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A NEW U.S. LOW-TEMPERATURE RESOURCE ASSESSMENT PROGRAM

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ABSTRACT

In Fiscal Year 1991, the United States Congress appropriated money for the Department of Energy to begin a new program in the evaluation and use of low- and moderate-temperature (20° to 150°C) geothermal resources. The objective of this program is to promote accelerated development of these resources to offset fossil-fuel use and help improve the environment.

The assessment program has resulted in digital databases reporting on 8,170 thermal wells and springs for 10 western states, an increase of 40% compared to the previous assessment in 1980. More than 900 resource areas were indicated and 45 of these have been identified as high-riority study areas for 150 near-term direct-heat utilization sits.

INTRODUCTION

Low- and moderate-temperature geothermal resources are widely distributed throughout the western and central United States. Numerous resources occur in the areas indicated in Figure 1, with individual reservoir areas 1 to 10 square miles in extent. In the northern Great Plains, major aquifers with fluid temperatures exceeding 50°C extend in a continuous manner for thousands of square miles. Geothermal resources also occur at certain locations in the East.

The last major effort in assessing the national potential of low-temperature geothermal resources occurred in the early 1980s (Reed, 1983). Since that time, substantial resource information has been gained through drilling for hydrologic, environmental, petroleum and geothermal projects, but there has been no significant effort to compile information on low- and moderate-temperature geothermal resources.

While there has been a substantial increase in direct-heat utilization during the last decade, the large resource base is greatly under-utilized. Since the thermal energy extracted from these resources must be used near the reservoir, collocation of the resource and the user is required. Development of a user facility at the site of the hydrothermal resource is often economically feasible. Direct-heat resources are typically used by small businesses, various types of local industry, communities, and individuals. These users generally cannot afford to hire the technical expertise required to delineate and develop geothermal resources from scratch.

To expand utilization of the direct-heat resource, a current inventory of these resources is needed by potential users, together with the information necessary to evaluate the reservoirs and the economics of potential uses. To stimulate the development of an industry, it is necessary to reduce risks of development and this can be done by providing resource data and by cost-sharing of demonstration projects.

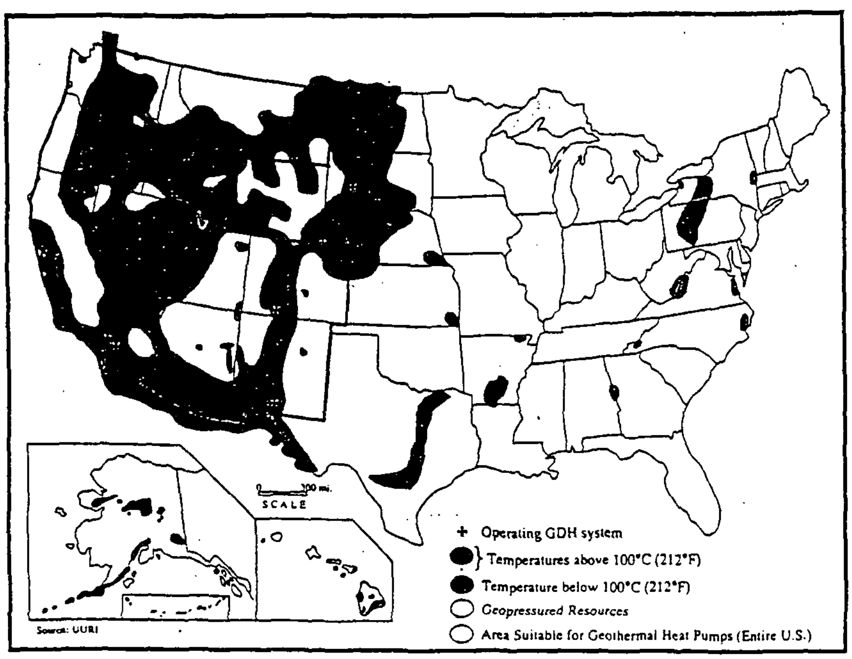

Figure 1. Geothermal Resource Areas of the United States.

