Geothermal Exploration Techniques: A Case Study

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ABSTRACT

The objective of this project was to review and perform a critical evaluation of geothermal exploration methods and techniques. The original intent was to publish the work as a handbook; however, the information is not specific enough for that purpose. A broad general survey of geothermal exploration techniques is reported in combination with one specific case study.
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1.0 SUMMARY

A major problem with each utility which considers geothermal exploration ventures is that the methods used in exploration are newly developed, are not standardized, and use a variety of techniques to interpret the data and to arrive at conclusions. In this report I will discuss exploration techniques, interpretation of results of exploration programs, and decision making using exploration results. In addition, a case study of an exploration program will be presented. The emphasis will be on hydrothermal resource exploration, but it will have applicability to other types of geothermal resources as well.

It is now apparent that geothermal reservoirs and their immediate environments have certain specific physical characteristics which are susceptible to detection and mapping by geophysical methods. My report will be devoted to the discussion of various geophysical surveys currently used in geothermal
exploration which can provide direct information about geothermal reservoirs. No detailed discussion will be presented of the other geophysical techniques which have been utilized in past geothermal surveys or have been recommended from time to time. These include methods such as gravity, magnetics, active seismics, seismic noise, airborne infrared, microwave radiometry, and satellite imagery. None of these techniques will be discussed in detail because none of them appear to be required to bring a geophysical investigation to the point where a deep exploratory geothermal borehole can be planned and sited. In an actual survey, problems might arise which some of these techniques could help to resolve, and some anomalies in the temperature or electrical resistivity patterns might be accounted for, but the choice of technique, and the justification for utilizing it at all, must arise in and be defined by the progress of the original survey.

Thermal gradient measurements and heat flow determinations are useful in large scale regional surveys, as well as in specific reservoir studies, since anomalous conductive surface heat flow can be used as an indicator of hydrothermal activity at depth (Combs and Muffler, 1973). As geophysical exploration techniques for guiding the site selection for deep drilling shallow thermal surveys are of limited value because of their rather low effective depth of penetration and the masking effects of shallow groundwater circulation, the measurement of
temperatures in deep boreholes is the only reliable method of providing information on the base temperature (Bodvarsson, 1964) of a given geothermal reservoir.

Electrical resistivity studies have provided data for the detection and mapping of geothermal systems, for subsurface geological and structural interpretation, and for monitoring of groundwater flow patterns (Keller, 1970). Although under favorable conditions an electrical resistivity survey can provide penetration to depths of one kilometre or more, the physical property that it measures is related not only to temperature but also to porosity and formation fluid chemistry, therefore, making geological interpretations of resistivity data difficult. A considerable number of different electrode configurations (Wenner arrays, constant spread Schlumberger arrays, Schlumberger soundings, collinear arrays, dipole-dipole profiling, roving dipole arrays, bipole-dipole arrays, rotating dipole arrays) have been used in direct current resistivity surveys (Keller and Frischknecht, 1966).

During the last few years, there has been a serious effort made to test various electromagnetic methods which are designed to monitor the naturally occurring electric and magnetic fields that are observed at the surface of the earth. The development and testing of the telluric and magnetotelluric methods in geothermal exploration has been motivated partly in an attempt to find a rapid and low cost method for reconnaissance
surveys of relatively large areas and partly in an attempt to increase the depth of penetration under the conditions of high near surface electrical conductivities which usually occur in geothermal areas (Hermance, et al, 1976; Combs and Wilt, 1976).

It has been known for some time that high temperature geothermal areas are characterized by a relatively high level of microearthquake activity (Ward, 1972). The study of these microearthquakes, and their precise hypocentral locations provide the data necessary to determine any active fault zones in a geothermal area, which may be functioning as subsurface conduits for the geothermal fluids. In addition, the results of a microearthquake survey can be used to speculate on the subsurface physical characteristics of the geothermal system (Combs and Rotstein, 1976). Pálmason (1976) has suggested that the main use of microearthquake surveys, at the present time, may be to try to predict the depth of water circulation in geothermal systems, something which cannot easily be accomplished with other geophysical methods.

In order to interpret the geophysical anomalies obtained, it is essential to convert the geological models and subsurface geological formations into their equivalent physical patterns of thermal conductivity, electrical conductivity, seismic velocity, density, magnetic susceptibility, porosity and/or permeability by laboratory measurements on actual rock samples where available; otherwise by the use of data for similar
geological materials. Finally, if a geophysical survey of any kind is undertaken, it is very important to be quite clear as to the precise reasons for doing the survey and, more importantly, whether or not the particular geophysical survey is likely to make any material contribution to the detection and delineation of the geothermal system and whether or not the results of the survey can provide useful modifications to the proposed geological model of the geothermal reservoir.

The unifying theme throughout this report is the attempt to develop a better method of identifying the geothermal systems that are the target of the search and of defining potential drilling sites for exploratory geothermal boreholes. Geophysical surveys should not, however, be discontinued when the discovery well is completed but should be continued with a change in direction as pertains to the target being sought, that is, to begin to examine water recharge and nature of the heat source, to consider prediction of permeable zones for future production well drill sites, and to aid in the ongoing environmental monitoring.
2.0 INTRODUCTION

Considerable volumes of rock at high temperatures are known to exist below all major geothermal areas (Eaton, et al., 1975; Healy, 1976; Muffler, 1976). Almost any type of rock, igneous, metamorphic or sedimentary may be involved. Although there can be little doubt that some types of recent igneous intrusions in the shallow crust and the associated cooling magmas constitute the ultimate heat sources for all high temperature geothermal systems, little is known about the form of the intrusions. When the permeability of a portion of the geothermal system is sufficient due to fractures or pores, meteoric water can circulate downward through the hot rock, extract and convect some heat content of the rocks, and return to the surface through springs or boreholes as thermal water or natural steam (White, 1968; 1973). When that portion of the system produces economic flow of fluid it is termed a hydrothermally convective geothermal system.

Geothermal systems often contain distinctive and fairly easily measured discontinuities in the physical properties of the subsurface rocks (e.g., regions of high heat flow, low electrical resistivity, attenuation of high frequency elastic waves). Clearly the ease with which these anomalies can be detected depends on the degree of contrast in the physical properties of the rocks comprising the geothermal system, and the contrasts between these rocks and those of its surrounding
subsurface. Currently, an accurate and unambiguous interpretation of geophysical data is only possible where the subsurface structure is relatively simple and known from drillhole data, and even then it is by no means always achieved. However, some boreholes, i.e., direct information about the subsurface physical properties, are always necessary before a geophysical survey can be properly interpreted. Nongeophysicists, as well as geophysicists, must be aware of the fact that particular geophysical techniques and interpretation of the resulting data can (or cannot) be expected to provide useful results in given circumstances. The role of geology and geophysics in the exploration for geothermal resources has been examined and discussed in several review papers (Bodvarsson, 1970; Banwell, 1970, 1973; Combs and Muffler, 1973; Combs, 1976). The emphasis has usually been placed upon discovery of hydrothermal reservoirs.

