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Exploring for Hidden Geothermal Systems

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ABSTRACT

By definition, hidden (or "blind") geothermal systems lack obvious surface manifestations such as hot springs, fumaroles, or hydrothermally altered ground. Most of the now-documented but previously-hidden geothermal systems (e.g., the geothermal reservoirs in the Imperial Valley of southern California, U.S.A.) were discovered accidentally, as a result of exploration drilling for oil and gas and/or mining activities. Although the occurrence frequency of hidden geothermal systems is unknown, a methodology is needed to identify promising targets for subsequent deep confirmation drilling. Based on theoretical calculations, Pritchett concluded that a combination of earth-surface electrical surveys (self-potential, magnetotelluric, and DC resistivity) in concert with other relevant information may be used to locate blind or hidden geothermal systems. Subsequently, Garg and coworkers used available geophysical and reservoir data from the Beowawe geothermal field (Nevada, U.S.A.) to demonstrate that electrical surveys may be employed to infer favorable subsurface geothermal reservoir characteristics. In this paper, we review the historical experience and the results of the theoretical studies. We suggest that a suite of electrical surveys together with shallow heat flow surveys and relevant local geological observations offers a promising approach to the identification and preliminary characterization of hidden geothermal systems.

1. INTRODUCTION

Geothermal systems are inherently open systems, and are often accompanied by surface outflows of mass and heat. Most of the presently known geothermal fields were discovered because of surface manifestations such as hot springs, fumaroles, and hydrothermally altered ground, i.e. using methods analogous to the exploration for oil by drilling on oil seeps. Hidden or "blind" geothermal systems are by definition systems that do not have readily identifiable surface manifestations. Although the frequency of occurrence of these concealed resources is largely a matter of speculation, there exists a need to develop a methodology for identifying promising targets for subsequent confirmation by deep drilling.

In section 2, we review the historical experience in discovering hidden geothermal systems located in the Imperial Valley of southern California, and northern Nevada. This is followed by a discussion of theoretical studies (section 3) which suggest that surface electrical surveys may be used to characterize geothermal reservoirs. It is concluded (section 4) that electrical surveys in combination with surface heat flow and geological data constitute a possible approach to the identification of hidden or blind geothermal reservoirs.

2. HISTORICAL EXPERIENCE

Many blind geothermal systems were discovered accidently as a by-product of drilling for oil and gas, and mining activities. In 1927, in a search for geothermal steam, a group of private investors drilled three holes in an area of mud pools and fumaroles approximately 4 miles north of the present Salton Sea field, Imperial Valley, California, USA (Koenig 1970). Although steam in commercial quantities was not found, a number of wells were drilled to produce carbon-dioxide. In 1957, a wildcat "oil" well drilled about 5 miles south of the 1927 boreholes produced geothermal brine at a temperature of approximately 600°F (~316°C) (Koenig 1970). The first indication of a deep, high-temperature hydrothermal system in the Orita area of the Imperial Valley (East Brawley KGRA) occurred in 1963 when the Wilson No. 1 exploratory oil well encountered hot geothermal brine at about 13,000 feet. The brine had a temperature of about 260°C and a salinity of 54,000 ppm (Rex et al., 1971)

In the late 1960s, the presence of other geothermal reservoirs in the Imperial Valley was suggested by Robert Rex of the University of California at Riverside (UCR) (see Koenig [1970]). Driven by a need to augment and improve the quality of Lower Colorado River waters and the promise of inexpensive power from geothermal resources, the United States Bureau of Reclamation (USBR) of the U.S. Department of Interior decided to fund a comprehensive exploration program at UCR in 1968 (Wong 1970, USBR 1971, Rex et al. 1971, Rex 1972). Among other activities, the UCR exploration effort involved the mapping of heat flow anomalies and the electrical resistivity (Rex et al. 1971, Combs 1972, Meidav and Furgerson 1972). Most of the UCR heat flow mapping was carried out on Imperial Irrigation District canal right-of-way lands. The UCR exploration program resulted in the identification of East Mesa, Heber, Dunes, and Glamis geothermal prospects.