LOW-TEMPERATURE PROGRAM

The program is a cooperative effort among a number of academic and state institutions working with potential direct-heat developers. The three principal institutions are the Geo-Heat Center at the Oregon Institute of Technology (OIT), the Idaho Water Resources Research Institute at the University of Idaho (IWRRI), and the Earth Science Laboratory of the University of Utah Research Institute (UURI). State geothermal resource teams (State Teams) compiling data for ten states in the west are also participating. The tasks for this project are discussed below.

Compilation of Data on Hydrothermal Resources

State Teams reviewed and updated their geothermal resource inventories which were completed as part of the USGS-DOE national assessment from 1977-1983 (Reed, 1983). Each state prepared a comprehensive digital database in table format and a resource map at a scale of 1:1,000,000. UURI and OIT have provided technical guidance and coordination, and UURI completed fluid chemistry analyses for participating states. Table 1 identifies the state agencies and principal investigators involved with the project.

The compilations included resources in the temperature range of 20° to 150°C. Many of these resources have the potential to supply energy to collocated cities within approximately 8 km of a resource as well as greenhouses, aquaculture, mining, and other process applications.

The State Teams, under subcontract to OIT and with guidance from UURI, reviewed drilling records and other information to identify new resources and verify temperatures and flow rates of springs and wells which may have changed substantially since the previous statewide geothermal resource inventory. The databases were organized into tables linked by common data-fields, using the preliminary database from the Utah Geological Survey as a model for uniformity in presentation (Blackett, 1993). Information contained in the tables includes: location (ID number, source name, county code, latitude and longitude); description (ID number, source name, type of source, temperature (°C), flow rate (L/min), depth of wells (m), current resource use, and references to relevant studies of geology, geophysics, geochemistry, hydrology completed for the site), and geochemistry (ID number, source name, pH, TDS, major cations, major anions, cation-anion balance, chemical species that may cause scale and corrosion products, and light stable isotopes).

Simultaneously, demographic and other data were collected and interpreted to evaluate potential heat loads, fossil-fuel displacement, utility electrical-demand reduction and load-leveling opportunities, and environmental benefits for potential geothermal direct-heat applications.

Preliminary Results - Resource Evaluation

State Teams for 10 western states initiated their resource evaluation and database compilation efforts in late 1992 and early 1993, and have now updated their resource inventories. Table 2 summarizes the catalog of 8,170 thermal wells and springs for these 10 western states; an increase of 40% compared to the previous assessment in 1983. More than 900 low- to moderate-temperature resource areas are indicated, and perhaps a greater number of isolated (singular) thermal wells or springs. Direct-heat use of geothermal fluids is documented at more than 250 sites, including commercial and municipal buildings, rapidly expanding greenhouse and aquaculture industries, and major space-heating districts in California, Oregon, Nevada, Idaho, and Colorado. More than 40 high-priority resource study areas have been identified, together with high potential for near-term direct-heat utilization at 150 new sites. Preliminary estimates indicate that 254 cities in 10 western state could potentially displace 18,000 GWh per year (17 million BOE) with geothermal district heating. The number of commercial and residential direct-heat users and the total energy use have increased dramatically in one decade. Some highlights from the participating follow.

Arizona. The 1992-1993 assessment shows a 100% increase in the number of thermal wells and springs. These wells and springs are defined as 35 low-temperature resource areas and an additional 205 singular thermal wells and springs. Arizona leads the nation in the use of geothermal fluids for aquaculture (Witcher, 1994).

California. The California Division of Mines and Geology reports 979 thermal wells and springs. Some 58 low-temperature resource areas have been identified with an additional 194 "singular" thermal occurrences. The 72 commercial direct-heat users include six district-heating systems, 48 resorts/spas, and 17 greenhouse, aquaculture or industrial concerns (Youngs, 1994).

