GEOPHYSICS AT THE GEYSERS

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INTRODUCTION

This chapter is intended to summarize the geophysical work carried out at The Geysers. The primary purpose is to present a summary of the geophysics carried out to define the local geology, the location and characteristics of the reservoir, and the heat source. Unfortunately, a significant amount of this information is not in the public domain and is not reported here. In general, the work that is reported was not focused on the regional scale but was aimed at determining the nature of the geothermal resources and/ or for monitoring the reservoir parameters. We first discuss the early history of the geophysical work at The Geysers, before the resource was heavily commercialized; we then summarize the work that was carried out after The Geysers came into significant production. After the history section we report the gravity and magnetics, electrical methods, and finally the seismic methods. We conclude with a brief summary and recommendations for future work.

PRE-1972 GEOPHYSICS AT THE GEYSERS

By far the largest portion of the geophysical work at The Geysers has been done since 1972. This work has been more varied, comprehensive, and better known than the earlier work because much of it has appeared in U.S. Geological Survey Professional Paper 1141 (McLaughlin and Donnelly-Nolan, 1981), in various papers published by the Geothermal Resources Council, and in other scientific journals. Post 1972 work will be only briefly mentioned in this section, but it will be discussed in the latter part of this chapter.

To the best of our knowledge, the first known geophysical work in this area was one private petroleum-related aeromagnetic survey and two gravity surveys carried out by two different investigators. One of these investigators, Robert Bowers (1958), obtained gravity data along State Highway 20, north of Clear Lake, as part of his thesis concerning geologic structure in northern California. The other investigator, J.F. Evernden, of the University of California at Berkeley, occupied a number of gravity stations along widely-spaced lines in northern California, also in the late 1950s. One line of the Evernden stations passed through Jimtown, Anderson Springs, Loch Lomond, and Lower Lake. This line passed just east of Mount Hannah near the center of the large gravity minimum that was later mapped in this area. However, these gravity readings were not reduced and the work was not published. These data were made available to the California Division of Mines and Geology (DMG) in about 1964 by Howard Oliver of the U.S. Geological Survey.

The first detailed published ground geophysical survey was the 1963 California Division of Mines and Geology (DMG) gravity survey, begun in connection with a mapping project in progress at that time in the Kelseyville 15-minute quadrangle (McNitt, 1968). The purpose of the gravity survey was to provide data that might be helpful in studying the geologic structure of the area. The survey was not aimed specifically at the geothermal resource. In fact, at that time many people believed that The Geysers steam field was a very limited resource, probably restricted to the immediate vicinity of the Big Sulfur Creek fault zone.

By about 1965, a reasonably good regional gravity map of the area had been completed (Chapman, 1966). This gravity map showed a major negative anomaly centered northeast of The Geysers. This anomaly could not be explained easily by the surface geology, but it appeared to be closely associated with the geothermal phenomena in the area, including The Geysers, and possibly the Clear Lake Volcanics. It was reasonable to believe that if this anomaly represented the heat source for the geothermal phenomena, it would have an important bearing on future geothermal exploration in the area. The map was published in 1966 to attract other investigators who might be interested in applying their particular expertise and methods to help explain the gravity anomalies.

After 1966, additional gravity data were obtained and reduced throughout The Geysers region to be used also for the compilation of a series of 1:250,000 scale gravity maps of California. The Santa Rosa sheet, which includes The Geysers area, was one of these (Chapman and Bishop, 1974). In the late 1960s the gravity efforts of DMG and the U.S. Geological Survey were greatly aided by funds from the U.S. Army Map Service, which were used to acquire new data over all of California. This funding also enabled DMG to cooperate with the U.S. Geological Survey to utilize computer methods in the reduction of all old and new gravity data in the state, including that in The Geysers area.

In 1968, DMG completed an aeromagnetic survey of the Geysers-Clear Lake area utilizing a light aircraft, and a fluxgate magnetometer (Chapman, 1975). This survey consisted of northeast-trending flight lines spaced about 3 miles apart. Navigation was done by noting landmarks along the flight paths. The magnetic data revealed strong magnetic anomalies associated with ultramafic rocks (serpentinite) in the area, but did not show anomalies that corresponded to the major negative gravity anomaly.

Other geophysical work done prior to 1973 includes microearthquake surveys by Lange and Westphal (1969), and Hamilton and Muffler (1972), discussed below, also recorded microearthquakes. A summary of the results of the known geophysical surveys in the area up to about 1972 was given in Chapman (1975).

The geophysical investigations that were initiated beginning about 1972 by the U.S. Geological Survey, universities, and others are discussed in more detail below.

GRAVITY AND MAGNETIC METHODS

Gravity and Magnetic Data

Gravity data obtained by several different investigators in The Geysers area beginning in 1963 have helped to identify and model the source of heat for the geothermal phenomena and have also been used to study the steam reservoir. The results of the gravity studies, which were done early in the history of geophysical investigations in The Geysers area, showed much promise and provided the impetus for much of the geophysical work that followed.

The initial gravity survey in the Clear Lake-Geysers area done by the California Division of Mines and Geology revealed a negative anomaly with an amplitude of about 25 milligals (mGal) centered near Mount Hannah (Chapman, 1966). It was clear from known geology and rock density considerations that although the Clear Lake Volcanics may cause a small part of the anomaly, most of it cannot be explained by rock units that are exposed on the surface. The geothermal phenomena, the relatively young volcanic rocks, and the gravity anomaly all suggested the presence of a low-density heat source below this area, i.e. hotter molten rocks would be less dense.

Additional gravity data were obtained by the U.S. Geological Survey (Isherwood, 1975) and later by Denlinger (1979). These investigators made more detailed interpretations of the data. Isherwood (1975) observed that the gravity anomaly is divided into two parts: a major anomaly centered near Mount Hannah, and a smaller anomaly near The Geysers geothermal field (Figure 1). Isherwood (1976) and Chapman (1975) both concluded that the most likely cause of the main anomaly is a partially molten intrusive body centered beneath the vicinity of Mount Hannah, and both proposed models that would satisfy the observed anomaly. On the basis of these models, the center of the low-density mass is believed to be at a depth of between 6 and 14 km, and the top perhaps as shallow as 4 km (Isherwood, 1981).

Isherwood (1976) also suggested that the smaller negative anomaly near The Geysers geothermal field might be caused in part by the low-density steam field itself in combination with a possible cupola of the magma chamber that reaches higher in the earth's crust in this area (Figures 1 and 2). This idea of a cupola of the magma chamber is supported by the discovery of intrusive rhyolite in some of the drill holes at The Geysers (Schriener and Suemnicht, 1980). These rocks probably represent part of the source of the gravity anomaly. This rhyolite is apparently too old (1.6 m.y. to 2.5 m.y.) for these intrusive rocks to be related to a present-day magma chamber, but they may represent an earlier pulse of magma from an intrusive system that is still active today.