Geothermal systems usually have irregular shapes and occur in rocks of complex structure and varying type. The current emphasis in geological and geophysical exploration is therefore upon detection of the geothermal systems and the determination of their relative physical properties, rather than on precise quantitative interpretation. Nevertheless some indication of the quality, size and depth of a geothermal system may often be obtained. In other words, geological studies and geophysical surveys are conducted in order to provide data for the location of geothermal systems, assess the nature of different portions
of the resource and to estimate locations for geothermal drillholes.

From the foregoing discussion, it is evident that the occurrence of geothermal systems, the differentiation into resource types and the subsequent development of geothermal reservoirs is more dependent on deep-seated tectonic processes and physical conditions than on any particular near-surface geological environment. However, it must be recognized that the total surface area thus far sampled by geothermal exploration is a very small fraction of the surface of the earth and the selection of regional exploration sites has been strongly biased towards areas with obvious surface thermal manifestations, i.e., near hot springs, geysers, fumaroles and pools of boiling mud. Surface manifestations may or may not reflect conditions at depth depending on the extent to which the thermal system is masked by overlying nonthermal groundwater horizons. Moreover, the presence of surface thermal manifestations implies that a geothermal system has been breached by fault movement or erosion, and its contents are being dissipated by this natural leakage. The larger the outflow and the longer period of time that the discharge has been continuing, the less are the chances that a commercially viable hydrothermal geothermal reservoir still remains.

Geothermal exploration, however, is moving beyond this stage of resource detection and assessment and has turned
toward the search for deep-seated and well-sealed geothermal reservoirs which are unmarked by any surface evidence (e.g., Cataldi and Rendina, 1973; Arnorsson, et al., 1976; Baldi, et al., 1976; Blackwell and Morgan, 1976; Combs and Rotstein, 1976; Swanberg, 1976; Williams, et al., 1976). New geothermal systems are being found by a process of geological analogy supported by geophysical measurements. However, the strategy of geothermal exploration and resource assessment is quite often hampered by the variability of the geologic environment, by a lack of understanding of the geothermal systems, by the lack of reasonable geological models to be tested by geophysical surveys, by a confusion about the results expected from a particular geophysical survey, and generally by a lack of a broad exploration experience base.

During the early development of petroleum exploration, almost every type of geophysical survey was used; however, it has been found that certain ones provide the necessary information for detecting petroleum reservoirs. A similar development is evolving in the application of geophysical techniques to geothermal exploration. In the past, there has frequently been some confusion over the precise purpose for which a given geophysical survey has been undertaken, and surveys of both conventional and innovative types - often made at considerable expense, have produced data and maps which now appear to have little bearing on the central problem of finding and delineating geothermal systems. Refinements in the geological models of the
geothermal systems, which are currently being sought (e.g., at Long Valley, California, U.S.A., Muffler and Williams, 1976) will be of value for suggesting geophysical targets, for calibrating the response of geophysical instrumentation, for explaining some of the observed non-relevant anomalies in the geophysical patterns and for constructing significant residual anomaly maps and will aid in distinguishing those portions of the systems which contain different types of geothermal resources. In order to interpret the geophysical anomalies obtained, it is essential to convert the geological models and subsurface geological formations into their equivalent physical patterns of thermal conductivity, electrical conductivity, seismic velocity, density, magnetic susceptibility, porosity and/or permeability by laboratory measurements on actual rock samples where available; or otherwise by the use of data for similar geological materials. Measurements under variable temperature, pressure and pore fluids are required. Finally, if a geophysical survey of any kind is undertaken, it is very important to be quite clear as to the precise reasons for doing the survey, and more importantly, whether or not the particular geophysical survey is likely to make any material contribution to the detection and delineation of the geothermal system and whether or not the results of the survey can provide useful modifications to the proposed geological model of the geothermal system.
3.0 PHYSICAL PROPERTIES AND GEOPHYSICAL EXPLORATION

A geophysical survey consists of a set of measurements made over the surface of the earth, in the air above and parallel to it, and in boreholes within the earth. The measurements are of the variations in space or time of one of several physical fields of force. These fields are determined, among other things, by the nature and structure of the subsurface, and because rocks vary widely in their physical properties, at least one of these properties usually shows marked discontinuities from place to place. These physical properties include thermal conductivity, electrical conductivity, propagation velocity of elastic waves, density, and magnetic susceptibility.

Geothermal systems often give distinctive and fairly easily measured discontinuities in physical properties (e.g., high heat flow, low electrical resistivity, attenuation of high frequency elastic waves). Clearly the ease with which discontinuities can be detected depends on the degree of contrast in the physical properties between the rocks comprising the geothermal system and the surrounding subsurface. Presently, an accurate and unambiguous interpretation of geophysical data is only possible where the subsurface structure is simple and known from drillhole data, and even then it is by no means always achieved.
Geothermal reservoirs usually have irregular shapes and occur in rocks of complex structure and varying type. The emphasis in geophysical exploration is therefore upon detection of geothermal systems and the determination of their relative physical properties, rather than on precise quantitative interpretation. Nevertheless some indication of the quality, size and depth of a geothermal system may often be obtained. In other words, geophysical surveys are conducted in order to provide data for the location of geothermal systems and the estimation of geothermal drillhole locations.

Considerable volumes of rock at high temperatures are known to exist below all major geothermal areas (Eaton, et al., 1975; Healy, 1976; Muffler, 1976). Almost any type of rock, igneous, metamorphic or sedimentary may be involved. Although there can be little doubt that some types of recent igneous intrusions in the shallow crust and the associated cooling magmas constitute the ultimate heat sources for all high temperature geothermal systems, little is known about the form of the intrusions. When the permeability due to fractures or pores is sufficient, meteoric water can circulate downward through the hot rock, extract and convect some of its heat content, and return to the surface through springs or boreholes as thermal water or natural steam (White, 1968; 1973).

The Geysers geothermal field in California represents a good example of the abovementioned phenomena. The steam field
is undoubtedly associated with the Clear Lake Volcanics of late Pliocene (?) to Holocene age (Hearn, et al., 1976; McLaughlin and Stanley, 1976; Donnelly and Hearn, 1976) and with a major gravity low which Chapman (1966) suggested was produced by a magma chamber at depth. From a detailed analysis of the gravity and magnetic data of The Geysers, Isherwood (1976) postulated that the gravity and magnetic anomalies are caused by a young intrusive body centered 10 km below the southwest edge of the Clear Lake Volcanics and teleseismic P-delay data indicate that the postulated intrusive body may still be partly molten (Steeples and Iyer, 1976). A gravity high separating the main gravity low from a smaller gravity low is most likely due to a dense cap rock that directs hydrothermal fluids from beneath the volcanic field southwest to The Geysers (Isherwood, 1976) through a fault zone (McLaughlin and Stanley, 1976) that remains permeable because of continued microearthquake activity (Hamilton and Muffler, 1972).