Colorado. The 1992-1993 assessment reports that there are 93 goethermal areas (usually less than 8 km^2 in size) in Colorado, up from the 56 reported in 1978; there are 157 geothermal sites compared to the 125 reported in 1978. Six goethermal areas are recommended for further investigation: Trimble Hot Springs,

Table 1. State Resource Assessment Teams

State	Agency	Principal Investigator
California	Division of Mines and Geology	Leslie Youngs
Colorado	Colorado Geological Survey	James Cappa
Idaho	Idaho Water Resources Research Institute	Leland Mink William Dansart
Montana	Bureau of Mines and Geology	Wayne Van Voast John Metesh
New Mexico and Arizona	New Mexico State University- Southwest Technology Development Institute	James Witcher and Rudi Schoenmackers
Nevada	Bureau of Mines and Geology	Larry Garside
Oregon	Dept. of Geology and Mineral Industries	George Priest Gerald Black
Utah	Utah Geological Survey	Robert Blackett
Washington	Division of Geology and Earth Science	Eric Schuster

Table 2. State Geothermal Database Summary: 1992-93 Low-Temperature Program.

	State PGA	AZ 1982	CA 1980	CO 1980	ID 1980	MT 1981	NV 1983	NM 1980	OR 1982	UT 1980	WA 1981
Thermal Well/ Springs	1993	1,003	979	157	912	267	455	265	2,193	964	975
	PGA	501	635	125	899	68	796	312	998	315	368
Moderate Temp. Wells/Springs (100°C < T < 150°C)	1993	0	32	0	20	0	16	10	88	3	1
	PGA	0	48	0	0	0	35	3	79	3	1
Low Temp. Wells/Springs (20°C < T < 100°C)	1993	1,003	957	157	1,915	97	433	255	2,047	710	970
	PGA	501	587	125	899	58	761	309	925	312	367
Low Temp. Resource Areas (20°C < Tes < 150°C)	1993	35	58	93	28	16	300	30	200	161	17
	PGA	29	56	56	28	15	300	24	151	64	10
Direct-Heat Utilization Sites (Commercial, district, resorts)	1993	2	72	28	29	15	21	7	29	16	4
	PGA	0	54	24	20	2	8	0	23	9	0
Greenhouses, Aquaculture, Industrial Processes	1993	5	17	4	17	4	8	6	7	6	0
Areas, Potential Near-Term Direct Heat Utilization	1993	4	2	4	51	2	2	4	25	7	24
Areas, High Priority Resource Study	1993	3	4	6	5	4	4	4	5	4	6

Comments: PGA - Previous Geothermal Assessment. Tres = Estimated reservoir temperature. The minimum low-temperature criteria is typically 20°C, but varies with climate.

Orvis Hot Springs, an area southeast of Pagosa Springs, the eastern San Luis Valley, Rico and Dunton area, and Cottonwood Hot Springs (Cappa, 1994).

Idaho. The Idaho Water Resources Research Institute lists 912 thermal wells and springs, more than the 899 reported in the 1980 inventory, but only half the total number of well and spring entries reviewed. Although district heating is well established at Twin Falls and Boise, there is high potential at about 50 sites for new direct-heat utilization, as well as some potential for electrical power development.

Montana. The Montana Bureau of Mines and Geology database contains information on location, flow, water chemistry, and estimated reservoir temperatures for 267 geothermal wells and springs. Low- and moderate-temperature wells and springs can be found in nearly all areas of Montana, but most are in the western third of the state. Five areas of Montana were chosen for future investigations of geothermal development based on the potential of the resource and its proximity to population centers. The areas identified are those near Bozeman, Ennis, Butte, Boulder, and Camas Prairie (Metesh, 1994).

Nevada. The Nevada Bureau of Mines and Geology includes 453 entries in a database which represents more than 3,000 wells and springs. More than 300 separate resource areas may be present in Nevada. Direct heat is utilized at 21 areas, including the Moana and Elko district-heating systems and the Duckwater (Big Warm) Springs aquaculture facility (Garside, 1994).

New Mexico. The Southwest Technology Development Institute reports 265 thermal wells and springs. Thirty low-temperature resource areas and perhaps 158 isolated thermal occurrences have been identified. New Mexico currently leads the nation with the largest acreage of geothermally-heated greenhouses on line, and expansion continues (Witcher, 1994).

Oregon. The new Oregon Department of Geology and Mineral Industries study identified 2,193 geothermal sites. More than 200 thermal areas have been identified. Geothermal fluids are used for heating over 625 buildings by businesses, organizations, and home-owners. Several greenhouses, aquaculture sites and industrial processes also use geothermal energy. Five high-priority resources study areas have been identified by DOGAMI and perhaps 25 businesses or organizations could utilize geothermal heating in the near term (Black, 1994).

