to the body may be used to infer the presence of the body. In fact, one of the most important data sources to define the magma lens under a frozen lava lake in Hawaii turned out to be the dispersion of Love waves. The loci of particle motion observed at an array of two-component stations were also useful in locating the tip of the magma lens.

Another interesting lesson learned from the lava-lake experiment is the importance of passive seismic experiments. We found numerous seismic events associated with the thermal stress caused by cooling of magma. The observed frequency of seismic activity was as high as 100/h after 15 yr of cooling, and the location of these events seems to define the magma lens most easily and with the best resolution.

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CHARACTERIZATION OF AND TECHNIQUES FOR EXPLORATION FOR HOT DRY ROCK

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In the outer 5-10 km of the Earth's surface the heat transfer mechanisms are twofold: conduction and convection. Modern studies have indicated that convection is a much more common mechanism and circulation exists to greater depths than had previously been recognized. Convective heat transfer plays a dominant part in the heat transfer in most geothermal areas,and subsurface water movements are thought to be intimately related to earthquakes. One of the main problems in the identification of the hot dry rock geothermal resource is lack of a better understanding of the circulation patterns and mechanisms in crystalline rocks below depths of 1 to 2 km.

Experience indicates that in general heat flow values in excess of about 5 $\mu cal/cm^2 s$ are found only associated with hydrothermal convection in the crust. This maximum heat flow value implies that conductive gradients in crystalline rock (with a thermal conductivity on the order of 6-8 mcal/cm·s·°C) will not exceed 50-80°C/km. Thus hot dry rock geothermal resources at temperatures above 200°C will not occur at depths less than 3 km except in very rare instances. If the exploration techniques for hot dry rock can be improved to the extent that pertinent rock properties can be determined below complicated surface variations of properties, then the areas included as part of the hot dry rock resource base can be increased several times. For example, by drilling through low thermal conductivity sedimentary basins, hot crystalline rocks may be found at relatively shallow depths because of the enhancement of the geothermal gradient in the basins (gradients of 100°C/km may be common even for typical heat flow values in the thermally anomalous areas of the western United States).

Conductive heat flow values in excess of the regional average (about 2 $\mu cal/cm^2 s$) not related to local hydrothermal systems are known to occur in large areas only as narrow rings around large hydrothermal convection systems associated with active magma chambers and/or associated with large regional heat flow anomalies. Such anomalies are associated with the Long Valley, Yellowstone, and Valles Calderas, and possibly others. The large regional heat flow anomalies exist along the Rio Grande Rift and the Snake River Plain. Obviously these areas are the most attractive for initial studies of hot dry rock exploitation, and indeed the Los Alamos project is already proceeding in the thermal conduction ring around the magma chamber underlying the Valles Caldera. Of secondary interest will be lower grade anomalies due to thermal refraction, regional concentration of radioactive heat production, or special structural situations such as crystalline rocks beneath thick sections of low-conductivity rocks.

Thus, in general, targets for hot dry rock geothermal exploitation will be areas near major volcanic and structural features. They will have heat flow values up to 2 or 2-1/2 times the regional average and although near major tectonic features, will have maintained a relatively low permeability. In general the target depths for 200°C temperatures will be a minimum of 2 km and more realistically depths of 2-5 km.

Although electrical exploration techniques play an important part in the exploration for and evaluation of conventional hydrothermal targets, their usefulness in hot dry rock exploration will be limited. Neither seismic nor electrical resistivity studies have the resolution capable of detecting the change in thermal characteristics associated with effects of only a factor of 2 change in heat flow, particularly given the geological "noise" in the structurally complex regions which will be of most interest. Likewise the geometry of the permeability of the crystalline rocks, occurring primarily as discrete, widely separated fractures, is not conducive to easy detection by electrical or seismic methods. Modeling and field tests verify these difficulties. Such techniques have a place in hot dry rock exploration only after other exploration has identified targets small enough to make practical the detailed (and expensive) studies that will be necessary to detect the small changes in physical properties that might be associated with the high heat flow and affected by the permeability and nature of thermal transfer at depth.

Heat flow studies of geologically outlined regional targets are the only way to identify the presence or absence of a hot dry rock prospect of the types described above. Furthermore, heat flow studies will be the most economical way to regionally explore (based on available broad-scale geophysical and geological studies) for the presence of hot dry rock resources.

GEOTHERMAL PROSPECTING AND THE ELECTRICAL CONDUCTIVITY CHANGES ASSOCIATED WITH MELTING*

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The relevance of electrical conductivity surveys as an exploratory tool for partial melt zones within the Earth's crust and mantle is discussed using results from σ measurements prior to and during partial fusion, under controlled oxygen fugacity, of basalt and the plagioclase feldspar, albite. Field measurements of electrical conductivity anomalies have often been cited as evidence for the existence of melt at depth. Laboratory data on the large σ increase associated with melting of albite[1] or basalt[1-3] and granite[4], which contain plagioclase feldspar (albite is the sodium-end member of the solid solution series) as a major component, are listed as justification for this interpretation.

Figure B-7 compares the σ of single-crystal albite measured at temperatures below melting as a function of time with the σ of powdered albite measured upon melting.[5] Data portrayed in the figure clearly show that the σ increases subsolidus, given sufficient time, to account for all the increase observed upon melting.

Figure B-8 shows the σ measured at temperatures below melting and upon partial fusion of basalt under controlled oxygen fugacity.[6] Data indicate the σ measured from this basalt is a complicated function of temperature, time, and oxygen fugacity. Generally, the σ decreases with time below approximately 900°C if oxygen fugacity is near the quartz-fayalite-magnetite buffer. Above 900°C, the σ increases with time for all oxygen fugacities studied. It is obvious from this figure that the σ change upon partial fusion (T = 1050°C) is dependent upon the time the sample resided at temperatures below the beginning of melting.

Figure B-9 portrays the σ as a function of time for this basalt at three different oxygen fugacities at 1050°C. Because of the similarity of this figure with Fig. B-7, we suggest that the σ increase is related to disorder in the

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*Work done under the auspices of the U.S. Energy Research and Development Administration under contract #W-7405-ENG-48 and supported by the National Aeronautics and Space Administration under an interagency work order agreement.

plagioclase rather than to partial melting. By analogy, we suggest that granite would behave similarly, if equilibrium were attained.

