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SELF-POTENTIAL SURVEYS OF THREE GEOTHERMAL AREAS IN THE SOUTHERN RIO GRANDE RIFT, NEW MEXICO

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Abstract—Self potential (SP) surveys appear to have important use as a primary tool in the exploration and delineation of hydrothermal upflow zones in the southern Rio Grande rift, New Mexico. SP surveys were completed over three distinct types of geothermal systems in the rift. At Rincon, a well-defined SP anomaly about 1 km long with a minimum of -122 millivolts (mV) was mapped over the highest temperature gradients and immediately adjacent to a radon anomaly. Two other SP minima of -57 and -74 mV at Rincon are untested with temperature gradient drilling but correlate with radon anomalies. At Radium Springs, several negative SP anomalies were mapped in an area north of a known upflow zone that currently produces fluids for greenhouse heating. The more significant anomalies had amplitudes of -92 and -146 mV. Six Radium Springs SP anomalies are immediately adjacent or over radon soil-gas anomalies, and limited temperature gradient information indicates at least one shallow upflow zone near the SP anomalies. The SP expression of the Tortugas Mountain part of the Las Cruces East Mesa geothermal area is quite complex. Several negative anomalies can be attributed to a "caliche effect" where stations on low ridges capped by well-developed, late-stage caliche produce large (-100 mV) anomalies over distances less than 20 m. This "caliche effect" presents a major noise source for SP surveys in arid regions. Elimination of caliche stations and filtering allowed interpretation of several -10 to -40 mV anomalies that may be a subdued expression of a deep (about 200 m) and broadly dispersed upflow zone(s).

INTRODUCTION

Convective low- to intermediate-temperature (<150°C) geothermal resources comprise the largest resource base with immediate development potential in the Rio Grande rift in New Mexico. Significant growth in geothermally heated greenhouses is occurring, and the two largest geothermally heated greenhouses in the nation are located in southern New Mexico. Direct-use endeavors require rapid, inexpensive, and relatively simple exploration methods.

Self-potential (SP) studies were initiated in 1990 to provide supporting data for the interpretation of soil-gas radon surveys over a geothermal system in the southern Rio Grande rift (Fig. 1). The initial surveys were then expanded to evaluate better the cost-effectiveness of the SP method as an exploration technique for concealed geothermal systems in the rift. These studies were first described by Ross and Witcher (1992) and are presented here in additional detail.

GENERAL TECTONIC AND GEOTHERMAL REGIME

The southern Rio Grande rift is a region with at least four major phases of extension in the last 35 Ma (Mack et al., 1994). While Pleistocene to Holocene faults are common in the area (Seager, 1980; Machette, 1987; Seager et al., 1982, 1987; Salyards, 1991; Gile, 1994), the last main phase of extension probably culminated about 3–9.6 Ma (Seager et al., 1984; Mack et al., 1994; Mack and Seager, 1995). No Quaternary silicic eruptive centers occur in this portion of the rift (Seager, 1975a; Seager et al., 1984). While Pleistocene and Holocene basaltic volcanism is widespread in the southern rift, the last basaltic volcanism in the SP survey areas is represented by the eruption of the Selden Basalt at 9.6 Ma (Seager et al., 1984).

The rift is characterized by high regional heat flow of >84 mWm^2 (Decker and Smithson, 1975; Reiter et al., 1975, 1978, 1979, 1986; Reiter and Barroll, 1990). Geothermal systems in this region are probably the result of high regional heat flow and deep circulation of meteoric water in regional deeply penetrating ground-water flow systems (Morgan et al., 1981; Witcher, 1988; Barroll and Reiter, 1990). A lack of silicic Quaternary volcanism reinforces a dominantly forced-convective model for resource occurrence.

The three geothermal systems discussed in this paper occur over a large, northwest-trending, compressional and basement-cored, Laramide Rio Grande uplift (Fig. 2) (Seager, 1983; and Seager et al., 1986, 1997). All three areas occur in late-stage, rift horst blocks that are internally broken by relatively close-spaced normal faults (Seager, et al., 1971; Seager and Hawley, 1973; Seager, 1975a; King and Kelley, 1980). While all these systems are in structurally high terrain at relatively low elevation, three geologically and geohydrologically distinct resources are surveyed. Each system represents an end-member type geothermal setting representative of many other systems found in the rift (Witcher, this guidebook). The survey areas provide an opportunity to compare SP signatures of particular types of rift geothermal settings.

SELF-POTENTIAL METHOD

Background

The self-potential (spontaneous polarization or SP) method has been used since the 1800s for mineral exploration. The method, which measures naturally occurring voltage differences at the earth's surface, has been used increasingly for engineering, hydrologic, environmental, and geothermal applications since the early 1970s (Corwin, 1990). Self-potential surveys have often been used in the exploration for high-temperature geothermal resources, but only to a limited extent for low- to intermediate-temperature systems. The method is relatively simple and inexpensive, and has detected anomalies related to thermal fluids in many geothermal systems. SP responses occur as a wide variety of amplitudes, shapes, and multiple anomalies and may be positive or negative in polarity (Corwin and Hoover, 1979; Ross et al., 1991). Corwin and Hoover (1979) described the thermoelectric coupling and electrokinetic coupling (streaming potential) effects that give rise to most anom-

