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MODELING SELF-POTENTIAL DATA IN THE ABRAHAM AND MEADOW-HATTON GEOTHERMAL SYSTEMS: THE SEARCH FOR UPFLOW ZONES

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ABSTRACT

Self-potential (SP) measurements may be used to locate upflow zones in geothermal systems. As geothermal waters move beneath the surface, the resulting pressure and heat variations are seen as anomalies in the electrical currents that are measured within or at the surface.

Beginning in 1991, Ross et al. collected SP data at Abraham and Meadow-Hatton Hot Springs, two of the largest thermal spring systems in Utah. In this paper, these data were modeled to determine upflow zones and source characteristics using a numerical modeling code. The code calculates the forward solution for fluid or heat flow models and the resulting self-potential anomalies. These results were matched to field data by iterative forward modeling; that is, we adjusted the model until field and numerical data agreed.

At Abraham Hot Springs, a 3 km, north-south trending, dipolar anomaly was measured, centered on a suspected fault zone. The anomaly was not coincident with the hot springs themselves. Modeling indicates that the upflow originates from about 200 m depth, ascends up the fault zone to a shallow aquifer, where it then migrates eastward to outflow at the hot springs. At Meadow-Hatton Hot Springs, two closely spaced negative anomalies, also about 3 km long trending north-south, were modeled to show two upflow sources at about 200 m depth. The flow likely ascends up fractured zones until it reaches a shallow travertine layer and disperses laterally, with very little outflow at the hot springs at present.

INTRODUCTION

Self-potential (SP), also known as spontaneous potential, can be generated by fluid flow (electrokinetic), heat flow (thermoelectric), or chemical flow (electrochemical) processes. Because the flow of electrical current and the flow of fluid or heat are coupled, each causes potentials in the other. For example, the pressure-driven flow of water through porous rock will generate an electrical potential within the rock that may be used to deduce characteristics of the flow or the medium (Sill, 1983).

Geothermal systems tend to have significant SP anomalies due to the high level of fluid flow and heat transfer. This makes the SP method a natural technique for locating the upflow zones and delineating the internal structure of these systems. Although SP field surveys can be both simple and inexpensive, the observed anomalies can come from a variety of sources unrelated to the geothermal activity. Interpreting the data is therefore a tricky business requiring some experience. Computer modeling provides a means of making sense of SP data by using the known geology and hydrogeology of the study site.

In this paper we apply a numerical modeling code to interpret SP data collected at Abraham and Meadow-Hatton Hot Springs in central Utah, sites of variable surface discharges of thermal waters. The computer code makes SP an effective geophysical tool for geothermal exploration, and helps us gain a further understanding of the structure and location of upflow zones.

Numerical models have previously been used to interpret geothermal anomalies in cases where there are clear or suspected relationships to the sources. Fitterman and Corwin (1981) used geometrical shapes to interpret a large SP anomaly at the Cerro Prieto geothermal field. Sill (1983) interpreted SP data at Monroe Hill using a thermoelectric model. More recently, Wilt et al. (1993) used a version of Sill's code to interpret SP data at Amedee Hot Springs. A combination of SP and magnetics was used to locate the upflow zones within fault planes of the geothermal prospect. A dipolar anomaly was prevalent in the surface voltage data centered on the fault trace. From the modeling, the source depths were estimated to be between 200 and 300 m. These predictions were later confirmed by drilling.

NUMERICAL MODELING

Computer code SPXCL is a finite difference modeling algorithm that calculates the response of embedded point sources within a rectangular, two-dimensional medium. The code calculates the electrical potential anywhere in the medium from thermal (heat) or pressure (flow) sources. Program SPXCL is the latest modification of a code originally written by Sill (1983). The new code features an expanded mesh, more flexibility on source positioning, and an easier system of data input and output.

The electrical potential is calculated using a three step process. First, using pressure or thermal sources, the primary potential (heat or pressure) is calculated throughout the medium. This calculation is simply a numerical solution to Darcy's Law or the Fourier heat conduction equation. Next, the cross-coupling coefficients are used to determine the location and strength of electrical current sources, due indirectly to the flow processes. These coupling coefficients are the physical constants that relate the flow process to the observed voltages. High coupling coefficients (usually hard rocks or clean sandstones) result in higher induced currents; changes in coupling coefficients in the direction of flow results in induced current sources. Finally, the voltage is calculated from the location and strength of the current sources and the resistivity distribution of the medium.

The two-dimensional model therefore requires input of three sets of physical properties for every mesh point. The location and strength of the flow sources must also be specified. The resulting voltages, pressures and temperatures can be used to fit field observations.

Data is interpreted via iterative forward modeling. That is, a model consistent with the known geology and hydrology is originally input and then iteratively modified to fit the SP voltages and/or pressures and temperatures. The process is far too non-unique for use in automatic inversion, but it is a very powerful tool in iterative forward modeling to apply to SP data in constructing a model of the hydrologic and thermal systems at geothermal sites.