It is evident that geothermal reservoirs and their immediate surroundings have certain specific physical characteristics that are susceptible to detection and mapping by geophysical methods. The temperature within the reservoir, i.e., the base temperature (Bodvarsson, 1964; 1970), is the most important physical characteristic of a geothermal system. Simply stated, the base temperature is the highest temperature observed in the thermally uniform part of a geothermal reservoir. The physical
and chemical processes within the geothermal reservoir depend critically on this quantity, and the technique of heat extraction has to be selected with regard to these temperature conditions (in combination with other parameters, primarily permeability). Additional important characteristics of geothermal reservoirs that can be determined to some extent by geophysical exploration are the probable dimensions of the reservoir, its depth, and the necessary physical conditions prevailing within it.

From theoretical calculations, Banwell (1963) and Goguel (1970) indicate that a reservoir with a base temperature of 250°C would need to have a volume of 2 to 3 cubic kilometres in order to justify exploitation for electric power production with present day economics and technology. This then is the size of the target to be sought by geophysical exploration, remembering that some of the larger geothermal systems already explored have volumes which may be from five to ten times larger.

The geothermal reservoir rock must have an adequate and suitably distributed permeability. A good geothermal well should produce at least 20 t/hr of steam; many wells produce at much higher rates (Budd, 1973; Tolivia, 1976; Grindley and Browne, 1976; Mercado, 1976; Petracco and Squarci, 1976; Barelli, et al., 1976; Burgassi, et al., 1976; Fukuda, et al., 1976; Katagiri, 1976). The maintenance of high flow rates implies a high degree of permeability in the reservoir, with
porosity performing only a secondary part. Permeability is not a reservoir characteristic that is easy to measure using geophysical techniques (Risk, 1976).

The principal geothermal heat carrier, water, must be available in adequate quantities. As hot geothermal fluids are withdrawn from wells or from surface manifestations, the hydrological balance of the system is restored, or partially restored, by the inflow of new or recharge water (White, et al., 1971). Knowledge of water movements in geothermal systems can be obtained with geophysical techniques (Hunt, 1970; Bodvarsson, 1976; Tolivia, 1976; Gupta, et al., 1976; Macdonald, 1976; Risk, 1976).

Retention of heat is increased and the upward movement of fluids from a geothermal reservoir is restricted by a cap rock which is simply a layer of rock of low permeability overlying the reservoir. The cap rock may be formed by a stratigraphic unit (Tolivia, 1976; Grindley and Browne, 1976; Kurtman and Samilgil, 1976; Petracco and Squarci, 1976; Swanberg, 1976). A cap rock may also be produced by self sealing due to the deposition of minerals from solution, mainly silica, or by hydrothermal alteration of rocks to clays and/or zeolites (Bodvarsson, 1964, 1970; Facca and Tonani, 1967; Bird and Elders, 1976; Grindley and Browne, 1976; Kristmansdottir, 1976). Cap rocks provide a recognizable geophysical exploration target because of the considerable contrast in physical properties.
The maximum depth at which a geothermal system might be found and exploited is limited on the one hand by the probability of decreasing porosity and permeability, and on the other hand by drilling costs. A provisional upper limit under present economic and technological conditions is perhaps 2 km depth to the top of the geothermal reservoir.

Since the base temperature constitutes the most important physical characteristic of a geothermal system, thermal exploration methods such as geothermal gradient measurements in boreholes and heat flow determinations, are of primary importance. Thermal exploration techniques provide the most direct method for making a first estimate of the size and potential of a geothermal system with surface geophysical exploration. Although geophysical methods other than thermal methods only provide an indirect determination of the base temperature of a geothermal reservoir, they provide an estimate of depth, lateral extent, permeability, water supply and cap rock distribution which cannot be obtained using thermal techniques.

The application of any geophysical method, other than thermal methods, in geothermal exploration is based on the fact that the physical property of the rock that is being measured is affected to some degree by an increase in temperature (Birch and Clark, 1940; Birch, 1943; Hochstein and Hunt, 1970; Keller, 1970; Murase and Mc Birney, 1973; Spencer and Nur, 1976; Adams and Watts, 1976). In the geophysical exploration for geothermal
reservoirs, the most reliable indicator of abnormal subsurface temperatures is the direct determination of an anomalous heat flow. Any alternative geophysical indicator is less reliable since it provides an indirect determination of temperature.

For example, the application of electrical and electromagnetic methods in geothermal exploration is based on the fact that the electrical conductivity of wet porous rocks increases rapidly with increasing temperatures. Variations in electrical conductivity may be due to changes in salinity or porosity (Keller, 1970), rather than the temperature. There is no unique relationship between temperature and the electrical conductivity of the subsurface. Electrical resistivity studies have provided data for the detection and mapping of geothermal systems, for subsurface geological and structural interpretation, and for monitoring of groundwater flow patterns. Although under favorable conditions an electrical resistivity survey can provide penetration to depths of one kilometre or more, the physical property that it measures is related not only to temperature but also to porosity and formation fluid chemistry, therefore making geological interpretations of resistivity data difficult.
4.0 EXPLORATION TECHNIQUES AND METHODS

4.1 State of the Art

The known geothermal fields of the world are all associated with various forms of volcanic activity, with faulting, with graben formation, and with tilting, uplift and subsidence of crustal blocks, all of which are probably the result of processes in the upper mantle (Healy, 1976; Muffler, 1976). The rock types present and the character of the volcanic rocks ejected are no more than a reflection of the composition of the crust in the immediate vicinity. This close spatial and genetic relationship of many geothermal systems to young volcanic centers has formed the basis for a new rationale for the search for geothermal resources. This approach, developed by Smith and Shaw (1975), is to identify large, young, silicic volcanic centers which may be molten or have hot intrusive rocks at depth that can function as a heat source for the overlying or adjacent geothermal systems.

The location and definition of geothermal systems is not in a very advanced state of development. Since magmas and other tectonic activity in the crust provide the necessary heat source for geothermal systems, large scale exploration for hidden high temperature resources can be recommended in regions of volcanism. However, as noted above, most, if not all, high temperature geothermal areas show a close connection with eruptive centers that have produced silicic lava (Smith and Shaw, 1975). This
is most conspicuous in Iceland where the volcanism is predominantly mafic. Only about five percent of the lava erupted is of the silicic type; nevertheless, three or four of the largest high temperature areas in Iceland are located near volcanic centers which have had a very recent history of silicic eruptions (Bodvarsson, 1970). The general location of geothermal systems are therefore determined by the location of these deep igneous masses which are the probable heat source.

Thus, regions selected for preliminary reconnaissance for geothermal systems are being found by a process of geological analogy. In order to assess the resource potential of these geological environments, it may be necessary to complete a program of detailed geological and structural mapping accompanied by an extensive program of age dating of the local volcanism. Most geochemical investigations pertaining to geothermal systems are dependent on surface thermal manifestations, e.g., hot springs, since no surface manifestations are expected in the immediate environment of sealed geothermal systems, there is a limited necessity for geochemical studies in the exploration phase.

