THE SELF–POTENTIAL METHOD: COST–EFFECTIVE EXPLORATION FOR MODERATE–TEMPERATURE GEOTHERMAL RESOURCES

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Key Words: Self–potential, Geothermal, Exploration, Geophysics.

ABSTRACT

The self-potential geophysical method is an established geophysical technique which measures naturally occurring voltage differences at the surface of the earth. UURI, in conjunction with state resource teams and private companies, has completed detailed SP surveys over ten geothermal systems throughout the western United States since 1989. Most of these resources are characterized by a small, fault-controlled upflow zone and an extensive outflow area at shallow depths. Survey procedures have been developed to obtain high-quality, low-cost SP data for survey areas of 2 to 8 square km. Although positive, negative, and multi-polar anomalies were observed, the better-defined anomalies are often minima, several of which exceed 100 mV.

1. INTRODUCTION

The self-potential (spontaneous, or natural potential; SP) method has been used increasingly for engineering, hydrologic, environmental and geothermal applications since the early 1970's (Convin, 1990). Self-potential surveys have often been used in exploration for high-temperature geothermal systems, but only to a limited extent for low- to intermediate-temperature (<150°C) systems. Although SP anomalies are often observed over geothermal systems, the expression may be positive, negative, dipolar or even more complex (Convin and Hoover, 1979). This varied expression is sometimes confusing and reduces confidence in and use of the method in geothermal resource exploration and development.

UURI has been evaluating the SP method as a cost-effective exploration technique for covered hydrothermal resources, and especially for low- to intermediate-temperature resources. Much of this work has been completed in support of Department of Energy-Geothermal Division (DOE/GD) programs for state-oriented resource assessment. Because the method measures natural electrical fields, survey costs are relatively low and the method can be employed for delineation of direct-heat resource areas. Since 1989, we have completed detailed SP surveys in three western states as indicated in Figure 1. The geothermal areas and surveys discussed here are located in the Basin and Range Province (Nevada and Utah) and the southern Rio Grande Rift Province (New Mexico).

2. SP SURVEY PROCEDURES

Conventional SP survey procedures were modified to increase survey accuracy and efficiency. A radial or "spoke" survey technique was used so that many potential measurements, generally at 60-meter spacings along the lines, could be made directly with respect to a central stationary electrode designated as a base station (Figure 2). The radial array has been especially useful for reconnaissance surveys, but perpendicular and parallel profiles have been completed from the same reference electrode when additional detail was required. This helped minimize cumulative errors which could result from looping between intersecting profiles or gradient-type measurements. When it became necessary to extend the survey multiple observations were completed for designated tie points so the potentials of all reference electrodes were standardized to the primary base station. The surveys were completed using a high-impedance Fluke™ digital multimeter and copper-copper sulfate porous-pot electrodes connected by a spooled, 1300 m, lightweight single-conductor copper wire. Areas of 5 km^2 were surveyed from a single reference electrode when surface conditions (topography, cultural features) permitted.

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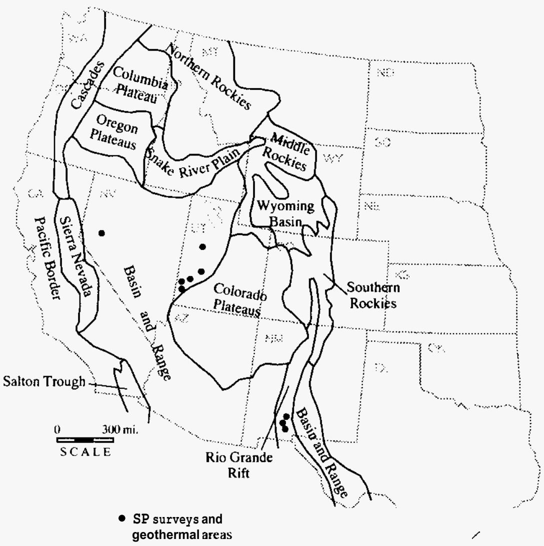

Figure 1 Location of self–potential studies and geothermal areas discussed in this paper Geologic provinces of the Western United States are modified from the physiographic provinces of Fenneman (1946).

