Deep Geothermal Exploration in New Mexico Using Electrical Resistivity

GEORGE R. JIRACEK
CHRISTIAN SMITH
GEOFFREY A. DORN
Department of Geology, University of New Mexico, Albuquerque, New Mexico 87131, USA

ABSTRACT

The electrical resistivity technique has played a vital role in the exploration for geothermal prospects in many parts of the world, and recently investigations have been initiated in New Mexico under federal and state support. Geothermal test hole GT-2 drilled by Los Alamos Scientific Laboratory in the dry hot rock volcanic terrain of the Jemez Mountains was the setting for the first deep-resistivity field tests. Subsequent measurements have been made in the Rio Grande rift surrounding a deep (3367 m) oil test well near Albuquerque. Resistivity studies employ the roving dipole reconnaissance mapping technique with two orthogonal current bipoles of 2-km length. Dipole-dipole and Schlumberger vertical resistivity soundings are used to estimate depths to resistivity anomalies. Interpretation of the data combines borehole resistivity logs (when available) with generalized inversion computer routines.

Resistivity mapping in the Jemez Mountains has revealed considerable heterogeneity surrounding the GT-2 site and a pronounced apparent resistivity low (<30 ohm·m) which seems to mark the western ring fracture boundary of the Valles Caldera. The fracture system may be a deep, hot-water plumbing system responsible for the electrically conductive zone, surface hot-spring activity, and the success of geothermal wells drilled nearby by Union Oil Company. Electrical measurements outside the caldera have probed to the resistive (>1000 ohm·m) Precambrian basement which is at 733 m depth at GT-2 and at 3339 m in the oil test well. A north-northeast trending resistivity low passing directly through the GT-2 drill site may influence the man-made fractures if the anomaly is basement controlled. Additional geothermal target areas in New Mexico have been selected for study based on available geological and geophysical information.

INTRODUCTION

Reconnaissance studies of the geothermal potential in the State of New Mexico have recently been initiated by state institutions using funds appropriated by the state for energy research. The investigations are concentrating in two major tectonic environments within the Basin and Range Province of New Mexico: (1) the Rio Grande rift, which bisects the state from north to south, and (2) the southwestern portion of the state (Fig. 1). Both regions have many features in common with other areas of more proven geothermal potential, such as active extensional tectonics, recently active volcanism, high heat flow, and hot springs. The majority of the over 60 known thermal anomalies in New Mexico occur within the two regions. Associated with the Rio Grande rift is the Jemez Mountains region (Fig. 1) where Union Oil Company has announced the drilling of a successful geothermal well in 1974 and where Los Alamos Scientific Laboratory (LASL) is conducting the world's first dry hot rock geothermal demonstration project (Smith, 1974).

The resistivity studies described in this paper are a portion of continuing, broader investigations which include detailed geologic, geochemical, and geophysical mapping. The measurements were initially supported by the National Science Foundation-Research Applied to National Needs (NSF-RANN) to study the electrical characteristics of a dry hot rock environment and to correlate resistivity measurements with borehole data and fracturing tests run by LASL in the Jemez Mountains. Extension of this work to other locations in New Mexico has resulted from subsequent state support. The major object of this multidisciplinary effort is to identify specific target areas and to lay the reconnaissance groundwork for future assessment on a commercial and scientific scale.

In addition to the Jemez Mountains region (project area no. 1 in Fig. 1), resistivity field tests have been made in the northern part of the Albuquerque-Belen basin in the Rio Grande rift (project area no. 2 in Fig. 1). The latter tests were undertaken strictly as a field trial in the rift environment where logistics were not difficult due to proximity to the University of New Mexico (UNM) and where deep drill hole data were available. This information, including downhole electrical logs, was released by Shell Oil Co. after Shell abandoned an 11 045 ft (3367 m) deep oil test well (Santa Fe Pacific No. 1) in this vicinity in 1972 (Black and Hiss, 1974). The drill hole did not indicate any geothermal potential at this location; the bottom-hole temperature was barely over 100°C.

Resistivity studies will be continued during the forthcoming field season in the Jemez Mountains and in new project areas nos. 3 and 4 in Figure 1. Project area no. 3 is at Radium Springs where surface waters measure over 85°C. Project area no. 4 is in the Animas Valley where an irrigation

Figure 1. Generalized map of New Mexico showing locations of project areas: (1) Jemez Mountains, (2) Rio Rancho, (3) Radium Springs, (4) Animas Valley.

well drilled in 1948 encountered steam at a depth of only 87 ft (27 m).

JEMEZ MOUNTAINS INVESTIGATIONS

Geologic and Geophysical Setting

The Jemez Mountains are a complex volcanic highland of Tertiary and Quaternary age which are situated along the western margin of the Rio Grande rift in north-central New Nexico. The mountains are crowned by the Valles Caldera, a near-circular depression about 12 to 14 mi (19 to 23 km) across (Fig. 1) which marks the collapse of the roof of a depleted magma chamber (Smith, Bailey, and Ross, 1961). Project area no. 1 includes a portion of the western topographic rim of the caldera and youthfully dissected volcanic plateaus and mesas. Where rivers have cut through the volcanics of the area, Paleozoic and Mesozoic sedimentary rocks are exposed. Drilling has confirmed that Precambrian crystalline basement rocks underlie the volcanic and sedimentary sequences outside of the caldera.