This argument suggests that field measurements cannot reliably distinguish between partial melt and a solid of similar composition, but slightly below the solidus. The situation is changed, however, if we assume a melt of basaltic composition present in a rock in which σ measured for olivines and pyroxenes under controlled oxygen fugacity[7,8] as the most likely σ for the host rock, a σ contrast of two to four orders of magnitude would be observed between a zone where the σ is dominated by partial melt and one where the σ is controlled by either olivine or pyroxene.

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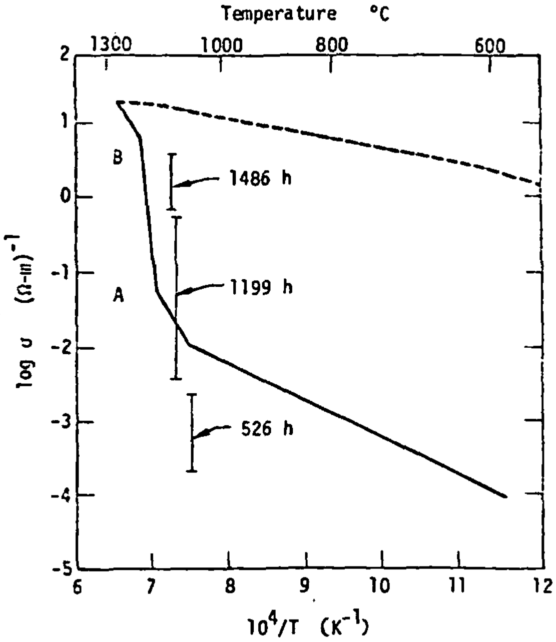

Fig. B-7.

The electrical conductivity of albite. The broken and heavy solid lines[1] show the increase upon melting. The vertical lines[5] show increases of similar magnitude can be achieved subsolidus as a function of time.

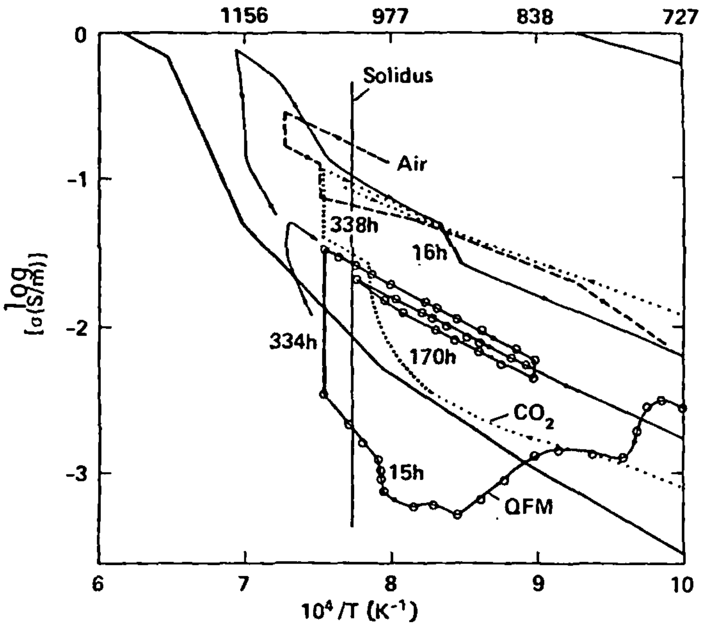

Fig. B-8.

The electrical conductivity of basalt.

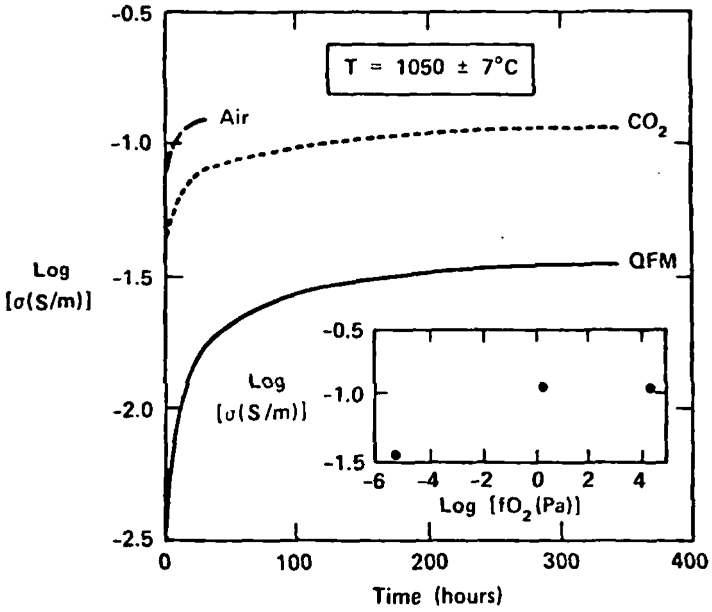

Fig. B-9.

Basalt σ as a function of time above the solidus. The insert shows σ as a function of fO_2 at 1050°C for the final σ measured.

NATURAL ELECTROMAGNETIC EXPLORATION METHODS

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THE TARGET

A regional exploration program for geothermal resources should focus on detecting deep, large-scale magmatic intrusions that generate and sustain a variety of shallower geothermal manifestations such as convective hydrothermal systems, hot dry rocks, or high-level magma chambers. This is somewhat analogous to indirectly exploring for oil through mapping basement structures using gravity, seismic, and electromagnetic techniques. Oil reservoirs are at best elusive primary geophysical targets, and the predominant effort in petroleum exploration is to map secondary targets, i.e., structures related to the migration and entrapment of oil. It seems that hot dry rock in and of itself is also a difficult primary geophysical target. For example, in terms of its electrical properties, hot dry rock at depth having a temperature of say 400°C will be difficult to differentiate from cold wet rock at a much lower temperature. On the other hand, field studies on exhumed fossil magma bodies along with laboratory studies suggest that the physical properties of active magma structures represent first-order geophysical targets in terms of their expected scale size and their physical contrast with surrounding country rock. It is not uncommon to find exhumed fossil magma bodies several kilometers to many kilometers wide.

Moreover, we see in Table B-I a summary of laboratory measurements by various workers on the conductivity of molten rock at 1200°C. A value of 3 mhos/m seems typical at this temperature. Field measurements on the conductivity of molten rocks, also inferred to be approximately 1200°C, are summarized in Table B-II.

Since we would expect the surrounding country rock to have an average resistivity of 100 Ω·m or greater, magma bodies represent a first-order contrast with their surroundings.