MODELING GEOTHERMAL SYSTEMS

To insure accurate modeling, the program SPXCL requires a two-dimensional structure. It is therefore most suitable to geothermal systems controlled by basin structure or faulting. The SP data from Abraham and Meadow-Hatton Hot Springs indicated that the anomalies were elongated, but they needed smoothing to remove perturbations in voltage that appear as small-scale anomalies. We applied a rough hand-smoothing of the data to accentuate large wavelength anomalies most likely related to deeper flow.

A profile line was then drawn across the contoured voltage structure, perpendicular to the trend. A plot could then be constructed of the surface SP voltage values along that line. This plot represented the original surface voltage data and provided the basis upon which the models from SPXCL were matched.

Information regarding geology, hydrogeology, and electrical properties was gathered for each site to begin constructing a model. These parameters include the permeability distribution, resistivity structure, and cross-coupling coefficients. These are either known from geology or hydrogeology of the site, or are estimates from previous experience. Source characteristics were derived based on educated guesses. The code allows the input of either a point or a line source. We started with a plausible parameter distribution in the input mesh and adjusted parameters until we obtained the closest match between observed and calculated data. Each model required about 20 s on a Sun workstation, or 30 to 60 s on a 486 or a Pentium PC.

ABRAHAM HOT SPRINGS

Geology. Abraham Hot Springs lies in the eastern Basin and Range province in the complexly faulted structural basins of the Sevier Desert in western Utah. These basins are further subdivided into smaller basins by numerous planar and listric faults. The Sevier Desert detachment, a west-dipping detachment surface 10° to 12°, separates crustal extensional features less than 5 km from deeper pre-Basin and Range structures (Ross et al., 1993).

The thermal hot springs that issue at Abraham have temperatures as high as 87°C (189°F) and flow rates ranging from 90 to 140 l/s (1427 to 2219 gpm). This is arguably the greatest flow rate of any hot springs system in Utah. The hot springs lie about 6 km east of Fumarole Butte, a Quaternary eruptive center that formed a broad basalt apron known as Crater Bench, believed to be early Pleistocene in age. A probable north-northwest trending fault (Oviatt, 1991) is located west of Abraham Hot Springs that likely provides the vertical permeability for geothermal flows within Crater Bench.

Data Collection. A total of approximately 22.0 line-km (13.6 line-mi) of SP data were collected in April and June 1991 and April 1992 (Ross et al., 1993). Figure 1 is a map of the Abraham Hot Springs area showing SP contours in millivolts and data collection points. The base station is located about 100 m (300 ft) west of the main hot spring. SP values measured at this base station are close to background voltage levels based on the distribution of zero contours on the map. The voltages measured at the roving electrode were typically low-amplitude and low-noise. The contours show a number of local high and low anomalies, but the general trend is negative values to the west of the fault and positive values to the east.

SP Modeling. The smoothed SP contours and the profile line A–A′ are shown in Figure 2 overlaying the raw SP contours of Figure 1. SP values to the west of the fault were predominantly negative, reaching on average −40 mV, while to the east, the values were predominantly positive, reaching on average +40 mV. Raw and smoothed SP data along profile A–A′ are shown in Figure 3. The smoothed data indicates there is a large dipolar anomaly centered on the fault trace.

Our geologic model, based on observations and published geology and geophysics (Mabey and Budding, 1987; Oviatt, 1991) is shown in Figure 4a. The SP model used for Abraham, Figure 4b, is based on this geologic cross section. In the model, two layers of Quaternary basalt overlay the alluvial sediments. These layers represent the basalt apron that resulted from flows erupting from Fumarole Butte. The lower layer, the weathered basalt mixed with Quaternary alluvium, is 75 m thick, highly resistive (100 Ω-m), highly permeable (300 mdarcies), and has a high cross-coupling coefficient (40 mV/atm). Although basalt normally has a low bulk permeability, a high value for permeability was given to this unit because it is likely highly fractured. The upper layer, the fresh basalt, has virtually the same properties as the weathered basalt, except the permeability is lower due to less fracturing. The alluvial sediments have low permeability (1 mdarcy), low resistivity (3 Ω-m), and a low cross-coupling coefficient (2 mV/atm). The vertical unit that resembles a dike represents the passage for fluid flow to ascend. It consists of highly fractured alluvial sediments and is coincident with the fault. It has a moderate permeability (10 mdarcies), moderate cross-coupling coefficient (9 mV/atm), and low resistivity (3 Ω-m). Pre-Tertiary sediments underlie the alluvial sediments with low permeability (1 mdarcy), low cross-coupling coefficient (2 mV/atm), and high resistivity (200 Ω-m).

A pressure point source was placed at 200 m depth, near the contact of the highly fractured conduit and the alluvial sediments. The source strength at this depth was estimated to be 300 l/s, about twice the observed flow rate at the surface. Our experience is to designate the source strength at least twice as much as the surface flow rate to account for dissipation of geothermal waters before they reach the surface. Physically, this point source represents the onset of open fractures where there is a change in the subsurface pressure.