Utah. The Utah Geological Survey compiled a database consisting of over 964 records on thermal wells and springs with temperatures of 20°C or greater; 300% of the previous geothermal assessment. Areas for future exploration and development interest include: southern Sevier Desert, where evidence suggests the possiblity of an undiscovered moderate to high-temperature system, and the eastern Escalante Desert, where high near-surface temperatures indicate a concealed geothermal system. Other direct-use opportunities for low-temperature geothermal resources are apparent within populated areas along the Wasatch Front (Blackett, 1993).

Washington. A detailed study by the Washington State Department of Natural Resources team has identified 971 thermal wells/ springs, 264% of the 1981 inventory, and several newly recognized low-temperature resources areas. Geothermal resource utilization is currently very low, but six counties are regarded as priority study areas, and as many as 49 potential users (commercial, private, or municipal) are collocated with promising resources (Schuster, 1994).

CONCLUSIONS

Low- and moderate- temperature geothermal resources are widely distributed throughout the western and central United States. Since the last major effort in assessing the national potential of these resources in the early 1980s, there has been a substantial increase in direct-heat utiliztion. However, the large resource base is greatly under-utilized. To expand utilization of the direct-heat resource base, a current inventory of these resource has been developed.

State Teams evaluations and compilations have resulted in the catalogging of 8,170 thermal wells and springs for 10 western states, an increase of 40% over the previous geothermal assessment in 1983. More than 40 high-priority resource study areas have been identified, together with high potential for near-term direct-heat utilization at 150 new sites.

In the future we hope to continue R&D on more cost effective methods for locating low-and moderate-temperature geothermal resources and on siting successful test and production wells. Part of this work will encompass development of improved well-testing methods and better hydrologic models of these hydrothermal resources. These tasks are expected to pay off in further discoveries of resources and in better methods to evaluate reservoir production and ultimate-development capacity at an earlier stage in the development cycle than is now possible.

ACKNOWLEDGEMENT

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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 (Corwin, 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 (Corwin and Hoover, 1979). This varied expression is sometimes confusing and reduces confidence in and use of the method in geothermal resource exploration and development.

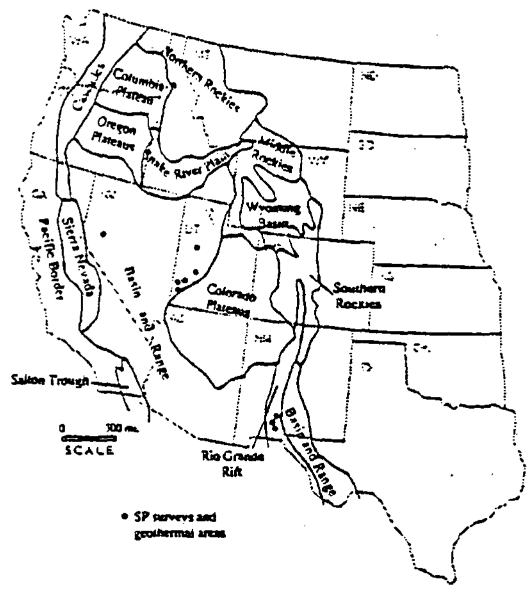

Figure 1. Location of self-potential studies and geothermal areas discussed in this paper. Geologic provinces of the Western United States are modified from the physiographic provinces of Fenneman (1946).

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.

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 Corwin 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

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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	47.9	-96,-71,-61,-50	2.1 x 0.7
Rincon, NM	>140	88	128	alteration; hot wells	6.7	37.5	-122,-77,-74,-34	2.4 x 1.3
Radium Springs, NM	>100	70	<75	hot springs; wells	6.5	27.8	-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 geothermometers. 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 km² at Newcastle (where the upflow zone was identified by shallow thermal gradient holes) to more than 10 km².

3.1 Anomaly Magnitudes and Extents

The anomalies identified in these surveys are generally located upgradient from the known outflow plume and are often 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 exceeding 80°C at a depth of 88 m, still above the water table. Geothermometers determined from fluid samples 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).