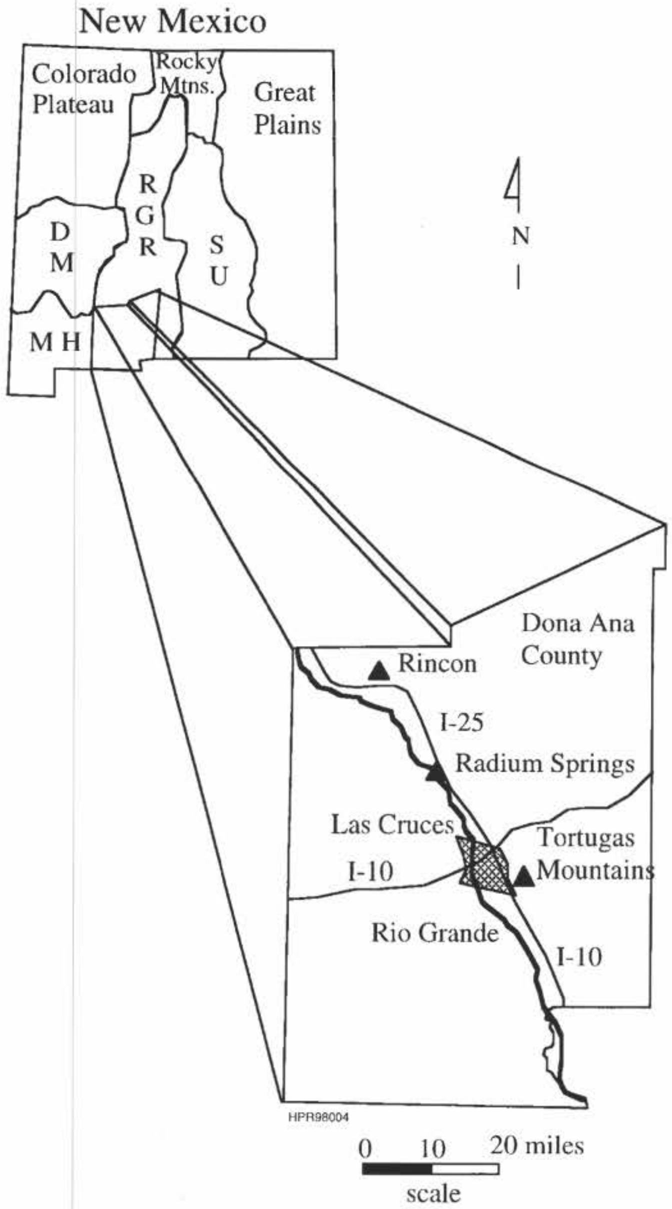

FIGURE 1. Geothermal systems of the southern Rio Grande rift, New Mexico, showing the location of study areas (filled triangles). Physiographic sub-divisions of the southern Basin and Range province are: DM = Datil-Mogollon; RGR = Rio Grande rift; SU = Sacramento uplift; MH = Mexican highland.

alies associated with geothermal fluid flow. Sill (1983) presented a rationale for the numerical modeling of self-potential data using primary physical flows (heat flow or fluid flow). Tripp et al. (1998) discussed three-dimensional modeling of SP data from primary flows (fluid flow, heat flow) and concluded that the inverse solution is ill-posed and must be constrained by other hard data.

Previous self-potential studies

Corwin and Hoover (1979) reported a 50 millivolt (mV) negative anomaly associated with Leach Hot Springs, Nevada and a 150 mV (peak to trough) dipolar anomaly associated with the Cerro Prieto geothermal field, Baja California. DeMoully and Corwin (1980) discussed a dipolar SP anomaly of about 500 mV (peak to trough) amplitude over near-surface geothermal activity at Beowawe, Nevada. Sill and Johng (1979) mapped a dipolar anomaly with a 100 mV low over the production zone at Roosevelt Hot Springs, Utah.

A study by Thanassoulas and Lazou (1990) reported an anomaly of -55 mV over the low-enthalpy Lagadas geothermal field in Greece. Ross et al. (1991) described the use of the method in exploring for concealed hydrothermal resources in the northern Basin and Range, and reported the occurrence of negative anomalies of -59, -108, and -116 mV associated with three low-to-moderate-temperature geothermal systems in the Sevier Thermal area of Utah (Wood's Ranch, Newcastle, and Thermo, respectively). They concluded that the method can be very cost-effective for the delineation of concealed geothermal systems when thermal fluids rise close to the surface.

Survey procedures

Surveys were completed using a high-impedance digital voltmeter and copper-copper sulfate porous pot electrodes connected by a spooled, 1270 m lightweight single-conductor copper wire. A basic radial or "spoke" survey technique was used so that many potential measurements, generally at 60 m spacings along the lines, could be made directly with respect to a central stationary electrode. This helped to minimize cumulative errors that could result from looping between intersecting profiles. When it became necessary to extend the survey, the potentials of the individual reference electrodes were standardized to the primary base station for the survey. The typical measurement accuracy for the surveys was ±2 mV, but this was often perturbed by cultural or telluric noise, or by infiltration due to recent precipitation.

RINCON GEOTHERMAL AREA

Geology and drilling results

The Rincon geothermal system is situated over the thrusted and deeply fractured convergent boundary of the Laramide Rio Grande uplift (Seager et al., 1986; Witcher, 1991, this guidebook). Shallow outflow from the confined, deep Laramide-age reservoir, is along late-stage rift structures in the East Rincon Hills uplift that comprise the Rincon transfer zone of the rift (Mack and Seager, 1995). The Rincon Hills uplift consists of variously indurated basin-fill sediments of Eocene to late Miocene age of a tectonically-disrupted older rift basin interior (Mack and Seager, 1995). Strata within the uplift generally dip homoclinally south to southeast between 20° and 35° (Seager and Hawley, 1973). Numerous relatively close-spaced faults cut the East Rincon Hills uplift. In general, structurally higher terrain, progressively older Tertiary rock, is encountered from south-to-north across the northwest-trending uplift.