Hydrothermal features in the Jemez Mountains are relatively rare compared to similar environments in western United States (Trainer, 1974). Most hot springs are found along the western margin of the Valles Caldera in the proximity of young (less than 1 million years old) rhyolite domes that apparently intruded along the ring-fractures marking the boundary of caldera collapse.

Geophysical studies of the Jemez Mountains have been recently reviewed by Jiracek (1974) as a portion of the preparation of the deep-resistivity project. Gravity evidence (Eaton, 1973) for a partially molten body beneath the Valles Caldera has not been supported by a preliminary search by LASL researchers of characteristic seismic signatures (K. E. Olsen, personal commun., 1974). These data were mainly derived from distant earthquakes or blasts since the seismicity of the Jemez Mountains is surprisingly low. The radial distribution of heat flow values (Potter, 1973) which are roughly two to four times the world average, suggests a source centered under the Valles Caldera. Geophysical studies in the Jemez Mountains are in a state of increased activity associated with the LASL dry hot rock geothermal tests; the current resistivity project is one of these efforts. According to conventional resistivity logging of the LASL GT-2 test hole, the volcanics are approximately 142 m thick and are variable in resistivity, in some cases highly resistive (over 1000 ohm·m). The underlying wet sedimentary section is relatively conductive, averaging about 15 ohm·m resistivity, whereas the crystalline basement below 733 m depth is typically highly resistive (1000 ohm·m and more).

Introduction to Resistivity Studies

The first major objective of the UNM project was resistivity reconnaissance surrounding the LASL dry hot rock drill site. In this context any structures mapped by resistivity might help explain the downhole fracturing results. In addition, since we would be able to correlate our data with LASL borehole logs, comments on the applicability of resistivity surveying in the dry hot rock environment of the Jemez Mountains would result. Furthermore, the resistivity results could aid in the placement of future drill holes in the area. Our second objective has been to attempt to detect and define hydraulically induced downhole fractures using resistivity. The orientation and extent of the fracture are variables required to permit completion of the dry hot rock geothermal system with intersection by a second hole. The water-filled fracture presents an electrically conductive target, possible of detection, in the resistive dry hot rock environment. The third objective has been the development of generalized inversion techniques to aid in the interpretation of the resistivity results.

Shallow Schlumberger Soundings

In order to measure the geoelectric section surrounding GT-2, two resistivity sounding lines intersecting the drill site and extending 3 km on either side of it were surveyed (Fig. 2). These lines were mainly surveyed for dipole-dipole soundings; however, they were also used for prior shallow resistivity soundings, for later bipole-dipole reconnaissance, and are intended to be used for future surface-downhole fracture detection tests. Shallow Schlumberger arrays to a maximum outer electrode separation (AB) of 1 km have been centered at points 500 m apart along the lines. The soundings were made using a commercially available resistivity unit which transmits only 25 milliamps at 11 Hz.

An average of results from two orthogonal Schlumberger soundings at GT-2 is shown in Figure 3 by the observed apparent resistivity data. The orthogonal sets of resistivity data were nearly identical, indicating local horizontality of the near-surface layers at GT-2. True resistivities and appropriate depths to model layers are shown in Figure 3 along with the corresponding theoretical values automatically fit by generalized inversion (Inman, Ryu, and Ward, 1973). The surface volcanics are characterized by high resistivity (800 ohm·m), but they are not nearly as resistive (3000 ohm·m) as a bottom volcanic layer which is responsible for the apparent resistivity increase beyond AB/2 spacing of 150 m. This deeper layer is an extremely dry volcanic tuff, above the water table, as confirmed by drilling analysis

