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DELINEATION OF FLUID UPFLOW AND OUTFLOW PLUME WITH ELECTRICAL RESISTIVITY AND SELF-POTENTIAL DATA, NEWCASTLE GEOTHERMAL AREA, UTAH

by

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ABSTRACT

An integrated geological, geophysical and geochemical study has been underway in the Newcastle geothermal area of southwest Utah. Electrical resistivity and self-potential studies were undertaken late in the study in an attempt to provide additional delineation and characterization of this blind geothermal system. The electrical resistivity data detect the outflow plume and, with numerical modeling, indicate the probable upflow zone of the thermal fluids. Self-potential data map a well-defined minimum between the higher temperature shallow gradient holes and this is interpreted to be the principal conduit of fluids which feeds the outflow plume.

INTRODUCTION

The Newcastle geothermal area, located on the southeast edge of southwestern Utah's Escalante Valley (Figure 1), is termed a "blind" hydrothermal system, meaning no surface manifestations of hydrothermal activity—hot springs, fumaroles, or alteration minerals—exist. Water well drillers discovered the system in 1975 by accident during pump-testing of a newly drilled irrigation well. The well delivered water to the surface at temperatures near boiling, and a temperature profile made after pumping depicted a geothermal aquifer at depths between 85 and 95 meters. Since then, geologists from the U.S. Geological Survey, University of Utah, and the Utah Geological and Mineral Survey have studied the system (Denton, 1976; Rush, 1977, 1983; Pe and Cook, 1980; Clement, 1981; Chapman et al., 1981; Blackett et al., 1989, 1990). Geothermal companies and local residents have drilled a number of exploratory wells and thermal gradient test holes. Presently, three commercial greenhouses, a Mormon church building, and various residences in Newcastle use the hot water for space heating.

GEOLOGY AND THERMAL REGIME

Regional Setting and Structure

The Newcastle area is located along the southeast margin of the Escalante Valley, an elliptical depression in southwest Utah, measuring roughly 70 by 45 km. The valley is situated near the Basin and Range—Colorado Plateaus transition zone. It is surrounded by mountains and hills composed primarily of Tertiary ash-flow tuffs ranging in age from 32 to 19 Ma and 13 to 8.5 Ma rhyolite and dacite flows and domes. The Antelope Range fault marks the southeast margin of the Escalante Valley.

Bedrock units at Newcastle range in age from Upper Cretaceous to upper Miocene, and consist of older sedimentary rocks overlain by a series of middle Tertiary ash-flow tuffs

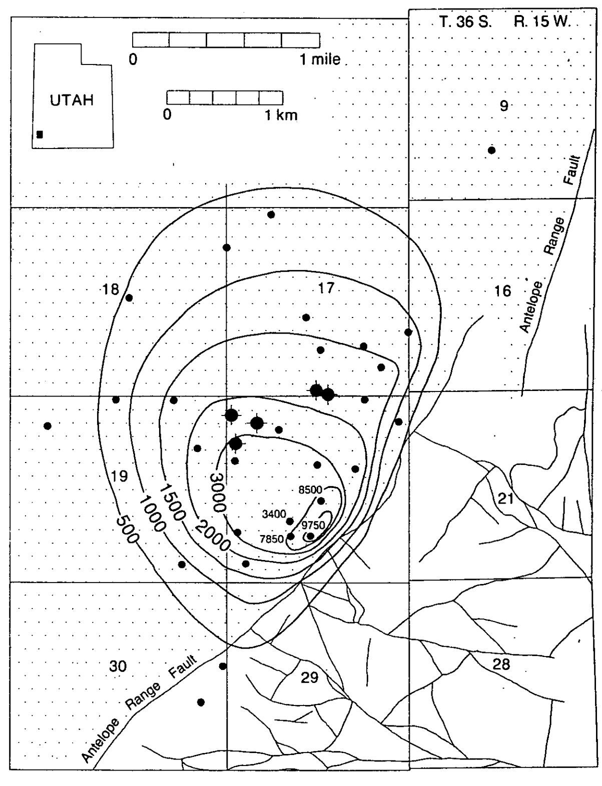

Figure 1. Location and heat flow distribution of the Newcastle geothermal area. Heat flow contours in mW m^{-2}. Large circles are thermal water supply wells, small circles are temperature gradient holes. Faulting within the range is indicated.