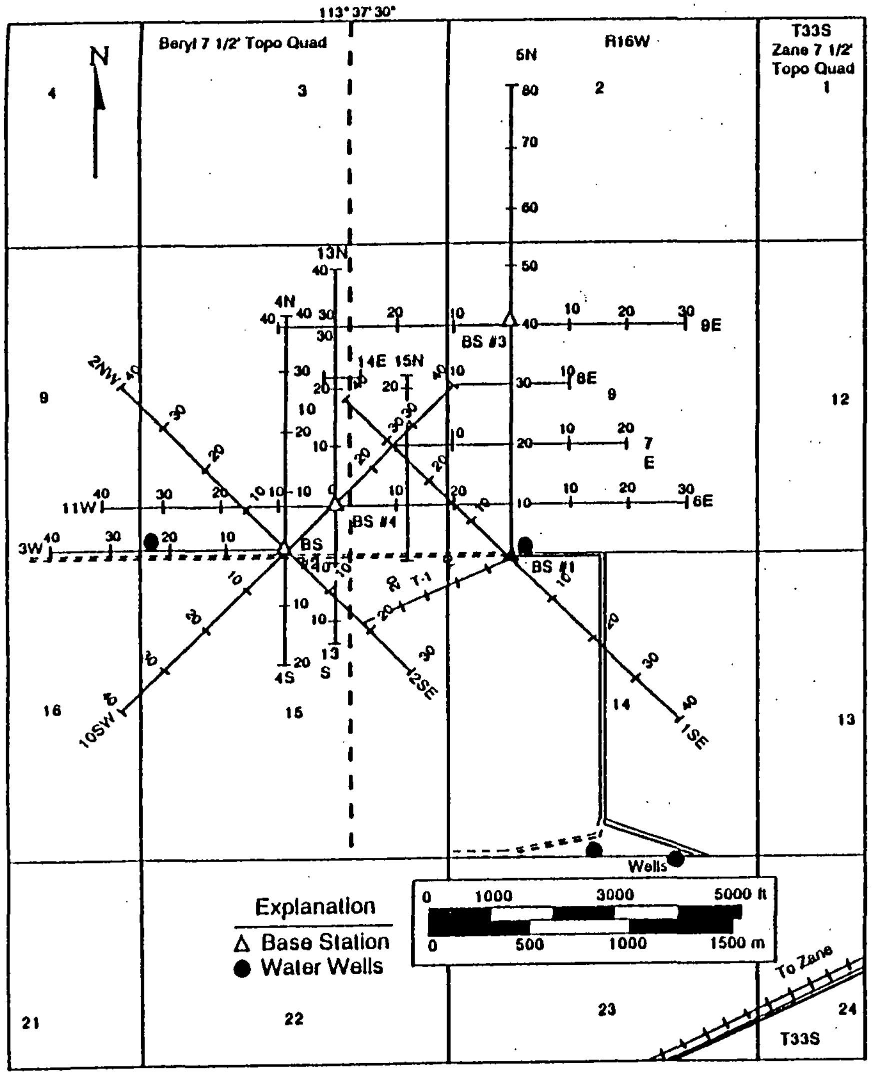

Figure 2. Map of self-potential survey profiles for the Woods' Ranch survey (Ross, et al., 1991) showing the reconnaissance coverage provided by radial survey lines and detailed coverage added by parallel and perpendicular lines, from the same base stations.

