DEEP RESISTIVITY INVESTIGATIONS AT TWO KNOWN GEOTHERMAL RESOURCE AREAS (KGRAS) IN NEW MEXICO: RADIUM SPRINGS AND LIGHTNING DOCK

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ABSTRACT

Using State and Federal support, the University of New Mexico has recently become engaged in deep electrical resistivity investigations of various geothermal sites in New Mexico. The field program at each location usually begins with reconnaissance resistivity mapping using the bipole-dipole or roving dipole technique. Resistivity soundings of more promising areas are then made subsequent to, or in conjunction with, the bipole measurements. The program is a portion of a combined geological, geochemical, and geophysical assessment of the State's geothermal potential.

Two resistivity project areas are recently designated KGRAs in southern New Mexico, Radium Springs and Lightning Dock. Resistivity reconnaissance and soundings at each area have provided independent evidence for structural control of the thermal anomalies. The resistivity results at Radium Springs agree with a fault-controlled barrier to a hydraulic connection between the valley containing the springs and a potentially vast reservoir to the north. A pervasive, but shallow, very conductive horizon sounded near idium Springs may contain thermal waters. The vicinity of the hot wells at Lightning Dock KGRA is mapped by small, low-resistivity closures suggesting ascension of thermal waters in a conduitlike structure. This structure may occur at the intersection of a mid-Tertiary caldera boundary and deflected, younger Basin and Range faults. A dipole-dipole sounding may have probed a deep hydrothermal reservoir beneath the wells; low-resistivity zones north of the hot wells, in the center of the valley, are likely due to saline ground water.

INTRODUCTION

Deep electrical resistivity investigations of geothermal target areas in New Mexico are currently in progress as a portion of a State and Federally funded exploration and assessment program. The total program includes geological, geochemical, as well as geophysical investigations of an applied and also a more basic research nature. For example, we are attempting to develop, evaluate, and test in the field various exploration techniques to determine their suitability in geothermal environments.

New Mexico's geothermal potential is concentrated along the Rio Grande rift, bisecting the State from north to south, and in the southwestern part of the State (Fig. 1). All areas classified as KGRAs (Known Geothermal Resource Areas) by the U.S. Geological Survey occur in these two regions of New Mexico. Electrical resistivity studies are concentrated in four areas of this province (Fig. 1). Project area 1 surrounds Los Alamos Scientific Laboratory's hot dry-rock demonstration site in the Jemez Mountains and project area 2 is in the Rio Grande rift north of Albuquerque. Preliminary results om our work in these areas have been reported by Jiracek and others (1976). Project areas 3 and 4 are recently designated KGRAs, Radium Springs and Lightning Dock, respectively; these two areas are the subject of this paper which discusses data obtained during the 1975 field season. The preliminary data has been presented and briefly discussed by Jiracek and others (1975).

Figure 1. Location map of resistivity project areas in New Mexico: 1) Jemez Mountains, 2) Rio Rancho, 3) Radium Springs, 4) Lightning Dock.

Field work utilized a 50-kw resistivity system. A trailer-mounted transmitter is used to introduce a square wave current, of typically 10 to 20 sec period, into the ground. The voltage measuring system uses the standard non-polarizing porous pot electrodes and battery-operated portable potentiometric chart recorders. Prior to recording the signals, they are passed through a self-potential nulling, low-pass (below 1 Hz), variable amplifer. Reconnaissance total field apparent resistivity mapping was accomplished in all areas using approximately 2-km-long current transmitting bipoles and orthogonal roving voltage measuring dipoles usually of 100-m length. Resistivity soundings were made by a combination of asymmetric Schlumberger, equatorial bipole-dipole, and polar dipole-dipole arrays.

RADIUM SPRINGS

Geologic and Geohydrologic Setting

There was little available literature to guide our initial electrical resistivity investigation of Radium Springs; the only references were contained in two hydrologic reports, listings of hot springs, and one revealing study of its geothermometry. During the fall of 1975, a geologic map of the area and several pertinent articles were published by Seager (1975a,b). His geologic investigations have influenced our present resistivity interpretations and will aid in planning our future experiments.