The East 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, Camp Rice Formation, of an aggrading ancestral Rio Grande show increasing alteration, induration, and color intensity as the fault is approached. Several beds of opal, interbedded in the ancestral Rio Grande deposits record hot-spring activity (Witcher, 1991). The SP survey area is over the hanging wall of the East Rincon Hills fault (Fig. 2). There is no current geothermal use at Rincon and the area is in the early stages of exploration.

Figure 3 shows the locations of radon soil-gas anomalies and temperature gradient boreholes in the Rincon SP survey area. A north-trending temperature gradient anomaly, centered at RAD-8, overlies the East Rincon Hills fault zone (Witcher, 1991). RAD-8 and Rincon SLH-1 show conductive temperature gradients between 850° and 560° C/km above the water table at 91 m. A rollover in temperature (85–72°C) occurs between 100 m and 177 m; however, temperatures again increase conductively from 177 m

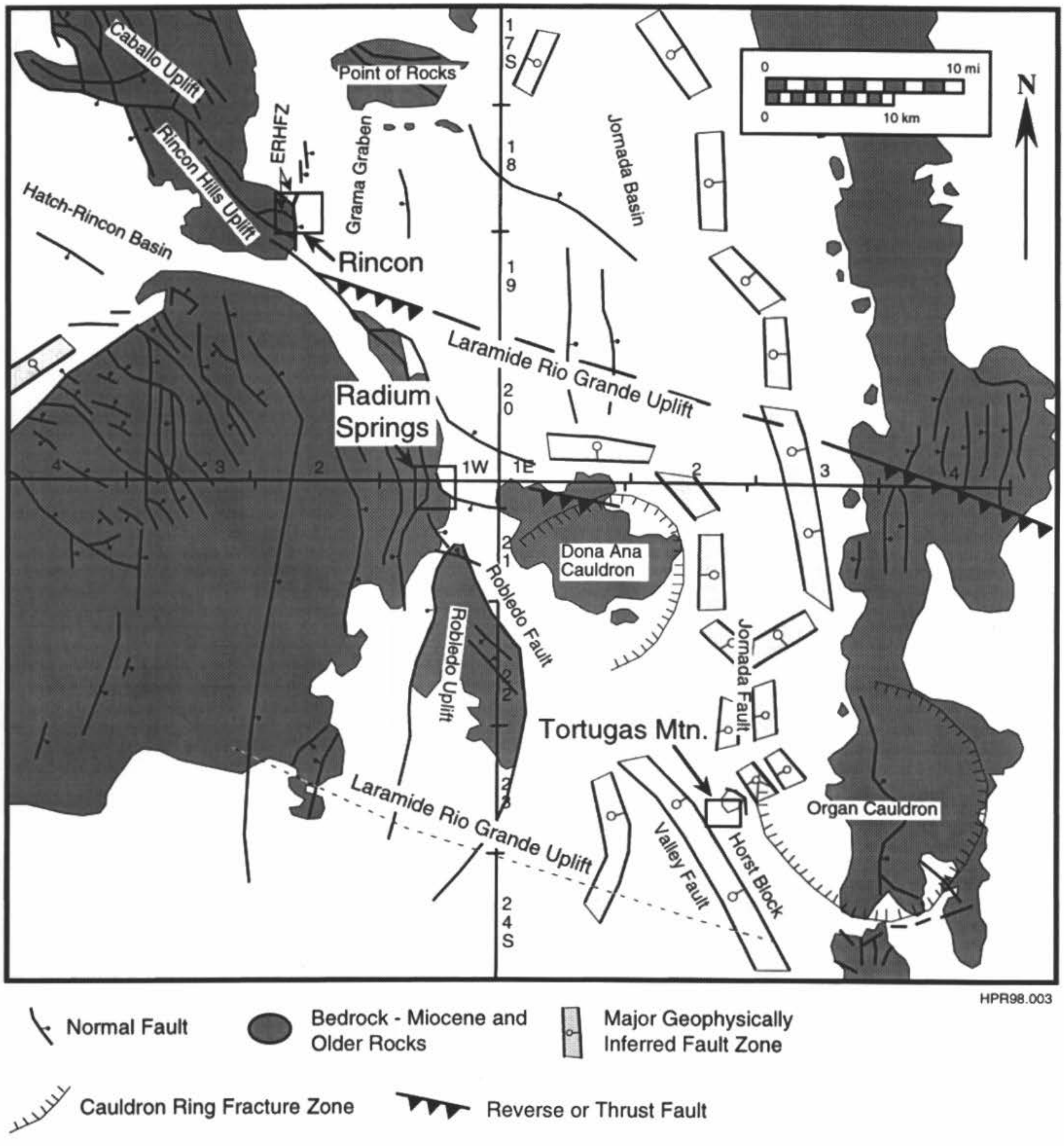

FIGURE 2. Regional tectonic map of the southern Rio Grande rift (after Seager, 1987). ERHFZ = East Rincon Hills Fault Zone.

to 371 m depth to 100°C (Witcher, this guidebook). Intense quartz cementation in the Camp Rice Formation is accompanied by disseminated sulfides, mostly <5% pyrite, at depths below 60 m. Two northwest-elongated positive, radon soil-gas residuals overlie the northern portion of the mapped temperature-gradient anomaly (Witcher, 1991). The radon anomalies are interpreted as either indicating the subsurface upflow zone or aureoles immediately adjacent to the upflow zones.