Denlinger and Kovach (1981) also analyzed the 3 to 5 mGal negative anomaly near The Geysers geothermal field (Figure 2). They concluded that the anomaly coincides with the present and past locations of The Geysers hydrothermal system, but that there might also be a component from a deep low-density source. They also produced a possible model for the field that has a volume of about 100 km^3 with a density contrast of -0.06 g/cm^3. However, the anomaly lies mostly southwest of the present steam field and it also extends for some distance both northwest and southeast of the field (Figure 2). This sug-

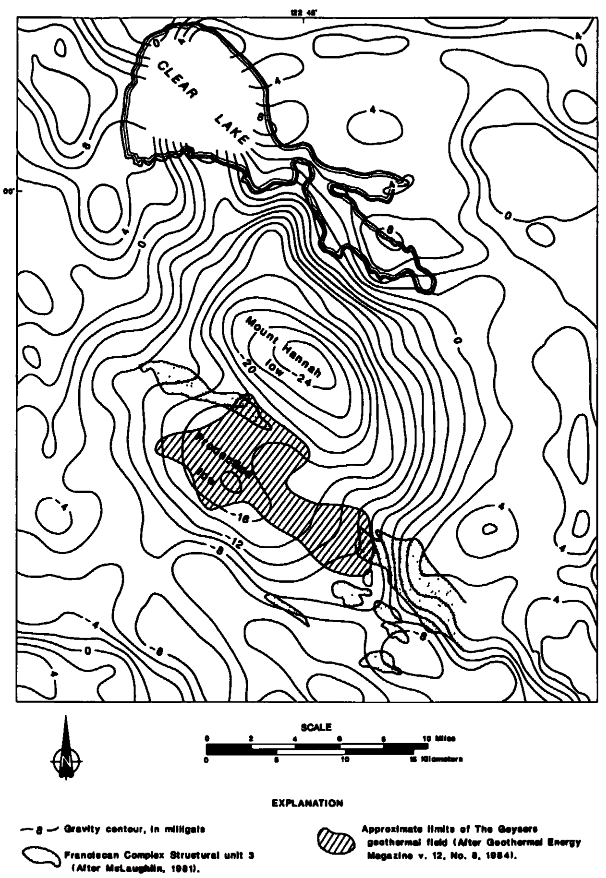


Figure 1. The Geysers area, California, showing residual gravity based on reduction densities of 2.67 g/cm^3. Contour interval, 2 mGal. From Isherwood (1975).

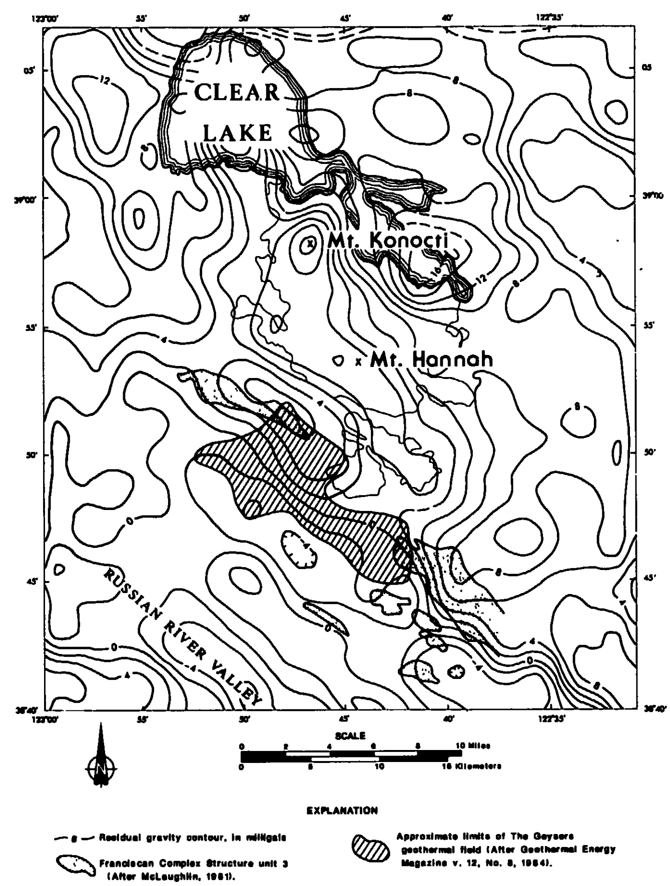


Figure 2. Residual gravity (at 2.67 g/cc) in the vicinity of The Geysers geothermal field, after removal of the field from a sphere buried at 13.5 km. Contour interval 2 mgal. After Isherwood (Figure 16, 1975).

gests the possibility that at least part of the anomaly may be caused by a melange unit, or some other unit, in the Franciscan complex.

An exposure of high grade Franciscan metamorphic rocks mapped by McLaughlin (1981) along the gravity ridge that separates the two negative anomalies also complicates the interpretation of the smaller negative anomaly (Figures 1 and 2). These rocks could be at least partly the cause of the gravity ridge, as similar rocks are associated with positive gravity anomalies in other parts of the Coast Ranges (Griscom, 1973). More detailed knowledge of the geologic structure and the densities of the various rock units is needed to determine how much near surface rocks influence the interpretation of the gravity data.

Aeromagnetic surveys were flown in 1968 by the Division of Mines and Geology (Chapman, 1975), and by the U.S. Geological Survey (1973) to assist in the interpretation of the geology of the Clear Lake-Geysers area and to help answer some of the questions raised by the gravity data. Most of the magnetic anomalies shown by these two maps evidently are caused by ultramafic rocks (serpentinite), but some are caused by the Clear Lake volcanic rocks (Isherwood, 1976). Isherwood (1976) studied the magnetic data in some detail and produced a pseudogravity map (Figure 3). He concluded that there is little resemblance between the pseudogravity map made from magnetic data and the gravity maps. Therefore, there is no evidence for a magnetic anomaly that would correspond to the major negative gravity anomaly.

Isherwood (1975) also showed that none of the magnetic anomalies in the vicinity of The Geysers have sources that are more than a few km deep in contrast to deeper sources both northeast and southwest of the area. In contrast to this, the source of the main negative gravity anomaly may have a center of mass as deep as 13.5 km (Isherwood, 1975). The lack of deep magnetic sources suggests that the Curie isotherm may be elevated in The Geysers area, as one might expect if there is magma at shallow depths in this area.

ELECTRICAL METHODS

Electrical Geophysical Surveys in The Geysers-Clear Lake Region

A variety of electrical geophysical surveys have been done in The Geysers-Clear Lake region of northern California for geothermal research and exploration purposes.

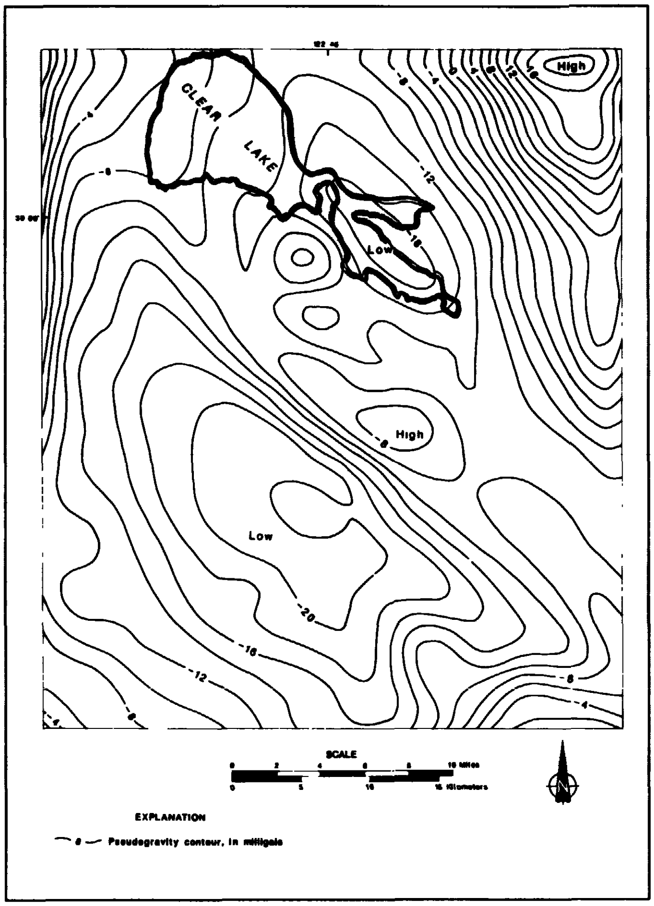


Figure 3. The Geysers area showing pseudogravity derived from filtered aeromagnetic data (5-km cutoff); density contrast. 0.15 g/cm^3; magnetization contrast, 0.003 cgs units; Contour interval, 2 mGal. (From Isherwood (1975).