Radium Springs is located at the northern end of the Mesilla basin, one of the southernmost grabens that comprise the Rio Grande rift. The springs emerge at the intersection of features produced by three major stages of tectonism: 1) Laramide uplift, 2) Oligocene rhyolitic volcanism, and 3) late Tertiary block faulting in the Rio Grande rift. The axis of a north-trending Laramide anticline passes approximately 3 km west of Radium Springs and, in the subsurface, it could provide a large, as yet unsuspected, reservoir for the waters that emerge at Radium Springs. This postulated reservoir for geothermal fluids could be governed by many of the confirmed relations found in anticlinal oil and gas traps. These relations have been explored by Smith (M.S. thesis in progress, University of New Mexico).

Two Oligocene volcanic centers have been mapped in the vicinity of Radium Springs. The silicic volcanism of these events gave way about 26 m.y. ago to basaltic-andesitic flows (Seager and others, 1975). The inference from this shift is that this age marks the beginning of active extensional tectonics in the Rio Grande rift.

Evidence for active rifting from early Miocene to Pleistocene time can be found in the area immediately surrounding Radium Springs. The Pliocene appears to represent the culmination of rifting and basaltic activity. Broad intrarift basins were segmented into prominent intrabasin horsts and grabens, and basalt dated at 9 m.y. was erupted (Seager, 1975b). A narrow intrarift horst separating the upper Mesilla Valley from the Jornada del Muerto basin to the northeast formed during this most recent stage of uplift. It is likely that the fault which bounds the horst is the same fault along which Radium Springs emerge (Seager, personal communication, 1976). The presence of this horst may be inferred from our resistivity studies.

Radium Springs lies on the contact of the intrabasin horst and the flank of a Laramide anticline and emerges along a fault or system of faults which have been active for much of the Cenozoic. They are undoubtedly controlled by these complex structural elements.

Two major ground-water studies have concerned the Radium Springs area in the upper Mesilla Valley, those of Conover (1954) and King and others (1971). The limited thickness of the aquifer in the valley near Radium Springs is governed by the pinching out of the Mesilla Valley where it abuts the uplift to the north. The aquifer thickness and width can be expected to increase southeastward down the valley.

The recorded surface temperature of Radium Springs is 85° C as reported by Summers (1965), who also published a chemical analysis of the waters. A thorough study of the geochemical indicators of subsurface equilibrium temperatures in the region was recently completed by Swanberg (1975a). His data for the Na-K-Ca geothermometer show temperatures in excess of 200° C both at Radium Springs and at a nearby well. Swanberg's work also postulated an intersection with a northern extension of the Valley fault which passes through Las Cruces to the south. Swanberg (1975a) reports no high geothermometry temperatures in the Jornada del Muerto, substantiating an earlier conclusion (King and others, 1971) of a ground-water barrier between it and the Mesilla Valley.

The search for a heat source for the Radium Springs area must consider the high heat flow (≥ 2 HFU) and a gravity high interpreted by Decker and others (1975) in the Las Cruces area. Their explanation is for either shallow basaltic crustal intrusions or local upwarping of the mantle.

Resistivity Investigations

Several questions to be answered concerning the origin, migration, and accumulation of the thermal fluids include: 1) Is Radium Springs an isolated phenomenon or do similar waters rise all along nearby faults? 2) Is there a structural barrier between the Jornada del Muerto basin, potentially a vast reservoir, and the upper Mesilla Valley? 3) Can any other potential reservoir for the thermal fluids be found? 4) What is the source of heat? To approach these questions, we have thus far conducted a two-phase electrical resistivity exploration program. Two regional surveys demonstrated that the Jornada del Muerto is structurally separated from the upper Mesilla Valley. Secondly, a series of shallow soundings near Radium Springs located the depth to the saline-water horizon, a deeper marine sequence, and the still deeper Precambrian basement. The two most fundamental questions—the location of a large reservoir of the thermal fluids and the source of their heat—were not answered. Both involve deeper probing, perhaps to several km.