Furthermore, the detection of geothermal systems, even if completely sealed against convection to the surface, should not be difficult. Calculation of the conductive temperature distribution in the rock over a hydrothermal resource of moderate temperatures and size with its upper surface at two kilometres depth, indicates that the resulting temperature anomaly would
approximately double the normal geothermal gradient over an area of a few square kilometres. Thus, surface thermal gradient measurements and heat flow determinations in shallow boreholes penetrating below the level of the local groundwater disturbance should suffice to locate the geothermal system. As geophysical exploration techniques for guiding the site selection for deep drilling, shallow thermal surveys are of limited value because of their rather low effective depth of penetration and the masking effects of shallow groundwater circulation. The measurement of temperatures in deep boreholes is the only reliable method of providing information on the base temperature of a given geothermal system.

There is a large variety of geophysical methods that can, in principle, be used to map the subsurface temperature distribution and determine fluid content. The problem is to select the most suitable method from the point of view of field operations, processing data, and the interpretation of the results in terms of realistic geological models. We are therefore concerned with the identification and development of geophysical methods to determine the depth and areal extent of large volumes of hot rock within the crust associated with the geothermal systems. Because of their considerable depth of penetration, and potential for delineating fluid zones, electrical, electromagnetic, and seismic techniques are the types of geophysical surveys which are particularly suited for studying the deep characteristics.
of the system. However, to date no definitive criteria and a lack of exploration experience precludes the establishment of a unique rationale for geothermal resource assessment.

It is evident that geothermal systems and their immediate surroundings have physical characteristics that are susceptible to detection and mapping by geophysical methods. The base temperature constitutes the most important physical characteristic of a geothermal system; therefore, thermal exploration techniques provide the most direct method for making a first estimate of the size and potential of a geothermal system with surface geophysical exploration. Although geophysical methods other than thermal methods only provide an indirect determination of the geothermal system base temperature, they provide an estimate of depth, lateral extent, permeability, water supply and cap rock distribution, parameters which cannot be obtained using thermal techniques.

Electrical and electromagnetic techniques in geothermal exploration measure electrical resistivity at depth. Since the electrical resistivity of the subsurface is influenced by temperature (Keller, 1970), the discovery of a resistivity anomaly can be indicative of a temperature anomaly. Porosity, salinity of interstitial fluids, and the content of clays and zeolites, as well as temperature, have large effects on the electrical resistivity and all tend to be higher within geothermal systems than in surrounding ground. There is
no unique relationship between the temperature and the electrical resistivity of the subsurface. Nevertheless, electrical resistivity surveys have proven to be the most reliable geophysical exploration technique, with the exception of direct thermal methods, for detecting and delineating geothermal anomalies.

During the last few years, a serious effort has been made to test various electromagnetic methods which are designed to monitor the naturally occurring electric and magnetic fields that are observed at the surface of the earth. The development and testing of the telluric and magnetotelluric methods in geothermal exploration (Hermance, et al., 1976) has been motivated partly in an attempt to find a rapid and low cost method for reconnaissance surveys of relatively large areas and partly in an attempt to increase the depth of penetration under the conditions of high near surface electrical conductivities which usually occur in geothermal areas.

It has been known for some time that high temperature hydrothermal areas are characterized by a relatively high level of microearthquake activity (Ward, 1972). The study of these microearthquakes, and their precise hypocentral locations provide the data necessary to determine any active fault zones within a geothermal system, which may be functioning as subsurface conduits for the geothermal fluids. In addition, the results of a microearthquake survey can be used to speculate on the subsurface physical characteristics of the geothermal system (Combs
and Rotstein, 1976).

No detailed discussion will be presented for the other geophysical techniques which have been utilized in past geothermal surveys or have been recommended from time to time. These include methods such as gravity, magnetics, active seismics, seismic noise, airborne infrared, microwave radiometry, and satellite imagery. None of these techniques will be discussed in detail because none of them appear to be required to bring a geophysical investigation to the point where a deep exploratory geothermal borehole can be planned and sited. In an actual resource survey, problems might arise which some of these techniques could help to resolve, and some anomalies in the temperature or electrical resistivity patterns might be accounted for, but the choice of technique, and the justification for utilizing it at all, must arise in and be defined by the progress of the original thermal or electrical resistivity survey.

4.2 Future Developments in Geothermal Exploration

From the foregoing discussion, it is evident that geothermal reservoirs and consequently geothermal fields owe their existence more to deep-seated tectonic processes and physical conditions than to any particular near-surface geological environment. Since the intrusion of magma into the upper crust can produce the necessary heat source for a geothermal system, we are concerned with the identification and development of geophysical methods to determine the depth and areal extent of these large
volumes of molten rock within the crust. Because of their considerable depth of penetration, electrical, electromagnetic, and seismic techniques are the types of geophysical surveys which are particularly suited for locating deep magma chambers.

In the central volcanic region of the North Island of New Zealand, where the Broadlands, Rotokaua, Tauhara, and Waiotapu thermal areas are situated, Keller (1970) conducted a large-scale regional electrical depth sounding using the time-domain/coil technique. With this electromagnetic survey, Keller (1970) located an apparent deep heat source which has been interpreted to be a slab of basalt with a partially molten interior (Banwell, 1970). From an extensive magnetotelluric survey of the neo-volcanic zone in Iceland, Hermance, et al., (1976) have found a systematically lower resistivity than was found in the older crust and have interpreted the lower resistivity to be partially caused by a small melt fraction, i.e., several percent, of basalt in the deep crust. Zablocki (1976) has used the prominent self-potential anomalies found at Kilauea Volcano in Hawaii, U.S.A., to determine the position of magma pockets on the flanks of the volcano.

Magma chambers and movement of magma within volcanoes have been recognized using seismological techniques, e.g., the seismic prospecting carried out by Hayakawa (1970) at Showa-Shinzan in Japan and by Fedotov, et al., (1976) at the Avachinsky Volcano

Since magmas in the crust provide the necessary heat source for geothermal systems, large scale exploration for hidden high temperature reservoirs can be recommended in regions of volcanism. However, most, if not all, high temperature geothermal areas show a close connection with eruptive centers that have produced silicic lava. The general location of geothermal systems are therefore determined by the location of these deep igneous masses which are the probable heat source driving the overlying meteoric convection system (White, 1968). Furthermore, the detection of such systems, even if completely sealed against convection to the surface, should not be difficult. There is a large variety of other geophysical methods that can, in principle, be used to map the subsurface temperature distribution. The problem is to select the most suitable method from the point of view of field operations, processing of data, and the interpretation of the results in terms of realistic geological models.