TABLE B-I

LABORATORY MEASUREMENTS ON CONDUCTIVITY OF MOLTEN ROCKS

1200°C

	mhos/m
MURASE AND MURASE AND McBIRNEY	
Alkali-Olivine Basalt (GOB)	2.6
Andesite (MHA)	1.3
Tholeiite (CRB)	1.0
Rhyolite Obsidian (NRO)	2.0
KHITAROV AND SLUITSKY	
Basalt	3
PRESNAL, SIMMONS, AND PORATH	
Synthetic Basalt	2.5
WAFF AND WEILL	
Latite	3.1
Tholeiite (Sample 1)	2.8
Tholeiite (Sample 2)	2.5
Andesite	2.4
Alkali-Olivine Basalt	2.1

TABLE B-II

FIELD MEASUREMENTS ON CONDUCTIVITY OF MOLTEN ROCKS
1200°C

KELLER (in Parkomenko)	
Hawaiian Lava Lake	3 to 5 mhos/m
KELLER (IUGG Report)	
Kilauea Iki Lava Lake	4 to 5 mhos/m
Halemaumau	6 to 8 mhos/m

Therefore, considering the present state of exploration technology, one should employ natural geoelectromagnetic techniques, not in detecting hot dry rock per se at depths of 2 to 5 km, but rather for detecting the presence of a deeper heat source — a molten magma body at a depth of 4 to 10 km.

A MODEL FOR A MAJOR HIGH-LEVEL CRUSTAL INTRUSION

One might assign the following parameters to a major high-level magma structure: a conductivity of order 1 Ω•m, a roughly spherical geometry with a diameter of the order of 10 km, and a depth of burial of 2 to 4 km. The country rock, if crystalline or metamorphic, would typically have a resistivity greater than 100 Ω•m. Since pulsations in the PC 3 - 4 band (20 - 80 s) have a skin depth of approximately 35 km in 100-Ω•m country rock, this period range and longer periods will probably be characteristic for delineating such structures.

Natural Electromagnetic Methods for Mapping High-Level Structures

The electromagnetic response of a spherical body will take two forms; one results from induced eddy currents caused by time-varying magnetic fields, and the other results from the distortion of regional electric currents (or telluric currents) by the presence of the inhomogeneous magma body in an otherwise relatively homogeneous earth. The geophysical methods employing these two phenomena are known respectively as the magnetic variation method and the telluric method.

The Magnetic Variation Method

A model for calculating the effects of the induced magnetic field is shown in Fig. B-10.

The term M-iN in the equation below represents the induced specific magnetic moment of the body and in turn depends on the induction parameter $(\sigma\mu w)^{1/2}$ R. Z_a is the anomalous vertical magnetic field amplitude, H_0 is the normal horizontal magnetic field amplitude, and z is the depth to the anomalous body. Typically, for the parameters in our model, the inductive response parameter would be of order unity or less. Therefore, the electromagnetic response would have a strong out-of-phase response with the anomalous field typically having a maximum which is 15% or less than the source field.

The magnetic transfer coefficient for the vertical field, for example, is given by

$$Z_a/H_0 = R^3\ (M-iN)\ 3 \times z/r^5,$$

which for the size-conductivity-frequency parameters we have chosen is of order 15% or less, decreasing inversely with period. At 1000 s, the induced vertical field would be of the order of 1% of the source field. Such an experiment would be useful only when a careful estimate of the unperturbed field elements can be established.

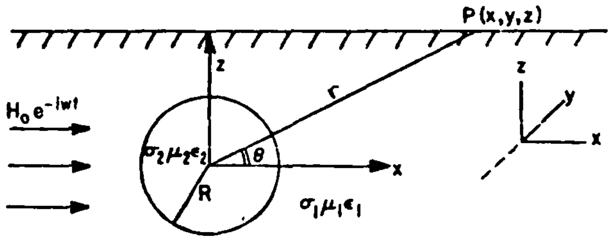

Fig. B-10.

Schematic of an anomalous body in a magnetic field.

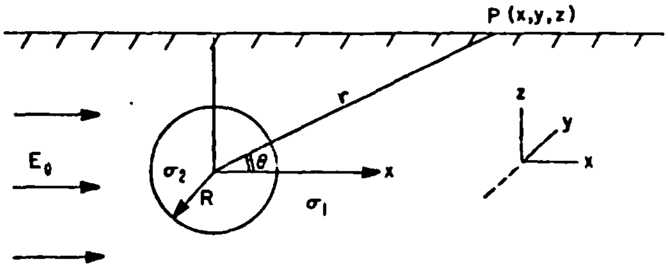

Fig. B-11.

Schematic of an anomalous body in an electric field.

The Telluric Method

A model for calculating the effects that a magma structure has on distorting a regional telluric field is represented in Fig. B-11.

The telluric transfer coefficient for the field component in the direction of the source field is given by

$$(E_x{}^a + E_x{}^o)/E_x{}^o = 1 - [(\sigma_a - \sigma_o)/(\sigma_a + 2\sigma_o)]R^3(2x^2 - z^2)/r^5,$$

where $E_x{}^a$ is the anomalous horizontal electric field,

$E_x{}^o$ is the normal source horizontal electric field,

σ_a is the anomalous electrical conductivity, and

σ_o is the electrical conductivity of material around the anomalous body.

We see from the leading term that the electric response is determined by the parameter $[(\sigma_a - \sigma_o)/(\sigma_a + 2\sigma_o)]$. We see that for a conductivity contrast of 100, this term is approximately unity and the induced electric dipole moment has reached saturation.

The telluric transfer coefficient is therefore of the order of 50% (as opposed to 15% or less for the magnetic transfer coefficient) and is, in theory of course, frequency independent.

In short, this means that the structure we are considering has a stronger effect on the telluric field than on the magnetic field. Generally, however, the telluric field is much more susceptible than the magnetic field to effects from shallow geologic structures such as sedimentary basins. Therefore, one must be cautious in applying to all cases an argument based on overly simplistic models.

The point to be emphasized, however, is that under reasonable field conditions and in a reasonable geological environment, both the magnetic variation and the telluric variation methods lead to significant geophysical anomalies. Moreover the dominant effect of the anomalous structure is not in terms of what may be called its "inductive" response but rather in terms of its "conductive" response; in other words, the effect the structure has on the distortion of a regional electric current field.

MODEL B: DEEP-SEATED ZONES OF MAJOR INTRUSIONS

There is increasing evidence suggesting that both magnetic variation methods and magnetotelluric methods have successfully detected major magmatic zones at intra-crustal depths.