The Blue Mountain geothermal area, located in Humboldt County, Nevada, was originally explored for gold. As a result of high temperatures encountered during exploratory drilling, the area was subsequently investigated for geothermal potential. Nevada Geothermal Power is currently developing the Blue Mountain geothermal field. Other producing blind geothermal systems in northern Nevada are Desert Peak, Soda Lake, and Stillwater. The Desert Peak geothermal area was identified as a result of temperature-gradient drilling that started to the north at Brady's geothermal area (Garside et al., 2002). Geothermal potential of the Soda Lake geothermal field was first identified in 1903 when a water well encountered boiling conditions (Garside et al., 2002). The Stillwater geothermal area was discovered in 1919 when Charles Kent hit hot water in a shallow well (Garside and Schilling, 1979).

3. THEORETICAL STUDIES

The preceding review indicates that many hidden geothermal systems were discovered as a result of drilling undertaken for water, oil and gas, and mineral resources. Since one cannot rely on accidental discoveries of hidden systems, it is important to develop an approach to identifying promising drilling targets using methods that are far cheaper than drilling itself. These methods should be regarded as reconnaissance tools, whose primary purpose is to locate high-probability targets for subsequent deep confirmation drilling. Pritchett (2004) performed a theoretical study to appraise the feasibility of finding "hidden" geothermal reservoirs in the Basin and Range physiographic province using electrical survey techniques that included (1) conventional DC electrical resistivity surveys, (2) electromagnetic resistivity surveys such as natural magnetotelluric (MT) and controlled-source audio-frequency magnetotelluric (CSAMT) surveys, and (3) surveys of earth-surface electrical "self-potential" (SP). The geothermal reservoirs are usually characterized by substantially reduced electrical resistivity relative to their surroundings. Solid rock itself is normally an excellent insulator, so electric current moving through the reservoir will pass mainly through the fluid-filled pore spaces and fractures. Therefore, the resistivity of the reservoir as a whole will depend upon the resistivity of the fluid itself (which decreases with increasing temperature and also decreases with increasing dissolved solids content) and upon the continuity of the current paths through the rock (which will tend to increase with increasing rock permeability, further reducing overall electrical resistivity).

In high temperature geothermal systems, hydrothermal alteration results in the production of low resistivity clays. This means that very often, the low resistivity zone corresponds to the low-permeability cap-rock, and not the geothermal reservoir. The self-potential (SP) technique is more diagnostic of subsurface permeability. The electrical potential distribution at the earth surface depends upon both the electrical resistivity of the earth and upon the distribution of natural subsurface electric current, according to Ohm's Law. The electric current, in turn, is caused by fluid flow dragging electrons along in the molecular-scale "electrical double layer" at the interfaces between the fluid and the rock surface (the surfaces of pores and fractures) – a process known as "electrokinetic coupling". As a result, the SP distribution measured at the surface is sensitive to the presence of subsurface convective flow, which is a feature characteristic of all liquid-dominated hydrothermal reservoirs.

Pritchett (2004) used the STAR geothermal reservoir simulator (Pritchett, 2002) to carry out a lengthy calculation of the evolution of a synthetic, but generic, Great Basin-type geothermal reservoir to a quasi-steady "natural state". Once this stable state was reached, the various electric postprocessors (Pritchett, 2002) were used to try to estimate what a suite of geophysical surveys of the prospect would see. This process was completed for eight different "reservoir models". Of the eight cases considered, four were "hidden" systems so that the survey techniques could be appraised in terms of their ability to detect and characterize such resources and to distinguish them from more conventionally-situated geothermal reservoirs. Based on these theoretical calculations for a generic geothermal system, Pritchett (2004) concluded that a heat flow survey by itself cannot be used to locate a hidden geothermal system. The best results are obtained from the SP and MT surveys, with DC resistivity a close third. To find "hidden" geothermal resources of the Basin and Range type, simultaneous SP and MT surveys, in combination with other pertinent information (e.g., heat flow surveys and geologic data) may be interpreted using mathematical "inversion" techniques to characterize the subsurface quantitatively.

Using existing data sets for the presently producing Basin and Range geothermal reservoirs can most readily test the efficacy of electrical surveys for characterizing the subsurface. For the latter purpose, it is necessary to document the cases where an adequate reservoir description of a Basin and Range geothermal power generation project and useful electrical surveys are both available. The requisite information is available for the Beowawe geothermal field located in Eureka and Lander counties, north-central Nevada. The geothermal area forms a part of the Basin and Range physiographic province, and is characterized by east-west extension, crustal thinning, Tertiary volcanism, and high heat flow (Olmsted and Rush, 1987). The average conductive heat flow in the region is 100-150 mW/m^2. A simplified geologic map of the Beowawe geothermal area is presented in Figure 1. The current geothermal production is principally from the fracture system associated with the Malays fault zone, oriented N50-70^{o}E.

