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Low-Cost Geothermal Exploration at Amedee Hot Springs, using Self-Potential and Magnetics

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Abstract

Effective low-cost geophysical techniques are critical for geothermal exploration. Two such techniques, ground magnetics and self potential, were applied to the Amedee geothermal prospect to map the orientation of controlling faults and to locate upflow zones within the fault planes. Field data collected at Amedee show a distinctive magnetic high, coincident with the basaltic ridge that forms the eastern boundary of the field, and a distinctive self potential (SP) anomaly coincident with the thermal area and the fault trace. A two-dimensional computer code was used to fit the ground magnetic data to a model of a dipping basaltic ridge. We combined this interpretation with existing data to assemble a two-dimensional structural model of the field. Using the above structural model we were able to apply a two-dimensional code to the SP anomaly at Amedee. With this code we fit the field data to a model containing discrete flow sources at depths from 200-300 meters within the fault plane. Subsequent drilling into the Amedee fault zone confirmed the validity of this approach.

Introduction

In this era of tight exploration budgets and even tighter schedules it is important to have low-cost exploration tools available to make quick decisions on geothermal prospects. In this short paper we examine an exploration problem that is sufficiently constrained by the known geology so that some relatively simple and low cost geophysical techniques can be used to solve it. In particular, we have applied the ground magnetic and self potential methods for exploration of a moderate-depth geothermal system in the basin and range province of eastern California.

The magnetic method was chosen to map the configuration of a dipping volcanic ridge. The western border of the ridge forms a permeable fault zone which serves as the plumbing system for Amedee Hot Springs. The high magnetic permeability of the volcanic rock and the simplicity of magnetic interpretation make it an ideal technique for modeling the structure of the ridge.

Self-potential anomalies associated with geothermal systems are thought to be due to the subsurface fluid and/or heat flow. For this reason this technique was chosen to map upflow zones along the Amedee fault zone. The advent of reliable data collection procedures (Corwin, 1990) and the development of a simple computer code to interpret field data (Wilt and Butler, 1990; Sill, 1982) make it an ideal technique for locating upflow zones in a well-defined geothermal system such as at Amedee.

In this short paper we describe the exploration problem at Amadee and the design of the field exercise to solve the problem. We also show the results of the field survey and how the final models compare with the known geology at the site.

Geologic Setting and Exploration Target

Amedee Hot Springs lies in Lassen county in northeastern California near the Nevada state line. It is located approximately 30 km southeast of Susanville and 100 km north of Reno, Nevada at the northeastern shore of Honey Lake (Figure 1).

The Honey Lake basin lies at the western margin of the Basin and Range geologic province where it intersects the Sierra Nevada mountains. The western margin of this northwest trending valley is the Sierra Nevada mountains, the eastern margin of the valley is a series of volcanic ridges which include the basalt covered Amedee mountains. Amedee Hot Springs forms a group of six springs at the eastern end of the valley clustered in a line along the north-northeast trending Amedee fault. It is one of three significant hot springs systems within the valley, all thought to be controlled by fluid flow on near-vertical faults (Mariner et al., 1976).

The Amedee and Wendell hot springs systems are thought to be the surface expression of a fairly large low temperature thermal system in granitic and metamorphic basement rocks at depths of 1.5 -2 km below the surface of the valley (GeothermEx, 1987). The deeper thermal waters communicate with the surface hot springs along vertical to sub-vertical normal faults, which often have distinctive scarps. The temperature of the hot springs at Amedee is boiling to near boiling (90 degrees C). Exploration wells drilled by Magma Energy Inc. have encountered thermal waters in excess of 103 degrees C at depths of 200 meters along the fault. The estimated temperature of the deeper resource, based on chemical geothermometers, is 120-130 degrees C.