Electrical methods have been successful in mapping some important details of the broader geology and localized structures that are related to steam fields. However, one enigma concerning the area, the possible existence of a major magma chamber, has not been resolved with past electrical geophysics. The key utility of electrical geophysics has been to provide structural details and to constrain the gravity models that have been cited as the main evidence for a magma chamber.

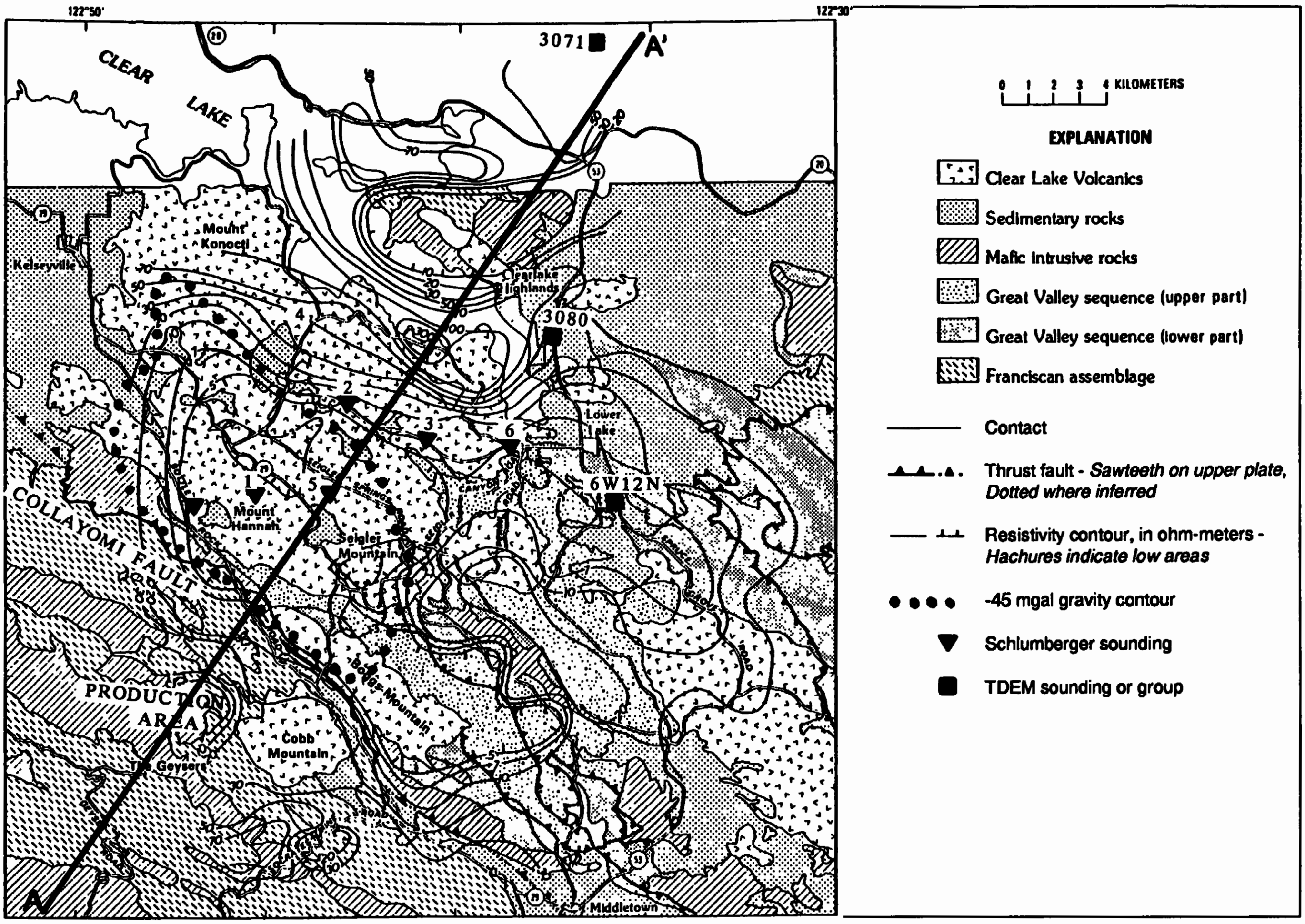
Electrical geophysical methods have been applied in a large number of geothermal areas worldwide (Lumb, 1981) because of the desire to develop a method for estimation of temperatures in possible geothermal settings and for mapping geologic elements, such as faulting and fracturing, important to evaluation of a possible resource. Electrical resistivity in rocks is largely controlled by pore fluids and by fluids loosely bound in clay minerals, although conductive carbon and metallic minerals may also radically reduce resistivities. A variety of electrical geophysical methods have been employed in The Geysers-Clear Lake region including direct current (DC), magnetotelluric (MT), time-domain electromagnetic (TDEM), and self-potential (SP) surveys.

A key requirement for interpreting electrical geophysical studies of a geothermal system such as that at The Geysers is knowledge of the correlation of resistivity with lithology. The Geysers-Clear Lake region is described in Chapman and others (this volume) and the general geological features are indicated in Figure 4. The resistivity of the Franciscan complex is quite variable, but generally in the range of 20 to 100 ohm-m in The Geysers region (Stanley and others, 1973; Keller and others, 1984). The Great Valley sequence is Late Jurassic to Late Cretaceous in age and consists of coarse, ophiolite-breccia and tuff near its base (McLaughlin and Ohlin, 1984) overlain by conglomerate, mudstone, and sandstone. It is separated from the Franciscan complex by the Coast Ranges ophiolite (exposed near the Collayomi fault, Figure 4), that is believed to represent the oceanic crust upon which the forearc complex of the Great Valley sequence was deposited.

Bipole-Dipole and Schlumberger Resistivity Surveys

The first electrical surveys in the region were those of Stanley and others (1973) who employed bipole-dipole mapping methods (Al'pin, 1966) and DC soundings using the Schlumberger array (Keller and Frischknecht, 1966), to study the shallow- to intermediate-depth (down to 5 km) structures in the region. In bipole-dipole resistivity mapping, the total electric field from a 3 to 5 km long current bipole is measured using short (typically 30 to 100 m) electric dipoles. The measurements are converted to "apparent" resistivities by reference to the field that would be measured over a homogeneous half-space. In the survey by Stanley and others (1973), five separate source bipoles were used to cover the main part of The Geysers-Clear Lake region. By using repeat measurements at individual stations from separate bipole sources, the individual resistivity maps were combined into a composite resistivity map by smoothing contours between areas of overlap from the five separate contour maps. The Schlumberger soundings (Figure 5) showed that the Clear Lake volcanic rocks are moderately resistive (30 to 500 ohm-m) and relatively thin (less than 500 m); for this reason, measurement sites very near the bipole source were not used in producing the contour map, so that deeper resistivity patterns could be investigated.

The bipole-dipole resistivity surveys revealed a large resistivity low of 2 to 5 ohm-m that trended northwest-southeast and appeared coincident with the most significant part of the gravity low centered on Mount Hannah (Figure 1). The low resistivities are typical of those in the very shale-rich Great Valley sequence, as indicated by electrical well logs from the Great Valley sections east of Clear Lake. However, recent mapping by McLaughlin and Ohlin (1984) suggests that the conductive section may be composed of carbonaceous shales that also occur in the Franciscan in this area.



Figue 4. Generalized geologic map (from Stanley and others, 1973) of The Geysers-Clear Lake region with apparent resistivity 5 ohm-m contour (dashed) from Stanley and others (1973). The dotted contour is the approximate position of maximum gradients from bouguer gravity map (data from U.S. Geological Survey, Don Plouff, pers. comm.), represented by the -45 mgal contour. Solid triangles are the locations of Schlumberger resistivity soundings; solid squares are the location of selected TDEM soundings or groups of soundings from Keller and others (1984); cross section A-A' is utilized in Figures 8 and 9.