The magnetic variation work of Schmucker in the southwest has long indicated anomalously high temperatures beneath the Basin and Range, an even more anomalous zone beneath the Rio Grande Rift, and relatively normal temperatures beneath the High Plains of West Texas.

Unfortunately, the geometry of the anomalous zone suggested by Schmucker, Gough, and Porath did not align very well with the anomalous upper mantle suggested from regional seismic and gravity work.

Several years ago we reported a reinterpretation of the magnetic variation data, shown in Fig. B-12, which placed the anomalous variations in temperature at a high level in the crust and upper mantle, rather than at 100 km or more as originally suggested by Schmucker.

Whether the anomalous conductor was at a depth of 100 km or only a few tens of kilometers, say at the base of the crust, was a question that motivated a series of magnetotelluric (MT) measurements by Brown University and our group at Lamont-Doherty Geological Observatory.

Figure B-13 shows MT data obtained by Lamont-Doherty during 1976 and earlier by Mobil Oil Company in the Hueco Bolson near El Paso, TX. The tectonic setting of the site is on the eastern margin of the Rio Grande Rift. At this site, the maximum principal resistivity values are for the electric field parallel to geologic strike and are least sensitive to contamination from near-surface geologic structures.

At short periods (0.1-1 s) the effect of the surface sediments is shown; from 1-10 s, resistivity increases as the signals penetrate to the resistive basement. At 100-1000 s, a resistivity minimum is encountered, which reflects the presence of a conducting layer at depth.

Figure B-14 shows the inversion of the apparent resistivity data of Fig. B-13 into true resistivity as a function of depth using a simple scheme developed by Francis Bostick at the University of Texas. In this figure there is a very well-defined layer at a depth of 25-35 km which has a surprisingly low value of resistivity of only several ohm-meters.

It is not clear from these data alone whether this layer is a basaltic lens close to its solidus temperature or whether it is a plexus of molten basalt at a much higher temperature. A volume fraction of 10-20% of molten basalt at 1200°C could readily account for a bulk resistivity value of several ohm-meters.

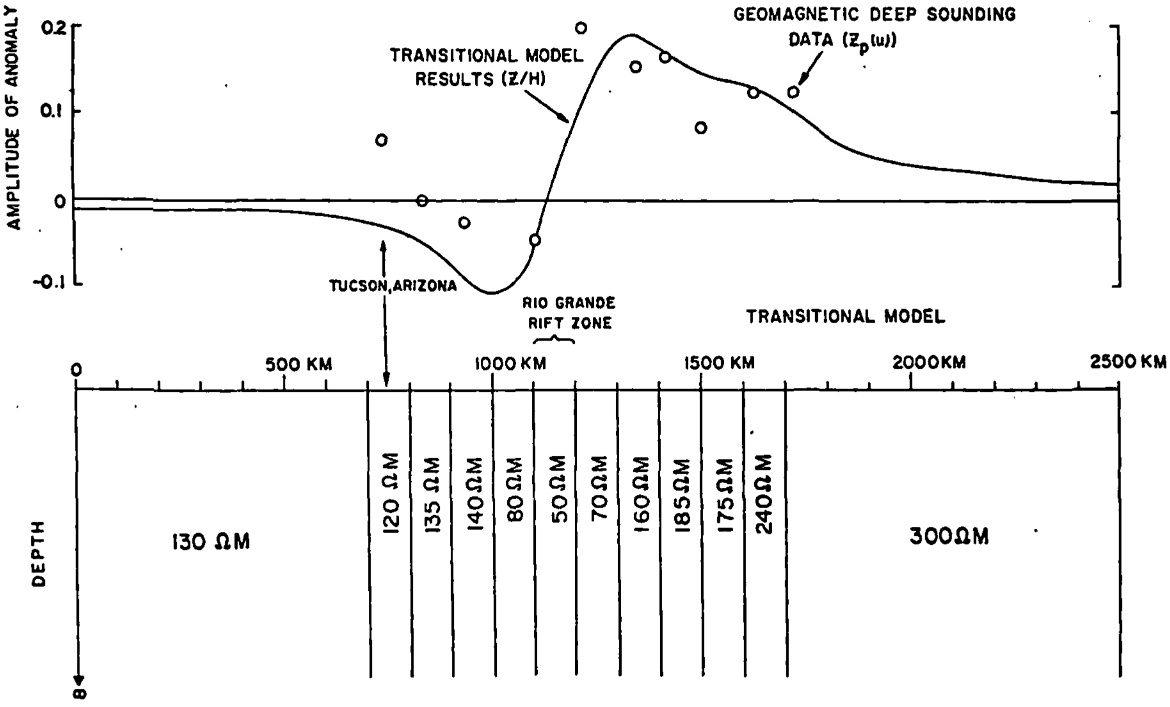

Fig. B-12.
Model used for interpretation.