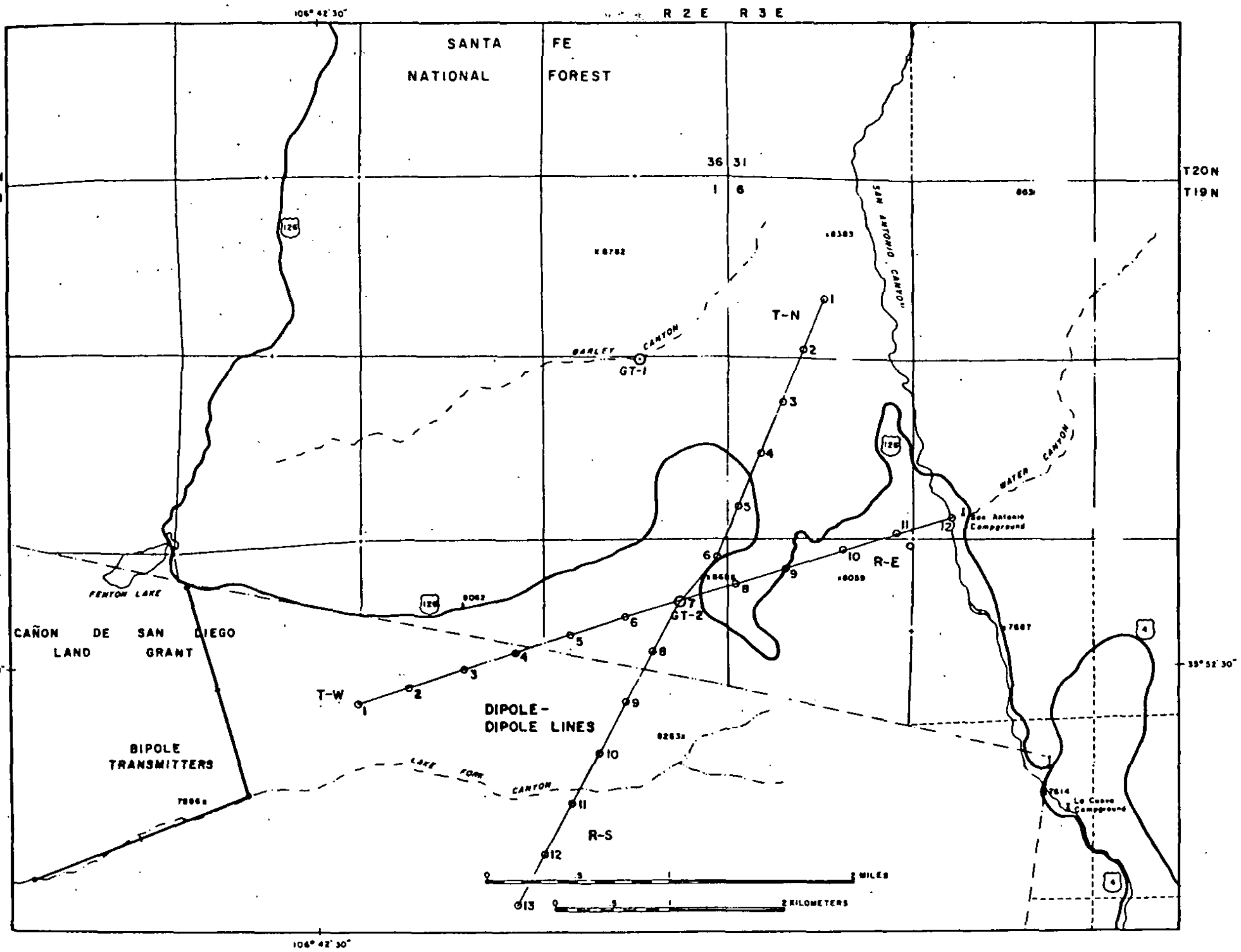

Figure 2. Project area in Jemez Mountains showing dipole-dipole survey lines intersecting LASL GT-2 drill site and locations of bipole reconnaissance transmitters.

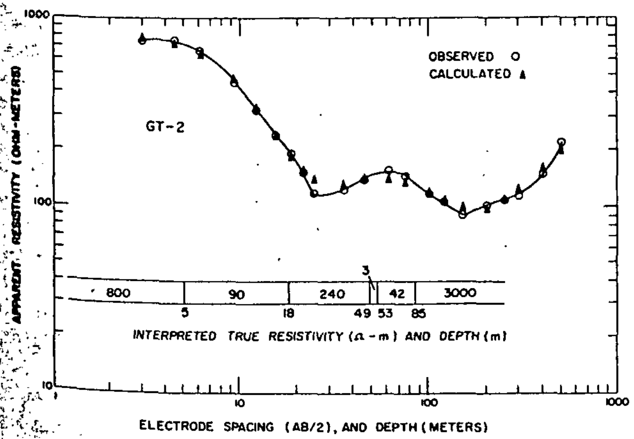

Figure 3. Average of two orthogonal Schlumberger soundings at LASL GT-2 drill site and six-layer model interpreted by generalized inversion.

and borehole resistivity measurements. Borehole resistivity logs show the highly resistive zone beginning at about 80 m depth, whereas the six-layer model places it slightly deeper, at 85 m depth. The conductive layer (3 ohm·m) interpreted between 49 and 53 m depth may be a clay layer in the tuff. The resistivity sounding in Figure 3 does not "see" beneath the surface volcanics at GT-2; a higher-powered resistivity unit was required for this application.

Deep Resistivity Equipment

To make electrical soundings below the volcanic cover, through the conductive sedimentary section, and into the Precambrian basement, a 50 kW resistivity system has been developed and fabricated at the University of New Mexico. The transmitter is unique in a number of aspects. For example, we had anticipated operating directly off the rural powerline to the drill site and fluctuations in line voltage were, therefore, expected. For the stability and repeatability needed for the fracture tests, we consequently designed a constant current source with a feedback loop including a large motor-driven auto-transformer.

The electrical resistivity receiving system uses the standard nonpolarizing porous pot electrodes, a self-potential nulling and low pass (below 1 Hz) filtering circuit, and battery-operated portable potentiometric chart recorders.