Self-potential survey

We initiated SP surveys at Rincon in late September 1990, approximately one month after the end of the rainy season, and identified two major anomalies. A second week of field work in early November extended the survey, closing off the anomalies and providing additional detail. One day of survey work in March 1991 repeated several profiles across the northeast anomaly. A total of

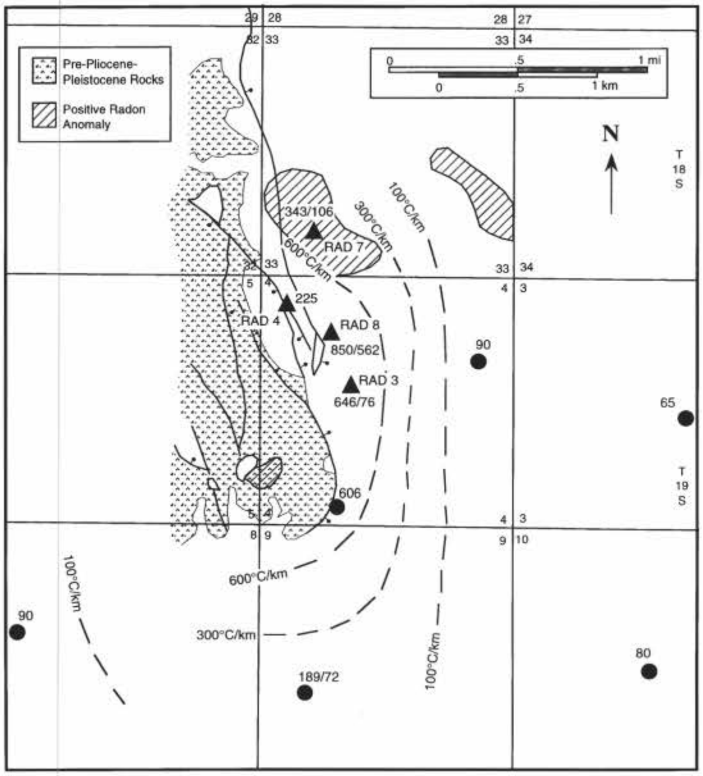

FIGURE 3. Generalized areal distribution of temperature gradients in the Rincon area. Simplified structural geology, and radon anomalies are also shown. Temperature gradients for each well (shown as filled triangles and circles) are measured gradient or range of gradients in °C/km. Drill hole SLH-1 is located at the site of RAD-8.

37.5 line-km of profiles were completed, including 8.4 line-km of repeat coverage, necessary to tie base stations together and to identify SP effects due to recent precipitation. The completed survey covers an area of 6.7 km² with station intervals of 60 m and 30 m along profiles (Fig. 4).

All self-potential values are referenced to a base station along a dirt road approximately 600 m east of the topographic escarpment of the East Rincon Hills in an area of low-relief (elevation about 1280 m) and low-voltage gradients. Weak positive values associated with washes to the south and east suggest this base station is near the regional background. A broad elliptical SP low has been defined that includes the eastern portion of the Rincon Hills, and which extends 2.4 km to the northeast with an average width of about 1.3 km. Three major minima occur within the broad low.

Anomaly A trends north-northwest along structure and includes minima of -122, -77, and -74 mV. High-frequency "noise" on the anomalies may result from rough topography and variable near-surface geology. Simple depth estimates suggest depths of 90–180 m to these sources. Drill hole RAD-8 is located near the center of anomaly A1. Minima values of -121 and -122 are measured approximately 30 m northwest and southeast of RAD-8. The 90 m of water-filled 2.5 cm iron casing does not intersect the water table and gives rise to a sharp, 80–100 mV positive anomaly that is too small to contour on Figure 4. RAD-7 lies north of minima A2. Drill holes RAD-3, -7 and -8 all lie along the trend of anomaly A, and currently define the Rincon geothermal system.

Anomaly B is a small but coherent minimum of -57 mV located 700 m north-northeast of RAD-7 in an area of low topographic relief at an elevation of 1013 m. Source depth estimates range from 100–150 m. Anomaly C is a broad minimum of -58 to -74 mV centered about 1220 m northeast of RAD-8. This anomaly varied in shape and amplitude during the three different survey periods, some of which were disturbed by recent precipitation. Source depth estimates vary from 100–200 m for the source, which lies over a broad area of low relief cut in Quaternary-Pliocene fluvial deposits. Anomalies B and C are untested by drilling and temperature observations. Witcher (1991) reports two anomalous radon soil-gas samples within anomaly C. Anomalies B and C may also be associated with upflow zones for thermal fluids, similar to anomaly A, and are considered good targets for temperature gradient drilling.

RADIUM SPRINGS GEOTHERMAL AREA

Geology and geothermal occurrence

The shallow geothermal system at Radium Springs is contained in a discordant, highly fractured rhyolite body of limited extent that intrudes the Palm Park Formation, an Eocene regional aquitard (Seager 1975b). Two geothermal test wells a few miles to the north and drilled to 2.44 and 2.74 km depth indicate a deep (>1 km depth) intermediate-temperature (>100°C) parent reservoir beneath the Palm Park aquitard in fractured Paleozoic limestone and Precambrian granite.