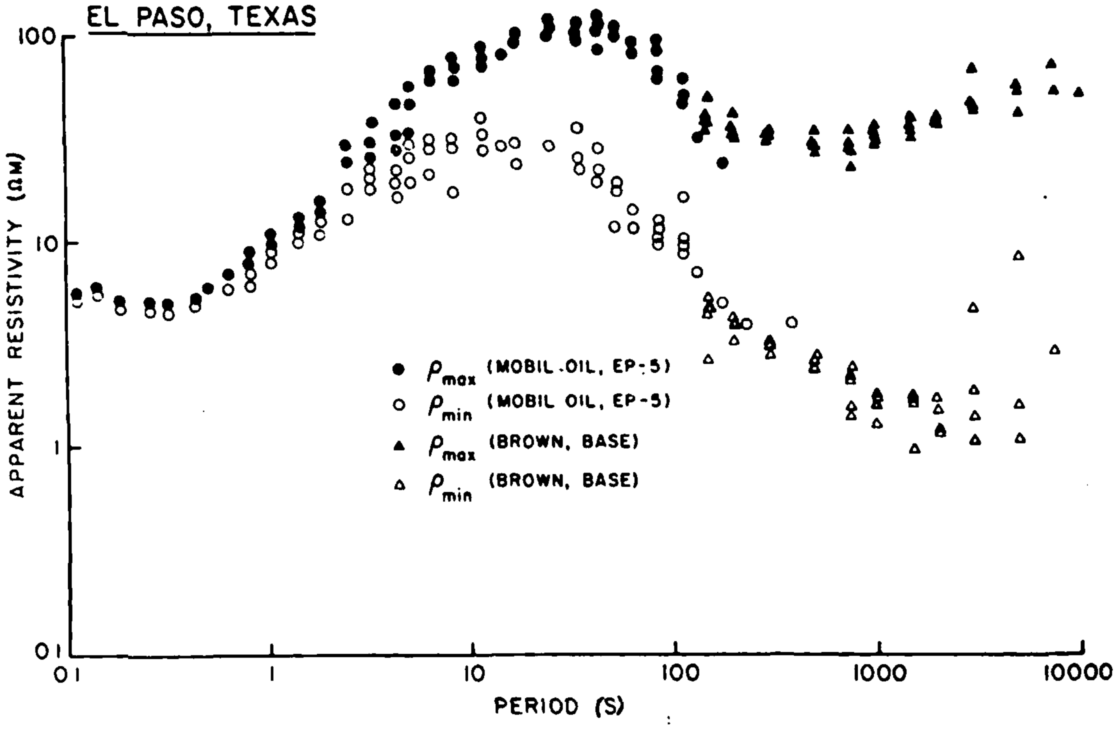

Fig. B-13.
Apparent resistivity vs period.

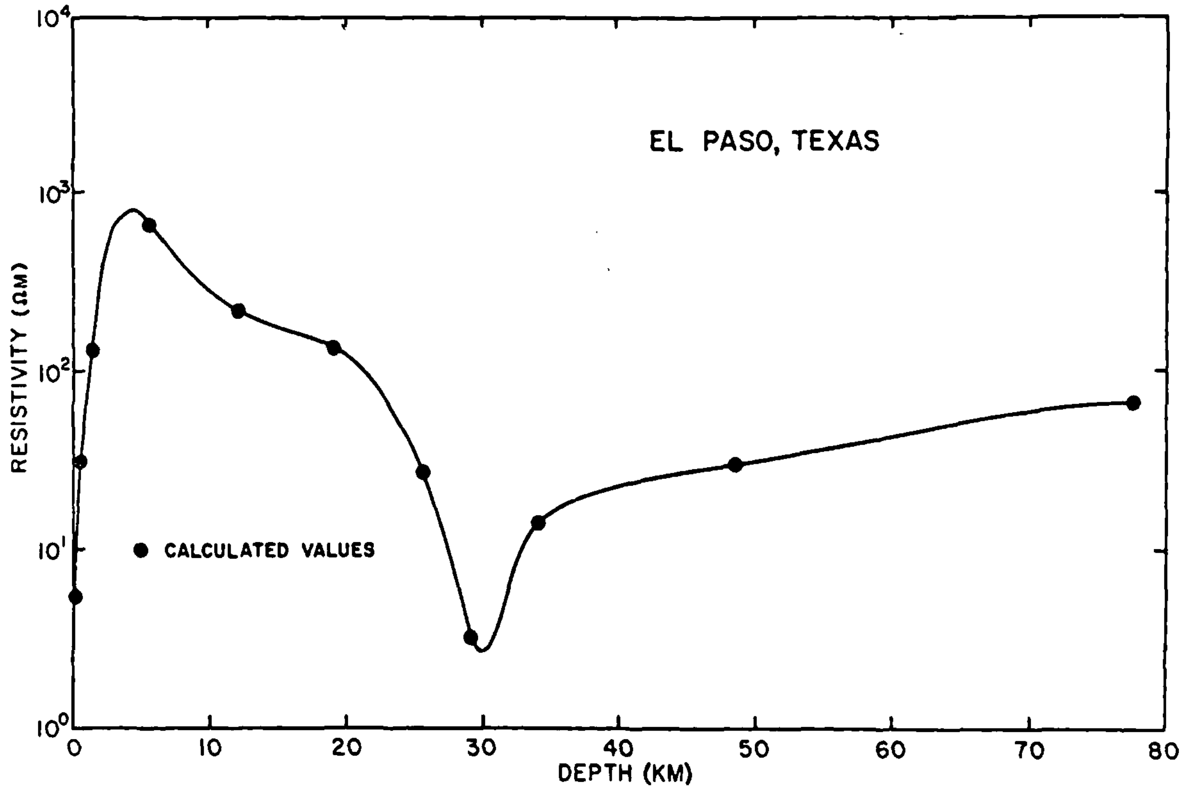

Fig. B-14.
True resistivity vs depth.

At this stage of our analysis we are probably seeing the effects of very hot, even molten materials at depths of only several tens of kilometers. A much more dramatic anomaly may be delineated beneath the deeper portion of the valley, to the west of the area surveyed in 1976.

THE STRATEGY

These simple theoretical and observational model studies suggest that geoelectromagnetic methods are quite capable of detecting the presence and defining the boundaries of major magma sources. Therefore, the following exploration strategy for employing natural electromagnetic techniques is proposed:

(1) A broad regional reconnaissance to define the characteristic variance of the electrical properties of the crust within and between geologic provinces.

(2) Detailed surveys of major geothermal centers. A typical survey area might be 100 km across with a station spacing of 5 to 20 km. This experiment would have the objective of detecting and defining the depth and lateral dimensions of major magma structures.

(3) Site evaluation studies of specific areas that may be drilled. A typical survey area may be 10 km across with a station spacing of 500 m to 2 km. The purpose of this experiment would be to laterally differentiate between zones of fractured rock and zones of more competent material.

In conclusion, it is important to recognize that natural geoelectromagnetic techniques are not strictly reconnaissance tools, but can be effectively employed at all levels of a systematic exploration program for geothermal targets.

THE TDEM METHOD

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Time-domain electromagnetic sounding (TDEM) is one of several methods for determining resistivities at considerable depths in the earth. Other methods include direct current (DC) sounding, magneto-telluric (MT) sounding, and geomagnetic deep sounding (GDS). Each of these methods has the potential capacity of locating conductive masses of hot or partially molten rocks at depths of 10 to several tens of kilometers in the earth.

In time-domain electromagnetic sounding, a time-varying electromagnetic field is generated by switching direct current on or off in a grounded length of wire, thus forming a step wave of current in that wire. A typical length for a grounded wire source, as the method is being used today, is 1 km, and currents of up to 600 A are being used routinely. Because the magnetic field reverses when the current flow in the wire changes, transient currents are induced in the earth. These are detected at a receiver site using some form of magnetometer, such as an induction coil, cryogenic or fluxgate magnetometer. The way in which the vertical component of magnetic induction varies with time is then interpreted in terms of a resistivity profile beneath the receiver.