Deep Dipole-Dipole Soundings

Dipole-dipole resistivity soundings were made along the two survey lines (Fig. 2) intersecting the GT-2 drill site prior to any fracturing attempts by LASL. Although dipole-dipole soundings are not fully completed along the survey lines, the initial measurements provided indications of the deep lateral resistivity variations near GT-2 and served to define a minimum transmitter-receiver spacing for probing to the Precambrian basement. Figure 4 illustrates results

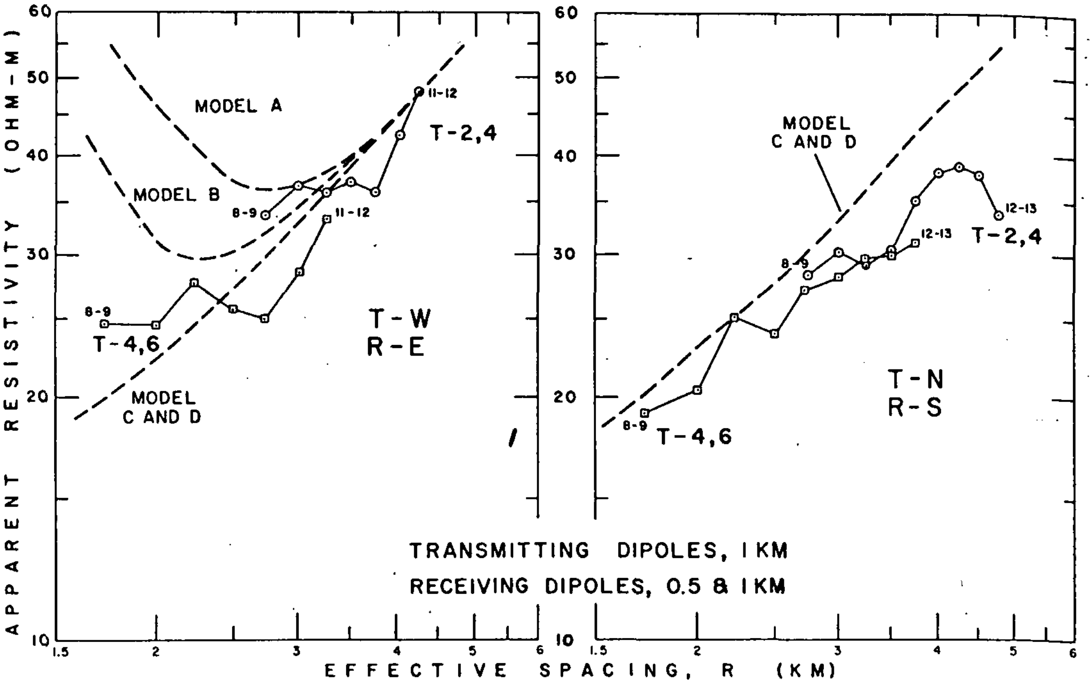

Figure 4. Dipole-dipole soundings along survey lines intersecting LASL GT-2 drill site and theoretical model calculations.

of the dipole-dipole soundings along the two intersecting 3-km survey lines. The plots are of apparent resistivity versus center spacing. This effective spacing varies from 1.5 km to nearly 5 km in Figure 4. Each set of curves relates to one of the survey lines. T-W, R-E is transmitter-west and receiver-east, whereas, T-N, R-S is transmitter-north and receiver-south. In each case a 1-km transmitting dipole was used across either stations 4,6 or 2,4 (Fig. 2). Receiver locations follow a 0.5-, 1.0-km dipole sequence 8-9, 8-10, 9-10, 9-11, 10-11, 10-12, 11-12, for transmitter-west, receiver-east (T-W, R-E); additional points 11-13, 12-13 are plotted for T-N, R-S. For further clarification, the receiver locations at the ends of the T-4,6 and T-2,4 lines are indicated in Figure 4. Notice that since the transmitter 4,6 and 2,4 sites vary by 1 km, there is an effective spacing change of 1 km for the *same* receiver position, for example 8-9. For a laterally homogeneous half-space, a plot such as in Figure 4 would result in the T-4,6 and T-2,4 segments plotting identically for the same effective spacings.

The first impression of the dipole-dipole results in Figure 4 is probably the observation that both sets indicate increasing apparent resistivity with increased spacing; also, slopes of the plots are nearly 45°. Such sounding curves are indicative of the electrical detection of a highly resistive layer encountered at depth. To confirm that the resistive layer probed is the Precambrian basement of the region, layered computer models have been calculated and are plotted in Figure 4 using dashed lines. Four such models are plotted on the T-W, R-E results, whereas only one of these models is plotted for T-N, R-S. Table 1 contains the layer parameters used to define layered model A. The upper six layers are precisely those calculated from the orthogonal Schlumberger soundings at GT-2 as shown in Figure 3. The 3000 ohm·m layer has been truncated at 100 m depth based on the lateral resistivity borehole log; and further, this log has been used to define five additional layers encountered at depth in GT-2. The bottom of the volcanics and the entire sedimentary column have been assigned an average resistivity of 15 ohm·m, whereas the sequence 1000, 2000, 300, 1000 ohm·m approximates the Precambrian basement. The 300 ohm·m layer represents a highly fractured zone with considerable water in the crystalline basement.

It is obvious that agreement between theoretical model A and the observed dipole-dipole data is poor, especially at the shorter effective spaces. To see what influence the resistivities of the near-surface volcanics have on the theoretical results, models B, C, and D have been calculated. Model B is the same as model A except the conductive layer 4 has been removed by incorporating it into layer 5 which is increased in thickness to 36 m. One expects this change to increase the apparent resistivity values, but instead the calculated values decrease in the range of spacings plotted in Figure 4. Such an apparent paradox has been recently discussed by Satpathy (1974) and can be qualitatively related to the redistribution of current lines in model B. Using models A and B, new earth models have been defined by decreasing the resistivity of layer 6 from 3000 to 300 ohm·m. The theoretical results for these models plot identically (models C and D of Figure 4) with

Table 1. Model A layer parameters.