Prior to exploration drilling and well discharge by Magma Power Company (Magma) in 1959 on the Beowawe Geysers Terrace (see Figure 1 for location), the area had the largest concentration of natural geysers in North America, second only to Yellowstone National Park (White, 1992). Discharge of geothermal wells was quickly followed by a drastic reduction in natural surface discharge. Exploration drilling by Magma indicated temperatures of 182 ^{o}C to 187 ^{o}C at relatively shallow depths (~200 meters) beneath the Beowawe Geysers Terrace (see Figure 2 for well locations). The discovery well at Beowawe, Ginn 1-13, was drilled by Chevron Resources Company (Chevron) in 1974 about 2 km southwest of the Geysers Terrace; a maximum temperature of 214 (+/- 1.5) ^{o}C was recorded in Ginn 1-13. Significantly, Ginn 1-13 was sited in an area devoid of any surface geothermal activity (Benoit and Stock, 1993). All three current production wells (Ginn 1-13, Ginn 2-13, and 77-13) are located in close proximity to each other (see Figure 2). Since late 1985, a dual flash power plant has been generating 16.7 MWe (gross) at Beowawe. About 80 % of the produced brine is injected back into the reservoir. Until 1993, injection was into well Batz 1, which is believed to be largely unconnected to the fracture system containing the geothermal reservoir. To provide pressure support to the geothermal reservoir, injection was switched to the current injection well 85-18 in February 1994.

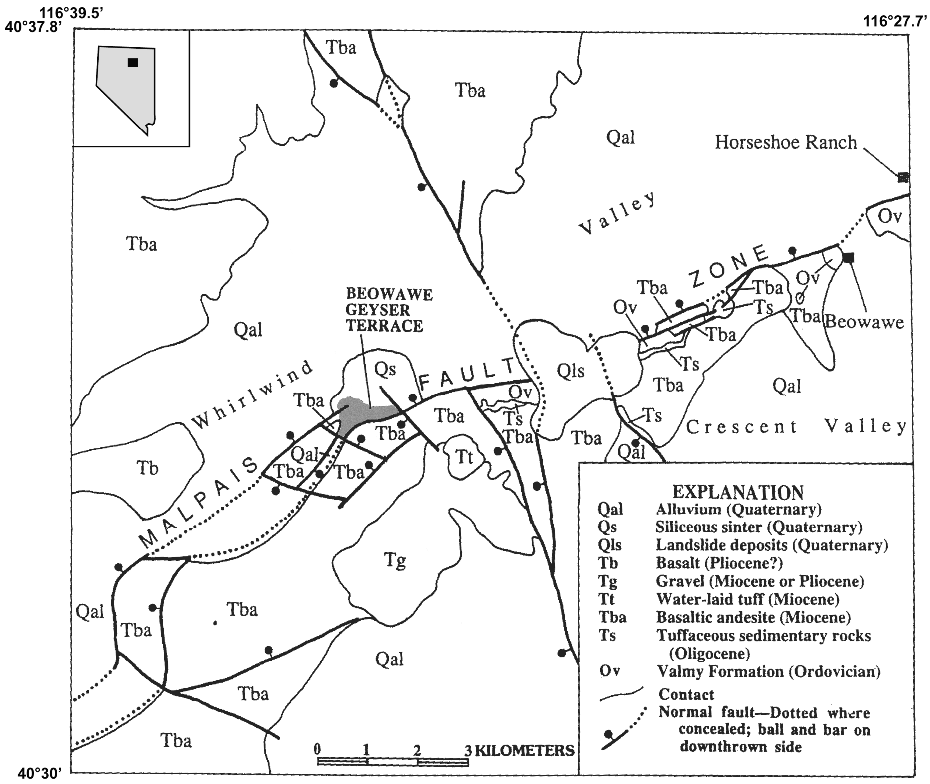

Figure 1: A simplified geologic map of Beowawe geothermal area. Reproduced from White (1992).