The TDEM method was apparently devised by Prof. Tikhonov, of Moscow State University, and has been used extensively in the USSR. Early development of the method is described in a collection of translated papers by Vanyan (1967).[1] The method has been used to a lesser extent in the United States, but research on the use of the method has been carried out by the U.S. Geological Survey, Colorado School of Mines, University of Wyoming, and University of Wisconsin. The only commercial use of the method is being made by Group Seven, Inc., of Golden, Colorado. This company is making 200 to 500 TDEM soundings per month in geothermal exploration. The present state of the art as practiced in the United States is reviewed in a collection of articles edited by Keller (1976).[2]

The depth to which the resistivity profile can be determined with the TDEM method depends on the strength of the transmitter, and on the resistivity in the earth. These control the distance from the source at which the magnetic induction can be detected reliably in the presence of electrical noise. It is practical to determine the resistivity profile to a depth of about 0.4 times the offset distance from the source. With a source moment of several hundred amperes fed to a wire 1 km long, a signal-to-noise ratio of 10: or 20:1 is obtained at a distance of 10-12 km in rocks with a resistivity of 0.5-1 $\Omega \cdot m$ (for example, in the Imperial Valley), and at a distance of 80-100 km in rocks with a resistivity of several thousands of ohm-meters (for example, in areas where the surface rock is crystalline).

The distance at which measurements can be made can be increased either by increasing the strength of the source, or by using some method of detecting weaker signals at the receiver, such as synchronous stacking. The range at which measurements can be made increases as roughly the cube root of the source strength or the sensitivity that can be used in the receiver. Thus, either factor must be increased by a factor of 10 to accomplish a doubling of the depth to which interpretations can be made. Because signal stacking requires a significant amount of time to accomplish an order-of-magnitude improvement in signal-to-noise ratio, in commercial applications, it appears to be more feasible to increase source strength than to use long-term signal processing.

The largest source equipment in use in the United States today is a 0.2-MW transmitter operated by Group Seven, Inc. The source is a super-charged diesel-engined generator set with a 440-V, 3-0, 60-Hz output that is rectified and switched to form a current step in a grounded wire. The one-way current obtained from the source is 300 A at about 600 V DC (180 KVA), which, when reversed, provides a current step with 600-A amplitude. The system is highly mobile, in that the engine/generator weighs 2721.6 kg(6000 lb.). The cost of the engine/generator is approximately $20 000.

The amount of current which can be provided to the grounded wire is about proportional to the power rating of the source over quite wide ranges because the resistance of the grounded wire can be reduced to quite low values. The largest mobile diesel generator which is commercially available has a rating of 0.75 MW. Use of this generator would permit use of current steps with an amplitude of 2000 A, approximately, and provide approximately a half-order of magnitude improvement in the depth which can be reached. Because the present depth capability is 3-4 km in highly conductive geothermal areas, use of the 0.75-MW source would provide a minimum depth of sounding of 5 to 7 km.

Consideration is being given to use of intense sources operating in the multi-megawatt range. Russian scientists have been using a magneto-hydrodynamic impulse generator with a rating of 20 MW to do TDEM soundings in Central Asia in a program directed toward earthquake prediction. Measurements are made periodically, once a month, at distances of 50 to 100 km, providing resistivity soundings at 20- to 40-km depth. The system is reported at 6350.4 kg (7 tons) and is installed on two trucks (one for the MHD generator itself and the other for the power supply for the MHD magnet). This system has been offered for use in the United States on dry lease at $125 000 per year for a 2-yr lease.

Fabrication of a comparable MHD generator in the United States appears to face formidable technical problems, but a possible alternative would be the use of a gas-turbine-powered generator operating at 20 MW. Such systems are being built in a semi-mobile form for stationary power-plant application. The gas turbine is derived from an aircraft engine, and so, is relatively light. The system, configured for TDEM soundings would weigh 36 288-45 360 kg (40-50 tons), and cost approximately $4 000 000.

In summary, TDEM methods are developed to the point today where soundings can be carried to 10- to 20-km depth in areas of moderate resistivity. Deep penetration in areas of low resistivity would require development of an intense source at considerable expense. The cost would appear to be well worthwhile to people who have used the TDEM method. It is perhaps the most effective method available for use in the search for conductive regions deep in the earth.

The advantages of the TDEM method over other induction methods (MT and GDS) center on the fact that the source is controlled and known, and that the detected field is highly localized. As a consequence, the resistivity profile beneath a receiver can be determined with considerably more precision and reliability than is possible with methods based on the detection of natural fields.

In my opinion, a reasonable evaluation of the method for use in the hot dry rock exploration application could be made in an area of moderate resistivity and with hot rocks at moderate depths using equipment comparable to the strongest source in use today (0.2 MW), which can be developed at low cost. Yellowstone is an obvious candidate for such a demonstration.

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GEOTHERMAL EXPLORATION

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Geothermal fields can be due to a variety of geologic processes and thus can exist in a variety of geologic environments. Categorization of these environments (McNitt, 1970)[1] plus the consideration of the near-surface geologic cover (Strangway, 1970)[2] lead one to the conclusion that a successful exploration program will be highly dependent upon the type of geothermal field being sought. This comes about because the physical parameters associated with the various geologic configurations not only vary considerably but also can be almost diametrically adverse in their effects when considering the method to be used or when analyzing the resultant data. For example, the electromagnetic techniques used in a region covered with volcanic ash or vesicular basalt must be greatly different if there is an ample near-surface water supply containing salts from those used where the region is dry, or the seismic techniques used in a region with ample water supply must be greatly different if the cover is volcanic ash or vesicular basalts, as compared to fine-grained sediments. Thus, the establishment of a fairly detailed model of the target and its environment are essential in setting up an exploration program.

Many attempts have been made to model geothermal anomalies, and a number of geophysical methods have been applied prior to drilling. So far, these predictive endeavors have met with little success. The main problem appears to be the difficulty of distinguishing, at intermediate depths, between hot, dry, nonporous rock and cool, wet, porous rock (using porous in the macro sense to include jointing and fissuring). None of the geophysical methods are quantitatively discriminative--perhaps a combination of several could be more diagnostic.