All of the geothermal areas discussed here occur in arid climates, and soil moisture conditions varied considerably. When electrode-ground impedance was high, or soil moisture content varied, electrode holes were prewatered to reduce noise levels. **As** reported by Convin and Hoover (1979), watering electrode holes prior to SP readings may cause substantial voltage variations as the free water infiltrates from the hole. in our surveys, electrode holes were sometimes watered the afternoon before reading. More typically, electrode holes were wet with a small amount of water while measuring station locations away from the survey base station. The SP values were then observed on the return, after waiting for SP values to stabilize at the last station on the profile. Individual station potentials were recorded to **1** mV, and net survey accuracy, evaluated by numerous repeat measurements, was generally within +/- 5 mV.

3. SP SURVEY RESULTS

The topographic relief was low to moderate (generally less than **200** m) in most of the survey areas. Surface materials included Quaternary alluvium, colluvium, lake beds, travertine domes, marshes, sand dunes, Quaternary basalt flows, and Tertiary volcanic tuffs. Table 1 summarizes some numerical aspects of nine detailed surveys

Table 1. Data Summary for Self–Potential Surveys of Geothermal Areas.

Area	Temperature (°C) Res*	Obs'	Depth (m)	Surface Manifestations	SP Survey Area (km²)	Line-km	Anomalies (mV)	Anomaly Size (km)
Newcastle, UT	>130	98	100	none; hot wells	1.5	9.8	-108,-44,-36	0.6 x 0.3
Woods Ranch, UT	>110	36	30	none; hot wells	8.0	25.0	-59,-43	1.8 x 0.9
Thermo, UT	130	90	0	domes; seeps	10.4	45.0	-116,-40,-30	2.5 x 2.0
Meadow-Hatton, UT	200?	-	0	----	6.5	29.5	----	----
Meadow (hot pools)	-	32;41	0	hot pools			0(?)	----
Hatton (hot springs)	-	63	0	domes; springs			-120,-74,-72,+60	1.0 x 0.7
Crater (Abraham), UT	140?	55-87	0	springs; pools	5.7	22.0	-46,-24,+14,-9	1.0 x 0.5
Carson Lake, NV	>100	>50	100	none; hot wells	10.9	41.9	-96,-71,-61,-50	2.1 x 0.7
Rincon, NM	>140	88	128	alteration; hot wells	6.1	37.5	-122,-77,-74,-34	2.4 x 1.3
Radium Springs, NM	>100	70	<15	hot springs; wells	6.5	21.8	-146,-92,-42,-34	2.5 x 1.3
Tortugas Mtn., NM	-	>50	90	none; hot wells	4.2	20.2	0 to -40 (?)	2.0 x 1.0

*Estimated reservoir temperature; 'Temperature in springs or shallow wells.

which were completed and the anomalies which were defined. Three surveys are described in more detail later.

The measured fluid temperatures for the areas studied range from 32°C to 130°C. Several resources have reservoir temperatures of 110°C to 200°C as predicted by chemical geothermcmeters. Five areas (Newcastle, Woods Ranch, Carson Lake, Rincon, and Tortugas Mountain) have no thermal manifestations at the surface but were identified as hydrothermal systems from thermal wells. The area covered by the SP surveys varied from 1.5 km^2 at Newcastle (where the upflow zone was identified by shallow thermal gradient holes) to more than 10 km^2.

3.1 Anomaly Magnitudes and Extents

The anomalies identified in these surveys are generally located upgradient from the known outflow plume and are ofteii closely associated with the probable upflow zone. The anomalies are well defined, perhaps because the depth to thermal fluids is typically less than 100 m. Only minor anomalies were observed over the laterally moving fluids in the outflow plume (Ross, *et al.*, 1990; 1993). The lateral extent of the anomalies (which may include several minima and maxima) often exceeded 2 km in the longest dimension.