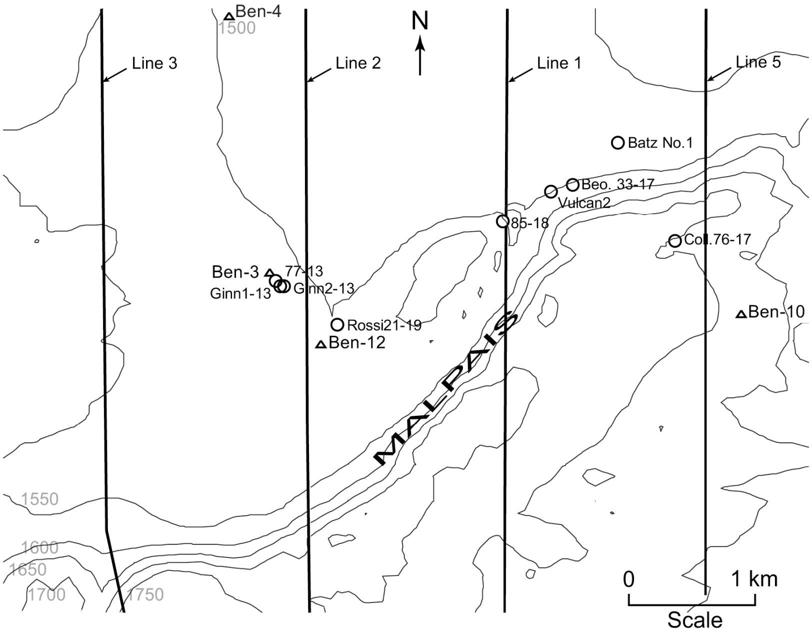

Figure 2: A topography map of the Beowawe area showing wellhead locations (circles) and dipole-dipole resistivity lines 3, 2, 1, and 5, and MT stations (triangles). The map covers an area of about 31 square kilometers (~6.4 km in the east-west direction and ~4.8 km in the north-south direction). Topographic contour interval is 50 m.

The generalized stratigraphy for the Beowawe geothermal area consists of a thick sequence of Miocene volcanic rocks (maximum thickness less than 1100 meters) unconformably overlying the Ordovician metasedimentary Valmy formation. The volcanic rocks are covered by a relatively thin layer of surficial alluvium, siliceous sinter, and playa sediments. A carbonate assemblage associated with the Roberts Mountains thrust underlies the Valmy formation. None of the geothermal wells has penetrated the carbonate assemblage. Beowawe geothermal reservoir is liquid-dominated, and boiling is limited to shallow depths. Maximum temperatures of 209-210 ^oC were measured in the Vulcan wells (Vulcan 1, 2 and 3) at depths of 180-200 meters (Faulder et al., 1997); these high temperatures are indicative of boiling or near-boiling conditions at shallow depths in the Geysers Terrace area. The deep thermal water (reservoir fluid) at Beowawe is dilute sodium-chloride brine with a total dissolved solids (TDS) content of about 1050 ppm. Except for higher calcium and magnesium content, the ratios of major anions in shallow waters in the Beowawe area are similar to those for the deep thermal water. The TDS content of the shallow waters is about 350 ppm.

Swift (1979) presented a review of ten geophysical surveys performed for Chevron in the Beowawe geothermal area. In the following, electrical surveys relevant to the present study are briefly described. McPhar Geophysics performed a dipole-dipole resistivity survey (~600 m dipole, n=1, 2, 3, 4, 5, 6, frequency = 0.125 Hz) along six north-south lines (Swift, 1979). Portions of lines 1 and 2 lie within the currently developed geothermal area (see Figure 2); lines 3 and 5 pass to the west and the east, respectively, of the geothermal borefield. Apparent resistivities of less than 10 ohm-m are present in the alluvium in the Geysers Terrace area (line 5). The resistivity anomaly drops down to ~600 m along line 3 located to the west of the Ginn wells (Swift, 1979). Twelve tensor MT soundings over a frequency range of 0.003Hz to 200 Hz were collected by Geotronics Corporation in and around the Beowawe geothermal area (Swift, 1979). The MT soundings are widely spaced (Figure 2). Only two MT stations, Ben-3 and Ben-12, fall within the Beowawe geothermal field. Both of the latter stations straddle DC line 2.