In order to investigate the depth extent of the resistivity low, seven Schlumberger soundings were made (locations shown in Figure 4, sounding curves in Figure 5). The data for sounding no. 1 were extended by using bipole number 1 as the current input and making electric-field measurements perpendicular to this bipole, resulting in "equatorial dipole" data (Al'pin, 1966) that is equivalent to Schlumberger sounding data. Interpreted results from sounding number one indicates that the conductive section in the Mount Hannah area has a minimum thickness of 5 kilometers.

Other detailed resistivity surveys using bipole-dipole methods were completed in the production area west of the Collayomi fault. These data indicated that the Franciscan melange units in the production area are more highly variable in resistivity than the conductive Great Valley and Franciscan section in the Mount Hannah region. The more typical resistivities for the production area rocks are 20 to 100 ohm-m, with several distinct highs and lows; the most anomalous part of the production area is a less than 10 ohm-m region that is partially coincident with the Dianna Rock fault zone mapped by McLaughlin and Stanley

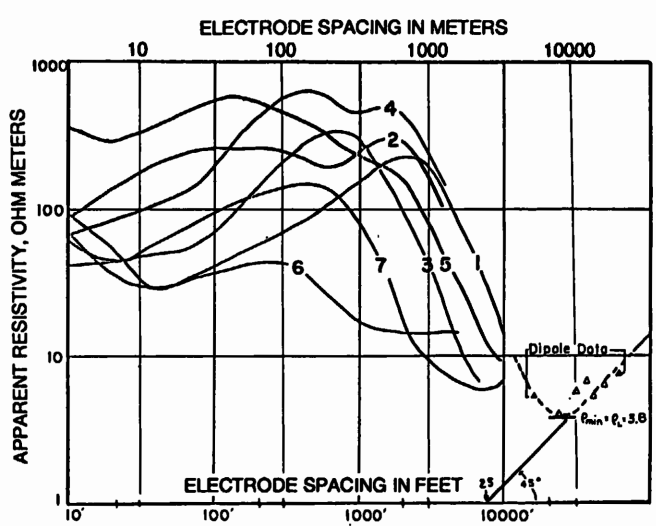


Figure 5. Schlumberger sounding curves (locations in Figure 4).

(1976). The lower resistivities appear to correlate with unmetamorphosed graywacke in the Franciscan and the higher values with greenstones and metagrawacke (McLaughlin and Ohlin, 1984). Keller (1984) has discussed other bipole-dipole data from the production area that show similar resistivity structures.

Time Domain Electromagnetic Soundings (TDEM)

Keller and others (1984) summarize the results from 247 TDEM soundings in the Clear Lake region. Although most of the surveys were done in the region east and northeast of Clear Lake, approximately 50 of the soundings were done in the area that overlaps with the resistivity mapping of Stanley, Jackson and Hearn (1973). The TDEM method employed by Keller and others (1984) utilized a large grounded ("Megasource") current dipole of 1 km length and with a input current of 2000 A. The vertical magnetic field was measured using a Josephson junction (cryogenic) magnetometer. The averaged time-domain signals for each sounding site were converted to apparent resistivities by using the appropriate asymptotic field relationships for a homogeneous earth. A sample TDEM sounding representing apparent-resistivity versus time is shown in Figure 6. The raw signal must be deconvolved to remove the effect of the measurement system transfer function. All of the soundings were modeled with a generalized linear inversion technique, using layered models, typically resulting in three layers that are similar to the models derived from the deep Schlumberger soundings of Stanley and others (1973). Models of four TDEM soundings with the induction electric log from the hole are shown in Figure 7. Note the good agreement between the first layer of 15 to 30 ohm-m resistivity (Clear Lake Volcanics) and the second layer of 3 to 9 ohm-m that agrees with the 5 ohm-m values found in bipole-dipole resistivity mapping on Boggs Mountain. Key sounding models from a north-south profile were presented by Keller and others (1984) and, in other instances, soundings within a given township were presented on aggregate plots (Figure 4). Models for TDEM soundings in the area north and east of Clear Lake indicate a 10 to 15 unit thick conductive section separated from the Mount Hannah conductive region by a northwest-trending resistive zone (40 to 600 ohm-m) along the southeast side of Clear Lake. The depth to the bottom of this conductive section east of Clear Lake agrees with the modeled depth to magnetic basement, assumed to be oceanic crust, in the area (McLaughlin and Ohlin, 1984).

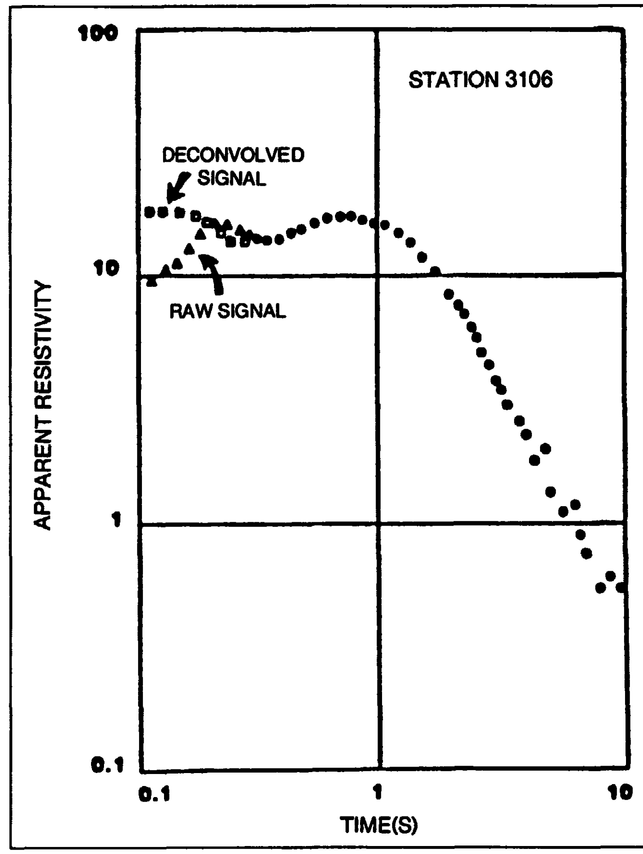


Figure 6. Example of TDEM sounding from Clear Lake region. From Keller and others (1984).

Self-Potential Measurements

Self-potential (SP) electrical surveys have been employed in past geothermal exploration (Corwin, 1976). The flow of geothermal fluids through a porous host rock should produce measurable voltages at the surface, if the system is shallow enough (Zablocki, 1976). A detailed SP survey was conducted by the USGS in the Mount Hannah region in 1973 (unpublished data). This survey produced results that were repeatable during reoccupation of individual survey loops. Anomalies of up to 300 mV were mapped in the Mount Hannah region. However, it was inferred that most of the anomalies were due to topographically controlled groundwater flow in porous, near-surface strata consisting of Clear Lake Volcanics and Great Valley sedimentary units. Subsequent drilling has shown that permeability of units on top of the geothermal system in the Mount Hannah region is very low and resistivities are also very low, producing conditions unfavorable for use of SP measurements in locating the tops of discrete geothermal anomalies.