In the past, there has frequently been some confusion over the precise purpose for which a given geophysical survey has
been undertaken, and surveys of both conventional and innovative types - often made at considerable expense, have produced data and maps which now appear to have little bearing on the central problem of finding and delineating geothermal reservoirs. Refinements in the geological models (e.g., Tolivia, 1976; Tomasson, et al., 1976; Bodvarsson, 1976; Macdonald, 1976) of the geothermal reservoir which are being sought will be of value for suggesting geophysical targets, for calibrating the response of our geophysical instrumentation, for explaining some of the non-relevant anomalies in the geophysical patterns and for constructing significant residual anomaly maps. In order to interpret the geophysical anomalies obtained, it is essential to convert the geological models and subsurface geological formations into their equivalent physical patterns of thermal conductivity, electrical conductivity, seismic velocity, density, magnetic susceptibility, porosity and/or permeability by laboratory measurements on actual rock samples where available; otherwise by the use of data for similar geological materials. Finally, if a geophysical survey of any kind is undertaken, it is very important to be quite clear as to the precise reasons for doing the survey and, more importantly, whether or not the particular geophysical survey is likely to make any material contribution to the detection and delineation of the geothermal system and whether or not the results of the survey can provide useful modifications to the proposed geological model of the geothermal reservoir.
5.0 GEOTHERMAL EXPLORATION CASE HISTORY: THE COSO GEOTHERMAL AREA

5.1 Introduction

Published case histories of geothermal fields are generally incomplete and only a few exist; however, the number of these publications is growing rapidly. Two of the earliest and best documented case histories are of geothermal fields in New Zealand. The Wairakei geothermal field has been summarized by Grindley (1965); the Broadlands geothermal field has been summarized by Combs and Muffler (1973). Several recent well-documented geothermal case histories have been completed either through the exploratory drilling phase or are presented as progress reports (e.g., Alfina, Italy, Cataldi and Rendina, 1973; Olkaria, Kenya, Noble and Ojiambo, 1976; Western Campania, Italy, Cameli, et al., 1976; Krisuvik, Iceland, Arnorson, et al., 1976; Marysville, Montana, U.S.A., Blackwell and Morgan, 1976; Parbati Valley, India, Jangi, et al., 1976; East Mesa, Imperial Valley, California, U.S.A., Swanberg, 1976; Raft River Valley, Idaho, U.S.A., Williams, et al., 1976; Long Valley, California, U.S.A., Muffler and Williams, 1976). Although no single comprehensive document on the Coso geothermal area has been published, a large array of technical data is available in published papers. In addition, the exploration and development of this geothermal area is continuing and much new data and technical evaluation are forthcoming. The following discussion of the Coso geothermal area is a summary of the published work.
5.2 Regional Setting and Geological Background

The Coso geothermal area is located primarily on the China Lake Naval Weapons Center in Inyo County of southeastern California (Fig. 5.1). The Coso geothermal area is situated in a tectonically active region (Hileman, et al., 1973) of young basaltic and rhyolitic volcanism (Lanphere, et al., 1975; Duffield, 1975) which has been recognized for a number of years as a potential geothermal resource area (Frazer, et al., 1943). Obvious surface manifestations of an anomalous concentration of geothermal energy include weak to moderate fumarolic activity, intermittently active hot springs, and associated hydrothermally altered rocks. Closely related evidence of a geothermal anomaly is provided by abundant late Cenozoic volcanic rocks, including a cluster of thirty-seven rhyolite domes which are indicative of recent shallow intrusion of magma beneath the area. It has been principally these geothermal features (Godwin, et al., 1971) that prompted the recent classification of the Coso region as a Known Geothermal Resources Area (KGRA).

The Coso Range and geothermal area are part of a ring fracture and volcanic system (Duffield, 1975) which straddles the boundary between the Sierra Nevada and Basin and Range Provinces (Fig. 5.1). The geologic setting of the Coso geothermal area consists of Mesozoic granitic and metamorphic rocks overlain by upper Cenozoic volcanic rocks and shallow Quaternary alluvial deposits in the scattered, small basins (Koenig, et al., 1972;
Figure 5.1 Location of the Coso geothermal system with index map of California. The more detailed map shows faults in the Coso Range area. Broad zones of arcuate faults are generalized as a single heavy line. Pleistocene volcanic rocks occur mostly within a highly faulted structural ridge in central and southern parts of the ring structure (After Duffield, 1975).
Duffield, 1975). The volcanic units (in apparent decreasing age) include: (1) widespread basaltic flows, (2) dacitic flows and tuff, and (3) rhyolitic domes and flows and basaltic cones and flows. These volcanic rocks are encompassed by an oval-shaped zone of late Cenozoic ring faulting measuring about 40 km east to west and 45 km north to south which defines a structural basin. Most of the Coso Range and a slice of the adjacent Sierra Nevada lie within this ring structure (Fig. 5.1). The youngest volcanic rocks are Pleistocene and with associated active fumaroles, occupy a north-trending structural and topographic ridge, the Coso rhyolite dome field, about 18 km by 10 km near the center of the basin.

Austin and coworkers (1971) recognized the significance of the late Cenozoic silicic volcanism in the Coso area and suggested the presence of an underlying magmatic heat source to provide energy for the geothermal phenomena at the surface. Chapman and others (1973) interpreted negative gravity anomalies in the geothermal area as possibly resulting from the youthful intrusion of underlying magma, consistent with the model suggested by Austin, et al., (1971). The research efforts of Duffield (1975) and Lanphere, et al., (1975) support this view. Other geological work in the Coso area includes a petrologic investigation of the volcanic rocks (Babcock and Wise, 1973; Babcock, 1975) in which the bimodal basalt-rhyolite is thought not to be comagmatic, with the basaltic rocks having a possible deep (mantle) origin.
In the Coso geothermal area, the ring structure and associated young volcanic rocks imply a caldera-like feature caused by uplift and fracture accompanied by extrusions and surficial subsidence. The entire area of the Coso ring structure (Fig. 5.2) has been extensively faulted with the Coso Range broken into a pattern of roughly north to northeast and northwest trending, steeply dipping faults. The geothermal area is characterized by arcuate zones (Austin, et al., 1971; Koenig, et al., 1972).

The volcanic rocks (Lanphere, et al., 1975) are a bimodal suite of rhyolite-dacite and basalt, which give K-Ar ages ranging from .04 to .96 m.y., with most between .05 and .15 m.y. The ring structure and associated volcanic rocks suggest a large underlying magma chamber that has periodically erupted lava to the surface during the past few million years. Thus a silicic magma chamber at depth is the implied heat source for the Coso geothermal system.

The youngest K-Ar age (Lanphere, et al., 1975) determined on the rhyolite domes was 41,000 ± 21,000 years B.P. for Sugarloaf Mountain which is located at the virtual center of the ring fault structure, the center of the rhyolite dome field, and is adjacent to Devils Kitchen, one of the major fumarolic areas. Fumaroles and hot springs are scattered throughout the central part of the Coso rhyolite dome field. Although geothermal activity in the form of fumaroles and hot springs has been known
Figure 5.2 Sketch map of the faults in the Coso geothermal area (modified from Duffield, 1975). Inner rectangle denotes extent of area where the detailed geophysical studies were conducted.
for many years (Frazer, et al., 1943), the geothermal manifestations were not studied in detail until the late 1960's (Austin and Pringle, 1970). A combination of field geological reconnaissance, photogeology, theoretical petrology, gravity and magnetometer measurements, and mineralogical investigations culminated in 1967 with the drilling of the Coso #1 drill hole (Austin and Pringle, 1970) into a fault zone along which the fumaroles and hot springs are localized at Coso Hot Springs (Fig. 5.2). The hole was drilled to 114 m and has a maximum temperature of 142° C.