A brief overview of a self-potential (SP) survey performed along 10 north-south lines by Terraphysics is given by Smith (1979). An asymmetrical dipolar SP anomaly is associated with the Geysers Terrace. DeMoully and Corwin (1980) describe results of another SP survey using a denser network of stations than that used by Terraphysics; the area covered by this survey lies within the northeast quadrant of Figure 2. The basic character of the SP anomaly remains unchanged within the two surveys, i.e., positive to the northwest and negative to the southeast of the Geysers Terrace. In regions with high topographic relief, negative streaming potentials may be generated by the downhill movement of groundwater. The self-potential data for the Beowawe area follow the general trend of topography with more negative readings at higher elevations. DeMoully and Corwin (1980) present several arguments against a topographic origin for the SP anomaly, and conclude that the anomaly is a result of geothermal activity along the Malpais fault.

To relate geophysical surveys to subsurface reservoir conditions, it is necessary to first establish the natural (i.e., pre-production) state of the system. It is not sufficient to merely prescribe a “natural state” based upon interpolation between measurements such as pressures and temperatures. In fact, it is essential that the natural state itself represents a quasi-steady solution of the partial differential equations that govern flow in the reservoir. The requirement that the natural state be itself a nearly steady state solution of the governing equations is an essential test of the model of the reservoir. The natural-state simulation was carried out using the STAR geothermal reservoir simulator (Pritchett, 2002). Details of the natural state model may be found in Garg et al. (2007). Computed pressures are compared with measured pressures in various wells in Figure 3. With the exception of Ginn 1-13, the computed pressures are in excellent agreement with the measured pressures. Even for well Ginn 1-13, the discrepancy between the computed and measured values is not very large. Agreement between computed and measured temperatures is also good (see, e.g., Figure 4).

STAR DC resistivity, magnetotelluric (MT), and self-potential (SP) postprocessors (Pritchett, 2004) were used to model the results of existing geophysical surveys (see Garg et al., 2007 for details). All the electrical postprocessors require the specification of a model for the electrical resistivity of reservoir rocks. In the volume common to the STAR and electric grids, Archie’s law (Archie, 1942) is adopted to relate formation electrical resistivity (Ω) to pore-fluid resistivity (Ω_F) and porosity (ϕ):

$$\Omega = \Omega_F / (C_A \phi^2)$$

In the above relation, C_A (Archie’s constant) is a dimensionless constant. Pore-fluid resistivity (Ω_F) is assumed to be a known function of liquid temperature and salinity (i.e., total dissolved solids).

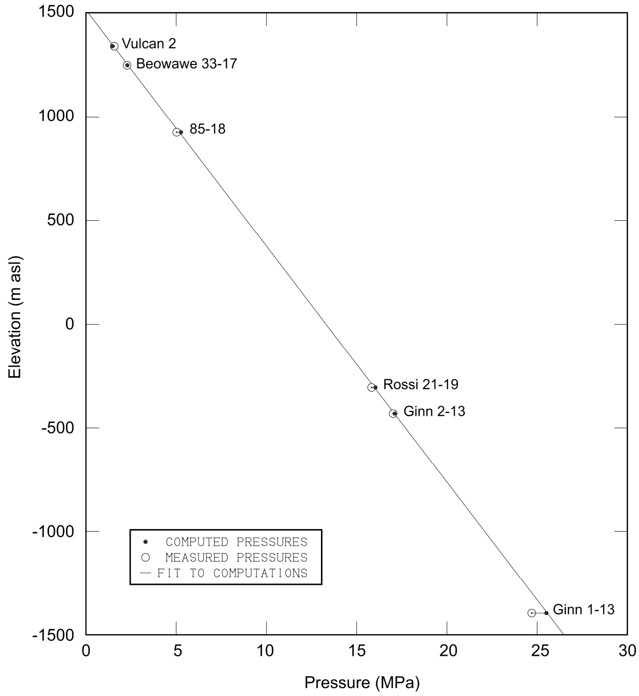

Figure 3: Comparison of measured pressures in Beowawe wells with computed pressures.