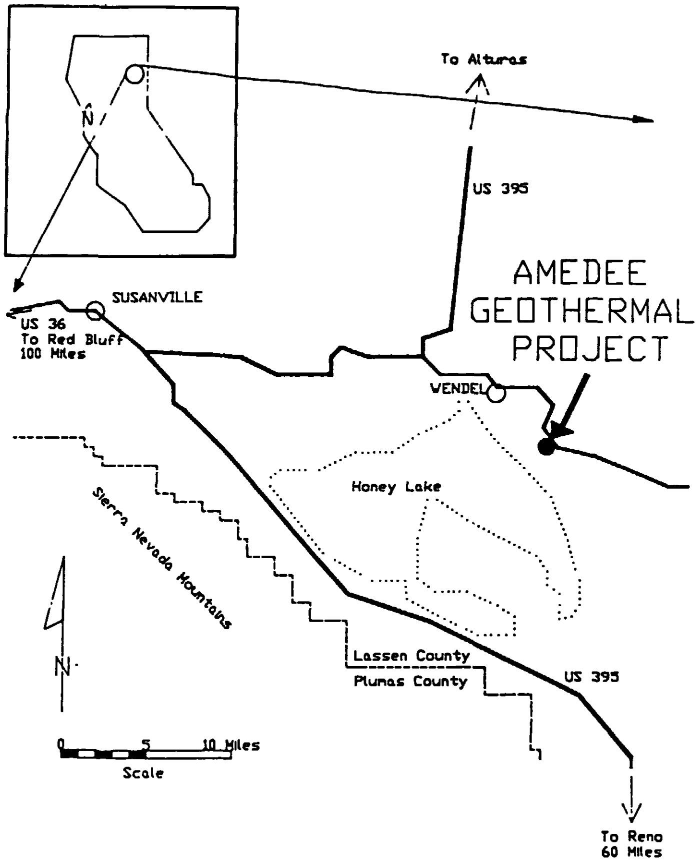

Figure 1 Location map for the Amedee Project.

A major attraction of the magnetic method is its simplicity. The procedure is simply to measure the earth's magnetic field on the surface (or in the air) in the prospect area and use variations in the measured intensity to determine the location and structure of magnetically susceptible bodies within the earth. Modeling the data is equally simple. Interactive 2-d and 3-d (prism) models are available for PC's and field data can be interpreted in a rapid and straightforward manner. The disadvantage of the method for geothermal exploration is that the models are non-unique (i.e. more than one interpretation is possible) and the method is only effective in mapping mafic volcanic rocks.

Self-Potential anomalies have long been associated with geothermal systems. The method is particularly intriguing because the anomalous voltages are due to the subsurface fluid or heat flow and not to a change in a secondary property such as resistivity. The advent of reliable data collection procedures (Corwin, 1990) and the development of a computer code to interpret field data (Wilt and Butler, 1990; Sill, 1982) make it an ideal technique for locating upflow zones in a well-defined convecting geothermal system such as at Amedee.

The SP voltages are related to the flow process through the cross-coupling equations.

$$Q = -C_{11}\nabla P - C_{12}\nabla \varphi \qquad (1)$$

$$J = -C_{21}\nabla P - C_{22}\nabla \varphi \qquad (2)$$

For the fluid flow case the coefficients are given as:

Q and J are the primary flow and current flow vectors,
φ and P are voltage and pressure respectively
∇ is the gradient symbol (spatial derivative)
$C_{11} = K$ is the hydraulic conductivity,
$C_{22} = \sigma$ is the electrical conductivity and
$C_{12} = C_{21}$ are the cross-coupling coefficients that relate the flow processes to the voltages. Similar cross-coupled equations can be derived for heat flow and chemical diffusion.

Equations 1 and 2 state that the fluid and current flow processes are coupled. That is, the observed voltages are directly proportional to the flow and flow processes can originate from an electrical potential. In general, fluid-flow processes do not generate very large electric fields although voltages in excess of one volt have been observed. Similarly, the imposition of electrical potential typically does not generate very large fluid flows, although this method is used for drying low permeability material, such as clay. Note that if we neglect the cross-coupling terms in equations 1 and 2 the equations decouple into the more familiar Darcy's law and Ohm's law.

SP data is interpreted using a numerical solution to equations 1 and 2. The code, developed by Sill (1982), and modified by Wilt and Butler (1990), first solves the steady-state flow problem from the distribution of fluid-flow sources and permeability. From the pressure distribution and a knowledge of the SP cross-coupling coefficients a subsurface distribution of electrical sources (charges) is calculated. From these sources and the resistivity distribution the voltages are calculated within and on the surface.

Because the code requires knowledge of the permeability, SP cross-coupling coefficients and electrical resistivity it can be difficult to use. Experience with the code has proven that the voltages are most sensitive to the distribution of sources and sinks and the parameter distributions are of secondary importance. Due to its complexity, the code is not suitable to use in an inversion and it is presently used in iterative forward modeling.