Near-surface geology of the Radium Springs area consists mainly of upper-Pleistocene fluvial sand-and-gravel terrace deposits less than 15 m thick that were laid down after downcutting events of an entrenching ancestral Rio Grande during the past 0.7 Ma (Mack et al., 1993). The terrace deposits are inset on the Palm Park Formation and lower and upper Santa Fe Group basin-fill deposits (Seager, 1975b). Windblown sand covers the terrace deposits over most of the north-central part of the survey area. The eroded tops

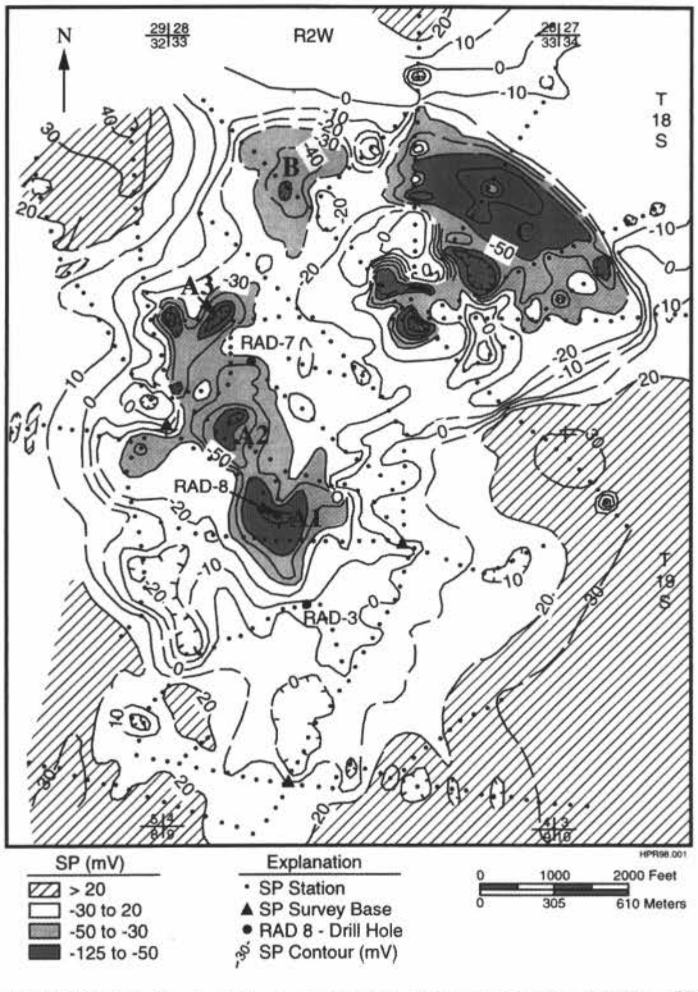

FIGURE 4. Self-potential survey results, Rincon area, New Mexico. SP contour intervals are 10 and 50 mV.

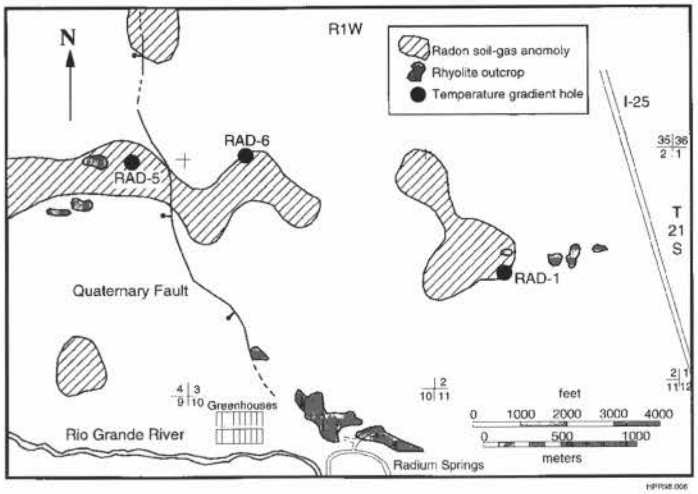

FIGURE 5. Positive radon soil-gas anomalies, selected geologic features, and temperature gradient hole locations in the Radium Springs survey area.

of fractured mid-Tertiary rhyolite intrusions in the Palm Park aquitard protrude through to the surface where the Quaternary clastic cover is thin. A late Pleistocene fault scarp trends west-northwest across the western margin of the SP survey area. Rhyolite outcrops, temperature-gradient boreholes, and radon soil-gas anomalies are shown in Figure 5.

An important geothermal resource occurs at Radium Springs (Figs. 1 and 2) where a 5.7-hectare, geothermally heated greenhouse utilizes fluids of the Radium Springs geothermal system. Geothermal water for heating is supplied by shallow (less than 75 m depth) wells at production rates up to 25.2 L/s and temperatures at around 70°C.

Self-potential survey

Detailed SP surveys were completed in an area of 6.5 km^2 northeast of the Rio Grande and southwest of I-25. Survey profiles cross production wells in the southern portion of the survey, but coverage here is incomplete because of the greenhouse facilities, grounded structures and the river. A deep geothermal well test, Hunt 25-34, lies just north of the survey area. A total of 27.8 line-km of SP profiles was completed, including 1.2 line-km of repeat coverage or tie lines. The station interval was generally 60 m except in areas of steep gradients where the spacing was reduced to 30 m. Topographic relief throughout the area was minor. Elevations varied from 1310 m in the north to 1210 m near the river. Loose sand and sparse vegetation typified the area. The survey was conducted in November 1990 and March 1991 to help evaluate three radon soil-gas anomalies mapped by Witcher, which are thought to indicate covered upflow zones, possibly contained within detritus-covered fractured rhyolite dikes.