capped by rhyolite and dacite flows. The oldest exposed units are the Iron Springs (Cretaceous) and Claron (Eocene/Oligocene) formations, consisting of fluvial and lacustrine deposits. These sedimentary units are overlain by more than 1,300 m of ash-flow tuffs that include the Isom Formation (26 Ma), Quichapa Group (Leach Canyon Formation, Bauers Tuff, and Harmony Hills Tuff—25 to 21 Ma), and the Racer Canyon Tuff (19 Ma). An aerially extensive volcaniclastic unit lies between the Harmony Hills and Racer Canyon Tuffs, and a thick sequence of volcaniclastic rocks (Volcaniclastics of Newcastle Reservoir) lie above the Racer Canyon Tuff.

Siders et al. (1989) identified a complex network of faults within the mountain range adjacent to Newcastle. Blackett et al. (1990), using fault-slip data and age relationships, determined that two primary extensional events were responsible for producing these faults. An older (15 to 8 Ma), southwest-directed extensional event produced generally northwest-trending faults, and a younger (less than 8.5 Ma) extensional event produced the Antelope Range fault and the associated Newcastle graben.

Modelling of detailed gravity data (Blackett et al., 1990) constrained the geometry of the Antelope Range fault. The model depicts the Antelope Range fault as dipping to the northwest at an angle of roughly 65°. The Antelope Range fault marks the southeastern edge of the Newcastle Graben, which is filled with approximately 1.6 km of unconsolidated to semi-consolidated sediments.

Thermal Studies and Conceptual Model

Using data from 27 temperature gradient test holes, Blackett et al. (1990) compiled a revised heat-flow map of the Newcastle geothermal system (Figure 1). The highest measured temperature of the system is 130°C, recorded in an exploratory well drilled near the original discovery well. Chemical geothermometers applied to analyses of fluid samples from the outflow plume suggest equilibration temperatures slightly above 130°C. The heat-flow distribution (shown in Figure 1) depicts a relatively high heat flow over the entire system. The throat of the system, where we feel geothermal fluid is flowing upward, is shown as a tightly constrained high abutting the mountain front, and is adjacent to the surface trace of the Antelope Range fault. From this location, heat flow contours appear broader-spaced to the north and are closer-spaced to the southeast and to the west. This suggests that thermal fluids move upward from depth along a relatively short segment of the Antelope Range fault, encounter a shallow, permeable aquifer and flow westward and northward into the Escalante Valley. Blackett et al. (1990) estimate the anomalous heat loss from the geothermal system to be 12.4 MW.

Using the evidence collected from geologic and geophysical investigations, Blackett et al., (1990) developed a conceptual model of the system. The model depicts recharge of meteoric water in the Pine Valley Mountains to the southeast. From there, fluids move downward along a broad northwest-trending structural zone to depths of 3 to 4 kilometers and encounter the northeast-trending Antelope Range fault zone. Thermal fluids rise along the Antelope Range fault and encounter water contained in valley-fill sediments. Precipitating minerals form a seal forcing thermal fluid to continue upward along the Antelope Range fault. Presently, fluid rises to a level a few tens of meters below the ground surface and discharges into a shallow aquifer. The throat of the up-flow zone remains untested by drilling.

ELECTRICAL RESISTIVITY SURVEY

Although the source of thermal fluids which feeds the moderate-temperature thermal plume had been roughly outlined by shallow temperature-gradient holes, a number of questions remained unanswered. None of the shallow holes penetrated the water table, and the position of the main conduit along a 4,000 foot (1,200 m) length of the Antelope Range fault was uncertain. In addition, it seemed worthwhile to characterize the electrical-resistivity expression of this otherwise well-documented blind geothermal system. Four dipole-dipole resistivity lines were completed in July 1989 to address these questions. The location of survey lines, the heat-flow anomaly, and a deep exploratory well, Christiansen #1 are shown in Figure 2.