Layer	Thickness (m)	Resistivity (ohm·m)
1	5	800
2	13	90
3	31	240
4	4	[illegible]
5	32	42
6	15	3000
7	633	15
8	105	1000
9	62	2000
10	100	300
11	∞	1000

an expected decrease in apparent resistivity. (Note that all models are asymptotic to the same 45° line as expected.)

The fact that model A does not agree well with the observed dipole-dipole soundings is considered evidence for lateral resistivity variations along the T-W, R-E survey line relative to the GT-2 site. Models B, C, and D show that near-surface resistivity changes can explain much of this variation. Regardless of these near-surface effects the model results conclusively tell us that at effective spacings of over 2 to 3 km, one is sounding the Precambrian basement which is at 733 m depth at GT-2.

Considering the T-W, R-E data in more detail we notice that there is a vertical offset of approximately 10 ohm·m between the T-4,6 and T-2,4 results. One possible explanation for this offset is that since the receiver locations are *identical*, increased resistivity occurs from transmitter stations T-4,6 to T-2,4. The increased resistivity could be either in the near-surface or deeper; the data in Figure 4 do not resolve this issue. Based on bipole-dipole results at greater effective spacings (to be discussed later in this paper), increased resistivity may occur at greater depth along the T-W line. Resistive basement at decreased depth going west along the line would, for example, be consistent with the results.

Another aspect of the T-W, R-E data requiring an explanation is the identically sharp increase in slope for the most eastern points on both T-4,6 and T-2,4 lines. Since this effect occurs at the same receiver locations for different transmitter locations, the cause is probably of shallow origin at the receiver end.

Comparing the T-N, R-S dipole-dipole data with the model C and D curve in Figure 4 shows that this survey line is generally more conductive than the T-W, R-E line. Also, since the two transmitter segments nearly overlap, the section appears more laterally homogeneous. A significant decrease in apparent resistivity is measured at the south end of the T-2,4 data. At effective spacings of 4 km or more, the effect of near-surface variations is greatly reduced (compared models A, B, C, and D at R = 4 km), so the decrease in resistivity probably has deeper origin either in the sediments or in the basement. Since receiver location 12-13 of T-4,6 at a spacing of 3.75 km does not "see" the conductive change, whereas R-12,13 with T-2,4 does, the data seem to favor basement origin.

Deep Bipole-Dipole Reconnaissance Mapping

Having established from the dipole-dipole soundings that Precambrian basement would be probed at effective spacings in excess of 2 km, a bipole transmitter was set up approximately 5 km from the GT-2 drill site. This bipole was of 2-km length and oriented with GT-2 in an approximately polar direction (the more nearly east-west bipole in Fig. 2). The large distance from the GT-2 site assured that resistivity measurements surrounding the site would be sensitive to the basement. Thus, our data would relate to the assumed dry hot rock environment of the crystalline basement. The reconnaissance measurements proceeded in perhaps a reversed sequence after the dipole-dipole soundings. The dipole-dipole soundings were done first to better detail the immediate vicinity of GT-2 prior to any fracturing tests.

The bipole-dipole or roving dipole technique (Keller, 1973; Zohdy, 1973; Stanley and Jackson, 1973) has proven effective in determining lateral boundaries of resistivity anomalies in geothermal localities. Also, the technique serves as a relatively rapid reconnaissance method for mapping large areas from a single transmitting source bipole.

Figure 5 is a plot of total-field apparent resistivity obtained by measurements from the east-west 2-km bipole using the roving dipole technique. Roving dipole lengths were typically 100 m at each receiver site. Over 100 receiver sites have been occupied at spacings as close to each other as 0.25 km and in many cases several site reoccupations have been made. Reoccupations were made to determine the repeatability of the results (<5% error) and to compare data obtained before, during, and after fracturing experiments in GT-2. The complexity of the resistivity patterns plotted in Figure 5 again emphasizes the lateral heterogeneity of the survey area.

From Figure 5 we see that GT-2 is in a fairly flat resistivity region of about 50 ohm·m. A resistivity low of about 25 ohm·m is located nearly 0.5 km northeast of the drill site and farther northeast in a broader low of about 30 ohm·m. Another low appears just within the Cañon de San Diego land grant to the south. The resistivity lows define the north-northeast trending pattern of low resistivity which runs directly through GT-2. The low resistivity is probably responsible for the decreased resistivity measured at the south end of the T-N, R-S dipole-dipole line (Fig. 4). A pronounced resistivity high of 125 ohm·m is 1 km north of the GT-2 site. The resistivity lows and highs may be associated with increased and decreased depth to the resistive Precambrian basement, respectively. However, other interpretations are possible. For example, resistivity lows may correlate with subsurface regions of hot geothermal waters which could relate to deep structures. The north-northeast trending low resistivity pattern passing through the GT-2 drill site may have such structural origin in which case man-made fractures would tend to follow along such a pre-existing weakness.