Interpretation. Figure 5 shows the fit of the modeled and smooth observed SP data. The high source strength used in the model, 300 l/s, was necessary to generate the large −40 and +40 mV anomalies. The source is placed on the left (west) side of the vertical contact between the alluvial sediments and the fractured conduit. The pressure gradient decreases in the conduit since it is more permeable, creating positive induced sources on the vertical contact that diminish the effects from the point source. However, the dipolar form of the anomaly is enhanced by the permeable overburden layers that induce positive sources at the lower overburden contact where vertical flow occurs across horizontal boundaries.

Although the depth required for heating the fluids, suggested by Ross et al. (1993), is about 3 km (9800 ft), the actual source from which fluids are released from a high pressure conduit to a lower pressure layer in the subsurface is expected to be much shallower. A likely scenario is that geothermal waters are circulated by convection to an area of highly fractured rock. The high permeability of the fractured zone causes a decrease in pressure. This area is designated as the source location in the model at 200 m depth. The flow

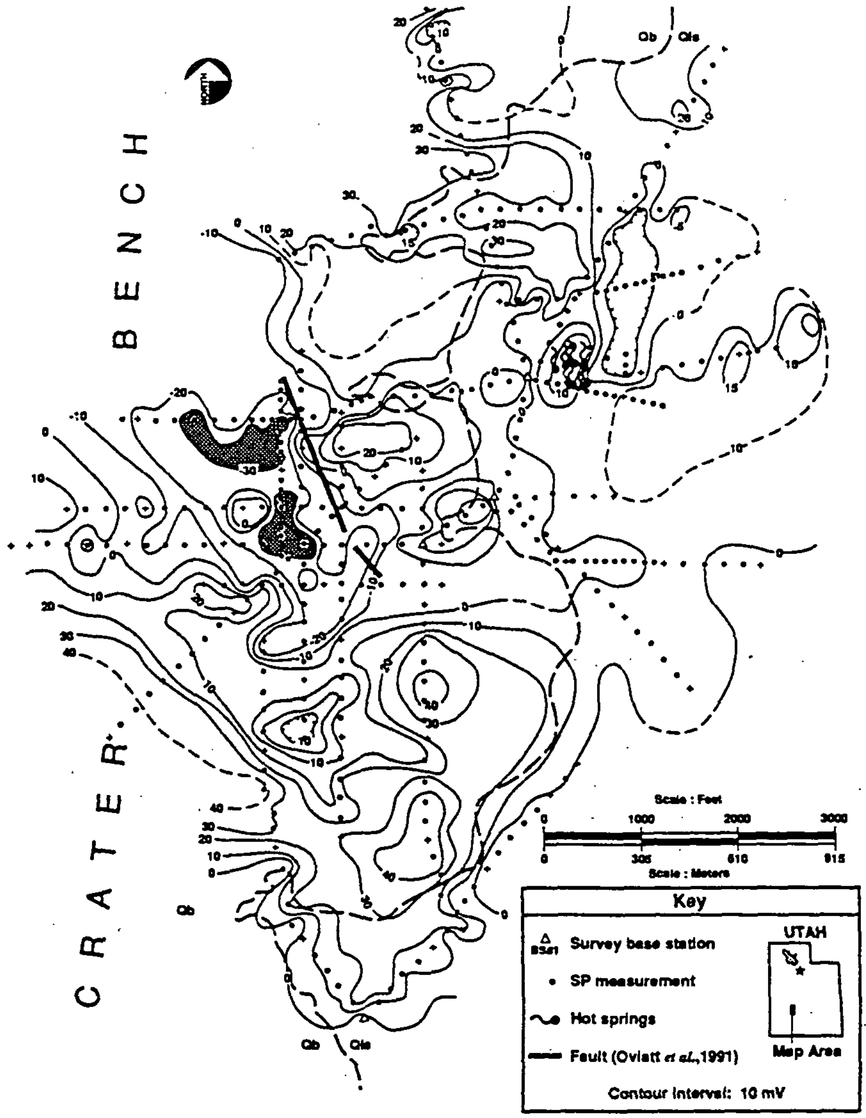

Figure 1. Location map of Abraham Hot Springs showing surface voltage values. SP contours are in mV. Data were collected in line arrays. Each data point is shown as a dot. The base station is shown as a triangle.

then ascends along the fractured zone conduit, encounters the basaltic overburden, and travels laterally until it discharges at the surface.

Although such a scenario appears to be consistent with the known geology of Abraham Hot Springs, the model does not match the observed data perfectly. We did not strive to obtain a perfect match due to the data manipulation required before modeling. Instead, we adjusted model parameters to see which ones the model was most sensitive to. We discovered that the model was most sensitive to small changes in the permeability and resistivity of model units, and changes in the source depth. The location and strength of the source in relation to the fractured zones also played an important role for aligning the dipolar anomaly correctly with the observed SP data. Even though it is non-unique, the final model in Figure 4b is a valid interpretation because it is consistent with the known and inferred geology.