Geothermal anomalies seem to have one thing in common--the introduction of heat by convection of either fluids or igneous rocks (see Fig. B-15). The figure shows the maximum recorded temperature in fluids as a function of the date of the most recent inflow of igneous rocks in several geothermal areas. The graph is very incomplete due primarily to the unavailability on short notice of scientifically determined dates. The Imperial Valley and Cerro Prieto temperature, undated, was placed on the graph only because it appears to be over a spreading center that is supposed to be active. The graph pictorially demonstrates the importance of exploring for geothermal anomalies in areas of geologically recent igneous activity. In addition, there is some evidence (Ishikawa, 1970)[3] that an acidic magma is more significant for generation of geothermal areas than a basic one.

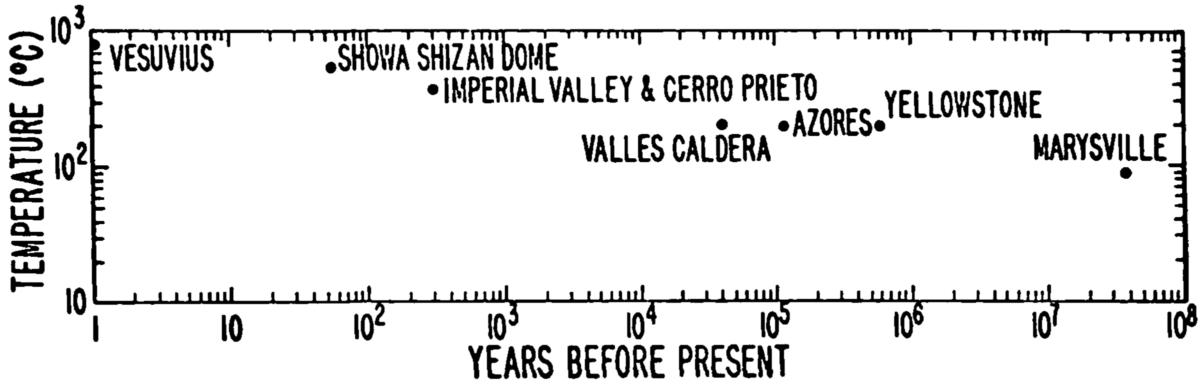

Fig. B-15.

Relation of temperature of fluids to time since the thermal event.

A reasonable model is needed for geothermal exploration. To the author's knowledge the available data for such a model are not definitive. Without such information, the best course of action appears to be the confirmation of the trend of highest temperature in youngest igneous rocks, particularly acidic ones; the search for several sites with such recently emplaced igneous rocks; and the drilling of a number of wells in several locations based upon the highest near-surface temperatures. Data from these wells and geophysical tests near the ones that meet the hot dry rock criteria should lead to diagnostic geophysical techniques for finding additional sites.

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GEOLOGIC CONSIDERATIONS FOR HOT DRY ROCK

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The strategy for hot dry rock exploration should initially be based on integrated study using geological and geophysical data including regional geology, heat flow, electrical properties, gravity, aeromagnetic, and other regional compilations —the prime basis should be geologic.

The geological considerations include:

(1) Volcanic Activity: Abundance, recency of eruption, and isotopic compositions indicative of mantle origin are important. Geological structures should include major accurate forms such as calderas and large stocks and necks. Basin lava types should be considered as well as intermediate and silicic types, because many provinces have bimodal activity, and viscous rhyolitic magmas may not reach the surface.

(2) Boundary Zones: Structural, seismic, stratigraphic, and geomorphic discontinuities and boundaries between provinces and sub-provinces should receive special attention, especially for evidence of activity.

(3) Active Faults and Folds: Active faults and related folds should be assessed by literature search and review of satellite and radar imagery, manned space, and other color and black and white photography. Faults of lengths of more than a few tens of kilometers should receive more careful analysis because they have a greater potential for mantle penetration and deep circulation. Intersections of two or more sets of conjugate fracture systems are especially favorable sites. Because many faults are genetically related to or grade into folds, the main folds should also be evaluated. Domal or anticlinal structures also may develop above concealed intrusions.

(4) Seismotectonic Relations: Should be correlated with geology for focal mechanism, fault continuity, and with boundaries of stable blocks that may provide suitable massive crystalline rock, especially those near active fault and volcanic zones.

The geological methods are appropriate, with increasing detail of mapping and scale of presentation as assessment proceeds from regional to site-specific studies. The photogeological and imagery analysis is sensitive to high-grade volcanic landforms and to high-grade to low-grade regions along active faults, and is useful to delineate zones of intensive internal shattering.

The limitations are mainly to surficial to shallow geological environments although indirect evidence of long faults and volcanic action are related to deeper processes.

The present state of knowledge for geologic methods is analysis, and for integrated studies of geological, geophysical, and economic considerations, it is adequate.

Further observations are needed to evaluate both active faults and volcanic provinces. Regional compilations using the methods of Cluff and others[1] and Slemmons [2,3] for the LASL Geothermal Test Site provide basic methodologies. An integrated study of this type for western United States and Alaska, with addition of Quaternary volcanic features, is critical for successful exploration. The studies by U.S.G.S., state divisions of mines and geology, and individual researchers should be integrated with age-dating data for the western United States regions.

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COMMENTS ON "EXPLORATION METHODS FOR HOT DRY ROCK"

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1. General

The geophysical and geological techniques and the investigation scheme for identifying likely prospects for hot dry rock geothermal resources divide naturally according to the scale of the study and the spatial resolution of the measurements.

The investigation should begin with a reconnaissance stage, using techniques with a horizontal resolution of several tens to several hundreds of kilometers. Useful input at this stage include regional studies of gravity and heat flow, and upper mantle studies of seismic velocity and Q, and of electrical conductivity. The goal of reconnaissance should be to identify broad regions of temperatures systematically high in both the crust and upper mantle.

The investigation logically proceeds to an exploration stage, using measurements with a horizontal resolution of several to several tens of kilometers. Useful input at this stage includes more detailed geologic, gravity, and heat flow surveys, and studies of upper crustal structure using seismic and electromagnetic methods. The goal of exploration should be to identify more localized regions of anomalously high crustal temperatures, say due to recent intrusives or to a magma body.

The investigation finally concentrates on the site-selection stage, using intensive surveys of selected small areas. The goal of the final stage is to select candidate sites for drilling based on a synthesis of geological and geophysical data.

2. Seismic Methods

The seismological tools for aiding in the identification of possible geothermal areas also can be divided according to the stage of the investigation.