5.3 Review of Geophysical Exploration Data

Several surface and airborne geophysical techniques have been used in order to detect and to initially determine the potential and extent of any geothermal systems in the Coso Hot Springs area. Koenig, et al., (1972) noted that color photography and snowmelt patterns (White, 1969) were of greatest utility in locating areas of presently active thermal fluid leakage. Infrared imagery appeared to be of value in delineating the arcuate structural patterns associated with the geothermal deposits (Koenig, et al., 1972).

The Coso ring structure and associated geothermal area (Fig. 5.2) is tectonically active, manifested in frequent earthquakes, as indicated by the pattern of regional seismicity shown in Figure 5.3. Epicenters from the California Institute of Technology seismograph network for the period
Figure 5.3 Regional seismicity as indicated by the epicenters for earthquakes of magnitude 2.3, located by the California Institute of Technology Seismological Network, 1953-1972 (modified from Hileman, et al., 1973).
1953 to 1972 are plotted in Figure 5.3 (Hileman, et al., 1973). These earthquakes are of Richter magnitude 3 or greater. These large seismic events appear to occur primarily outside of the immediate area of the rhyolite dome field and the attendant surface geothermal activity, as may be noted in the area demarcated by a rectangle in Figure 5.3.

Before 1974, no well-funded, comprehensive scientific study of the Coso area existed, but several investigations were made as time and money permitted. Interest naturally focused on the rhyolite dome field in the center of the Coso ring structure, because of the obvious geothermal potential of the dome field. The Coso rhyolite dome field is indicated by the rectangular area in the center of Figures 5.2 and 5.3. The regional geological and geophysical studies are summarized in these figures. The local geophysical investigations which were confined to the Coso rhyolite dome field, i.e., in the rectangular area of Figures 5.2 and 5.3, are presented in the next few pages and figures.

As already indicated, many investigators were aware that the Coso Range probably contained significant geothermal resources because of copious young volcanism, fumaroles and hot springs. The inference that a young silicic-magma chamber at some depth was the heat source responsible for the geothermal activity was drawn by early workers (e.g., Austin,
et al., 1971) and supported by later work (Koenig, 1972; Chapman, et al., 1973; Duffield, 1975). Combs (1975) found that heat flow is generally high throughout the rhyolite dome field, with values ranging from about 2 HFU to 18 HFU, all being greater than the world-wide average of about 1.5 HFU. The highest values of heat flow occur near Sugarloaf Mountain which is located at the virtual center of the ring-fault structure, the center of the Coso rhyolite dome field, and is adjacent to Devils Kitchen, one of the major fumarolic areas. Seismic noise (Teledyne Geotech, 1972), electrical resistivity lows (Furgerson, 1973), microearthquake epicenters (Combs and Rotstein, 1976) and high heat flow (Combs, 1975) are concentrated in the rhyolite dome field area (Fig. 5.4).

A detailed geothermal seismic noise survey was completed by Teledyne Geotech (1972). The results of the noise survey of the Coso geothermal area clearly show the presence of high noise levels with three separate high frequency anomalies (Fig. 5.5). The largest of these anomalies with the highest amplitude is associated with the Coso Hot Springs. Of the two other anomalies, one is close to the fumarolic area known as Devils Kitchen, while the third is not connected with known surface activity. These data imply a correlation between geothermal phenomena and high seismic noise level.

The geothermal noise survey was followed by a total field resistivity investigation (Furgerson, 1973). The granitic host
Figure 5.4 Summary map of the geophysical studies of the Coso rhyolite dome field.
Figure 5.5 Seismic ground noise map of the Coso rhyolite dome field. Contours are given in decibels relative to $1 \text{ (millimicron/sec)}^2 / \text{Hz}$ at 4-16 Hz (modified from Teledyne Geotech, 1972).
rock has an apparent resistivity of 200 ohm-m or more, whereas the surface thermal manifestations appear to have resistivities below 50 ohm-m (Fig. 5.6). Thus, from the results of the roving dipole technique there seems to be a contrast in apparent resistivities by a factor of about 10 between the normal and the geothermally effected regions. The dipole maps may be used in locating or extending some of the faults and/or the fractures which appear to control at least the surface geothermal activity and probably the deeper plumbing of the presumed geothermal system.

Combs and Rotstein (1976) conducted both active and passive seismic investigations in the central Coso rhyolite dome field. The microearthquake activity changed considerably during the periods of recording, including some days which had only a few events while others included as many as one hundred or more distinct local events per day. In order to quantify the seismicity of the Coso geothermal area, Combs and Rotstein (1976) counted events with S-P times of less than 3 seconds for the station near Cactus Peak (Station #2 in Fig. 5.7). Intermittent high noise during the local day time made event counting less certain; therefore, they examined only the number of events per day for the 12 hour period between 2100 and 0900 local time. Strain release in the Coso geothermal area seems to occur primarily in swarm-type sequences as can be noted by the continuous occurrence of microearthquakes, whereas earthquakes outside the area
Figure 5.6 Total field apparent resistivity map of the Coso rhyolite dome field. The minimum apparent resistivity in ohm-metres for the two source dipoles is contoured (modified from Fig. 21, Purgeron, 1973).
occur primarily as mainshock-aftershock sequences. The area is definitely undergoing current tectonism.

Combs and Rotstein (1976) located 78 microearthquakes ranging in magnitude from -1.0 to 2.5 out of the hundreds which were recorded (Fig. 5.7). These 78 microearthquakes include events obtained on both seismograph systems as well as events occurring throughout the total recording interval. Most of the seismic activity occurred between the two young volcanoes, Cactus Peak (97,000 yrs; Lanphere, et al., 1975) and Sugarloaf Mountain (41,000 yrs; Lanphere, et al., 1975), although all surface manifestations are observed around Coso Hot Springs and to the east of Devils Kitchen. Events clustered around the Coso Hot Springs and extending to the south are all shallow with focal depths between 1 and 3 km. Focal depths increase from the Coso Hot Springs area toward the west and northwest. Most of the events were located in the western portion of the Coso geothermal area near the zone of volcanic manifestations, that is, near the rhyolite domes. These events are usually deeper ranging from 5 to 10 km. There appears to be a positive correlation between areas of high seismic noise (Fig. 5.5) and areas of microearthquake activity (Fig. 5.7) as well as an inverse correlation between the focal depth and the amplitude of the noise.