Data Collection and Interpretation

SP and magnetic data were collected at Amedee by one of the authors (W Teplow) along seven pre surveyed east-west trending profiles (Figure 2). SP was collected using the two-point method described by Corwin (1990) in which a base station is established at one end of the line and voltages are measured with respect to this point. Stations were spaced between 10 and 30 meters apart with the closer stations located over the thermal zones. Individual lines were tied using north-south traverses.

Field data were collected in about three days using a two person crew. SP field equipment consisted of commercially available copper-copper sulfate electrodes, several hundred meters of lightweight wire, a wire reel and a high impedance voltmeter. Magnetic data were collected with a commercially available proton precession total-field magnetometer.

Results and Interpretation

Contour maps of the magnetic intensity and the self potential voltage at Amedee are given in Figures 3.

As suspected, the volcanic Amedee mountains produce a long north-south trending magnetic intensity high with a steep magnetic gradient in the hot springs area on the western flank of the mountains. The size of the maximum anomaly is consistent with 0.5 kilometer or more of fault throw; the dip and orientation of the fault can be determined from modeling. The magnetic low on the eastern side of the plot may be due to lower susceptibility of rocks in this portion of the mountain or to the effects of remnant magnetization, where the volcanic rocks are magnetized during the time they were extruded. The Amedee basalts would therefore be magnetized in the direction of the Cenozoic magnetic pole, which is about 30 degrees different in inclination and 20 degree different in declination from the present pole.

The self potential map shows a 3 km long north-south trending anomaly centered over Amedee hot springs. The anomaly has a high gradient in the hot springs area with a relative high to the west and low to the east. It is significantly reduced to the north and south of the hot springs, suggesting that the primary deep sources lie below the existing hot springs. The dipolar shape of the anomaly and 50-60 millivolt maximum is consistent those observed in other geothermal areas (Corwin and Hoover, 1979).

The contour plots reveal that the magnetic and SP anomalies in the Amedee area are approximately two-dimensional. Hence we concentrated our interpretation along individual east-west profiles across the predominantly north-south structure. With each of these profiles we used 2-D magnetic interpretations together with published subsurface resistivity information and well data to derive a two-dimensional structural

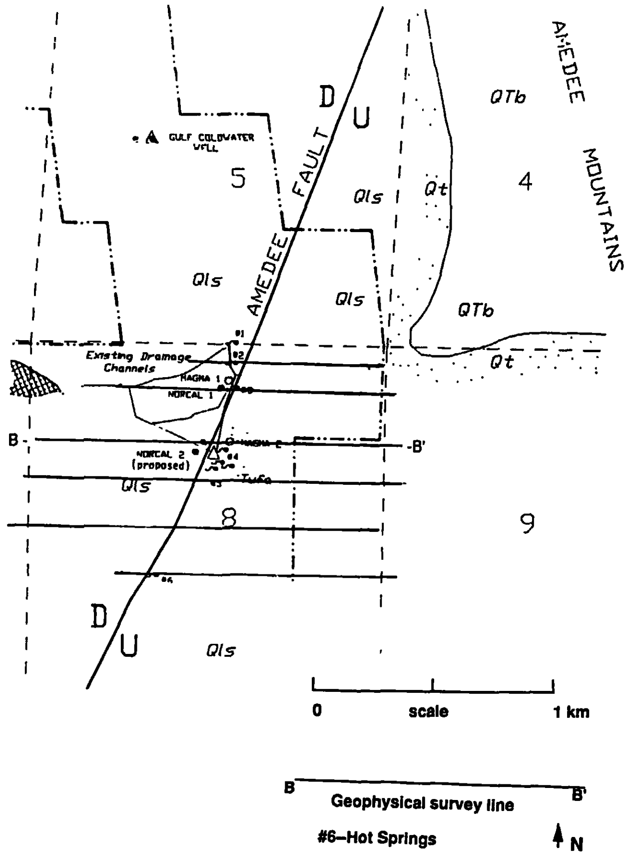

Figure 2 Location of SP and Magnetic Surveys at Amedee.

model. We then use this model together with a permeability and cross-coupling coefficient distribution as an input for our SP modeling code. The initial permeability distribution and cross-coupling coefficients are "educated guesses" based on typical values for the rock types encountered (Wilt and Butler, 1990).