MEADOW-HATTON HOT SPRINGS

Geology. Meadow-Hatton is located in the eastern Black Rock Desert, also in the eastern Basin and Range province of western Utah. The Meadow-Hatton Hot Springs system consists of the Meadow Hot Springs and the Hatton Hot Springs. Hatton Hot Springs has a temperature recorded at 63°C (145°F) and a flow rate of 0.1 l/s (1.6 gpm). The hot springs issue from the edge of a 2 km long, northeast trending travertine mound that has long fissure ridges, terraces, sloping mounds, and raised pools. Meadow Hot Springs experiences variable flow rates, from no discharge to significant discharge, indicating that the flow is likely dispersed underground near the surface.

Data Collection. Figure 6 is a map of the Meadow-Hatton Hot Springs system with SP contour lines in millivolts and data collection points. The SP survey totaled 29.5 line-km (18 line-mi). The field studies by Ross et al. (1993) document that three coherent anomalies with amplitudes of -70 to -120 mV exist 300 to 1000 m north of Hatton Hot Springs suggesting a possible upflow zone where some venting occurs and fluid moves at low rates to the springs. No significant anomalies were observed at Meadow Hot Springs, perhaps in part due to low surface resistivities.

Figure 7 shows the smoothed SP contours with the profile line B–B′ used for modeling. There are two predominantly negative regions, with adjacent anomalies reaching about -50 mV. In Figure 8, the SP surface voltages along the profile line are plotted. The large negative anomaly is divided into two major negative peaks with small positive flanks on either side.

SP Modeling. Our geologic cross section and model used for Meadow-Hatton are shown in Figures 9a and b, respectively. Thermal fluids rise along fractures which cut valley fill sediments (both alluvium and lake beds) both at Abraham and Meadow-Hatton Hot Springs, so there is some similarity in the geologic models. The model proposed for Meadow-Hatton consists predominantly of alluvial sediments, with low permeability (1 mdarcy), low cross-coupling coefficient (2 mV/atm), and fairly low resistivity (10 Ω-m). These sediments are underlain by the basement rock, perhaps pre-Tertiary sediments. The geothermal waters ascend via two conduits (fractures). These are modeled as dike-type features that feed mounds on the surface with low permeability (1 mdarcy), low cross-coupling coefficient (0.01 mV/atm), and moderate resistivity (10 Ω-m). A layer of the dry, porous travertine extends out from the dome on either side, having high permeability (800 mdarcies) and high resistivity (100 Ω-m) above the water table. Two sources are located at 200 m depth each on the outside contacts of the conduits and have rather high flow rates (190 l/s and 200 l/s).

The dome of mixed alluvium and travertine is about 20 m high and expands laterally 600 to 900 m. The input mesh for SPXCL