To define the seismic velocities and Q of the upper mantle and to infer the lateral distribution of temperature at depth, one can use the phase and group velocities and attenuation of long-period surface waves over regional paths, the travel time delays and relative attenuation of teleseismic body waves, and the amplitudes and velocities of P_n and S_n waves from natural or artificial sources. Such studies have already been carried out for large portions of western North America.

At the exploration stage, a number of related seismic studies can be accomplished using a movable array, perhaps several tens of kilometers in aperture, of relatively broadband seismometers (10 s to 10 Hz). The recordings of natural events from such an array can be used to: (1) model crustal shear velocity from the dispersion of short-period Love and Rayleigh waves; (2) construct three-dimensional block models of crustal velocity using body wave travel times and the inversion technique of Aki, Husebye, and Christoffersson;[1] (3) measure anomalies in the propagation direction of short-period teleseismic body waves such as might be produced by a lens of low-velocity material in the crust; (4) measure variations in apparent Q for body waves, including possible screening of high-frequency P and S waves by magma bodies.

At the site-selection stage, detailed active-seismic surveys may be desirable. Shallow reflection surveys and short refraction lines, including fan shooting about an expected low-velocity intrusion, are two possibilities.

It should be emphasized that even the above combination of seismic measurements should be regarded only as complementary to a thoroughly integrated geological and geophysical program.

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GEOELECTRICAL EXPLORATION FOR HOT DRY ROCK

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The electrical properties of rocks, especially resistivity, vary over a larger dynamic range than any of the other physical properties characterizing the geologic system. Crustal rocks at depths of 2 to 5 km, the region of interest in geothermal power exploration, commonly have compressional seismic velocities in the range of 3 to 6 km/s, densities in the range 2.5 to 3.3 g/cm^3, magnetic susceptibilities in the range 10^{-5} to 10^{-2} cgs, but electrical resistivity commonly may range from 10^{-1} to 10^{5} $\Omega{\cdot}$m, or by 6 orders of magnitude.

Very little surface geoelectrical work has been done in areas of known hot dry rock, with the exception of work by LASL and the Univ. of New Mexico near the Valles Caldera. Problems are expected to arise in interpretation of surface electrical measurements for qualification of possible hot dry rock systems because of the opposing effects of "hot" and "dry" on the electrical resistivities. The exploration for hydrothermal systems is simplified because of the superposition of resistivity decreases from moisture and high temperature. Laboratory studies are helpful in predicting the efficiency of surface measurements to establish the presence of hot dry rock systems. Measurements needed for such predictions are somewhat sparse, but those available point out that small percentages of water and other fluids can significantly reduce resistivities at elevated temperatures and depths of 2 km or more. In addition, zeolite, serpentine, and hornblende alteration can significantly lower the resistivity of an otherwise resistive rock mass. Both of these effects will tend to mask the presence of a nearly "dry" (and most importantly, an unfractured) rock system with feasible "hotness". Examples of magnetotelluric data from the Snake River Plain show that complex geologic and mineralogic models must be considered when interpreting the data in terms of possible temperature distributions. These models and companion theoretical rock property models bear directly on the hot dry rock exploration problem.

COMMENTS ON THE GEOTHERMAL EXPLORATION PROBLEM

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It seems clear that a sound exploration program should incorporate a number of available methods. An integrated modeling effort should be used, to include all constraints in producing a composite model.

Notwithstanding the above, I will comment specifically on use of the magnetotelluric (MT) method.

The electrical conduction mechanisms, and most of the other physical parameters, for *in situ* low-permeability rock are not clearly understood, and further study is indeed in order. However, the MT method should be considered a presently viable tool for reconnaissance and detailed exploration of geothermal systems. This claim is empirically based. Through the observations of a great number of MT sites in surveys in the main U.S., Canada, and Alaska, by Geotronics, the occurrences of an anomalously shallow conductive basement zone has been found to correlate geographically with known geothermal systems in a regional sense and with other geophysical and geological data (including hot springs, etc.) in a detailed sense. Thus far, no known inconsistency has been observed in the assumed high conductivity-high temperature relationship.

The MT sounding for a given site provides (1) an estimate of true resistivity vs. depth ranging from shallow sedimentary zone to the conductive basement zone; (2) directional information on the structure, in the form of a vector defining the axis of maximum lateral change vs. depth (with 180° ambiguity), and (3) the normalized complex vertical magnetic field component which can normally be used to remove the 180° ambiguity in the lateral structural gradient. In addition to the above sounding information, the nonminimum-phase signature (discussed in the meeting) promises to be an indicator of an extremely conductive anomaly.

The present cost per MT site, including processing and interpretation, is about $1700. For reconnaissance surveys of say 10-mile site spacing, the cost would be about $170 per line mile.

It is my opinion that the MT method would serve singly as a good geothermal reconnaissance tool, providing enough information to define the regional extent of a geothermal system. The cost should be competitive with other methods, some of which would not provide as much information on the structure.

SOME COMMENTS ON ELECTRICAL TECHNIQUES USED IN EXPLORING FOR HOT DRY ROCK

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Geoelectrical and fixed-source electrical techniques have been used with some success in prospecting for deeply based hydrothermal systems, by capitalizing on the additive combination of moisture and heat, which produces anomalous low-resistivity thermal systems. However, hot dry rock systems are expected to produce a more complex picture due to the opposing hot and dry effects on apparent resistivities.

An obvious desirable capability for any deep measuring system would be the ability to discriminate between hydrothermal and dry rock geothermal systems. Normal geoelectric prospecting techniques such as magnetotellurics, or fixed-source electric and magnetic methods can delineate low-resistivity areas, but cannot provide much information as to the source, especially in complex geologic environments.

Our experience has shown that all rocks, mineralized and unmineralized, display frequency-dependent resistivity signatures.[1] Due to the differing nature of the conduction mechanisms in hot dry and hot wet rocks, it may be possible to differentiate between these two thermal sources by using spectral resistivity measurements.

If there is a consistent, measurable difference between resistivity spectra for hot dry and hot wet rocks, we have solved part of the problem. Applying this information to obtain meaningful discriminatory field results may be quite formidable. However, if a perpendicular sounding array is used in an expanding configuration (Kinghorn, 1967),[2] it may be possible to mitigate the near-surface resistivity effects and permit concentration on the features at depth.

The application of this variable-frequency, variable-spacing electrical technique could prove quite satisfactory in delineating hot dry rock environments, if the electrical conduction mechanism in this type of rock permits its detection.

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