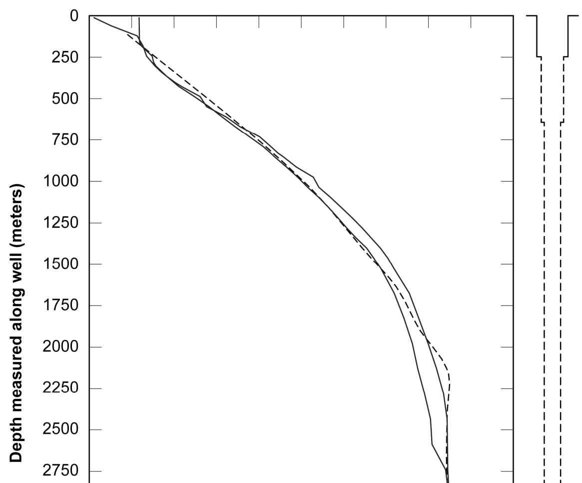

Figure 4: Comparison of computed (dashed line) temperature distribution with measured (solid line) temperatures in Ginn 1-13 well.

Although in recent years, DC methods have begun to be supplanted by electromagnetic methods (e.g., MT, CSAMT), DC surveys do remain a viable technique under many practical circumstances. The DC resistivity survey does not map the actual resistivity distribution within the subsurface; it yields the so-called "apparent resistivity" distribution. The "apparent resistivity" is usually associated with a point on the ground surface midway between the current and voltage electrodes for a dipole-dipole survey, and represents a volume average of electrical resistivity over a region of finite size that increases with the electrode spacing. McPhar Geophysics performed a dipole-dipole resistivity survey (~600 m dipole, n=1, 2, 3, 4, 5, 6, frequency = 0.125 Hz) along six north-south lines (Swift, 1979). Portions of lines 1 and 2 lie within the currently developed geothermal area (see Figure 2). In a dipole-dipole survey, both the current and voltage electrodes have the same spacing a (a = 600m in the present case). The distance between the centerlines of current and voltage dipoles is "(n+1) a".

The DC postprocessor was used to compute the apparent resistivity along portions of McPhar Geophysics lines 1 and 2 lying within the STAR computational grid used to simulate the natural state of the Beowawe geothermal field. A comparison between computed and measured apparent resistivities for line 2 is shown in Figures 5. It is evident from Figures 5 that the measured "apparent resistivity" varies considerably with distance along the lines and with depth (i.e., for different values of n). The apparent resistivity is relatively high at shallow depths and declines with depth. Although the agreement between the computed and measured values is not perfect, the computed profiles reproduce most of the important features of the measured profiles.

The magnetotelluric (MT) method uses naturally occurring electromagnetic (EM) waves as sources to map the resistivity structure (Vozoff, 1991). EM time-series data are decomposed into spectra, providing "apparent resistivity" as a function of frequency. The depth of penetration is inversely proportional to the square root of frequency; thus, lower frequencies can be used to map the deeper resistivity structure. Twelve (12) tensor MT soundings were collected by Geotronics. Only two of them, Ben-3 and Ben-12, fall within the currently exploited geothermal field (see Figure 2), and straddle DC profile Line 2. The STAR MT postprocessor (Pritchett, 2002) was used to compute the "apparent resistivities" using the natural state and DC resistivity model described earlier. The computed MT response is compared to the observed sounding curve of Ben-3 in Figure 6.