Most of the observed anomalies were minima, several of which exceeded -100 mV in amplitude. A maximum of **60** mV, surrounded by larger minima, was observed over the Hatton thermal mound. A local maximum of +14 mV with a dipolar minimum of -9 mV occur directly over the Abraham Hot Springs thermal mound. No significant (>5 mV) anomaly was associated with three warm pools at Meadow Hot Springs. No definite anomaly could be associated with the probable upflow zones of the Tortugas Mountain area, which is the source of thermal fluids for the large Las Cruces -East Mesa reservoir. Although a broad, low-amplitude anomaly may be present, it is obscured and dominated by geologic and near-surface noise (Ross and Witcher, 1992).

3.2 Newcastle, Utah SP Survey

The Newcastle geothermal system is located in a broad basin in southwestern Utah, near the Basin and Range - Colorado Plateau transition zone (Figure 1). Geologic, geophysical and temperature data indicate that thermal fluids rise beneath alluvial cover at the intersection of older northwest-oriented faults and fractures mapped in Tertiary volcanic bedrock with the northeast-oriented, basin bounding Antelope Range fault (Blackett and Shubat, 1992). This fault displays Quaternary movement. Temperatures of 130°C have been recorded at a depth of **100** m; fluids of 89°C are produced from a broad outflow plume to heat greenhouses and a church (Ross, *et al.*, **1994).** This is a covered geothermal system - there are no surface thermal manifestations.

A SP survey completed in 1989 (Figure 3) defined a near-circular minimum of **-108** mV (Ross, *et al.*, 1990). The minimum is located between three shallow temperature-gradient holes which recorded temperatures of 72°-94°C at depths of 12-15 m. Dipole-dipole electrical resistivity data mapped a near-vertical, low resistivity zone, interpreted as a thermal fluid upflow zone, coincident with the SP minimum. Secondary minima of **-44** and -36 mV occur to the southwest, above the covered Antelope Range Fault.

3.3 Rincon, New Mexico SP Survey

The Rincon geothermal area is located in the southern Rio Grande rift at the eastern margin of the East Rincon Hills uplift (Figure 1). The indurated sedimentary clastic rocks and Tertiary volcanic flows of the Rincon Hills are bounded on the east by a late Pleistocene fault, the East Rincon Hills Fault. East of the fault, downdropped fluvial sand and gravel deposits show increasing alteration as the fault is approached (Witcher and Schoenmackers, 1990; Witcher, 1991). Drill testing of a radon soil-gas anomaly indicated temperatures excecding 80°C at a depth of 88 m, still above the water table. Geothermometers determined from fluid samplcs of other boreholes suggest a deep reservoir with temperatures above 140°C.

A self-potential survey completed by Ross and Witcher (1992) defined a broad, elliptical SP low, approximately **2.4** km long and 1.3 km wide (Figure **4).** The largest of several minima, -120 mV, is located near drill hole RAD-8 which recorded 85°C at a depth of 88 m. Secondary SP minima of -77 and -74 mV extend the area of interest and provide additional drilling targets.

3.4 Crater Springs, Utah SP Survey

The Crater Springs geothermal area is adjacent to a Quaternary eruptive center known as Fumarole Butte. Basalt flows erupted from the butte formed a broad volcanic apron as much as 150 m thick known as Crater Bench. Thermal springs issue from Abraham Hot Springs located on the east side of Crater Bench, and have formed an extensive thermal mound over Lake Bonneville sediments. Spring temperatures are as high as 87°C and flow rates are between 90 and 140 L/s (Rush, 1983).

A self-potential survey was completed which included the main thermal springs, much of the elevated thermal mound, lake bed sediments, and the eastern part of the Quaternary basalt flows (Ross, *et al.*, 1993). The mapped potentials (Figure *5)* are referenced to a base station east of the edge of the basalt flow and west of the thermal mound. Statistical studies indicate that this base station is close to background potential. This survey documents a weak dipolar anomaly **(+14** mV, -9 mV) associated with the higher part of the thermal mound, and coherent minima of **-46** and -24 mV one km west of the hot springs. These minima occur over basalts immediately west of a northwest-trending fault. Thermal fluids may rise from depth along this fault, then flow along the base of the basalts to Abraham Hot Springs, as postulated by Mabey and Budding (1987).