We first conducted a bipole-dipole roving reconnaissance survey from a pair of 2-km bipole transmitters, covering an area of approximately 65 sq km. A water well served as a common electrode for the bipoles. Figures 2 and 3 are the two total-field apparent resistivity maps generated from the two bipole sources. The upper two-thirds of the figures cover the Jornada del Muerto; the upper Mesilla Valley begins at Radium Springs and extends to the southeast along the Rio Grande.

Figure 2 shows the total-field pattern generated using the east-west bipole transmitter. The broad low to the north is undoubtedly due to the geometry and water-saturated fill the Jornada del Muerto. The water quality within the Jornada grades from good on the southeastern end to poor at the northern end of the area. Increasing thickness of water-saturated strata coupled with the decreasing water quality also would produce the low-resistivity pattern. The lowest resistivity contour (10 ohm-m) coincides, on either end of the bipole, with Seager's (1975a) postulated Jornada fault.

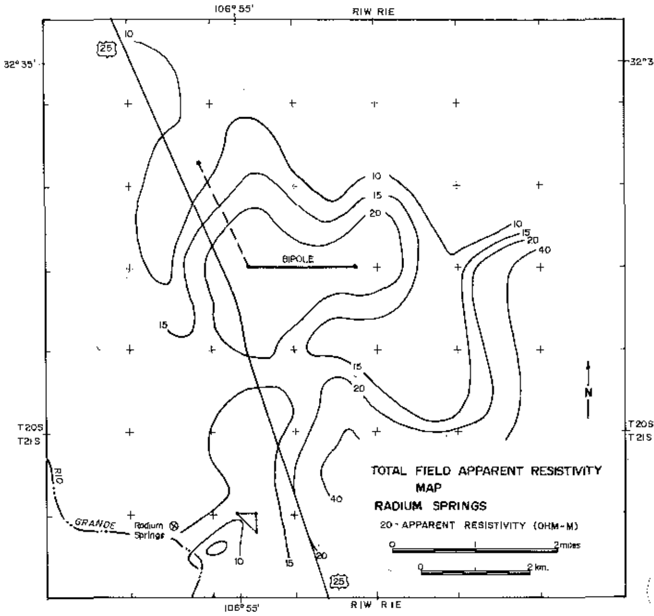

Figure 2. Total-field apparent resistivity map of Radium Springs project area derived from E-W bipole transmitter.

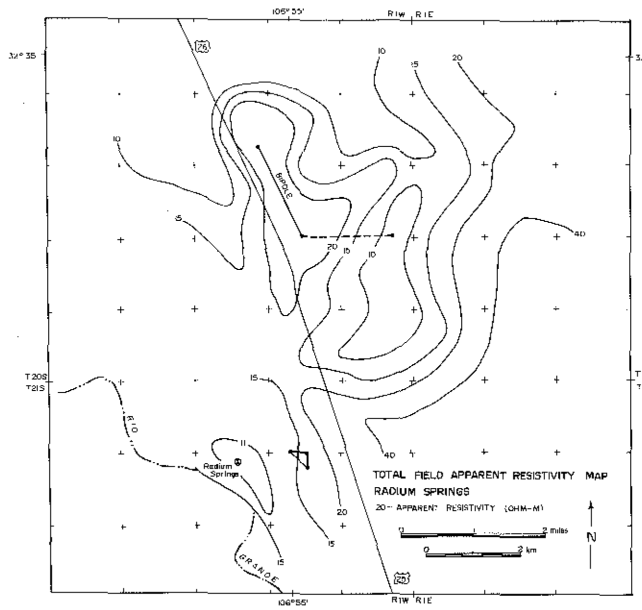

Figure 3. Total-field apparent resistivity map of Radium Springs project area derived from NNW bipole transmitter.