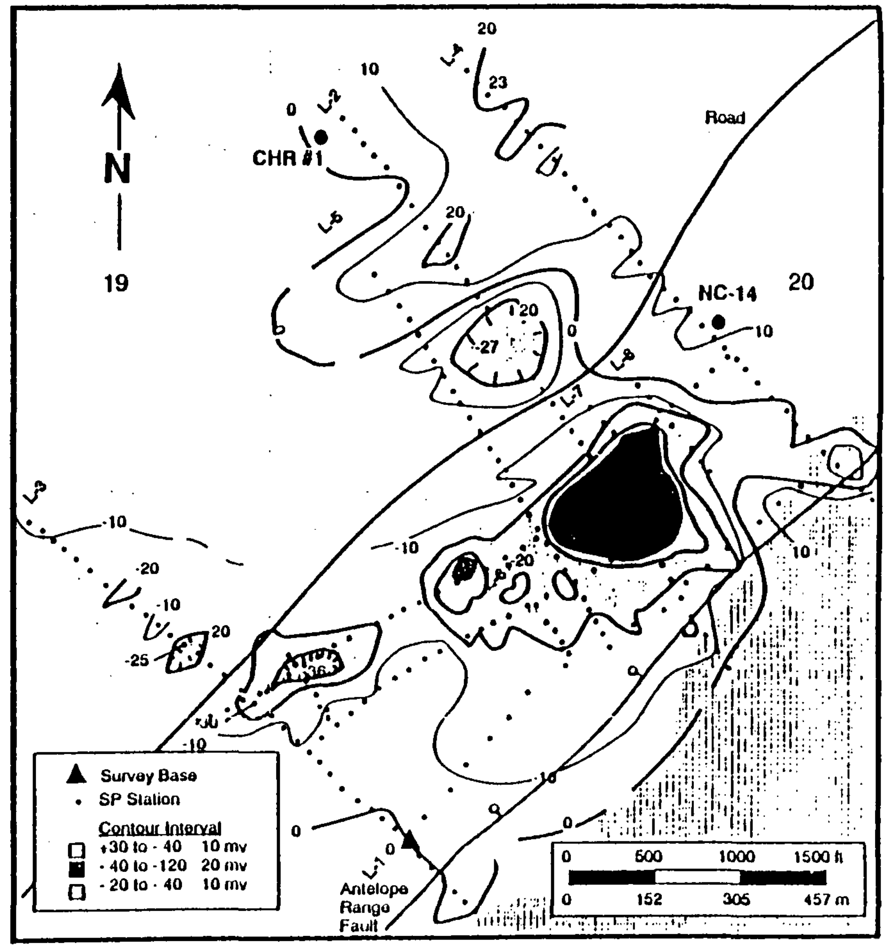

Figure 3. Self-potential survey results for the Newcastle geothermal area, Utah. Anomaly minima of −108, −44, and −36 mV occur over the buried Antelope Range fault.