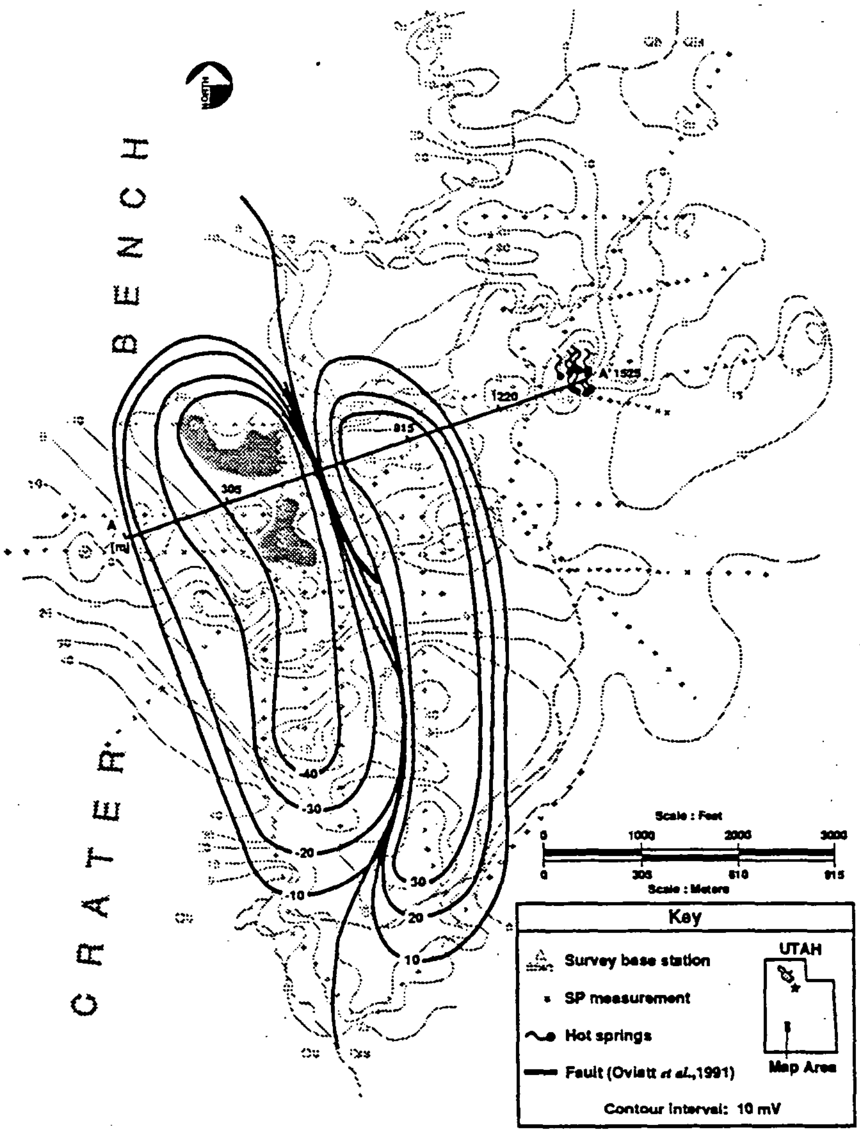

Figure 2. Abraham Hot Springs smoothed surface voltages. SP contour interval is 10 mV. The profile line A–A′ intersects the elongated SP anomaly.

requires a rectangular array of model units. Thus, to include the travertine mound, there must be a model unit representing air surrounding the mound. The air is given a high permeability, low cross-coupling coefficient, and high resistivity.

Interpretation. Figure 10 shows the fit of the observed and model-generated data. There is good correlation in the magnitudes of the peaks. Like the model for Abraham Hot Springs, the highly negative anomalies (-50 mV) measured require large flow rates at the sources. The two sources are located on the outside contacts of the two highly fractured zones of alluvium and travertine, with a low cross-coupling coefficient. The higher cross-coupling coefficient of the surrounding alluvial sediments produces a gradient parallel to the primary flow that in turn creates sources of conduction current. These are responsible for the two large negative peaks. The small positive peaks are slight dipolarities resulting from the vertical flow through the highly permeable travertine layer.

The model suggests that geothermal waters, brought up from deeper convection, may have encountered a positive pressure gradient at the fractured conduits at about 200 m depth. However, there is no evidence of flow within the travertine dome above the water table and hence above the source area at present. We believe that the hot waters migrated laterally in the permeable travertine layer to outflow at Hatton Hot Springs where minor seeps occur, and probably northwest beneath conductive soils, to the Meadow-Hatton pools area. In other words, the source of upflow still exists, but the water does not discharge at Hatton Hot Springs.

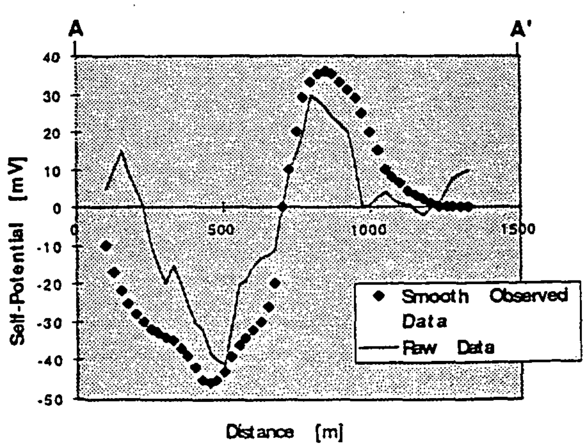

Figure 3. Plot of surface voltage along the profile line A–A′ shown in Figure 2 for smoothed and raw SP values.

CONCLUSIONS

Modeling using SPXCL is an excellent first step in locating the upwelling fluids that supply hot springs. SPXCL provides a means of using self-potential data to help delineate the driving mechanism in a geothermal system when the source is fast-flowing and relatively near the surface. We have shown through these two studies at Abraham and Meadow-Hatton Hot Springs that models consistent with known geology can locate the source depth, strength, and location.

As with any geophysical technique though, SP modeling does not come without limitations. The solutions derived are restricted to a point or line source, the code cannot account for three-dimensional variations, and the solution is not unique. However, given