In the southeast corner of Figure 2, the steep contour gradient and the high resistivity values (~ 40 ohm-m) are associated with the Dona Ana Mountains which are remnants of an Oligocene volcanic center. These rocks may extend as far north in the subsurface as our high-resistivity pattern suggests. The steepest gradients, east of the transmitter, correspond to the region where the intrusives would be downdropped to the north by the Jornada fault.

There is evidence to the southwest of the transmitter suggesting the presence of a structural barrier to any hydraulic connection between the Jornada and Radium Springs. This evidence is the geometry of the 15 ohm-m and 20 ohm-m regions in secs. 35 and 36, T. 20 S., R. 1 W., where the resistivity pattern forms a saddle separating the low-resistivity regions associated with the Jornada basin to the north from the low-resistivity area near Radium Springs to the south. This saddle extends to the east where it links with the higher (> 20 ohm-m) resistivity region associated with the Dona Ana Mountains. Were there a connection between Radium Springs and a reservoir of thermal fluids in the Jornada, a low-resistivity trend connecting the two would have appeared.

Resistivities lower than 5 ohm-m were recorded near Radium Springs. Tightly nested contours near the springs delineate the areal extent of saturation by the thermal waters as sensed by current from the E-W source. The fact that the lowest resistivity values were not recorded precisely at the springs may indicate a sensitivity to an accumulation or source of waters down the Mesilla Valley from the springs. The pattern of the contours could indicate the region of greatest storage of thermal and/or saline waters in the valley fill.

This speculation seems to be substantiated by the closed resistivity lows surrounding Radium Springs generated by data from the other (NNW) bipole source (Fig. 3). The density of data points is greatest in the area immediately surrounding the springs, resulting in the position of the low-resistivity contours in the Mesilla Valley being as accurate as any from either bipole source.

Comparison of Figure 2 with Figure 3 reveals which of the contours of each figure are products merely of bipole orientation effects and which are governed by subsurface changes in earth resistivity. Figure 3 preserves the essential features noted in Figure 2: 1) the low-resistivity zone centered about the hot springs as discussed above; 2) the saddle between the hot spring low-resistivity zone and 3) much more extensive low-resistivity marking the Jornada del Mueto to the north; and 4) the region of highest resistivity associated with the Dona Ana Mountains. An interesting difference between the figures is found in the extreme northeast corner. Over 5.5 km along the perpendicular bisector to the N. 26° W. transmitter, the most distant data points represent the deepest soundings made in the Jornada. Thus, the higher resistivity values recorded here in Figure 3 may reflect the resistive basement rock of the Jornada basin.

The second phase of our exploration program concentrated on the low-resistivity anomaly surrounding the hot springs and extending south down the Mesilla Valley. Using the 400-m bipole sources located about 1.5 km due east of the hot springs as indicated in the lower portion of Figures 2 and 3, three bipole-dipole equatorial soundings were made. Figure 4 is a plot of one of these soundings, showing the results of data taken along a line perpendicular to the E-W bipole, which traverses due south.

The survey line running due west of the N-S bipole source passed over an outcrop of volcanic tuff and directly through Radium Springs. The outcrop of highly resistive tuff deformed the sounding curve, making it unsuitable for layered interpretation. However, if the local effect of the resistive dike were smoothed out of the curve, there would be a virtual point-for-point correspondence between the data from the lines passing through Radium Springs and southern traverse. The third sounding ran southwest, bisecting the other two. It produced a very similar resistivity curve with slightly lower values than the other two soundings.

The close agreement among all three sounding curves reveals a pronounced lateral electrical homogeneity in the upper Mesilla Valley. This indicates that there is no hidden shallow structural inhomogeneity within the valley near the hot springs. The obvious exception to this observation is the presence of the highly resistive rhyolitic dike at Radium Springs.