One of the most interesting aspects of the results is in the eastern portion of Figure 5. Here, the resistivity increases dramatically to values of almost 175 ohm·m, forming a distinct resistivity ridge running nearly north-south. The values then abruptly decrease farther to the east, down into the 20 ohm·m range. Our data coverage is not detailed enough to complete the contours where question marks are indicated in Figure 5, but in the southeast corner, along Highway 4 and north of Water Canyon, the apparent resistivity values drop from over 120 ohm·m to 47 ohm·m, in distances of about 0.25 km. Presumably this dramatic decrease in resistivity trends generally north or slightly north-northwest.

There are a number of possible explanations for the resistivity patterns which appear on the eastern portion of the survey map; Figure 6 provides one possibility. Here, apparent resistivity is plotted versus effective spacing along the T-W, R-E dipole-dipole sounding line beginning in the west and extending nearly 10 km east of the center of the east-west bipole transmitter. These measurements are nearly in-line or along a polar bipole-dipole sounding curve. Also plotted in Figure 6 is the elevation of the measuring points from a high of nearly 2650 m at GT-2 down to almost 2350 m in the valley to the east. From Figure 6, there is obviously some inverse correlation of the apparent resistivity with elevation, that is, the highest resistivity (120 ohm·m) is at the lowest elevation and the lower resistivities are measured at higher elevations, for example, at GT-2. The

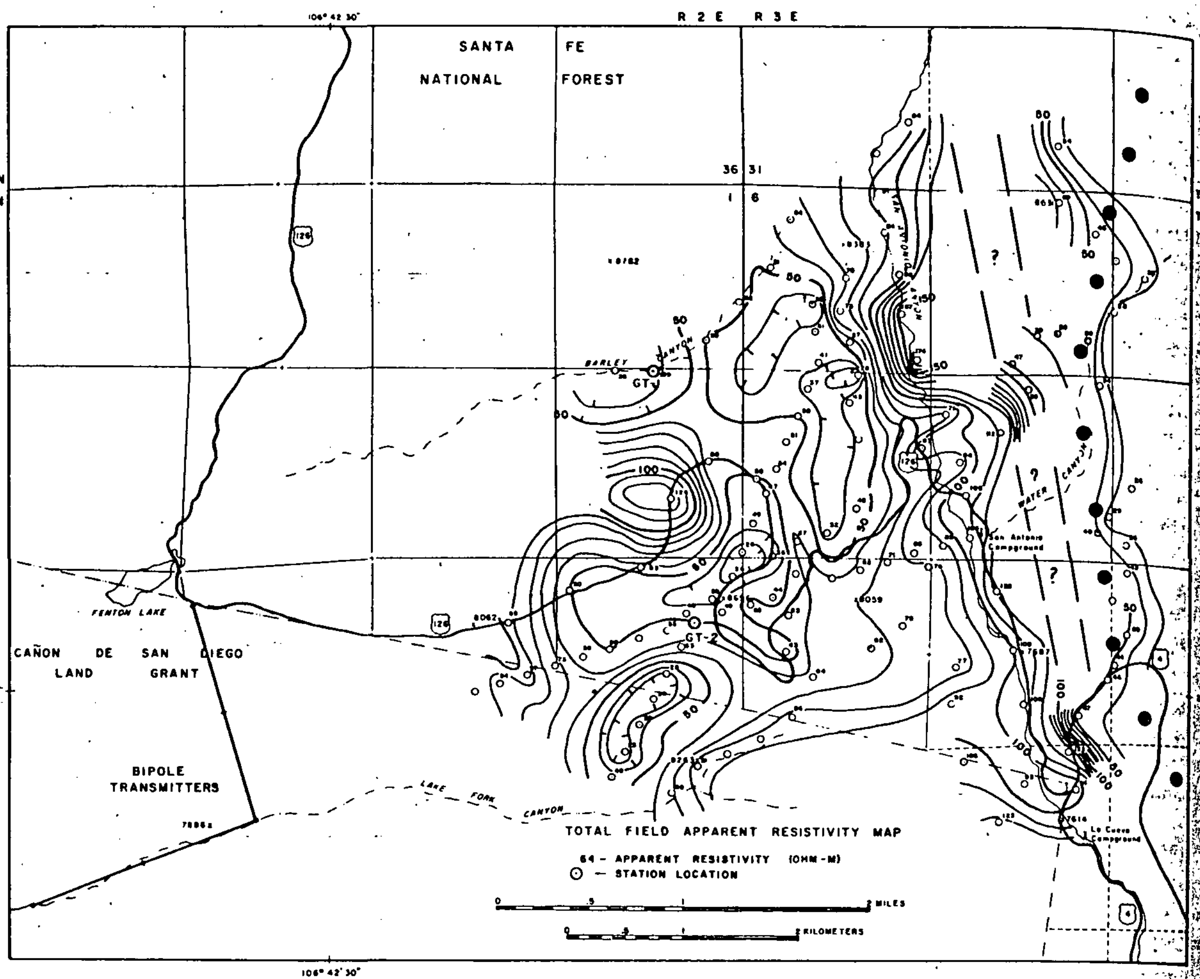

Figure 5. Total-field apparent resistivity map surrounding LASL GT-2 drill site. (Mapped values pertain to more nearly eas bipole transmitter.)