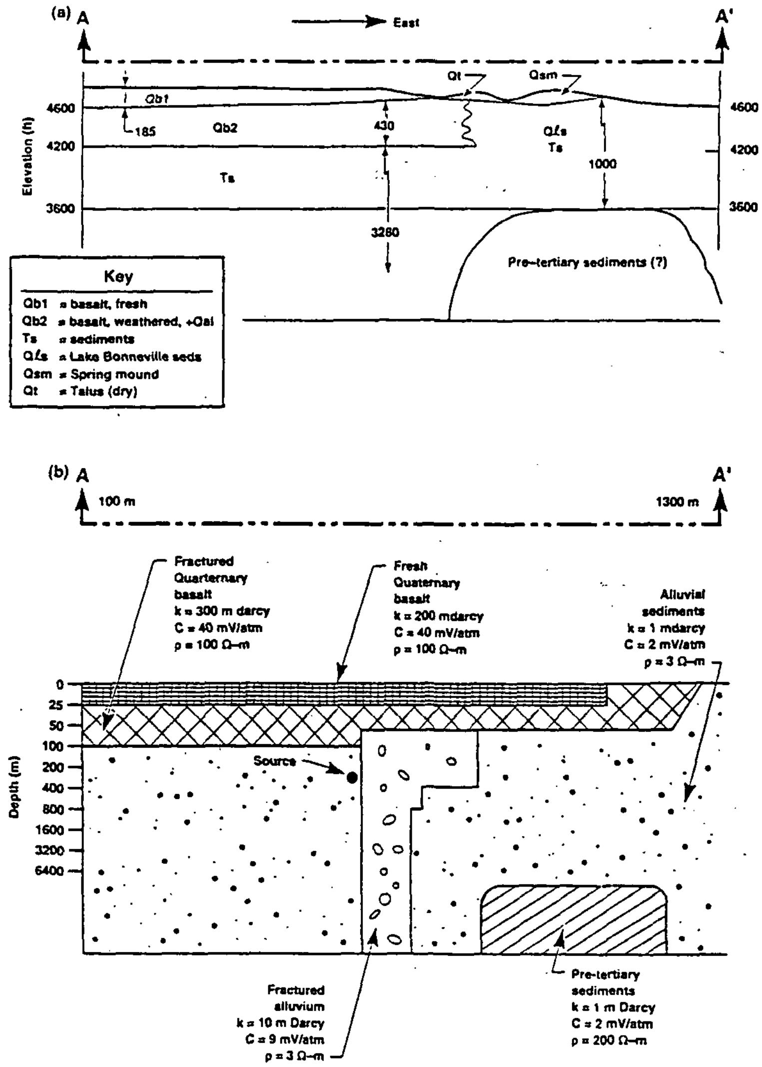

Figure 4. (a) Geologic cross section of Abraham Hot Springs. (b) Model used in the SPXCL interpretation.

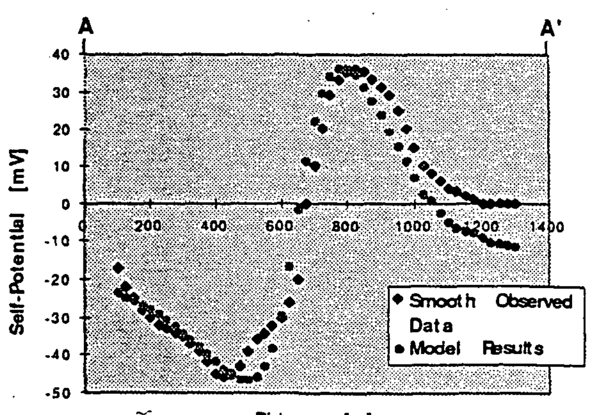

Figure 5. Plot of surface voltage values generated from the model compared to the smooth observed values.

enough background information on a site, a model can be constructed to characterize geothermal sources that is both accurate and realistic.

ACKNOWLEDGMENTS

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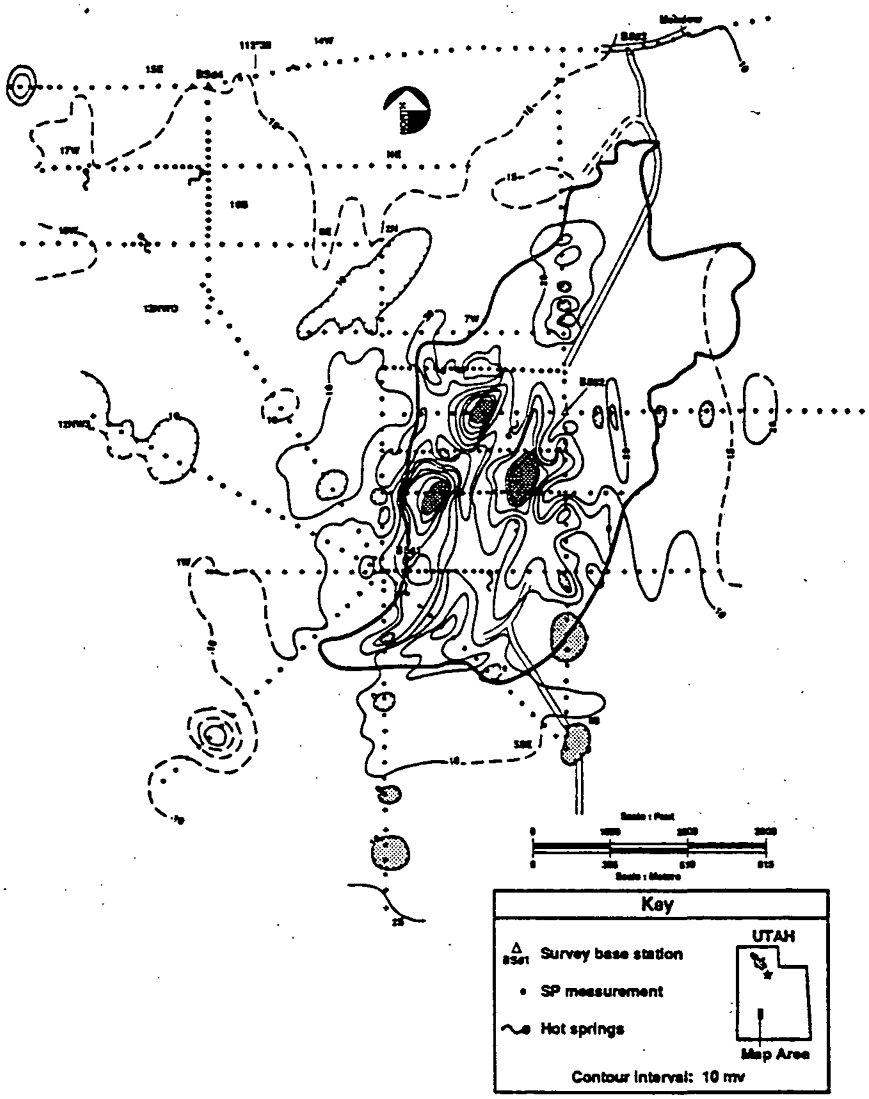