The SP method has also been used to map faults where the changes in water flow patterns and resistivity affect the natural electric potentials. Another method for locating faults that has not been used in The Geysers region is telluric profiling, which has been used in other geothermal areas for this purpose (in the Raft River area of Idaho, for instance, Williams and others, 1976). The commonly employed version of telluric profiling uses an in-line set of measurement dipoles to measure gradients in the electric field that are related to geologic contacts and faults. This rapid, reconnaissance electrical method should be of con-

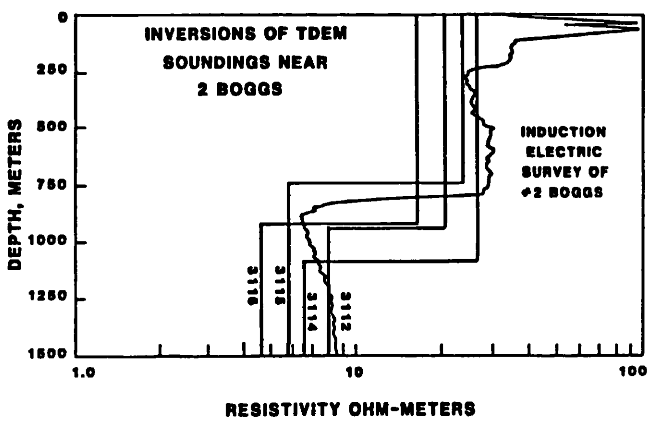


Figure 7. Inversions of four TDEM soundings from Boggs Mountain (Figure 4) and induction electric log from Boggs No. 2 well Reproduced from Keller and others (1984).

siderable value in mapping permeable fault and fracture systems in The Geysers-Clear Lake region.

Magnetotelluric Surveys

Magnetotelluric (MT) soundings are frequently used to investigate the crust at large depths (Kaufman and Keller, 1981) and have been used extensively in studying geothermal areas (Keller, 1984). The only published MT results from The Geysers-Clear Lake region are described by Kaufman and Keller (1981). Forty soundings were done over the region, including several in The Geysers production area. This initial survey was followed by a more extensive, but unpublished survey (G. V. Keller, pers. comm.). In the initial survey described in Kaufman and Keller (1981), one-dimensional (1-D) modeling resulted in a four-layer model consisting of a resistive upper layer correlative with the Clear Lake Volcanics and parts of the Franciscan complex, a second layer with low resistivity representing conductive parts of the Great Valley sequence and Franciscan complex, a third layer representing the resistive crust below the Great Valley and Franciscan deposit, and a fourth, conductive layer representing possible thermal effects. These models indicated an anomalously shallow fourth conductive layer (6.4 km depth) in the area just south of Clear Lake. However, the higher quality data from more recent surveys, together with more rigorous modeling, (G. V. Keller, pers. comm., 1990) show that the structure on this fourth layer may be related to the shallower, thick conductor associated with the Great Valley and Franciscan complexes. Other results from this more recent MT survey are not known.

An example of a high-quality MT sounding (provided by Unocal Geothermal Division) from an unspecified location in the Clear Lake volcanic field is shown in Figure 8. On the assumption that the electrical grain of the region is two-dimensional (2-D), the two curves show MT resistivity data rotated to the strike direction (approximately NNW, as in Figure 4) called the transverse electric (TE) direction and the data rotated normal to strike, called the transverse magnetic (TM) direction. Although 2-D analysis of these data are called for, layered (1-D) models for the two curves are indicated on Figure 8. The thickness of the elongate, narrow conductive structure that occurs in the Mount Hannah region will be most accurately represented in 1-D models of the TM data (Wannamaker and others, 1984). As indicated in Figure 8, this value is about 7 km, compared to a minimum of 5 km from the Schlumberger sounding data.

The key question that might be resolved with deep MT soundings is the possible existence of a magma chamber beneath The Geysers-Clear Lake region as proposed by Chapman (1975) and Isherwood (1976). If magma does exist beneath the region, its resistivity would be 0.3 to 3 ohm-m, depending upon percentage of partial/total melt and water content (Wannamaker, 1986). A zone of partial melt and steam filled pores could have higher resistivities. In the Mount Hannah region where the resistivity of the Great Valley-Franciscan rocks is 3 to 5 ohm-m, it would be difficult to detect melt components that were contiguous with these rocks. If the assumed base of these conductive rocks is at about 7 km, the resistive zone beneath these conductive rocks would have to be greater than 5 km before a layer of magma beneath it could be detected as a separate conductor. The MT data in Figure 8 do not show any evidence for such a conductive magma layer at depths of less than 20 km. This latter conclusion is based upon the simplification that both the upper crustal conductor and the magma are horizontal layers of infinite extent, which is not the case, of course. For the realistic case of spherical or disk-shaped magma body, Wannamaker and others (1984) have demonstrated the difficulty in detecting such a conductor with MT measurements. In view of the highly conductive upper crustal structures and the probable limited extent of the postulated magma body, it is unlikely that MT surveys would be able to confirm or deny its existence.

Several audio-magnetotelluric (AMT) soundings have been made in The Geysers area (Long and Senterfit, 1976). These data represent scalar MT data at frequencies of 7.5 to 18,600 Hz, in contrast to normal MT data that is tensor in nature. Because of the higher frequency range, the AMT soundings mapped largely the upper 1 km of the geology, but found resistivities similar to those obtained from the bipole-dipole resistivity survey in The Geysers area that ranged from 10 to 70 ohm-m.

SEISMIC METHODS

In general, the rock parameters affecting the seismological properties (propagation velocities and attenuation)