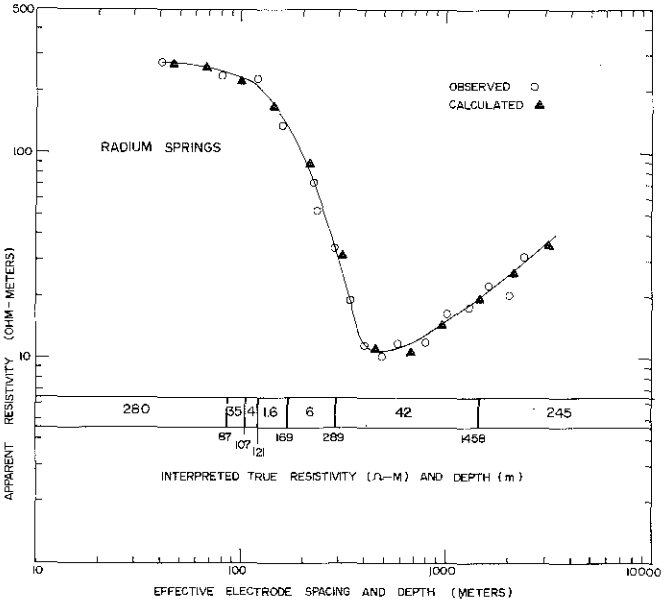

Figure 4. Combined asymmetric Schlumberger and equatorial bipole-dipole sounding at Radium Springs and seven-layer model interpreted by generalized inversion.

A computer-generated model for the true resistivities of the sediments that nearly duplicated the observed apparent resistivities is shown by the line graph on Figure 4. The upper two layers, with resistivities of 280 and 35 ohm-m, extend to a total depth of 107 m. Of the two, the upper can be expected to reflect the surficial, unsaturated piedmont-slope sediments flanking the valley; the lower represents water-saturated sediments within the valley. This interpretation does not reflect known conditions within the valley where the soil is saturated within a few m of the surface. It must be remembered that this survey is an equatorial sounding from a source more than 1 km away from the valley center. At shallow depths, therefore, this curve will reflect the more resistive alluvial deposits of the uplands and not the near-surface aquifer and/or water quality variations within the valley fill.

The second set of layers generated by the computer displays remarkably low resistivity values (4, 1.6, 6 ohm-m) extending to a depth of 289 m, with a total thickness of 182 m. The lowest value is sandwiched by a pair that commonly reflects extensive clay zones. It is, however, so conductive that additional factors must be considered. As these soundings were conducted near Radium Springs it is reasonable to postulate that the 1.6 ohm-m, 48-m-thick layer is the product of admixture of the saline fluids that appear at the hot springs and the clays suggested by the other low values. Whether the low-resistivity value indicates the presence of hot saline waters cannot be determined from our data. The final two layers of progressively greater resistivities in Figure 4 may represent the Paleozoic sequence and the electrical basement, presumably Precambrian rock.

LIGHTNING DOCK

Geologic and Geohydrologic Setting

In 1948 attention was first drawn to the geothermal anomaly in the Animas Valley now known as Lightning Dock KGRA. Several shallow wells drilled in the area hit steam and boiling water (101.5° C) at the top of a rhyolitic rock at a depth of 27 m. Other than the Valles caldera, the Lightning Dock area is the only identified hot-water convection system in New Mexico with indicated subsurface temperatures in excess of 150° C (Renner and others, 1975). The area of this anomaly is clearly outlined in winter when the snow melts immediately upon falling within a radius of roughly 0.4 km from the hot wells. There is abundant evidence for numerous extinct hot springs on both sides of the Animas Valley, with a north-south distance of more than 100 km. Hot-spring deposits grade into low-temperature veins of fluorite, psilomelane, calcite (including travertine), and opaline silica.