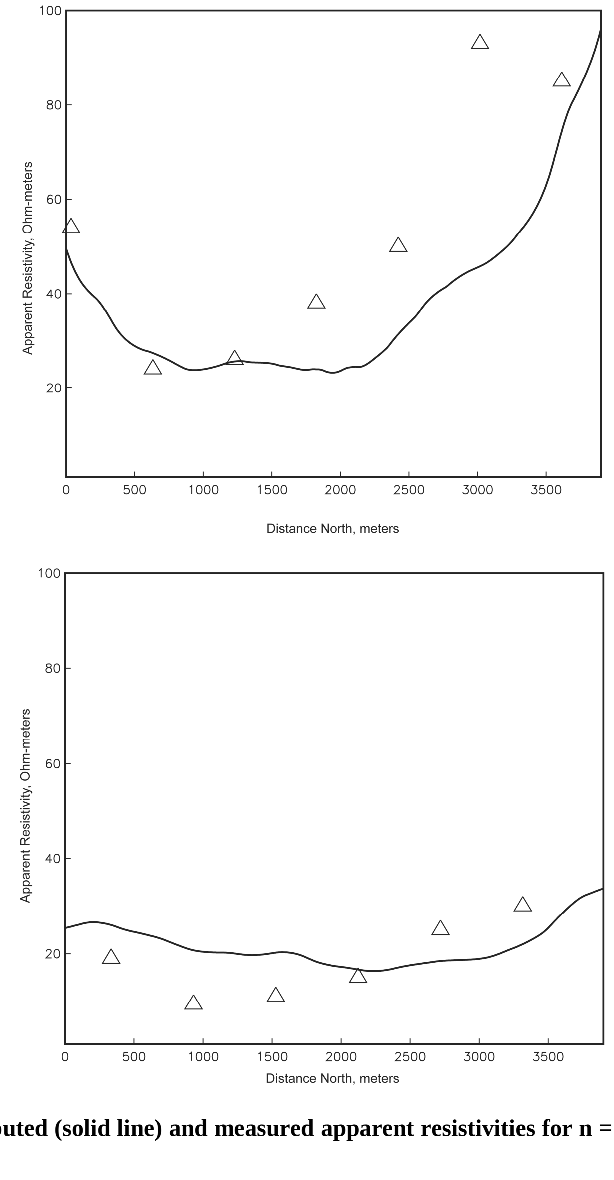

Figure 5: Comparison of computed (solid line) and measured apparent resistivities for n = 2 (top) and n = 5 (bottom) along line 2.

Although the computed and observed MT sounding curves have the same general shape and show a decline in resistivity with increasing depth, there exists a quantitative discrepancy between the observed and predicted MT responses. The observed results need to be multiplied by a factor of 3 for Ben-3 and by 2 for Ben-12. Moreover, 1-D inversions of the MT data yield resistivities much less than those from the dipole-dipole interpretation. These discrepancies cannot be explained by typical scatter in the original data and warrant explanation. Some possible reasons for this difference include “static shift” and horizontal or vertical anisotropy (Garg et al., 2007).

The DC resistivity and MT surveys respond to the subsurface resistivity structure of the geothermal reservoir, but these surveys provide no direct information about the permeability structure and fluid transport within the reservoir. The self-potential (SP) or spontaneous potential method, wherein the resistivity or conductivity of the earth is not measured, is based on measurements of variations in the natural DC voltages over the surface of the earth. These natural voltages are related to chemical and physical processes in the subsurface, i.e., they result from the interaction of ground water with conductive bodies such as sulfide or graphite deposits, from high geothermal gradients, or from the movement of underground fluids. It is these latter two that make the SP method useful in geothermal exploration. Under natural-state conditions, geothermal fields are often characterized by self-potential anomalies caused by upflow of hot fluids from depth. Anomalies of several hundred millivolts amplitude of this type have been observed. Modeling of the observed self-potential distribution can provide important insights into natural state flows. Two self-potential (SP) surveys were performed in the Beowawe area. Initially, Terraphysics carried out a self-potential survey along 10 north-south lines (Swift, 1979). An asymmetrical dipolar SP anomaly, associated with the Geysers Terrace, was observed in the latter survey. DeMoully and Corwin (1980) describe results of another SP survey using a denser network of stations than that used by Terraphysics. Although the self-potential data for the Beowawe area follow the general trend of topography with more negative readings at higher elevation, a topographic origin is unlikely for this anomaly (DeMoully and Corwin, 1980). The latter authors concluded that the Beowawe SP anomaly is a result of geothermal activity along the Malpais fault.

The STAR SP postprocessor was used to compute the self-potential distribution within the area included in the natural state calculation. The computed self-potential distribution is illustrated in Figure 7. Although the computed SP distribution disagrees in detail from the measured potential distribution (compare Figure 7 with Figure 3 of DeMoully and Corwin, 1980), both the computed and measured SP distributions display the same general behavior. The self-potential anomaly is positive to the northwest and negative to the southeast of the Geysers Terrace area. The broad agreement between the computed and measured anomalies strongly suggests that the Beowawe self-potential anomaly is caused by hot water upflow within the Malpais fault zone.