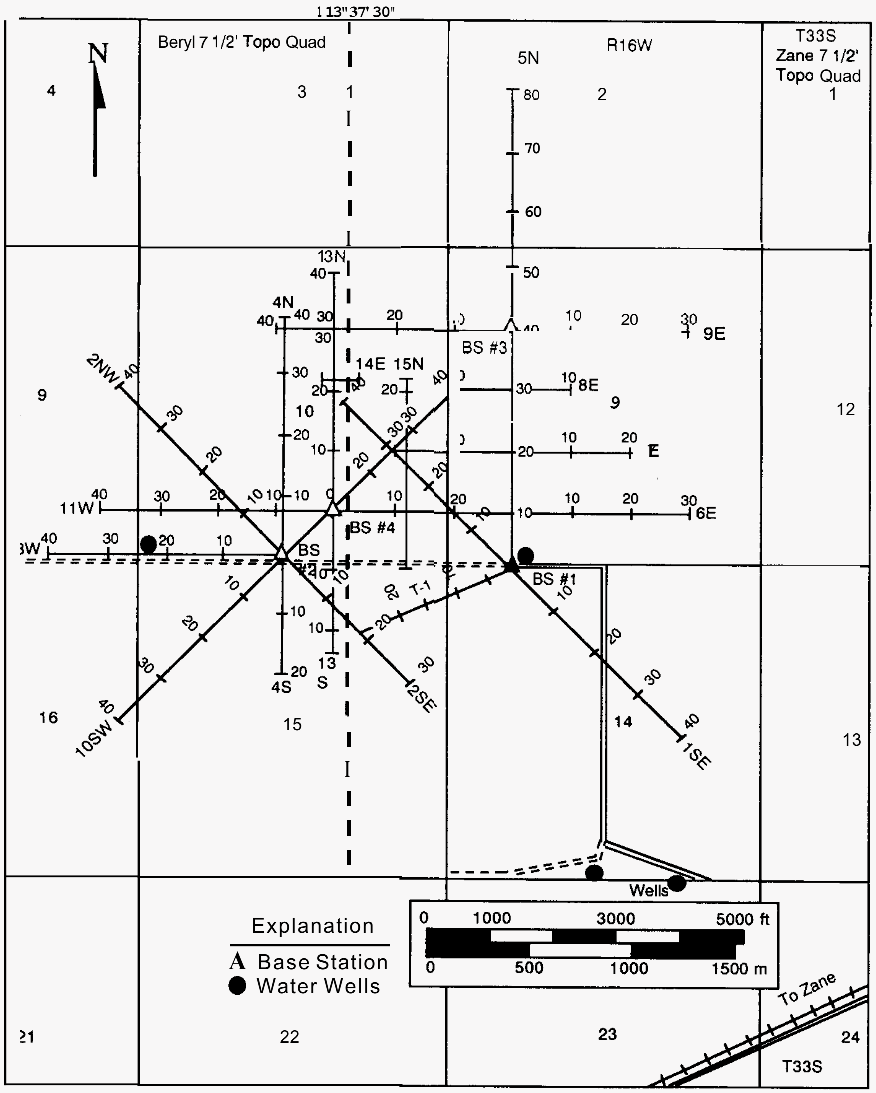

Figure 2. Map of self–potential survey profiles for the Woods' Ranch survey (Ross, et al., 1991) showing the reconnaissance coverage provided by radial survey lines and detailed coverage added by parallel and perpendicular lines, from the same base stations.