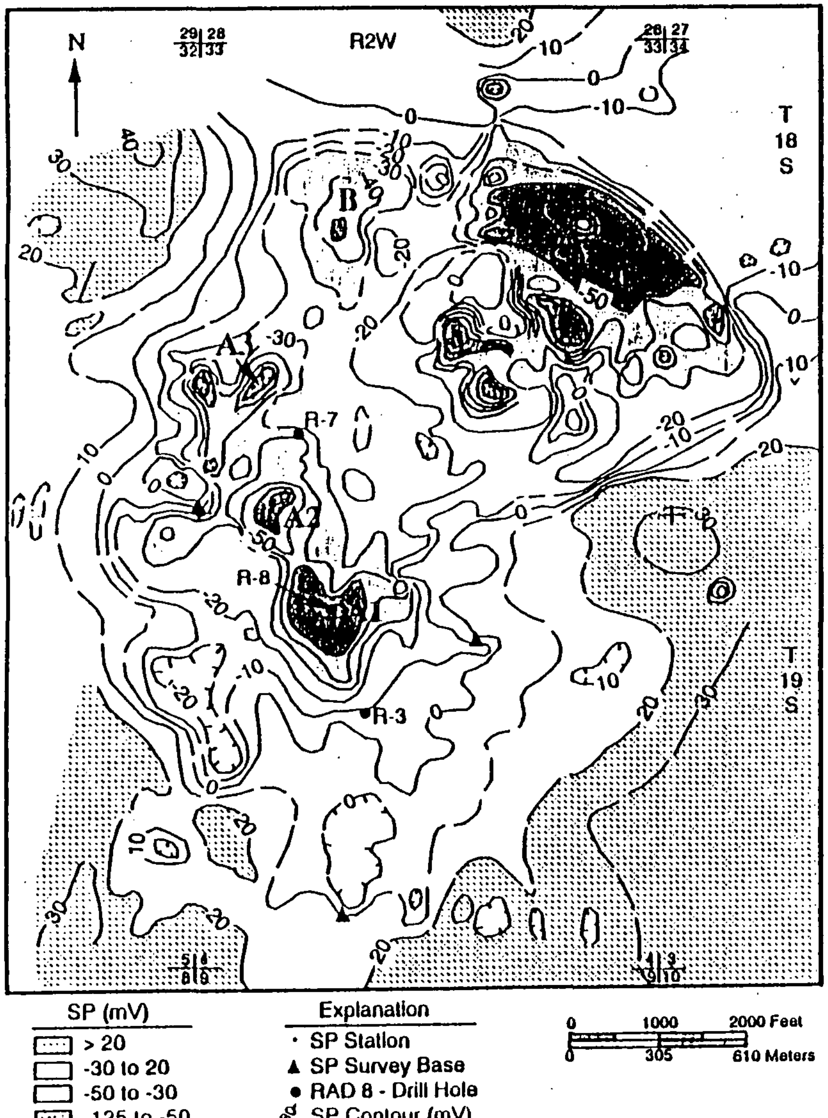

Figure 4. Self-potential survey results for the Rincon geothermal area, New Mexico. SP contour intervals are 10 and 50 mV. The broad area of low potential is 2.4 km (northeast) by 1.3 km (northwest).

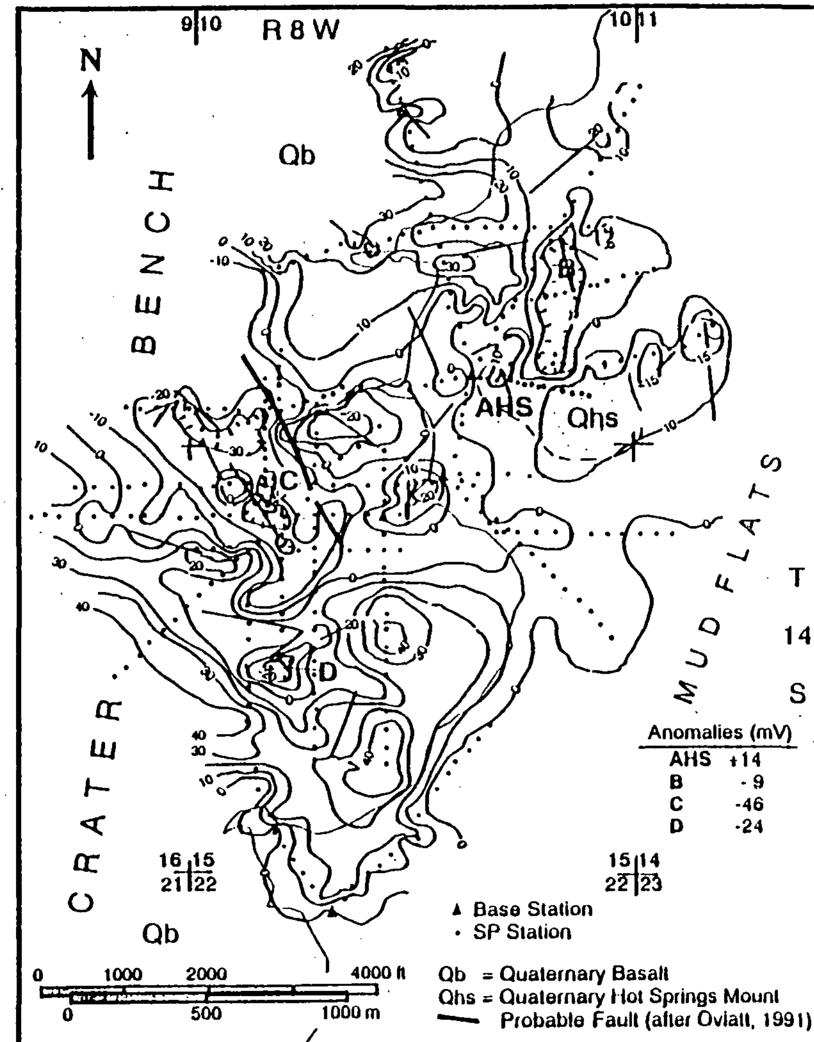

Figure 5. Self-potential contour map for the Crater Springs (Abraham Hot Springs–AHS) geothermal area, Utah. Contour interval is 10 mV with supplemental –5 mV and +15 mV contours.

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 trend 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.

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