Figure 6. Location map of Meadow-Hatton Hot Springs showing surface voltage values. SP contours are in mV. Data were collected in line arrays. Each data point is shown as a dot. The base station is shown as a triangle.

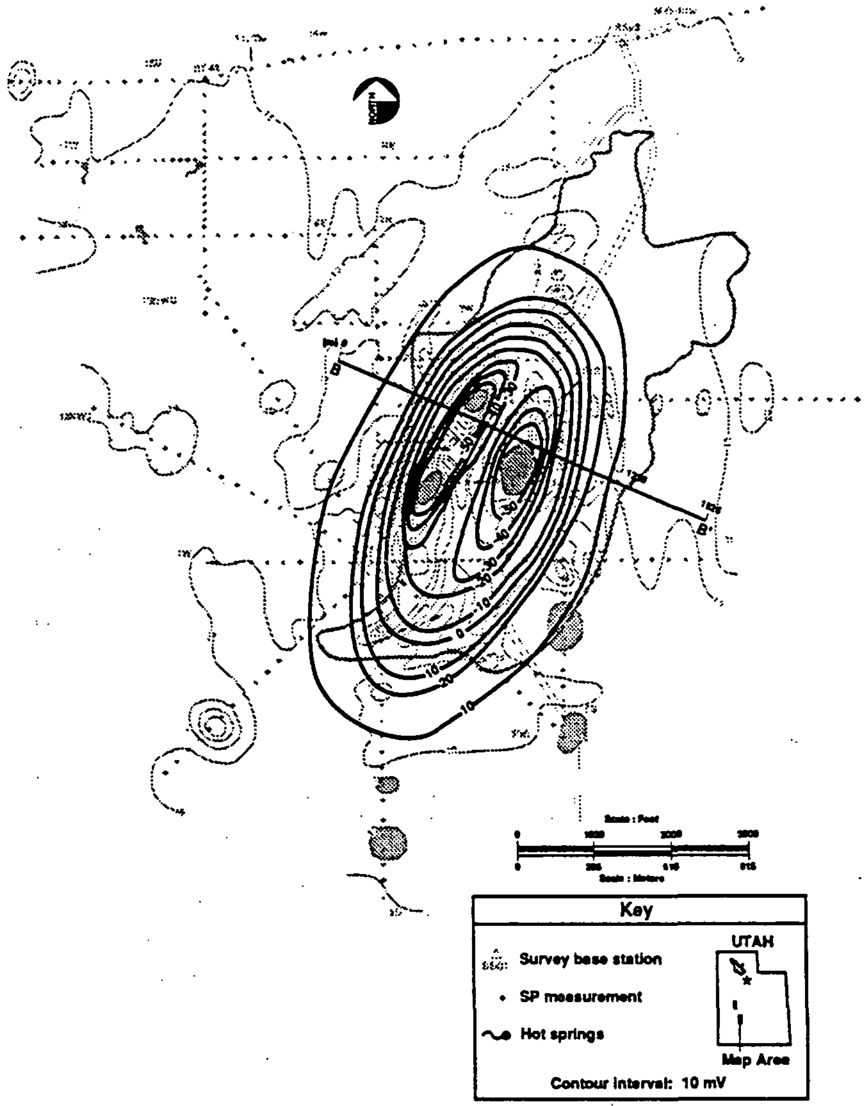

Figure 7. Meadow-Hatton Hot Springs smoothed surface voltages. SP contour interval is 10 mV. The profile line B–B′ intersects the elongated SP anomaly.