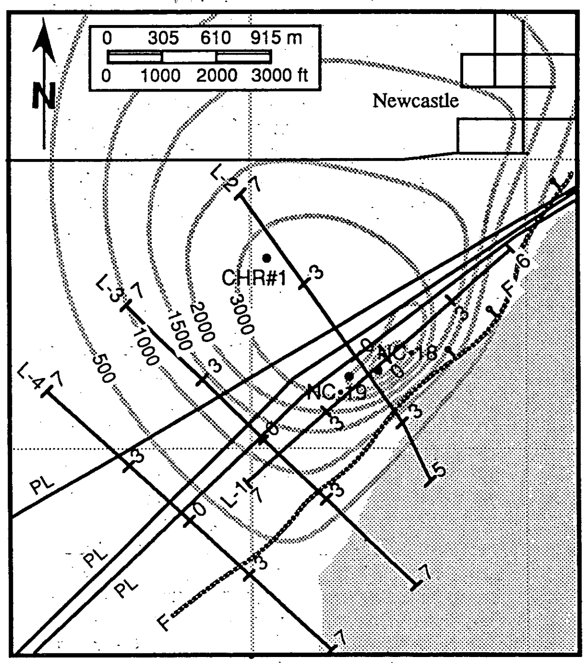

Figure 2. Location of resistivity profiles with respect to heat flow anomaly, high temperature gradient holes, Antelope Range fault, and high voltage transmission lines. Outcropping volcanic rock is shown as a shaded pattern.

Execution of the survey was complicated by three high voltage transmission lines which cross the heart of the shallow temperature anomaly, and by fences, stockyards, and irrigation in progress 300 to 1,500 m to the northwest. Cultural (grounded structures) avoidance techniques developed by the mining industry (Nelson, 1978) and careful line placement were employed to minimize the effects of these features. The dipole-dipole array is well suited to the avoidance of cultural features and simultaneously maps both lateral and vertical resistivity variations. A dipole length of 152 m (500 ft) was chosen to provide a reasonable compromise for detail in mapping the outflow plume and possible source areas which would extend to greater depths.

Line NC-1 was located to roughly parallel the Antelope Range fault and the power-line corridor, and to remain one dipole length (152 m) or more from the power lines. Electrode stations were chosen to fall midway between the nearest transmission line towers and to avoid all towers to the extent possible. Powerline noise was obvious on the larger separations but the resistivity values are considered accurate. This profile showed moderate to high apparent resistivities for depths greater than 91 m, except for a narrow low-resistivity (4 Ω•m) zone between stations 4 and 5 SW.

Line NC-2 was chosen to cross the temperature anomaly, the Antelope Range fault, and the power lines in a near perpendicular orientation and electrode positions were chosen to minimize cultural effects. No significant powerline noise was noted on this line and Lines NC-3 and NC-4 which had a similar orientation. The observed data (Figure 3a) show very low apparent resistivities (5 Ω•m) west of Station 1 NW on separations n = 1 thru n = 5, and much higher values to the southeast. Figure 3b compares the computed apparent resistivities for the numerical-model solution for these data. Low-resistivity values often match to within 1 Ω•m, and higher values within 10 percent, indicating a good fit to the observed data.