Microearthquakes clustering around the Cactus Peak area (Fig. 5.7) were examined in an effort to compare the relative

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Figure 5.7 Epicenters of 78 microearthquakes associated with the Coso rhyolite dome field.
attenuation of events arriving at the seismograph sites along different ray paths. Ray paths, between Cactus Peak and seismograph sites #3, #8, and #7 pass through an anomalously high temperature, shallow crustal zone, whereas they do not from Cactus Peak to site #5 (Fig. 5.4 and 5.7). At seismograph station #7, the P-arrivals for eight events studied arrived slightly early, while the S-phase was quite late. Site #7 is at least 10 km from the hypocentral region for the Cactus Peak events. Ray paths may pass through regions with quite different ratios of $V_p$ to $V_S$ which could explain the P- and S-residuals.

The S-phases are attenuated at sites #3, #8, and #7 indicating that the elastic waves have passed through a high temperature, shallow crustal zone. Similar phenomena are not apparent on records obtained at seismograph site #5. These characteristics indicate a local geologic body with properties different from those of its surroundings. These anomalous seismic phenomena substantiate the high heat flow data obtained (Combs, 1975).

Using a reduced Wadati diagram and a least squares linear regression analysis, Combs and Rotstein (1976) obtained a value of 1.57 for the ration of $V_p$ to $V_S$ compared to values of 1.73 to 1.87 usually obtained in laboratory and field investigations. With the P-wave velocity of 4.75 km/sec determined from the calibration blasts, they obtained an S-wave velocity of 3.30
km/sec. These velocities infer a Poisson's ratio of 0.16 compared with values 0.25 to 0.30 which are normally observed. The low value for Poisson's ratio observed for the Coso geothermal area indicates that the shallow subsurface is either deficient in liquid water saturation or more likely that the void spaces (cracks) are filled with steam. These data indicate that the Coso geothermal system is a vapor-dominated system rather than a hot-water system.

Heat flow determinations are the most effective geophysical technique for locating subsurface geothermal anomalies. Broad regions of anomalously high heat flux can be defined by a few carefully located heat flow boreholes. If the regional heat flow so determined is significantly higher than normal, we can infer the presence of hydrothermal convective systems and/or young, hot intrusive rocks. Hence, in an earlier study (Combs, 1975) ten sites were chosen for the locations of heat flow holes. These locations were based on data from a detailed geothermal noise survey (Fig. 5.5) conducted by Teledyne Geotech (1972) and some electrical resistivity studies (Fig. 5.6) conducted by Furgerson (1973).

The heat flow sites (Fig. 5.8; Combs, 1975) were chosen such that they coincide with a number of different phenomena from the seismic noise survey and the electrical resistivity studies. Four areas were chosen on a basis of the coincidence of the following information:
Figure 5.8 Initial borehole locations in the Coso rhyolite dome field with heat flow determinations in units of μcal/cm²·sec. The symbol ◆ indicates that no geothermal gradient was obtainable from the borehole.
(a) high seismic noise--low electrical resistivity,
(b) high seismic noise--high electrical resistivity,
(c) low seismic noise--low electrical resistivity,
(d) low seismic noise--high electrical resistivity.

In addition to these four holes, six others were placed throughout the area in the presumed hot areas as well as in potentially non-productive areas in order to determine the magnitude of the background heat flow for the area. For example, one hole, site #10, was drilled into the basalt flows on the eastern edge of the Coso Hot Springs area.

Temperature measurements were completed in nine of the heat flow boreholes (Combs, 1975). The tenth hole, UTD-Coso #4, was only 7 m deep and therefore no temperature measurements were made. Below a depth of 40 m, the geothermal gradient, thermal conductivity, and therefore the heat flow values for each 10 m interval, are quite consistent. This is indicative of a steady state thermal condition in the subsurface. Heat, in the upper few hundred meters of the subsurface associated with the Coso geothermal area, is being transferred by a conductive heat transfer mechanism with a value of approximately 15 μcal/cm²-sec. This is typical of geothermal systems throughout the world and is approximately ten times the normal terrestrial heat flow of 1.5 HFU. The background heat flow for the Coso region is about 2.5 HFU. It should be noted that all the localities on land where heat flow has been reported in excess of 5 HFU have been obtained either on active volcanoes or in geothermal areas.
For example, Boldizsar (1963) reported that the heat flow in the Larderello, Italy, geothermal area varies from 6 to 14 HFU. Horai and Uyeda (1969) indicate that the conductive heat flow is 15 HFU at the Matsukawa, Japan, geothermal area; whereas, Dawson and Fisher (1964) find the heat flow as high as 40 HFU in the Wairakei, New Zealand, geothermal area. Therefore, the heat flow values obtained at the Coso geothermal area are typical of values obtained in other geothermal areas. The Coso heat flow values are significantly higher than the worldwide average and indicate that most of the region is characterized by abnormally high subsurface temperatures and high geothermal gradients.

In the fall of 1975, intensive study of the Coso ring structure was begun, including (1) geologic mapping, (2) geochemistry of the late Cenozoic volcanic rocks, (3) geochronology of the late Cenozoic volcanic rocks, (4) geochemistry of geothermal fluids, (5) further study of gravity, (6) aeromagnetics, (7) additional geoelectric and electromagnetic surveys, (8) both active and passive seismic investigations, (9) patterns of arrival times for teleseisms, (10) first-order leveling, (11) geodimeter trilateration, and (12) additional shallow heat flow determinations. These investigations involve personnel of the U. S. Geological Survey (USGS), Battelle Pacific Northwest Laboratories (PNL), China Lake Naval Weapons Center (NWC), and The University of Texas at Dallas (UTD).
To date, sixteen shallow (< 100 m) heat flow boreholes have been drilled into the Coso geothermal system. Determination of the preliminary heat flow values have been made for fourteen of the holes and these are presented in Figure 5.9. The rectangle in the middle of the figure denotes the rhyolite dome field investigated in the geophysical surveys presented in Figures 5.4 through 5.8. The geothermal gradients measured in these shallow boreholes range from 28° C/km to approximately 350° C/km. Thermal conductivity measurements were made on both cores and drill cuttings with the values ranging from 3.2 to 7.7 mcal/cm-sec-°C. As is shown in Figure 5.9, the preliminary heat flow determinations range from 2.0 to 18.0 HFU.