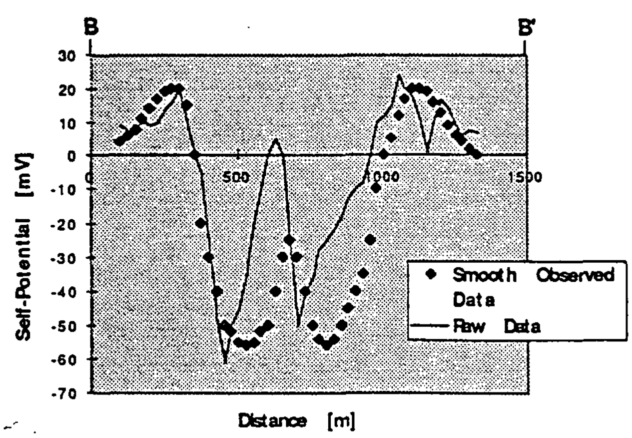

Figure 8. Plot of surface voltage along the profile line shown in Figure 7 for smoothed and raw SP values.

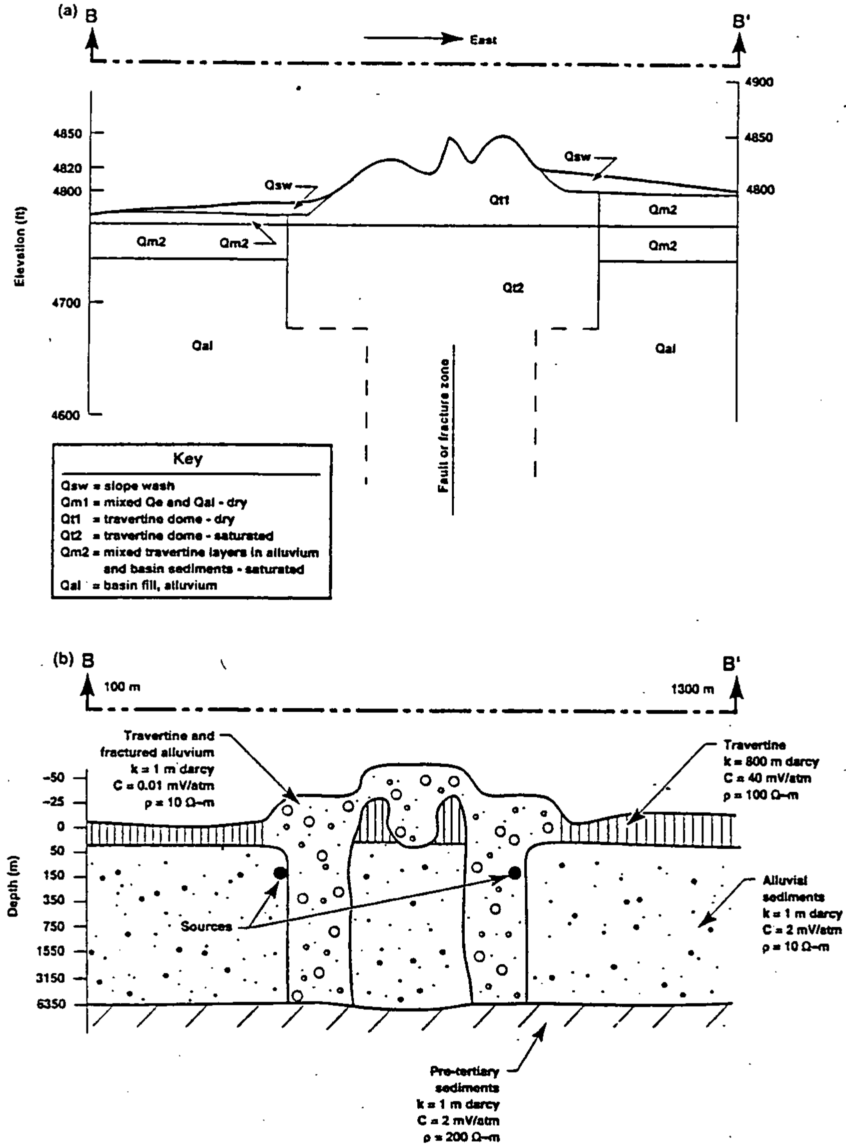

Figure 9. (a) Geologic cross section of Meadow-Hatton Hot Springs. (b) Model used in the SPXCL interpretation.

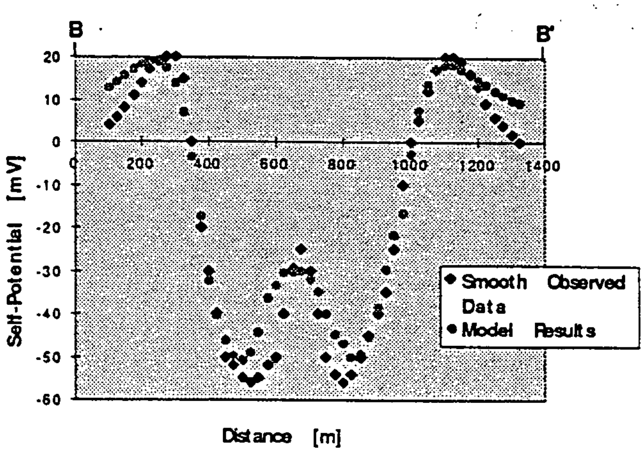

Figure 10. Plot of surface voltage values generated from the model compared to the smooth observed values.

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