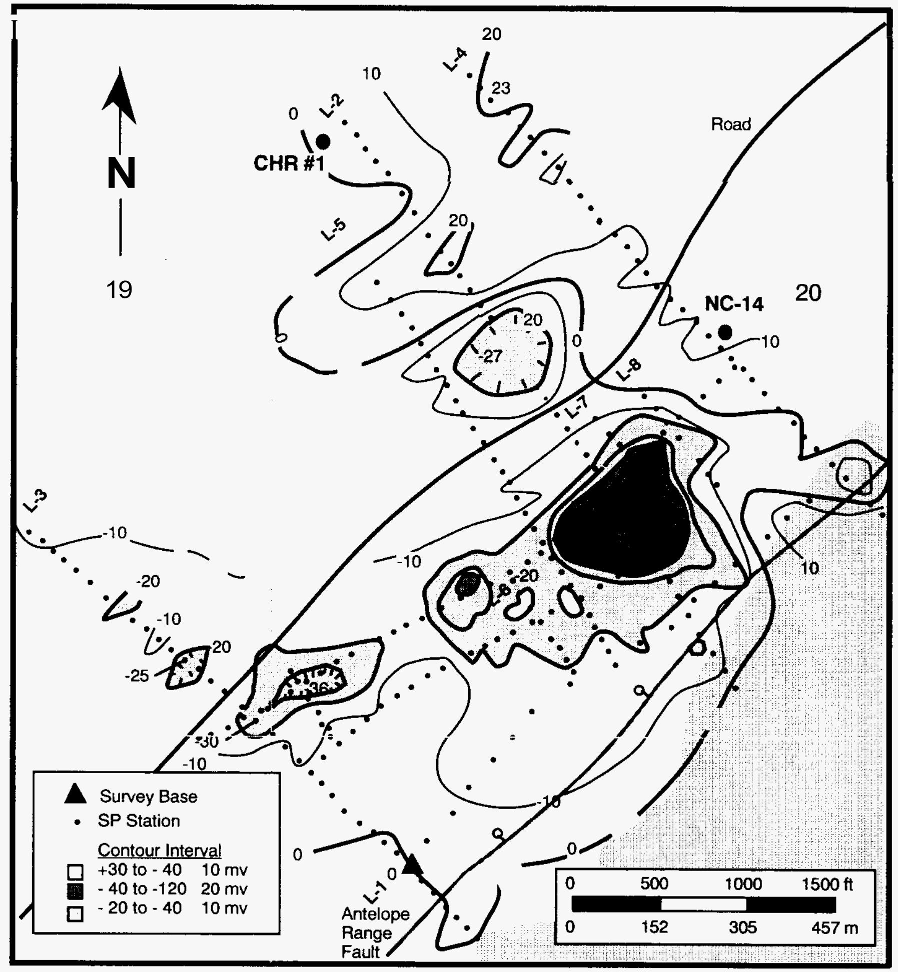

Figure 3. Self–potential survey results for the Newcastle geothermal area, Utah. Anomaly minima of –108, –44, and –36 mV occur over the buried Antelope Range fault.