The model used for Amedee consists of three distinct regions; a surface layer 50-60 m thick, a thick (200-300m) wedge of older alluvial deposits, and a buried volcanic ridge dipping 60-80 degrees on its western flank and 30-40 degrees towards the east (Figures 4 and 5). The surface layer has a high permeability (500 mD), moderate resistivity (20 ohm-meters) and a low value for the coupling coefficient (5 mv/ atm). The second layer has a low permeability (1.0 mD) , low resistivity (5 ohm-meters) and a high coupling coefficient (46 mv/ atm). this unit probably represents Pleistocene Lake Lahontan sands, clays and silts. The volcanic ridge has a low permeability (0.1 mD), high resistivity (100 ohm-meters) and a low cross-coupling coefficient (2.5 mv/atm).

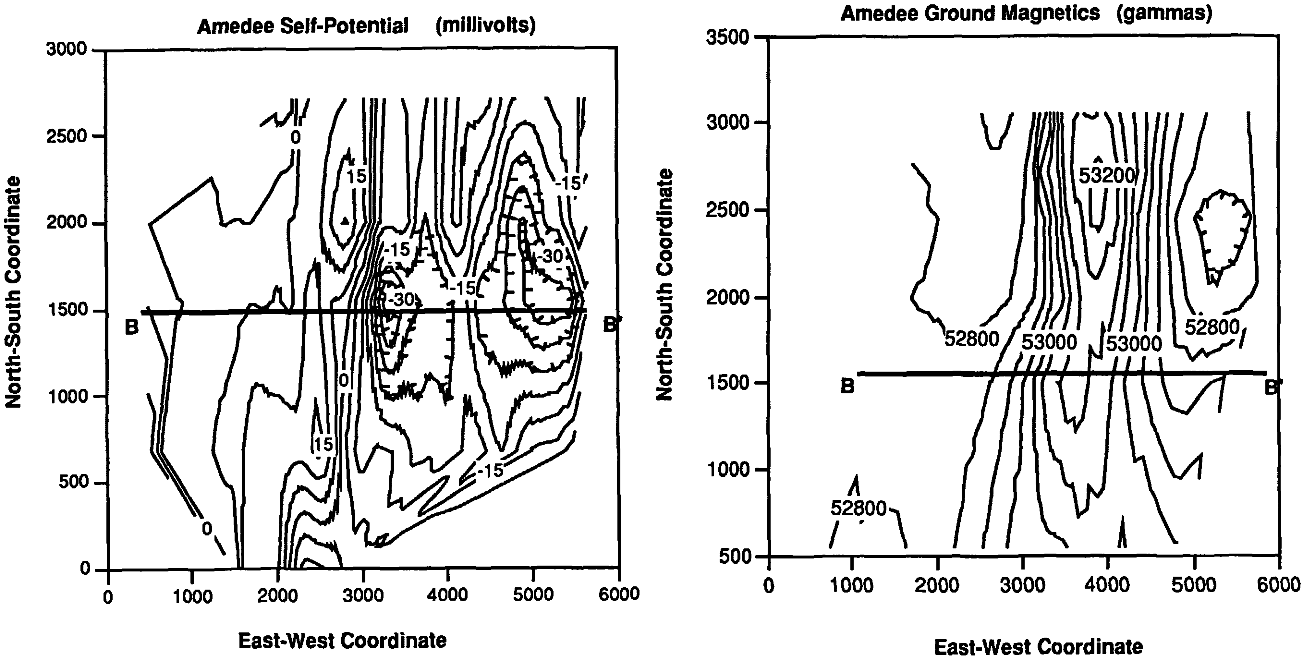

Figure 3 Self Potential and magnetic contours over the Amedee project.

Self Potential data were fitted to model generated data using iterative forward modeling. That is, we started with a parameter distribution, as given above, and adjusted the model until the calculated and observed data fit. This typically required 8-10 hours to fit the data for each model where the individual computer runs were one minute or less on a modern (386 or 486) PC.