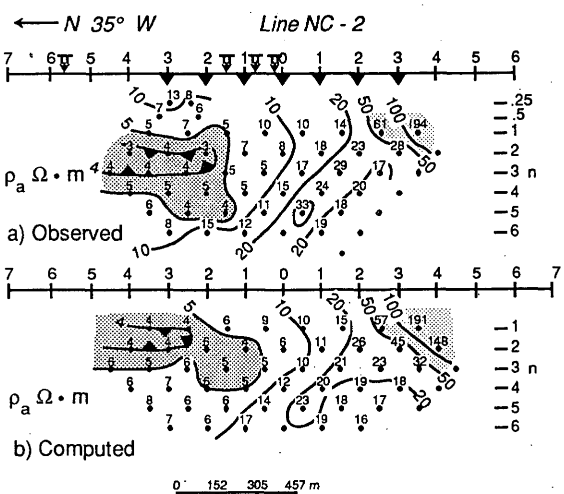

Figure 3. Observed apparent resistivity data (a) and computed apparent resistivity values (b) for the model solution, Newcastle line NC-2. Powerline locations are indicated.

Line NC-3 was located to provide additional detail for the low-resistivity zone detected on Line 1, subject to powerline avoidance limitations. A similar pattern to NC-2 is seen in Figure 4, but fewer low-resistivity values were recorded, and it appears that we are seeing

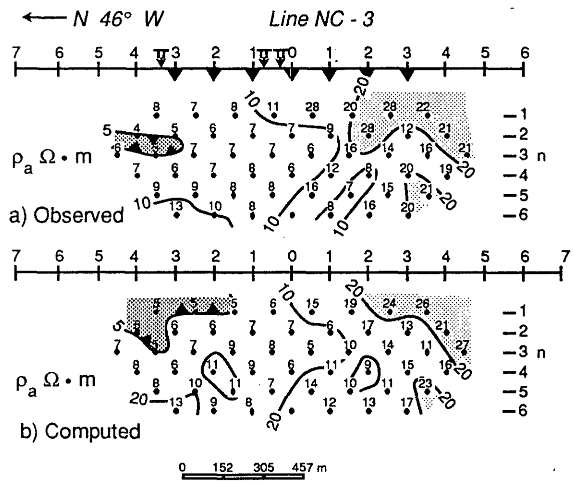

Figure 4. Observed apparent resistivity data (a) and computed apparent resistivity values (b) for the model solution, Newcastle line NC-3. Powerline locations are indicated.

through a low-resistivity layer. Line NC-4 was located on a similar orientation 610 m to the southwest to determine if a pervasive low-resistivity clay layer might explain the low resistivities observed on Lines NC-2 and NC-3, instead of a localized thermal plume. Much higher near-surface resistivities, and higher deep resistivities were observed on this line.

INTERPRETATION

The utility of dipole-dipole resistivity data is greatly enhanced by numerical modeling to provide accurate dimensions and resistivity values as a solution to the observed data. Although the model solutions are nonunique and intrinsic resistivities, layer thicknesses and widths are inexact, the model solutions often provide a good geometric model for a geothermal system or a mineral deposit. Figure 5 shows the two-dimensional numerical model solutions for Lines NC-2, NC-3, and NC-4. The models for lines NC-2 and NC-3 show low-resistivity (4 Ω•m) zones rising from depths greater than 200 m downslope from the mapped or inferred position of the Antelope Range fault. The low-resistivity zones continue to the northwest as a layer, approximately 150 m thick on Line NC-2 but only 100 m thick on Line NC-3. The model solutions are sensitive to the thicknesses of these layers but only a limited number of layer thicknesses were modeled. Both model solutions clearly indicate a near-vertical, 4 Ω•m resistivity body which extends to depths of 300 m or more, based on the goodness of fit to observed data for a number of trial solutions. These bodies are mainly above, but cut by the steeply dipping Antelope Range fault. The solution for Line NC-4 shows higher resistivities for layers in the alluvium. The higher resistivities (50 to 200 Ω•m) thought to be more typical of the volcanic rocks of the range are 300 m southeast of the inferred range bordering fault.