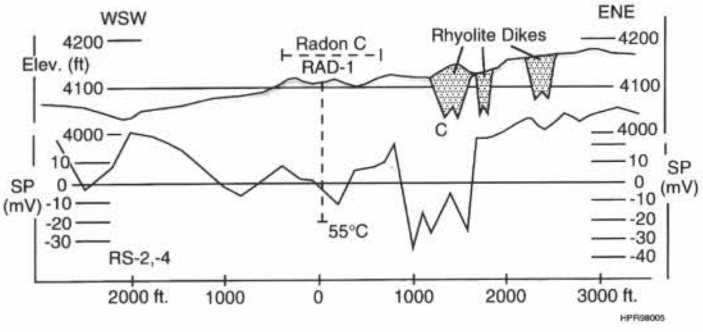

FIGURE 7. SP profiles RS-4 and RS-2 that define anomaly C and cross rhyolite outcrops to the east, Radium Springs, New Mexico.

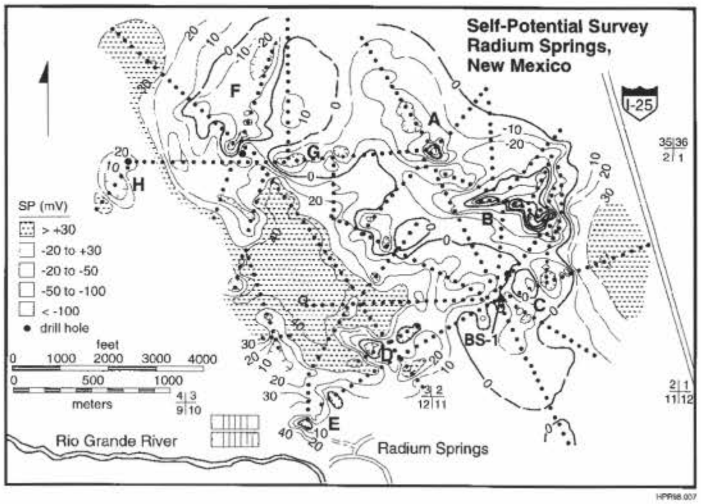

FIGURE 6. Self-potential survey results, Radium Springs area, New Mexico. SP contour intervals are 10 mV and 20 mV.

Figure 6 shows the final SP map for the Radium Springs survey. All potentials are referenced to a background potential (0 mV) at base station 1 (BS #1) in a low-gradient area in the southeast part of the survey. Low-frequency maxima of 30–40 mV are mapped at the eastern and northwestern limits of the survey, and a broad high of 30–50 mV occurs in the southwestern part of the survey, 610–1520 m north of the Rio Grande. A number of sharp minima are superimposed upon this relatively smooth potential field, some with a weak dipolar appearance. In general there is little correlation between the SP and topography, but locally higher SP values were often noted in and near sandy washes. Eight anomalies (A through H) with amplitudes of 20 to -146 mV are labeled on Figure 6.

Anomalies A and B are the most significant minima with amplitudes of -92 and -146 mV, respectively, and dimensions of 300–800 m. The source depth estimates for the anomalies are shallow

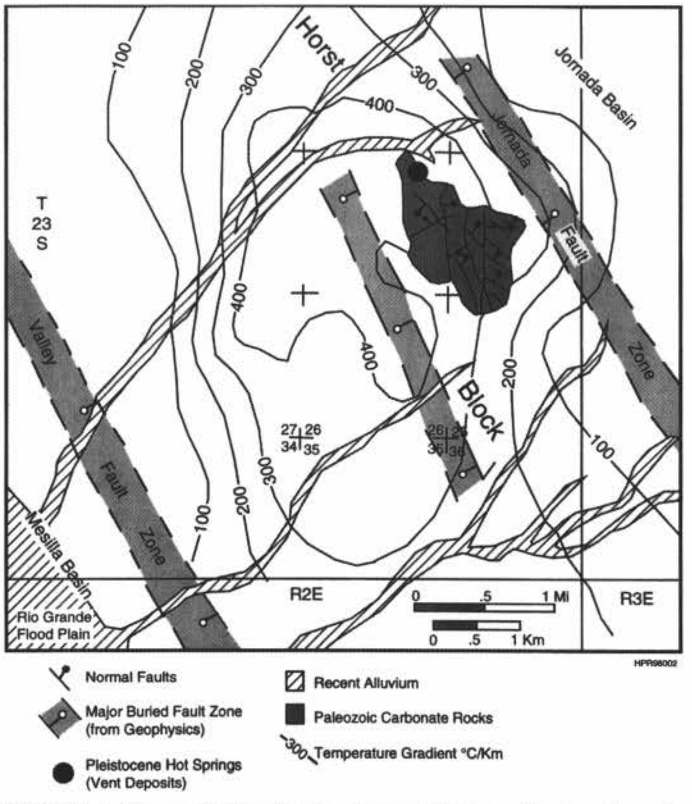

FIGURE 8. Generalized geology and temperature gradient contours for the Tortugas Mountain area.

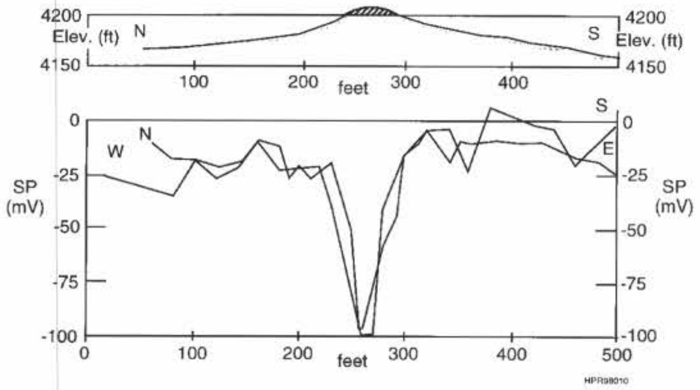

FIGURE 9. Detailed N–S and W–E SP profiles across a small caliche capped hill in the central part of the Tortugas Mountain survey area.