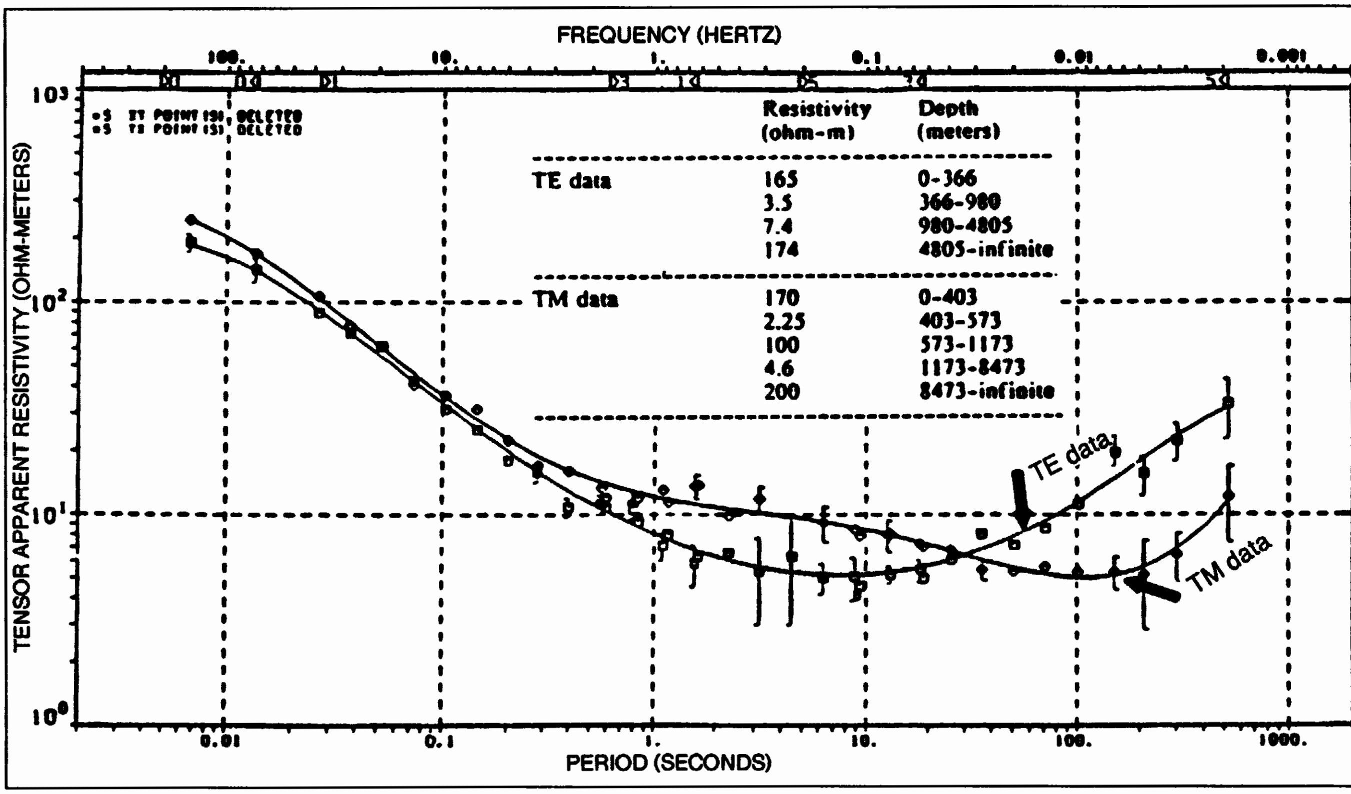


Figure 8. Sample MT sounding from Clear Lake volcanic field in Mount Hannah region (exact location proprietary). The error bars represent two standard deviations. TM and TE designations for data curves are discussed in text. Layered models for the TE and TM data are shown in the inset table.

can be divided into two categories, static and dynamic. Examples of the static properties are porosity, temperature, pressure, density, pore content, and fracture characteristics. Examples of dynamic properties are fluid movement, phase changes, stress release, thermal expansion and hydrothermal alteration, or any other physical or chemical processes that may affect the static properties. As far as the seismological methods are concerned there are two broad categories, active and passive techniques. In the active techniques one would include reflection, refraction, Vertical Seismic Profiling (VSP), P- and S-wave delay, and cross-hole imaging. Passive methods include the seismic travel times and attenuation, microearthquake (MEQ), teleseismic travel time and ground noise studies. Each of the methods mentioned above is often used in combination with another at many different scales of application.

Passive Methods

One of the earliest published reports on MEQs at The Geysers was done by Lange and Westphal (1969) who reported that the recorded seismicity was shallow ≤5 km) and at a rate of four events per day. In 1972, Hamilton and Muffler (1972) observed a similar activity localized in the production area. At that time, the power generation was 82 MW. As time passed and the steam production rate increased, the MEQ activity also increased. By September 1976, with a power generation of 550 MW, the activity rate had increased to 25 to 30 events per day (Majer, 1978; Majer and McEvilly, 1979). In the early studies, the magnitudes and detection thresholds were not well defined but most likely the magnitude zero seemed to be the lower detection threshold of these surveys.

By 1984, (Everhart-Phillips and Oppenheimer, 1984) with production at 1,000 MW, it had become quite clear that there was a direct relationship between production and seismicity Figure 9. (Oppenheimer, 1986) shows the location of earthquakes with ≥M 1.2 for the periods: (a) 1976-1978 and (b) 1982-1984. Note that the activity spreads out to the areas of the new power plants. The net mass withdrawal doubled from 1976 to 1984 as a consequence of the increased number of wells.

Since the early work on microseismicity at The Geysers, a number of authors have reported the empirical link between production activities and seismicity (Marks and others, 1978; Ludwin and Bufe, 1980; Peppin and Bufe, 1980; Allis, 1982; Bufe and others, 1981; Denlinger and Bufe, 1982; Ludwin and others, 1982; Eberhart-Phillips and Oppenheimer, 1984; Oppenheimer, 1986; Stark and Majer, 1989) to name just a few. Most of these authors agree

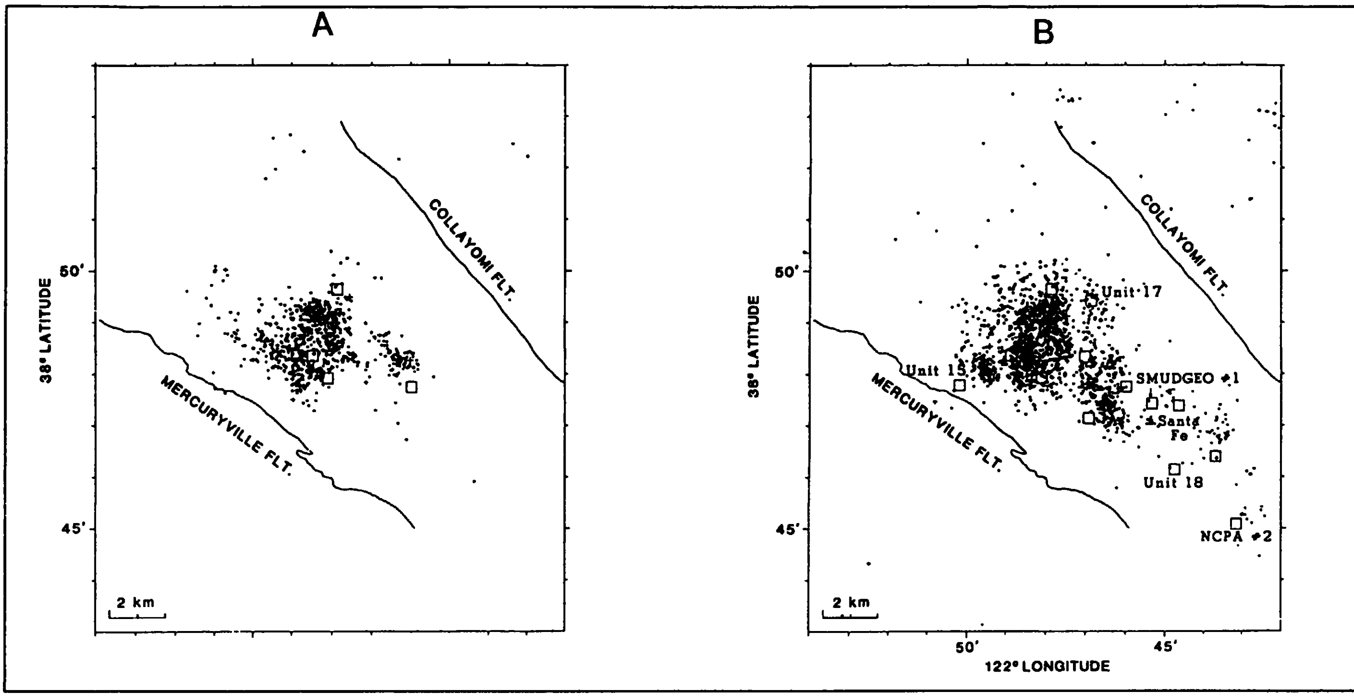


Figure 9. The locations of magnitude 1.2 and larger events for The Geysers regions: (a) 1976 to 1978 and (b) 1982 to 1984 (Oppenheimer, 1986).

that the seismicity is not associated with any dominant through going fault system. The activity occurs somewhat at random and is clustered in the production region. Most of the events are strike-slip and normal in nature (Oppenheimer 1986), but also exhibit some thrust activity at shallow depths. Again, as noted on the early surveys, the seismicity is very shallow, and almost all less than 5 km in depth below the surface. The lack of seismicity below 5 kilometers in The Geysers field may indicate that the rocks at this depth can not fail in a brittle fashion due to elevated temperatures. Iyer and others (1981) using teleseismic P-wave delays in the detected low velocity zones at 5 to 10 kilometer depths beneath the Mount Hannah region, also indicating elevated temperatures.

Most of the seismic arrays used at The Geysers have relied on analog recording with low frequency (100 Hz) response. The station spacings were on the order of several kilometers, thus yielding location errors of 0.5 to 1.0 km. In the last several years, several arrays with high frequency digital bore hole 3-component recording have been installed at The Geysers. One such array was installed in the northwest Geysers (Figure 10) by Geothermal Energy Operators (GEO) and is now operated by the Coldwater Creek Operating Company. Its purpose is to monitor MEQ activity associated with production activities. Shown in Figure 11 is a cross section of a month's activity during 1989 in the vicinity of injection wells (Weiser, 1989). This figure obviously shows a spatial relationship between seismicity and injection. Note that this is a cross section for events between the 7,000 and 10,000 foot depth. Above the 7,000 foot depth, the events are diffuse in plan and cross section. These data show the dramatic improvement that is possible with modern high frequency digital data from 3-component bore hole stations.