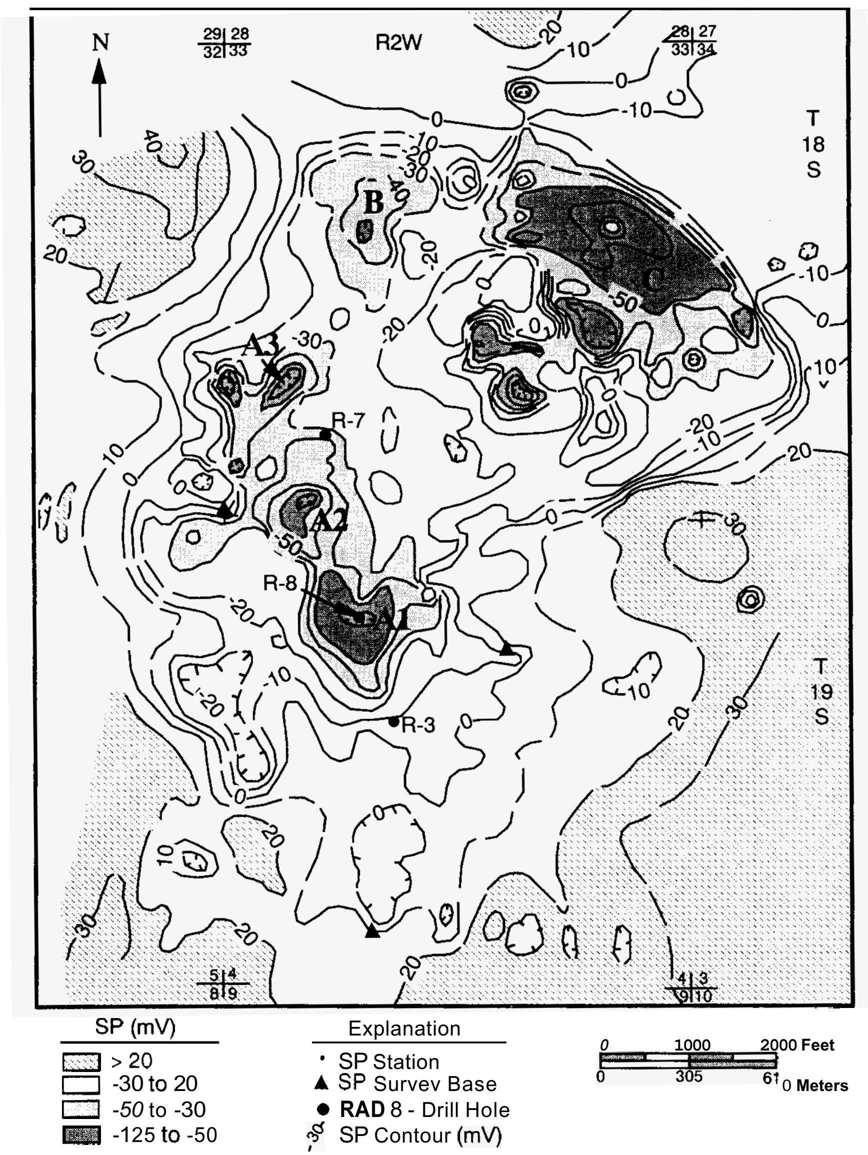

Figure 4. Self–potential survey results for the Rincon geothermal area, New Mexico. SP contour intervals are 10 and 50 mV. The broad area of low potential is 2.4 km (northeast) by 1.3 km (northwest).