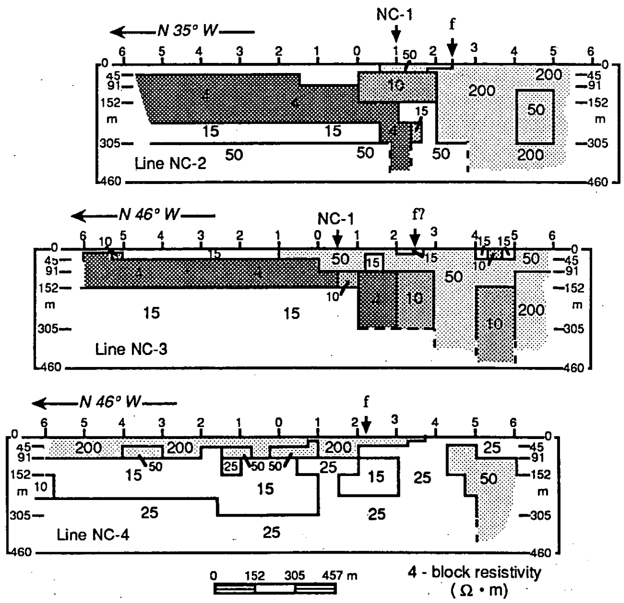

Figure 5. Numerical model solutions for Lines NC-2, NC-3, and NC-4. The low resistivity bodies (shaded) are interpreted as the fluid conduits and outflow plume.

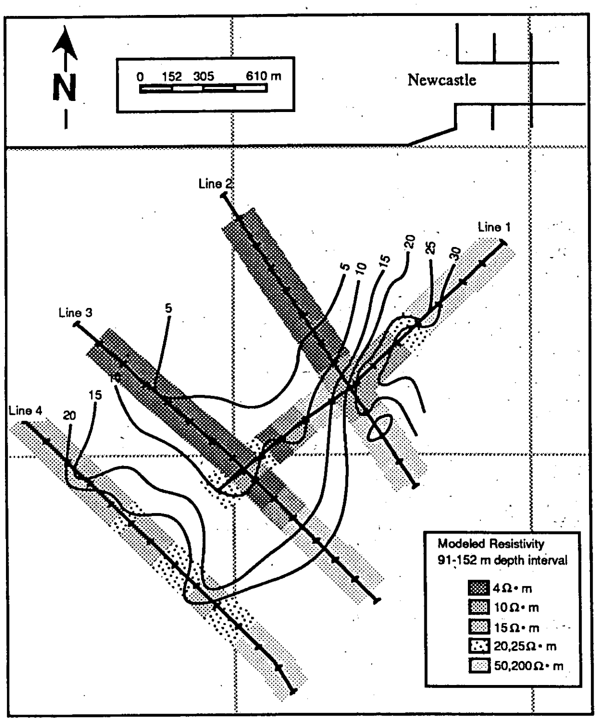

Figure 6. Contoured third separation (n = 3) apparent resistivity and modeled intrinsic resistivity for the depth interval 91-152 m.

Figure 6 presents the modeled resistivity distribution for the depth interval 91-152 m (300-500 ft) and compares this to the contoured third separation (n = 3) observed resistivity values. Both representations indicate a boundary to the thermal plume on the south and east.

The model solutions for Lines NC-2 and NC-3 indicate depths of 45 to 150 m, and 90 m respectively to the top of the conduit zone. Models for both lines indicate depths of 45 m to most of the interpreted outflow plume but disagreement between observed and computed resistivity values for solution models suggest the top of the plume may be somewhat deeper, perhaps as deep as 60 m. Water supply wells on the northwest end of Line NC-2 produce from depths of 85-95 m. Temperature reversals and isothermal zones in temperature gradient holes to the northeast and southwest suggest a depth to the top of heated groundwater at 75 m to 100 m. Shallower depths can be expected near the source of the plume where lines NC-2 and NC-3 are located.

SELF-POTENTIAL SURVEY

Self-potential (spontaneous-polarization or SP) surveys have often been used in the exploration for high-temperature geothermal resources. The method is relatively simple and inexpensive, and often gives encouragement for the presence of a thermal resource. SP responses occur as a wide variety of amplitudes, shapes, multiple anomalies, and may be positive or negative in polarity (Corwin and Hoover, 1979). Zablocki (1977) documented an outstanding 400 mV anomaly in the Hawaiian East Rift Zone which seems to be closely associated with the Puna geothermal resource.