4. CONCLUSIONS

The objective of any geothermal exploration program is to locate areas underlain by hot rock, to estimate the volume and temperature of the fluids as well as the permeability of the rocks at depth, and to predict the productivity of as yet undrilled geothermal wells. Although at present there do not exist any reliable estimates for the numbers of hidden or blind geothermal systems, it is desirable to develop a paradigm for identifying and characterizing hidden geothermal reservoirs with commercial potential. Pritchett (2004) performed a theoretical study to investigate the efficacy of several geophysical techniques for exploring geothermal reservoirs, and concluded that a suite of electrical surveys (DC resistivity, MT resistivity, and self-potential) is needed to define the characteristics of hidden “Basin and Range” type geothermal systems. None of the methods taken alone can provide unambiguous indication of a geothermal system. The DC and MT resistivity methods respond to the subsurface resistivity distribution. Both the hot and permeable geothermal reservoir rocks, and impermeable clays and shales have low resistivities. However, clays and shales cannot support the vigorous upflow needed to sustain geothermal systems. Again, a self-potential anomaly can be caused by topography driven cold water flow, but ordinary cold ground water aquifers do not normally exhibit low resistivities. Thus, if the regional heat low is high, and the electrical resistivity and self-potential anomalies coincide, the possibilities of finding a productive geothermal reservoir may be enhanced.

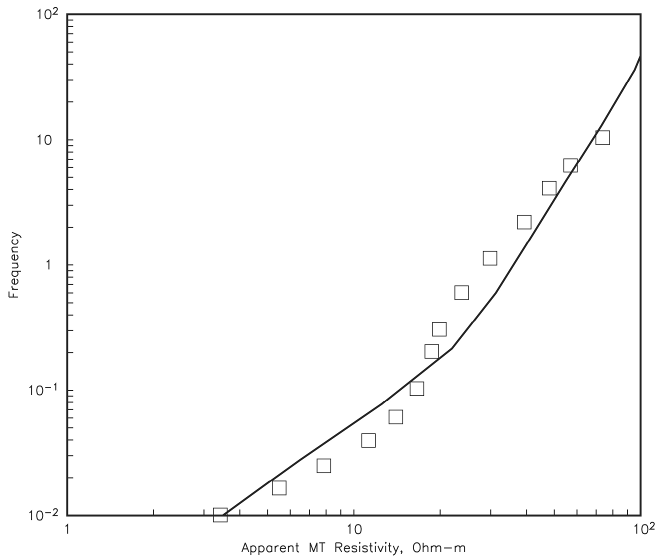

Figure 6:. Predicted MT response (solid line) at site Ben-3 based on 3-D model of natural state and dipole-dipole DC resistivity data. The TE mode of the MT data, multiplied by a factor of 3, are shown as rectangles.

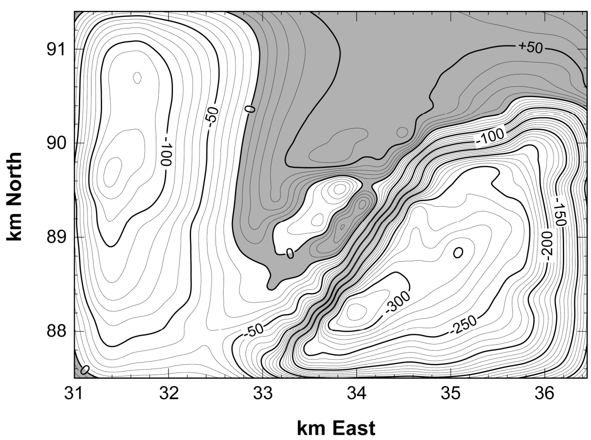

Figure 7: Computed self-potential distribution in the area included in the natural state model. Shaded (white) corresponds to positive (negative) SP values. The contour interval is 10 mV.

Results of the present work support the view that a suite of carefully designed electrical surveys (DC, MT, and SP) may be employed to infer favorable subsurface geothermal reservoir characteristics. While the use of electrical surveys in geothermal exploration is well established (see e.g., Ward et al., 1981, and Wright et al., 1985), these surveys have not been generally employed to delineate subsurface reservoir properties. Of course, it is important to stress that a single example (i.e., Beowawe geothermal field) cannot establish a general method for locating and characterizing hidden geothermal systems. This study should be duplicated using existing data sets from other geothermal reservoirs – both within and outside the "Basin and Range" physiographic province. Once the suggested methodology has been adequately validated on the basis of existing data sets, it should constitute a useful strategy for locating and characterizing as yet undiscovered hidden geothermal reservoirs.

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