(20–100 m). No rhyolite is observed at the surface in these anomalous areas and the nearest temperature-gradient test RAD-1 is 500 m distant (Fig. 5). Radon soil-gas anomalies are mapped along the southern flank of the SP minima.

Anomaly C includes a rhyolite outcrop in the northeast part of the anomaly. Again, a radon soil-gas anomaly flanks the western margin of the SP minimum. Drill hole RAD-1, 250 m west, provided a temperature measurement of 55°C at a depth of 90 m, and a shallow temperature gradient of 267°C/km. Figure 7 illustrates SP profiles RS-4 and RS-2 that define anomaly C and cross rhyolite outcrops to the east. Anomaly D has two small minima aligned in a northeast trend and shows no relationship to soil-gas radon anomalies or rhyolite outcrops.

Anomaly E occurs along the western portion of a fractured rhyolite, where four wells have been drilled to produce fluids for the greenhouses. The anomaly is not well defined due to a 15-m escarpment, greenhouses to the west, the river, and the well locations. Well casings for two wells may contribute to the minimum, but two others apparently do not. The complex topography and surface features preclude a simple characterization of the SP response of this part of the geothermal system.

Anomalies F and G are closely correlated with a large uncorrected soil-gas radon anomaly reported by J. C. Witcher (unpubl. report to DOE, 1990) but only weakly correlated with an emanation-corrected radon anomaly. Drill hole RAD-6, within 300 m of both minima, recorded a temperature of 52°C at 90 m depth, and a temperature gradient of 241°C/km. A weak, local SP minima, anomaly H, occurs near rhyolite outcrops, a strong radon anomaly, and drill hole RAD-5 (32°C at 90 m).

The sources of these several SP anomalies have not been tested by drilling and temperature measurement, but several anomalies overlie or immediately flank radon soil-gas anomalies, nearby rhyolite outcrops or anomalous temperatures in nearby drill holes. We believe that anomalies A, B, C, F, G, and H may result from local upflow zones for thermal fluids, where fractured rhyolite and fault zones provide hydrogeologic windows across the Palm Park aquitard.

TORTUGAS MOUNTIAN GEOTHERMAL AREA (LAS CRUCES EAST MESA)

Geology, geophysics, and geothermal data

The Las Cruces East Mesa geothermal field, as defined by numerous temperature-gradient measurements, is an elongate area more than 25 km (N–S) by 4 km (E–W), east of Las Cruces (Figs. 1 and 2). The Las Cruces East Mesa thermal anomaly coincides with a mostly alluvium-buried, northwest-trending horst block. The horst block is internally fractured by probable Oligocene or Miocene extensional faulting. Tortugas Mountain is a faulted and rotated local exposure of Paleozoic carbonate rocks within the horst block (King and Kelley, 1980). The geohydrologic window or upflow zone for Tortugas Mountain is broad with many zones of vertical fracture permeability.

The area covered by the SP surveys overlies the western portion of the horst immediately west of Tortugas Mountain. Temperature gradients above the water table (100–120 m depth) exceed 400° C/km for much of the survey area. Also, no faulting of upper Tertiary basin-fill sediments or Quaternary surficial deposits is observed in the survey area (Seager et al., 1987). The survey area is underlain by a variety of surficial deposits, many resulting from the progressive Pleistocene entrenchment of the Rio Grande (Gile et al., 1981). A series of geomorphic terraces are inset with thin sand and gravel upon older clastic sediments. The upper and older geomorphic surfaces have strongly developed petrocalcic soil horizons (Stage II to IV of Gile et al., 1966). Figure 8 summarizes the pertinent temperature and geologic data for this covered hydrothermal system. Figure 8 also shows fault locations interpreted from borehole, seismic, and resistivity information.

Currently, geothermal fluids from the Tortugas Mountain resource are used to heat 0.8 hectare of commercial greenhouses, provide space heat and domestic hot water for a district heating system at New Mexico State University (NMSU), and heat for an NMSU geothermal research greenhouse and geothermal aquaculture facility.

Self-potential survey

Self-potential data were obtained in two survey periods in March and October 1991. A total of 20.2 line-km of survey data were taken, including 3.4 line-km of repeat data, in an area of 4.2 km^2. The survey sought to identify specific upflow zones in this broad, diffuse geothermal system. A high level of geologic noise, expressed as coherent lows of -20 to -100 mV, was found to be associated with several caliche-capped ridges of low topographic relief (3–10 m). Figure 9 shows detailed N–S and W–E SP profiles across a small, caliche-capped hill in the central part of the survey area. Data reduction included deleting 110 caliche or near-caliche sta-