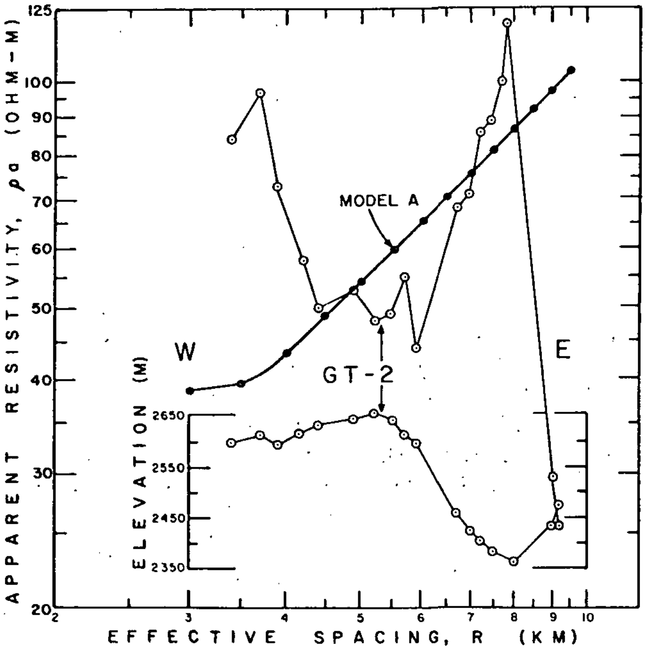

Figure 6. Polar bipole-dipole sounding, corresponding topography, and theoretical calculation based on layered model appropriate to LASL GT-2 findings.

correlation is certainly not one-to-one; for example, lowest resistivity (about 25 ohm·m) is not at the hig elevation. However, a correlation with elevation is sugg ed. Besides the expected focusing and defocusing of elec cal equipotential surfaces associated with topography, might also associate these variations with depth to Precambrian basement. That is, at lower elevations, if measurement is taken closer to the resistive Precamb basement, higher apparent resistivity values would ref its proximity. On the topographic ridges one may be fa from the basement; hence, with a thicker conductive Pa zoic section, lower resistivity values are "seen".

The observed resistivity ridge seen in map-view in Fi 5 and in profile in Figure 6 may be in part due to above elevation considerations, but an interpretation in ing structure is considered more important. That a discontinuity has been crossed is quite evident by comp the model A theoretical bipole-dipole curve in Figure the observed results. The model A curve in Figu a plot of the polar results from theoretical bipole mapping over a layered model appropriate to the findings (Table 1). The resistivity ridge, particularly pronounced decrease on the eastern side of the obviously inconsistent with the layered model. Such are, however, in agreement with that expected when tr ing a fault in a direction toward a marked decre resistivity. Several maps illustrating this effect have been published by Furgerson and Keller (1974).

Such a fault-like geologic feature mapped near the resistivity ridge is the caldera ring-fracture whose location was inferred by Smith, Bailey, and Ross (1970) and is marked by the dots in Figure 5. The higher ground on the eastern side of the elevation profile in Figure 6 is due to one of the young rhyolitic domes which have presumably intruded along the ring-fracture system. The agreement of the more distant bipole-dipole results (Fig. 6), with the shorter spaced dipole-dipole soundings (Fig. 4) would indicate that the lateral discontinuity occurs over a considerable depth range—shallow to deep. A shallow extension produces an abrupt resistivity change directly over the lateral discontinuity; therefore based on the resistivity results, the Valles Caldera ring-fracture would be displaced about 1 km to the west from its inferred position. The fracture boundary is undoubtedly of finite horizontal width; the resistivity change may, therefore, mark the western margin of the zone. On the basis of the preceding discussion, a hydrological interpretation of the resistivity ridge on the eastern side of the survey area may now be made. The ring-fracture system on the west side of the Valles Caldera may be acting as a deep, hot-water plumbing system which is responsible for the electrically conductive anomaly. Additional support for this interpretation comes from the hot-spring activity in the vicinity and the successful geothermal wells drilled by Union Oil Company approximately 2 km to the east. Whether this phenomenon extends well into the Valles Caldera or along its total margin we cannot say. In this context it may be significant to remark that the hot springs and the most recent volcanics occur only in the vicinity of the measured resistivity anomaly, that is, along the western margin of the caldera.

Measurements from the nearly north-south bipole mapped in Figures 2 and 5 are unfortunately not completed since this source was implaced later than the east-west transmitter. These results might help confirm the various observations above; as pointed out by Keller, Grose, and Crewdson (1974), incorrect interpretations and "false" anomalies can result from geometrical effects when resistivity reconnaissance is done using only one bipole source. The limited results from the north-south transmitter are in agreement with the major trends observed by the east-west source.

RIO GRANDE (RIO RANCHO) INVESTIGATIONS

To test the electrical sounding capabilities and techniques in the geothermally promising Rio Grande rift, an accessible area on Rio Rancho Estates north of Albuquerque (Fig. 1) was selected for field trials. As mentioned earlier, the specific area shows locally little promise as a geothermal prospect; however, complete borehole logs to a total depth of 11 045 ft (3367 m) are available. The crystalline basement of Precambrian age was encountered in the Shell Oil Co. Santa Fe Pacific No. 1 test well at 10 955 ft (3339 m) depth and is overlain by a sequence of Cenozoic, Mesozoic, and Paleozoic sediments, a setting characteristic of the Rio Grande rift. A laterolog survey run down the hole revealed variable resistivities in the sedimentary sequence; generally the values were less than 10 ohm·m. The Precambrian basement exceeded 2000 ohm·m resistivity.