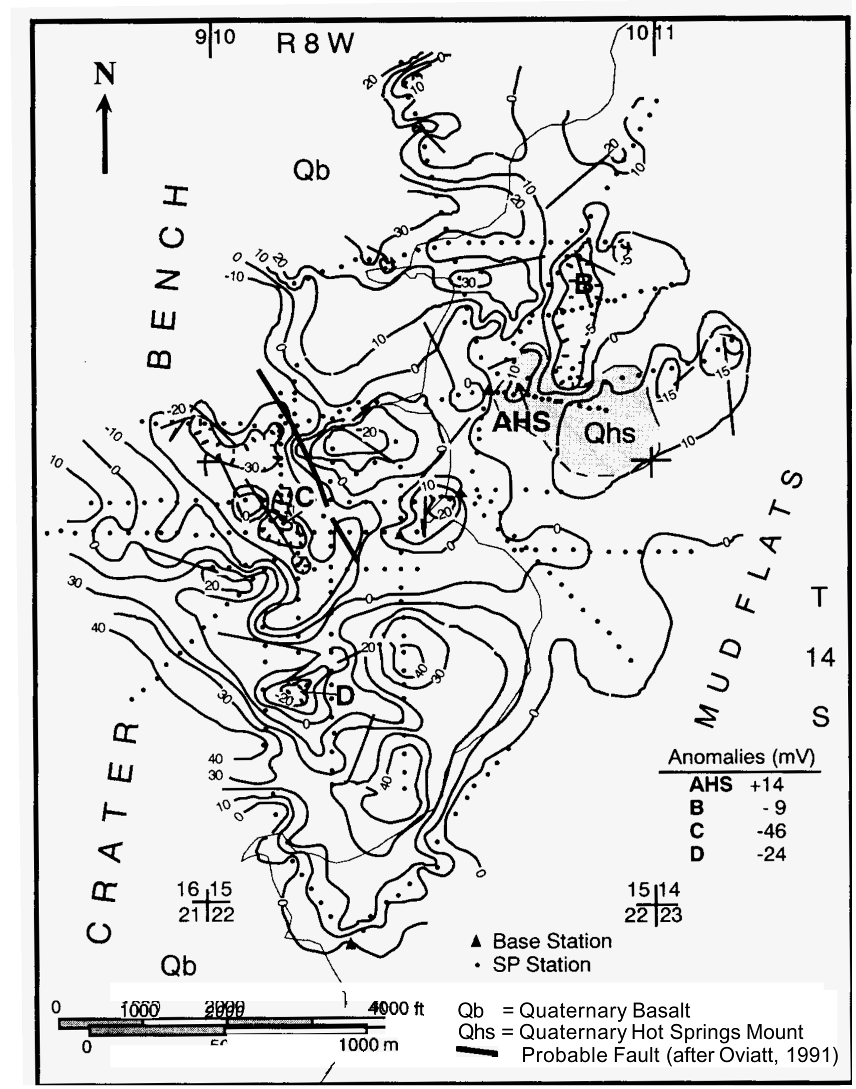

Figure 5. Self–potential contour map for the Crater Springs (Abraham Hot Springs–AHS) geothermal area, Utah. Contour interval is 10 mV with supplemental -5 mV and +15 mV contours.

4. DISCUSSION

Self-potential surveys were completed over nine hydrothermal systems with varied near-surface geologic conditions. Only low-amplitude variations were observed over shallow outflow areas but well-defined anomalies, generally minima, are associated with several probable upflow zones.

Several types of noise were identified during the conduct of the surveys. Three high-voltage transmission lines which tread parallel to the Antelope Range fault at Newcastle, UT give rise to large amplitude, high-frequency voltage variations for survey profiles parallel to and near (0-300 m) the transmission lines. Good SP data were obtained by choosing a base station 500 m from the power lines and main survey profiles perpendicular to the powerlines. Near-surface ground water flow from recent heavy rains gave rise to SP data with poor repeatability during the Rincon, NM survey, to the extent that several profiles had to be repeated at a later time. Systematic, long period (10 s to several min) variations were often observed at stations some distance (1000 m or more) from the reference electrode, and these were attributed to telluric current variations. Observation times as long as 15 to 30 min were sometimes required to determine a good SP value by averaging over many cycles.

Dry sand dunes and dry, sandy washes often gave rise to positive anomalies (10 to 35 mV) unrelated to geothermal fluids, and small hills capped by caliche gave rise to well-defined negative anomalies (-20 to -110 mV) which dominated the response of deeper sources. Careful geologic observations and very detailed SP profiles with station spacings as small as **5** m helped to identify these geologic noise sources.

No significant SP anomaly was defined near the three hot pools of the Meadow, UT thermal area. This may be due in part to low-resistivity clays at the surface which attenuate voltage differences at depth, or due to low flow at the pools during the survey period. The SP anomalies associated with the Hatton thermal mounds, 1.5 km to the southeast, may identify the main upflow area for these pools. Any SP anomaly which may be associated with a deep upflow zone of the Tortugas Mountain, NM hydrothermal system is obscured by large-amplitude (-100 mV) anomalies associated with caliche-capped topography.

A limited amount of quantitative interpretation has been completed to date, primarily to establish source depths. Source depth estimates for most of the high frequency anomalies are typically 50 to 200 m, which is generally consistant with the known geology of these shallow geothermal systems. Numerical modeling is in progress using algorithms described by Sill (1983), and Wilt and Butler (1990), but electrical resistivity data are generally not available, and cross-coupling coefficients must be assumed. These results will be reported in later publications.

5. CONCLUSION

Detailed self-potential surveys of 1.5 to 11 km^2 have been completed to characterize the SP expression of known hydrothermal areas, and to provide targets for drill testing and fluid sampling of several covered hydrothermal systems. Basic survey coverage was often completed by a two-man crew in five days, but additional profiles with short electrode intervals (30 m) and verification by repeat profiles often doubled the total survey time. Self-potential surveys were shown to be quite cost-effective for identifying new targets for drill testing in known hydrothermal areas. The more common SP expression for this type of shallow, fault-controlled fluid upflow zone appears to be a negative anomaly.

6. ACKNOWLEDGMENTS

This work was supported, in part, by the U.S. Department of Energy Contract No. DE-AC07-90ID12929 to the University of Utah Research Institute. Such support does not constitute an endorsement by the U.S. Department of Energy of the views expressed in this publication. The Utah Geological Survey and New Mexico State University contributed personnel and technical support for this work. We thank Bob Turner for preparing illustrations and Stacey Haggin for her assistance with word processing for this paper.

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