The available heat flow holes have been essentially restricted to the obvious thermal anomaly of the rhyolite dome field; however, in order to more accurately delineate the thermal regime of the Coso ring fracture system as defined by Duffield (1975) and to characterize the potential geothermal resources of the Coso geothermal system, there will be a need for additional shallow heat flow boreholes. These additional holes must be distributed throughout the ring structure and into the surrounding terrain. This is essential for further evaluation of the thermal regime throughout the entire Coso ring structure and for characterization of the geothermal resources through the development of a realistic thermal/geological model for the Coso geothermal system. Therefore, eight to twelve additional heat flow holes will be drilled outside the rhyolite dome field (Fig. 5.10).
Figure 5.9 Map of shallow borehole locations and preliminary heat flow value in HFU (Combs, 1975). The large oval-shaped feature denotes the approximate outer limit of the Coso ring fracture system as determined by Duffield (1975).
Figure 5.10 Approximate location of future heat flow borehole sites in the Coso ring fracture structure.
5.4 Predrilling Geological Models

Recent mapping by Duffield (1975) in the dome field has shown that the basement rocks in the vicinity of Sugarloaf Mountain and generally throughout the south and central parts of the silicic volcanic-dome field are thoroughly shattered, with large areas broken into blocks a metre or less in diameter. There is no reason to believe that this shattering does not extend to significant depth so that a borehole in the central region of the Coso rhyolite dome field most likely will penetrate shattered, permeable rock to depths of 1 km or more. The high thermal gradient and low Poisson's ratio (Combs, 1975) suggest that it is also likely that steam will be encountered at shallow depth. A major fumarolic area, Devils Kitchen lies about 1.5 km south of Sugarloaf Mountain. In addition, a heat flow borehole north of Sugarloaf Mountain used by Combs (1975) had to be abandoned when steam was encountered at about 20 m.

The thickness of a possible zone of steam is difficult to predict, but some preliminary results from the study of local earthquakes (Fig. 5.7) suggest a possible hot and dry or hot and vapor-dominated zone to several kilometres depth (Combs, 1975; Combs and Rotstein, 1976). Briefly, an anomalously low Poisson's ratio for the granitic basement rocks beneath the rhyolite dome field was observed. This anomaly may result from the presence of steam in fractures in the basement rocks (Combs, 1975; Combs and Rotstein, 1976). However, since the low Poisson's
ratio indicates unusually compressible rock, the anomaly might also be caused by large porosity resulting from the probable extreme shattering of these rocks as indicated by the geologic mapping of Duffield (1975). Such shattering and the presence of steam might together cause the observed anomaly.

Exactly what rocks will be penetrated by intermediate depth to deep boreholes at Coso will only be known by drilling, followed by a careful examination of the petrology and physical properties of the recovered cuttings and core. However, the upper Cenozoic rocks at Coso form only a thin veneer over a Mesozoic crystalline basement which is composed principally of granitic plutons and lesser amounts of metamorphic rocks. An E-W cross-section of interpretations of existing geological and geophysical data is presented in Figure 5.11. The heat source for the system is believed to be a silicic-magma chamber possibly still partially molten, at a depth of about 5 to 8 km below the surface.

Intermediate depth (1500 m) slim boreholes will provide a partial test of the current models for the Coso geothermal system by penetrating the top of what the surface geological and geophysical studies suggest may be a several kilometre thick, naturally permeable zone of hot, crystalline rocks, with or without steam-filled voids.

5.5 Future Development and Data Acquisition

Definition and characterization of the extent of any and all of the geothermal resources within the Coso ring fracture system will be dependent on the drilling of at least 4 to 6 slim...
Figure 5.11 Predrilling conceptual geological model of the Coso geothermal system.
holes. The site for the first of these slim drill-holes was recommended on October 28, 1975 by Drs. C. F. Austin, W. A. Duffield, and Jim Combs in a letter to Dr. William McSpadden of Battelle PNL. The recommended first slim hole drill site within the rhyolite dome field will serve several purposes: (1) to examine the existence of a viable heat source at depth, (2) to provide subsurface data for evaluation of the predrilling geological model, and (3) to verify the possibility of a vapor-dominated hydrothermal or hot dry rock geothermal system within the rhyolite dome field area.

The description of the tentative locations and the rationale for the six intermediate depth slim holes, including slim hole #1, are presented in summary form in Table 5.0 and diagrammed in Figure 5.12. These six holes provide a cross pattern through the Coso ring fracture system from which an E-W and a N-S subsurface thermal cross section can be derived. They provide for the examination of several combinations of geology, heat flow, electrical resistivity, seismic ground noise, gravity, microseismicity, and aeromagnetics.

Since the geology and geophysics serve not only to site the 1500-metre slim holes but also to provide a basis for extrapolation to other geothermal systems, the various geophysical surveys and slim holes must not be restricted to the obvious thermal anomaly of the rhyolite dome field. They must extend throughout the entire Coso ring structure and into the surrounding terrain, in order to obtain information on background levels.
### TABLE 5.0 RATIONALLE FOR AND DESCRIPTION OF DRILL SITES FOR SIX INTERMEDIATE DEPTH SLIM HOLES

<table>
<thead>
<tr>
<th>SLIM HOLE DRILL SITE</th>
<th>GENERAL DESCRIPTION OF LOCATION FOR DRILL SITE</th>
<th>RATIONALE FOR LOCATION OF DRILL SITE</th>
</tr>
</thead>
</table>
| 1                    | As specified in letter to Dr. William McSpadden on Oct. 28, 1975 by Austin, Duffield and Combs. | * Center of thermal anomaly in zone of high heat flow.  
* Center of resurgent ridge and associated rhyolite dome field, within Coso ring fracture system.  
* Zone of electrical resistivity low and seismic noise high.  
* Optimum location for high temperatures. |
| 2                    | North end of Upper Cactus Flats, NW of shallow heat flow hole PNL-1. | * North side of resurgent ridge, within Coso ring fracture system.  
* Examine three dimensionality and subsurface distribution of the thermal anomaly.  
* Penetrate unshattered basement rocks in northern part of rhyolite dome field. |
| 3                    | Near shallow heat flow hole PNL-5. | * West side of resurgent ridge, within Coso ring fracture system.  
* Provide subsurface thermal cross section.  
* Determine subsurface environmental conditions.  
* Examine effects of deep ground water recharge from Sierra Nevada-Owens Lake. |
| 4                    | East of UTD-Coso 10 shallow heat flow hole in 3 my. old lava flows. | * East side of resurgent ridge, within Coso ring fracture system.  
* Provide subsurface thermal cross section.  
* Examine subsurface environmental conditions.  
* Determine thermal pattern where ground water recharge may be limited. |
| 5                    | Etcheron Valley. | * Determine the physical properties and subsurface environmental conditions of the basement rocks outside of the Coso ring fracture system. |
| 6                    | West end Airport Lake in Pleistocene lava flows. | * South side of resurgent ridge, within Coso ring fracture system.  
* Examine the subsurface environmental conditions of recent lava field.  
* Examine the effect of the major WNW fault zone on the subsurface temperature distribution. |

* Location of drill sites indicated schematically in Figure 5.12

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Figure 5.12 Proposed drill sites for six intermediate depth slim holes in the Coso geothermal system.
of heat flow and other geophysical parameters. The tentative drill sites for the six intermediate depth slim holes (Fig. 5.12), are therefore appropriately spread over the entire Coso ring structure and not merely concentrated in the central silicic volcanic dome field.
6.0 REFERENCES


Duffield, W. A., 1975, Late Cenozoic ring faulting and volcanism in the Coso Range area of California: Geology, v. 3, p. 335-338.