At the present time there are several arrays operating in The Geysers region. These arrays are routinely collecting microearthquakes down to magnitude -1. With this ability future studies, utilizing improved locations, will obviously be able to improve on early studies and hopefully determine a more precise relation between production activities and seismicity.

Another passive method is the ground noise method. It has been postulated that the geothermal environment produces nondiscrete "noise" from fluid movement, boiling, slow or low level rock slippage or other dynamic processes occurring in the geothermal reservoir. If there was such noise generated by indeterminate causes it might be possible to explore for, or monitor, these geothermal noises by listening for continuous sounds. Ground noise studies were popular in the early 70s, but due to lack of resolution they are not used as often today. One study carried out at The Geysers was by Liaw and McEvilly (1977). In this study, they concluded that the noise pattern in the 3 to 20 Hertz range was surface noise and the pattern of the noise was due to the characteristics of the near surface, not due to "geothermal noise." Properly carried out, using sensors in arrays to prevent spatial aliasing, it is possible to detect signals from sources beneath the surface. The problem seems to be that this noise is at such a low level that it is very difficult to detect.

Active Methods

Due to the rugged terrain and inhomogeneous surface geology at The Geysers, active studies have not been used as extensively as passive studies. The active studies have been low frequency, i.e., P-wave delay studies from distant sources (natural and artificial) and higher frequency, i.e., Vertical Seismic Profile (VSP) and reflection studies.

To date there have been two published VSP studies carried out at The Geysers. Both of these studies were carried out to detect the extent of fracturing within the reservoir using P-wave and S-wave vibrators. The first study was done by Majer and others (1988) in the Wildhorse 5 well on GEO property in the northwest Geysers. Although the study was cut short due to the failure of the geophone in the hot well, anomalous shear wave behavior was detected above the reservoir. A 11 percent anisotropy observed in S-wave velocity was attributed to fracture content. This was one of the first studies that observed S-wave splitting in a geothermal field and led to many other studies on fractured rock using S-wave behavior to detect anisotropy due to fractures. The second VSP was also carried out by Majer (1988), but in the felsite body in the South Geysers in a Unocal production well. This study was also terminated prematurely due to geophone failure in the hot well, but anomalous V_P/V_S ratios were seen in the production intervals.

There has been but one published reflection study at The Geysers (Denlinger and Kovach, 1981). In general, the energy was scattered in the production zone and very little structure was imaged. There were reflectors at 2.5 to 3.0 km depth detected, possibly a lower boundary to the reservoir rock. Majer et al. (1988), also saw reflectors at the same depth in the VSP data. In any case, seismic reflection has been somewhat less than satisfactory at The Geysers, due to the complicated structure, high degree of fracturing, and very difficult surface conditions.

Another type of study, although one might argue that it belongs in the passive category, is velocity inversion from active and passive sources. Majer (1978) used quarry blasts to roughly image the P-wave structure through the main production zone. A high velocity upper cap over a lower velocity section in the "main steam zone" was detected. Eberhart-Phillips and Oppenheimer (1984), and Eberhart-Phillips (1986) also did velocity inversion using arrival times from explosion and earthquakes to map out the P-wave velocity structure. These were done at regional scales thus providing little detail. These studies also found that P-wave velocities were faster between the Mercuryville and Collayomi faults in the production region.

The most detailed velocity inversion to date was done by O'Connell (1986). O'Connell used a tight array of 3 component stations in the production area to invert for P-

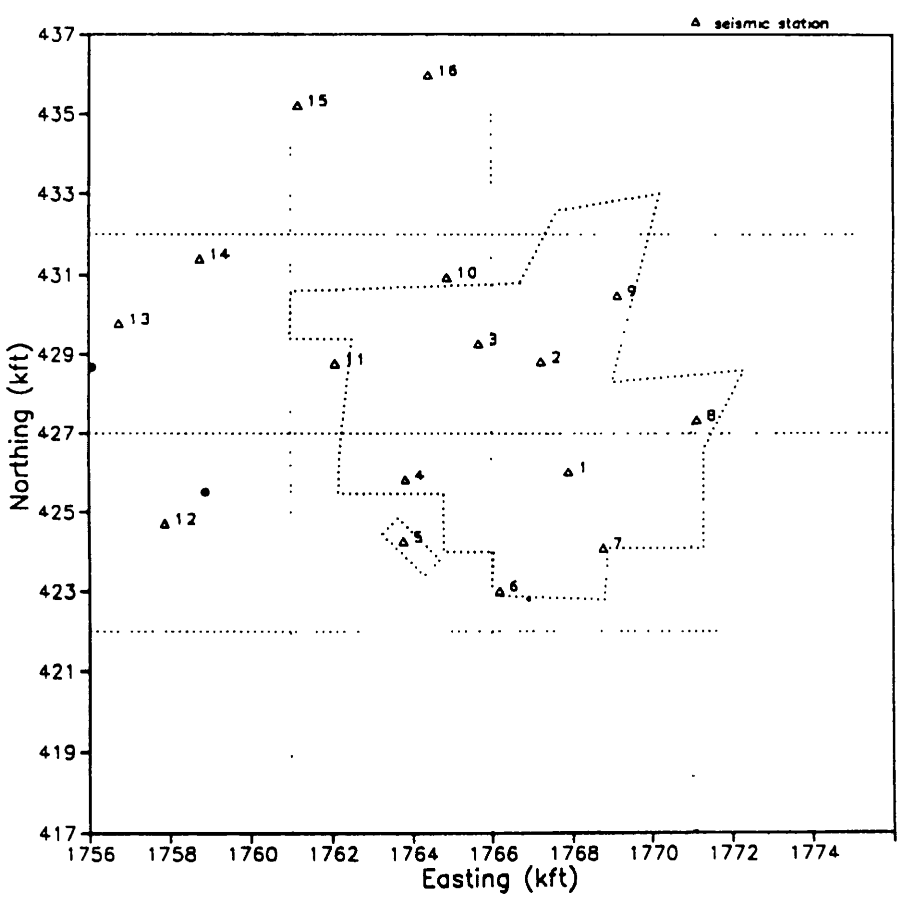


Figure 10. The digital array of 16, 3-component bore hole stations being used to monitor the seismicity of the northwest Geysers region by the Coldwater Creek Operating Company (Weiser, 1989).