The Animas Valley with Lightning Dock KGRA is in the Basin and Range province of New Mexico. Field mapping of the Pyramid Mountains, the range on the east side of Animas Valley (which includes Lightning Dock Mountain), suggests that the Pyramid Mountains are a complex of mid-Tertiary volcanics upon which Basin and Range tectonism has been superimposed. At least one and perhaps two rhyolitic calderas, their associated resurgent domes and ring-fracture extrusives, have been mapped (Elston, personal communication, 1976). These calderas are only partially preserved in the Pyramid Mountains because the Basin and Range faults transect them, downdropping their western half below the sedimentary cover in the Animas Valley. Thus, this new geologic evidence suggests that the Lightning Dock thermal anomaly may be structurally controlled by the intersection of the margin of a mid-Tertiary caldera with a north-trending Basin and Range fault zone which has been active in Holocene time. A fault noted by Reeder (1957) parallels the mountain front for several km in the valley. It probably represents only the most recent episode of continued Basin and Range faulting.

Several years after the hot wells were drilled, a shallow (1- to 2-m) temperature and temperature gradient survey was conducted in the surrounding area (Kintzinger, 1956). Th overall result of Kintzinger's ground temperature mapping w a fan-shaped anomaly over the hot wells, spreading to the north. This shape is by no means surprising given the hydrologic information later published by Reeder (1957). The flow of ground water in the Animas Valley is from south to north, with some local contribution from the flanking mountains. Given a northerly shallow flow of low-temperature ground water, the thermal waters rising at the location of the hot wells would be spread in the pattern that Kintzinger reports. Reeder also published chemical analyses and speculated about the proximity of the recent fault to the hot wells as evidence for structural control for the occurrence of the high-temperature waters. Recently reported geochemical temperatures throughout the Animas Valley are generally low; a base temperature near 170° C is indicated for the hot wells (Swanberg, 1975b).

Resistivity Investigations

Reconnaissance roving dipole resistivity measurements were completed during 1975 using more than 200 receiver locations covering an area of more than 125 sq km. Figure 5 is a total-field apparent resistivity map of the area surrounding the hot wells, indicated in the right center of the figure. The 2-km-long, approximately northwest-oriented bipole transmitter located in the valley to the west of the hot wells was used to generate the map. There are several interesting features on this map:

1. Resistivity generally increases toward the boundaries of the valley to the east and west.
2. Resistivity generally decreases toward the center of the valley, in the vicinity of Valley View Church, and to the north.
3. There is a tight, closed, low-resistivity area associated with the thermal anomaly at the hot wells.
4. There is a high-resistivity ridge trending from about Cotton City northeast through the valley.

Figure 6 is another bipole-dipole total-field apparent resistivity map of the same area. This map was generated using the 2-km-long, essentially E-W bipole transmitter, and shows essentially the same features as Figure 5.

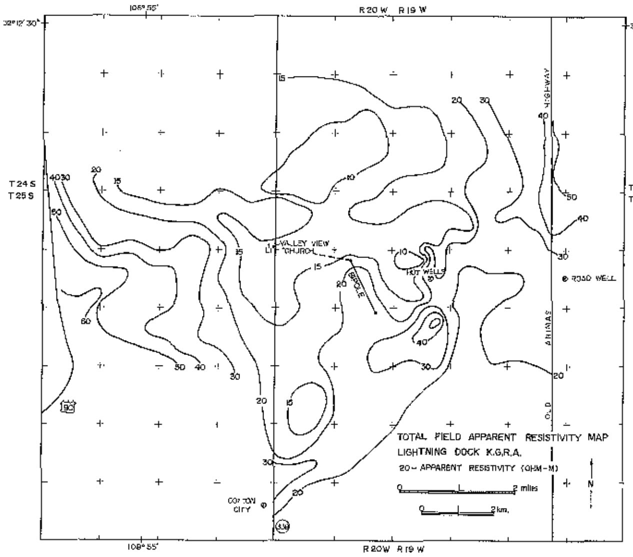

Figure 5. Total-field apparent resistivity map of Lightning Dock project area derived from N-W bipole transmitter.