A self-potential survey was completed at Newcastle in November 1989. By preparing and watering potholes hours prior to reading, noise levels less than one millivolt (mV) were achieved. All potential differences were referenced to a low-gradient area in the southeast portion of the survey, where lines 1 and 3 intersect (Figure 7). A standard station spacing of 30 m (100 ft) was decreased to 15 m in high-gradient areas across the main anomaly.

The survey mapped a well-defined 108 mV minimum near the two highest temperature gradient holes, NC-18 and NC-19. The amplitude of the anomaly relative to background SP variations make it appear as a bullseye, but closer inspection of profiles which define the anomaly indicate a 2:1 elongation along the strike of the Antelope Range fault (Figure 8). Other features of the SP map in Figure 7 include a small -30 mV anomaly near the road on Line 3, and a coherent +20 mV anomaly on the northwest portions of Lines 2 and 4.

Interpretation

Self-potential anomalies have been documented for a number of geothermal resource areas (Corwin and Hoover, 1979; Sill and Johng, 1979; Zablocki, 1977; and others). Positive and negative anomalies of short and long wavelength, and dipolar or multiple-pole anomalies are observed, complicating the interpretation. Corwin

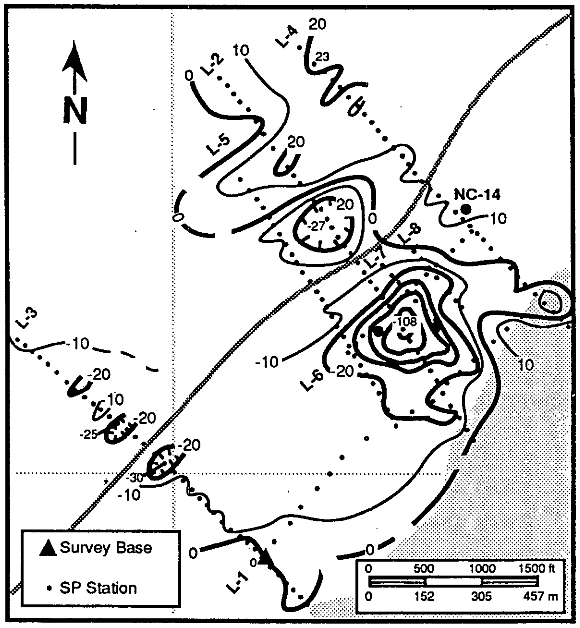

Figure 7. Self-potential map for the Newcastle geothermal area. All values are referenced to the base station at the intersection of Lines 1 and 3.

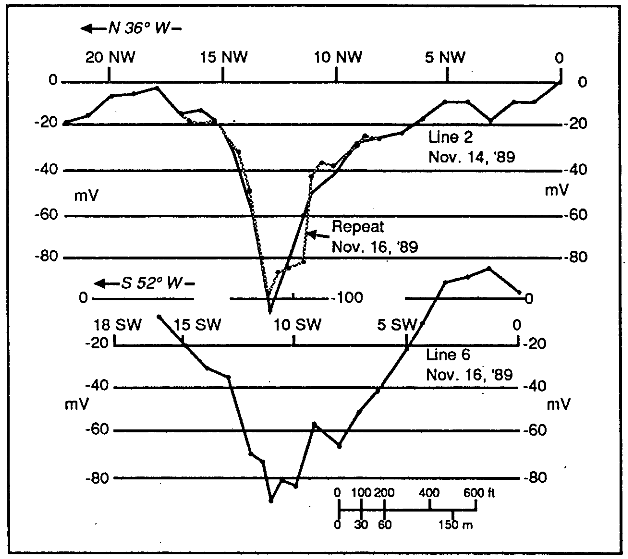

Figure 8. Self-potential profiles for Lines 2 (northwest) and 6 (northeast) across the SP minimum. Data for a repeat profile on Line 2, recorded two days later, are also shown.

and Hoover (1979) and Sill (1983) identify both electrokinetic and thermoelectric components to most geothermal SP anomalies, and Sill (1983) has demonstrated rather successful numerical modeling of SP data from primary flows which is appropriate for convection systems.