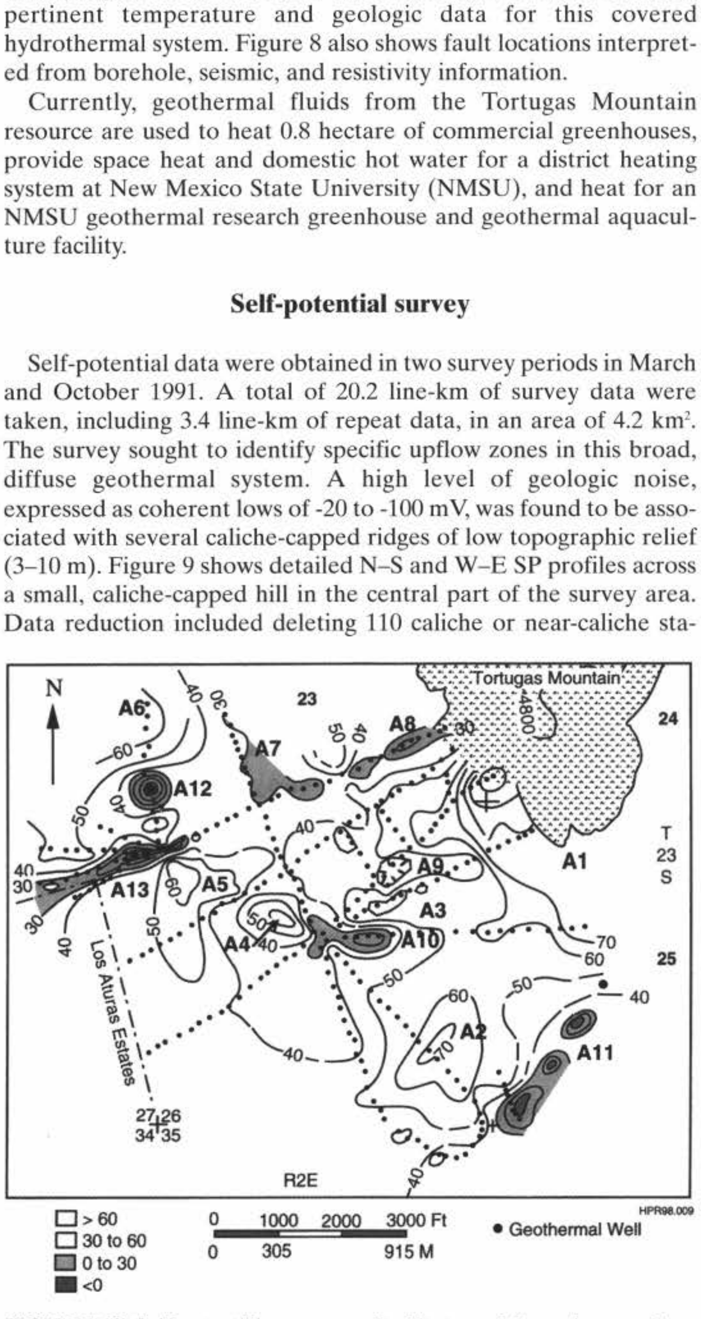

FIGURE 10. Self-potential survey results, Tortugas Mountain area, New Mexico. SP contour interval is 10 mV.

tions from the set of 500 stations, and simple three-point averaging of the remaining data set. The resulting SP map reproduced here as Figure 10 is relatively free of near-surface effects.

Inspection of the residual SP map, topography, and local geology suggests a local background value of about +45 mV, referenced to Base Station 1 near the center of the survey. Fourteen specific anomalies were identified. Positive anomalies of 15–30 mV are associated with sandy washes (Fig. 10, A2, A4, A5, A6). Two well-defined minima (A12 and A13) are attributed to drill casing and perhaps a buried pipeline. Two well-defined minima, A7 and A10 (-15 to -40 mV) and a weak low (A9) all occur near the eastern margin of higher temperature gradients, a low resistivity zone, and several northwest-trending faults inferred from seismic and electrical resisitivity data. It is likely, but not certain, that these areas of low SP reflect the upflow zone(s) of thermal fluids rising along a well-distributed fracture zone. Two other minima, A8 and A11, may result from an incomplete removal of near-surface effects.

DISCUSSION

Self-potential surveys in the southern Rio Grande rift have been very productive in defining target areas for temperature gradient drilling and thermal fluid sampling. At the recently discovered Rincon geothermal system, a well-defined minimum of -122 mV was mapped near the hottest drill holes, and extends for a strike length exceeding 1 km. Two other minima of -57 and -74 mV should be tested as possible thermal upflow zones. At Radium Springs several negative anomalies were mapped in an area north of the geothermal production zone, but near anomalous temperature gradient holes. The more significant anomalies had amplitudes of -92 and -146 mV, but several smaller anomalies were also mapped. All anomalies arise from relatively shallow depths (20–100 m) with no surface indications of a thermal upflow zone.

The self-potential expression of the well-studied Tortugas Mountain part of the Las Cruces East Mesa geothermal area is quite complex. Many negative anomalies can be attributed to a "caliche effect" where stations on low ridges capped by Stage III and IV caliche produce large (-100 mV) anomalies. This effect could readily dominate SP surveys in this and other arid areas and presents a major noise source to SP surveys. Elimination of the caliche stations and simple filtering of the data resulted in a usable survey map. This residual map defined three weak (-10 to -40 mV) minima in the north-central part of the survey area which correlate well with other geophysical indications of a possible upflow zone of the geothermal system. The SP expression may be more subdued because of the increased depth to the geothermal fluids (200 m) or because the upflow zones are broadly dispersed along a number of fault zones or fracture intersections.

It would be speculative to suggest that all the well-defined SP anomalies result from thermal fluid upflow zones, but this appears to be the case for several negative anomalies with supporting temperature and radon soil-gas indications. These anomalies are therefore considered good targets to drill and test for the presence of shallow thermal fluids for greenhouse or other space-heating projects. The self-potential method should be considered as a primary tool for the exploration and delineation of shallow hydrothermal upflow zones in the southern Rio Grande rift. The relative simplicity and low cost of the method makes it well suited to the exploration and testing of low- and moderate-temperature hydrothermal resources.

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