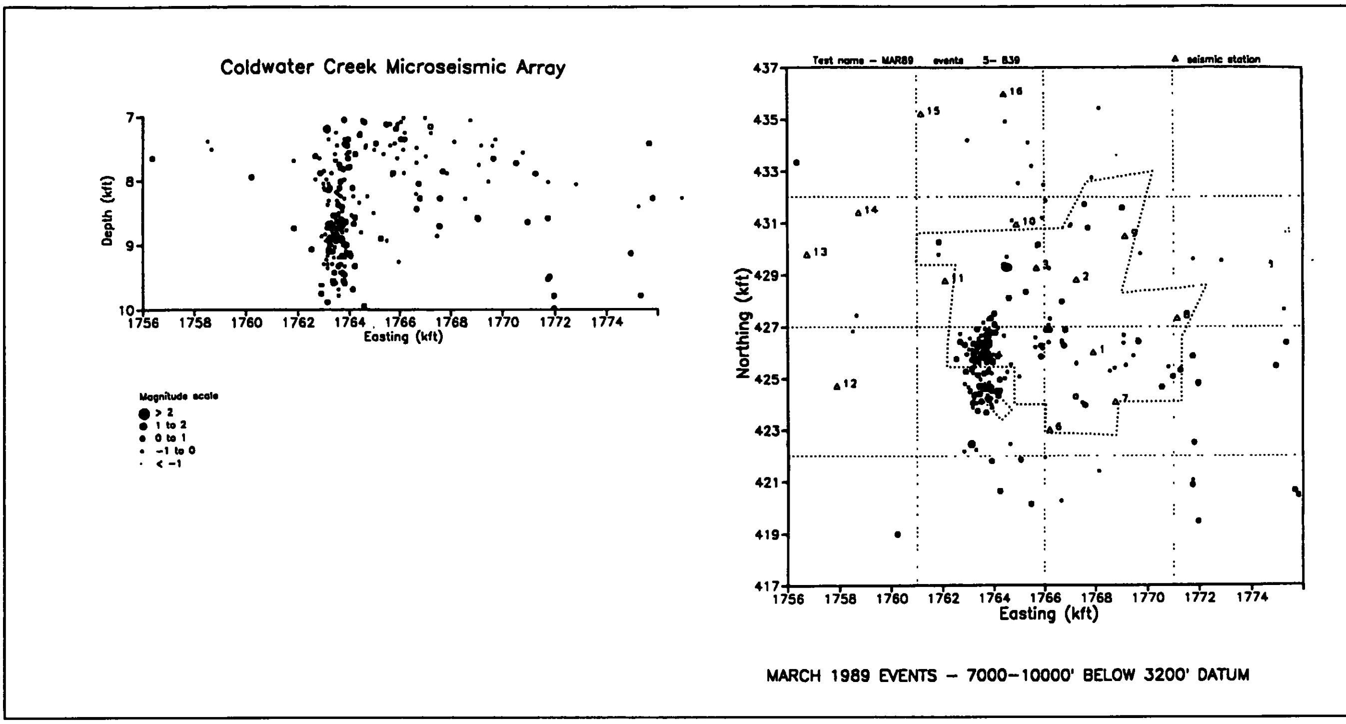


Figure 11. Cross section (left) and plan view (right) of events (M≥-1) located by array in Figure 10, for a one-month period of 1989 during an injection period (Weiser, 1989).

versus S-wave velocity data. The result is shown in Figure 12. As can be seen, the saturated "condensed" zone and the "undersaturated" production zone show up very nicely. Although this is a field wide averaging, it does show detail between the top and bottom of the reservoir:

In general, the "active" studies have not yet shown enough resolution to be of practical value to the operators. However, with increased station coverage, and 3-component high-frequency digital recording, it is anticipated great improvements in velocity structure will be obtained.

SUMMARY AND RECOMMENDATIONS

A number of geophysical methods have been employed in the study of The Geysers-Clear Lake region, but many of the data remain unpublished. Of the published results, gravity data indicate a low-density mass near Mt. Hannah that has been interpreted as a possible magma body at depth. Alternatively, electrical data from this area may indicate a thick conductive and low-density section of shale facies sedimentary rocks as another explanation. Other geophysical evidence including large teleseismic P-wave delays (Iyer and others, 1981), anomalous heat flow (Jamieson, 1976; Walters and Combs, this volume) and the lack of seismic activity below a depth of about 5 km (Bufe and others, 1981) appear to support the magma body hypotheses, or at least temperatures that are elevated enough to cause density changes and elastic property changes. A dominant feature of the data is a thick, conductive and low-density section of shale-facies sedimentary rocks in the Mount Hannah region. Another thick conductive section north and east of Clear Lake is probably associated mostly with conductive Franciscan sedimentary rocks that do not have a significant density contrast with other melange units. Limited SP profiling in the Mount Hannah region indicate that this method may not be useful in locating local geothermal activity, but conceivably could be useful in locating faults.

Very little published information is available on electrical surveys in The Geysers production area, but the variability of the physical properties of the Franciscan units in the production area has been demonstrated by the bipole-dipole surveys discussed in this review. It seems clear from these data and from data published by McLaughlin and Stanley (1976) that highly fractured zones in the production area can be mapped, but not with high enough resolution for picking drilling targets, in an area as complex as The Geysers. Possibly the combination of seismic methods and electrical surveys could be used to locate the ideal structural conditions for steam production. This concept needs to be tested with coincident surveys using high-resolution EM soundings and possibly P- and S-wave reflection and/or VSP data. Recent advances in cross-hole seismic and electrical methods may eventually be applied in this region if these methods can be adopted for high temperature operation. Because of the complexity of this region seismic reflection may prove difficult to interpret. However, because of the abundant MEQ activity tomographic imaging of the shallow system may be possible with recent methods developed using joint 3-D inversion

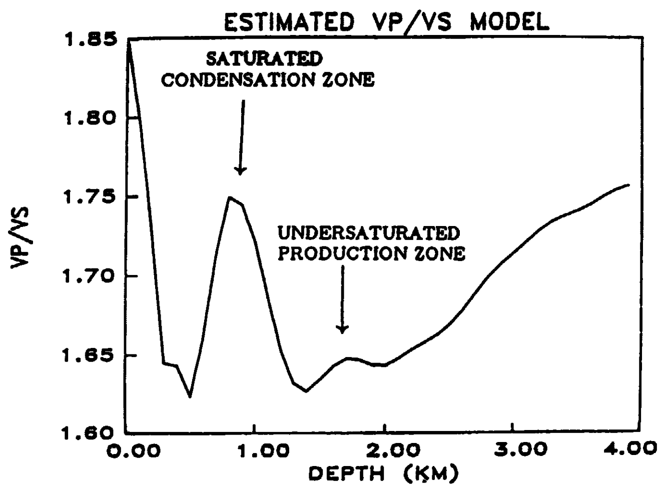


Figure 12. A VP/VS model obtained by O'Connell (1986) using MEQs in the main production zone at The Geysers.

of source and velocity structure. Deeper structure could also be obtained using regional and teleseismic data. In an overall sense more effort should be placed on integrating the geophysical measurements by jointly interpreting various data sets. A good example would be gravity and magnetics. Ultimately the geophysical data should also be interpreted along with such parameters as fluid injection rates, mass balance, and other reservoir properties.

By no means have the mysteries of The Geysers region been unraveled to date. Basic questions such as existence of a magma chamber, the extent of the heat source, and the mechanisms involved in the production of the geothermal resource are mostly unanswered. Geophysics has however started to unravel the complex environment in The Geysers region. To continue this effort the geophysics should be done in an integrated fashion and interpreted with as much information as possible. Crucial to this process is the interpretation with reservoir parameters such as fluid injection patterns and characteristics, available well log information, and any other data that may be available. By proceeding in this fashion one may then be able to make significant progress in providing useful information.

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Discussion with George Keller and Robert McLaughlin were essential parts of preparation of this review of the electrical geophysics and related geology. Interpretation of the gravity and magnetic data was discussed with William Isherwood who did much of the original work of this kind in the area. Dallas Jackson was a co-investigator and field partner in the resistivity surveys during 1973 and conducted the SP surveys in the Mount Hannah region. Adel Zohdy provided the algorithms for processing the bipole-dipole and equatorial dipole data. The MT data in Figure 8 were supplied by Richard Dondanville of Unocal Geothermal Division and is greatly appreciated. Permission to acquire resistivity data in The Geysers production area was also graciously extended through efforts of John Kilkenny of Unocal. We also would like to thank Mark Walters of the Coldwater Creek Operating Company for providing the MEQ data for the NW Geysers region. Obviously numerous investigators were involved with the compilation of the results reported here which we would like to thank. Lastly we would like to thank the support of the private and government agencies that have funded the work over the years.

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