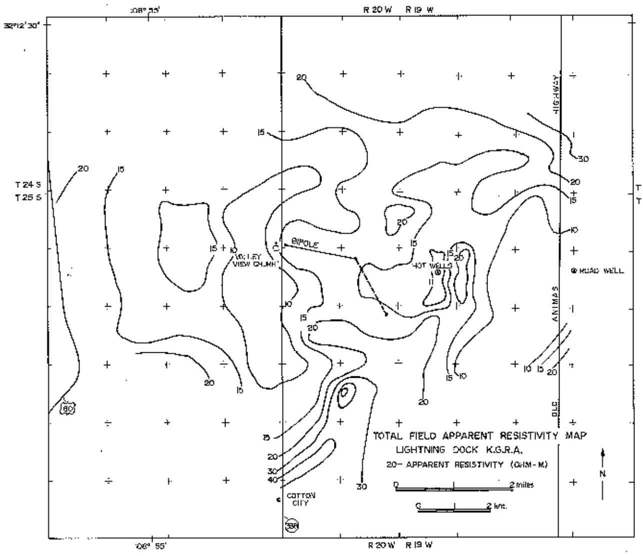

Figure 6. Total-field apparent resistivity map of Lightning Dock project area derived from E-W bipole transmitter.

The regions of highest apparent resistivity (~ 60 ohm-m) at the eastern and western margins of the figures are due to the proximity of more resistive basement rock. On the western edge, the Peloncillo Mountains are composed of a thick sequence of Paleozoic marine sediments and granite stocks. To the east the Pyramid Mountains contain a monzonite stock possibly related to resurgent doming of the older of the two calderas. Steplike Basin and Range faults are probably responsible for these resistivity highs.

The decrease in resistivity toward the center of the valley, in the vicinity of Valley View Church and to the north, is probably due to increasing thickness of water-saturated sedimentary strata and increasing salinity of the waters. These conclusions are supported by gravity data (Swanberg, personal communication, 1975) and by the northerly flow of ground water.

An isolated, closed, low-resistivity contour is associated with the hot wells in both Figures 5 and 6. Such a pattern is expected where there is a near-surface conductive anomaly like the boiling, slightly saline waters encountered by the wells. The geometry and location of these closures relate to the bipole source orientations and in either case indicate that the thermal waters are rising within a constricted zone or conduit at depth. This conduit could possibly be a flexure in Basin and Range faults caused by deflection at the caldera margin.

The pronounced, high-resistivity ridge extending through the hot wells region to the northeast presents further evidence for such deflection in faulting. A high-resistivity ridge, present in both figures, independent of transmitter orientation, reflects structural variation in the near subsurface. This ridge may indicate a simple but abrupt change in the depth to basement produced by a fault. It may, however, reflect the presence of the proposed caldera margin. The northwest ridge on the resistivity maps is directly on trend with the projection of the caldera margins mapped on the surface in the Pyramid Mountains.

Southeast of the hot wells, in both figures, is another low-resistivity region separated from the lows in the center of the valley by the high-resistivity ridge. This region could be produced by a slight increase to basement in that direction. Such an increase could be accompanied by thickening of fill within the mid-Tertiary caldera.

Figure 7 is a deep dipole-dipole pseudo-section sounding made with 500-m dipoles extending along the line of the E-W bipole transmitter from Valley View Church on the west to Road Well on the east (Figs. 5, 6). The lowest values (< 4 ohm-m) are found at the deepest sounding; the highest (> 24 ohm-m) are in the center below the hot wells.

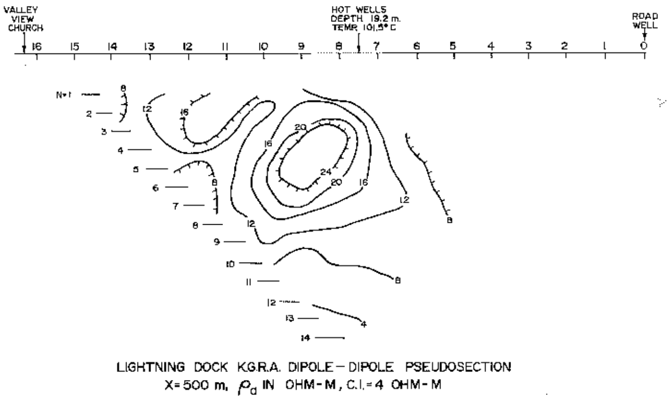

Figure 7. Dipole-dipole pseudo-section sounding through hot wells at Lightning Dock KGRA.