In Figure 4 we show the fit of calculated to observed SP data using the model at the base of the figure. The curve shape is similar to a step with an overshoot at the top of the step and undershoot at the bottom. The model for B-B' includes a primary source (fluid coming out) at a depth of 220 m on the western flank of the ridge and a sink (fluid going back in) at a depth of about 70 m on the eastern flank. A simple model for the fluid flow is that hot water, originating from open fractures along the western margin of the volcanic ridge, ascends along the fault plane and partially outflows at the surface at the hot springs. Other thermal water probably remains in the shallow aquifer and flows laterally until it encounters fractures at the eastern margin of the ridge. At this point it flows downwards thereby comprising a "sink".

Note that model requires a "source" to generate the SP voltages. This does not mean that water is being spontaneously generated downhole but rather that there is a local pressure increase, primarily due to thermal effects, that is causing the vertical flow. The magnitude of the pressure sources given in the plot do not translate to well flow rates but are a rough indication of the overpressure due to the thermal effects. An additional shortcoming is that the model requires point or line sources to generate the flow. These are probably poor representations of the actual physical mechanisms.

In general, the fluid flow sources identified by modeling the SP data appear to be coincident with a region of high SP gradient associated with the Amedee fault. The fluid sources are probably associated with fractures within the volcanic unit along this linear feature. The estimated depths of the sources range from 200 to 300 meters which corresponds to waters in the 100 to 110 degree C range.

Discussion and Conclusions

The self potential and magnetic modeling at Amedee has yielded a model consistent with the known geology and well data. The magnetic data has defined the fault trace and it approximate dip angle. The coincidence of the SP anomaly with the fault identified with the magnetics strongly suggests that fluid flow is occurring along the fault. Drilling into the fault at two locations has confirmed this assertion. The model provides reasonable estimates for source locations of the upwelling fluids that supply the hot springs. The model is not, however, unique. As with any potential method other combinations of sources and parameter estimates could yield similar calculated results. However, the availability of surface geological data (fault trace) helped constrain the interpretation.

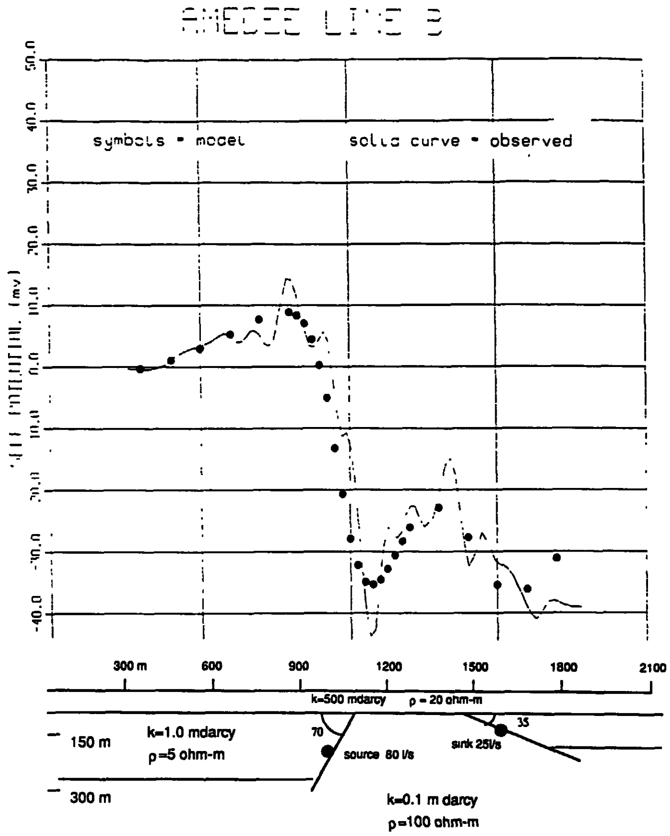

Figure 4 SP profile B-B' and the model used in the interpretation.

This type of modeling must be viewed as a first step in quantitative modeling of SP anomalies in geothermal areas. The imposition of point "pressure sources" and the overall neglect of temperature effects are serious shortcomings of the method. A more satisfying alternative would be to couple the SP voltages to the velocity of the fluid flow rather than a source term. This is a suitable alternative for thermally driven flow systems of the type that produce geothermal anomalies. It would also allow for SP calculations using a fluid-flow simulator so that we could more realistically model the system.

This latter approach is the focus of new research being conducted at Lawrence Livermore and Lawrence Berkeley Labs. Progress on the development of codes and the interpretation of field data is forthcoming.

Acknowledgement

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