The short wavelength, 108 mV negative Newcastle anomaly is similar in amplitude, polarity, and wavelength to an anomaly over the Dome fault at Roosevelt Hot Springs (Sill and Johng, 1979). Modeling results by Sill (1983) and Sill and Johng (1979) which can be applied to the present study indicate that the Newcastle anomaly is probably produced by a point or small three-dimensional source at shallow depth. Negative thermoelectric and electrokinetic effects could be produced by this type of source. The correspondence with high near-surface temperatures, and a probable fluid conduit indicated by resistivity data and geologic mapping, leave little doubt that the SP source nicely defines the main zone of upwelling thermal fluids, the throat of this thermal system. A quantitative interpretation of the Newcastle SP anomaly is in progress. Our interim interpretation for this SP source indicates a depth to the top of 20 to 60 m, and a source area with dimensions of about 60 by 100 m. Temperature gradient and hydrologic data independently confirm thermoelectric and electrokinetic components of the SP source.

SUMMARY

Figure 9 summarizes the principal data sets defining the source of fluids for the Newcastle thermal-fluid plume. Northwest-trending faults mapped in bedrock intersect the Antelope Range fault, believed to dip about 65 degrees northwest, near coincident SP and low resistivity anomalies. A smaller, -30 mV SP anomaly is somewhat offset from the deep low-resistivity zone on resistivity line NC-3 approximately 600 m to the southwest. The data suggest that major fault intersections provide the primary conduits for thermal fluids. While some of these zones may be sealed with mineral precipates, the SP data seem to identify the open conduits.

A limited effort in dipole-dipole resistivity and self-potential surveys has been important in tieing together several other data sets at the Newcastle geothermal area, and has yielded a specific target area for drilling the principal conduit to the thermal plume. Each survey was completed in one week, including mobilization from 280 miles away. These methods may be cost effective for other moderate-temperature resource areas where electric power production is not the intended goal. Furthermore, these electrical surveys were completed in an area of extreme surface development of grounded structures, without an adverse effect on the survey data. Electrical resistivity and self-potential surveys should be conducted in the early exploration stage for other blind Basin and Range geothermal systems. The methods are not new, but were certainly effective in this application. The SP data indicate a very finite source region for the thermal fluids near the buried intersection of the Antelope Range fault and a northwest trending fault.

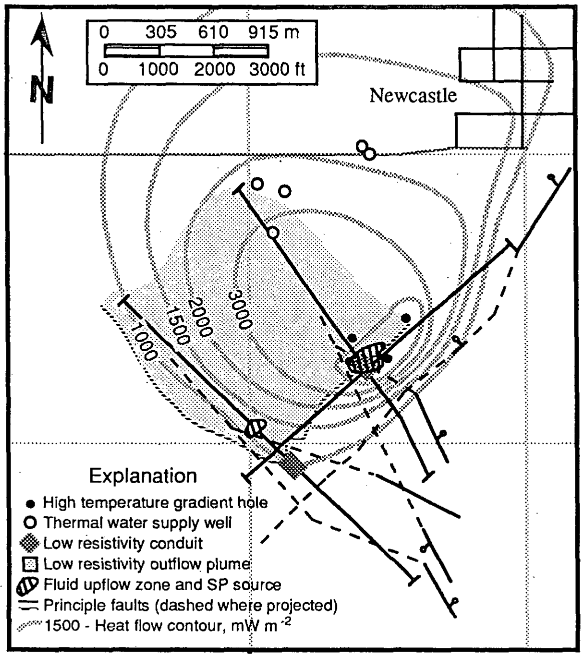

Figure 9. Interpretation summary showing probable fluid conduits indicated by resistivity and SP data, the outflow plume, and faults projected beneath alluvium.

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