The low-resistivity regions near the surface at either end of the sounding are the low-resistivity areas in the valley and to the east, detected by the bipole-dipole surveys. The conductive region intersecting the surface near stations 8, 9, and the hot wells might indicate the conduit for the ascending thermal waters. The high-resistivity regions might be due to the resistive volcanics of the caldera boundary.

This interpretation is certainly not unique; e.g., a similar pattern of highs and lows as in Figure 7 could be generated by a restricted three-dimensional conductive body (thermal waters around the hot wells) in a homogeneous half-space. Numerical modeling of a number of plausible models is in progress.

The low-resistivity region at the bottom of the section is less than 4 ohm-m. It is probably due, at least in part, to the fact that both the transmitter and receiver were located in low-resistivity sediments for that portion of the sounding. However, it could also be due to a relatively low resistivity region at depths on the order of a few km.

A combined asymmetric Schlumberger and bipole-dipole equatorial sounding was conducted on the E-W bipole transmitter, and to the north perpendicular to it, through the thickest section of valley fill (Fig. 8). The triangles are points

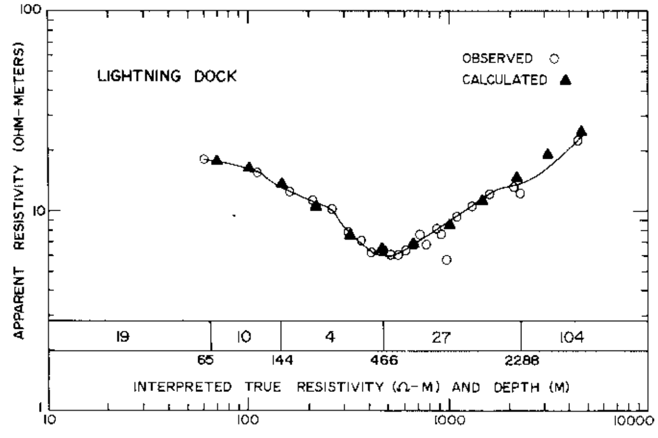

Figure 8. Combined asymmetric Schlumberger and equatorial bipole-dipole sounding at Lightning Dock and five-layer model interpreted by generalized inversion.

calculated by the linear inverse computer routine which generated the model indicated. These results indicate a low-resistivity layer (4-10 ohm-m) between 65 and 466 m in depth. This is probably due to water saturation in this zone, with a more aerated zone above and decreased permeability below.

Limited self-potential results from the past field season indicate a negative anomaly over the hot wells.

CONCLUSIONS

Electrical resistivity investigations in New Mexico have revealed a variable complexity of geothermal reservoirs. Resistivity reconnaissance and soundings can prove useful in unraveling these complexities. Interpretations of the resistivity results must take into account the unique geologic and geohydrologic setting of each area and must be accompanied by an understanding of the characteristics of various resistivity techniques. The results from some methods, e.g., bipole-dipole reconnaissance, are not as well understood as others; experience and more extensive numerical comparisons will increase the applicability of these techniques.

Specifically, reconnaissance resistivity mappings near Radium Springs KGRA have confirmed the lack of hydraulic connection between a vast reservoir to the north and the valley containing the springs. A very conductive, but shallow zone which may contain thermal waters has been sounded in the valley.

At Lightning Dock KGRA, the vicinity of the hot wells is expressed by small low-resistivity closures suggesting ascension of thermal waters in a conduit-like structure. This structure may have been produced by the intersection of a mid-Tertiary caldera ring-fracture and deflected, younger Basin and Range faults. Low resistivities mapped in the central portion of the valley are likely saline waters; however, a dipole-dipole sounding near the wells may have probed a deep hydrothermal reservoir.

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