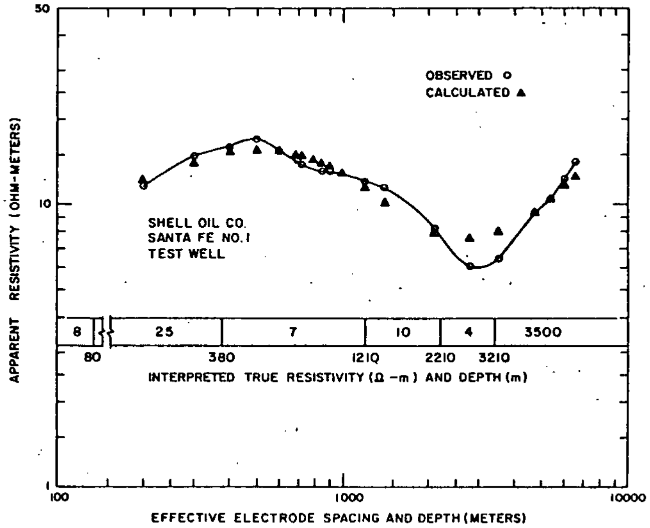

Figure 7. Preliminary results of combined asymmetric Schlumberger and equatorial bipole-dipole sounding near oil test well on Rio Rancho Estates and six-layer model interpreted by generalized inversion.

Resistivity reconnaissance surrounding the oil test well proceeded, as in the Jemez Mountains, by using two orthogonal bipoles each of 2-km length. Data is still being processed, but it has been immediately apparent that the geoelectric section is much more laterally homogeneous than in the Jemez Mountains. A preliminary example of combined sounding data obtained in the survey using asymmetric Schlumberger and equatorial bipole-dipole soundings (Zohdy, 1970) is plotted in Figure 7 by the circles. The triangles are the interpreted points obtained by generalized inversion. The interpreted depth to the resistive basement (3210 m) compares favorably to the drill hole depth (3339 m). This result, along with the overall mapping results (not presented here), provides optimism for the success of resistivity exploration in the geothermally promising sections of the Rio Grande rift. One such area, Radium Springs (project area no. 3), will be the location of the next deep-resistivity mapping and soundings.

CONCLUSIONS

The completed phase of shallow and deep electrical resistivity studies has served to emphasize the complexity and heterogeneity for the region surrounding the LASL geothermal drillhole in the Jemez Mountains, New Mexico. Thus, the "uncomplicated" geology (Smith, 1974) desired by LASL for their tests does not seem to be the situation at the current test site.

Results from theoretical geoelectric models appropriate to the GT-2 borehole findings diverge considerably from the observed data in the vicinity of the drill site. One pronounced lateral variation on the eastern side of the survey area is almost certainly due to the western ring-fracture boundary of the Valles Caldera. The ring-fracture system may be acting as a deep, hot-water plumbing system which is responsible for an electrically conductive anomaly, the hot-spring activity of the region, and the successful geothermal wells drilled nearby by Union Oil Company. Judging from the resistivity results, the ring-fracture may extend nearer to LASL's GT-2 site than mapped geologically. This may influence the downhole man-made fracture results. Even more significant to these tests may be the north-

northeast-trending resistivity low which passes directly through GT-2. If this anomaly is controlled by basement structure, it might present a zone of weakness along which man-made fractures would propagate.

In view of the general findings above we think the usefulness of electrical resistivity investigations in the dry hot rock environment of the Jemez Mountains has been established. Based on our experience we would recommend that future dry hot rock site selection be based on prior resistivity studies coupled with thermal gradient or heat-flow measurements. The latter measurements are necessary since there is, as yet, no proven way to electrically distinguish dry hot rock from dry cold rock in the temperature range of interest. Both environments would present high resistivity.

Deep-resistivity feasibility tests in the Rio Grande rift have provided optimism for continued and expanded geothermal prospecting in New Mexico using electrical methods.

ACKNOWLEDGMENTS

Appreciation is first extended for the fine cooperation of M. C. Smith and the entire Los Alamos Scientific Laboratory Geothermal Division Q-22 which he directs. A number of students very ably assisted in the projects; these include T. Summers, Jr., G. T. Forsythe, M. T. Gerety, W. H. Schrandt, J. M. Hardy, and P. R. Jamison. Numerical interpretational assistance has been extended, in particular, by R. J. Phillips of Jet Propulsion Laboratory, Pasadena, California, and by A. Dey and J. H. Beyer of the University of California, Berkeley. We have also benefited greatly from the knowledge and experience of Tsvi Meidav who is a part-time Visiting Research Scholar at the University of New Mexico. Equipment design and fabrication has been the responsibility of T. Summers, Sr. Finally, the projects could not have been undertaken without the financial support of the National Science Foundation-Research Applied to National Needs, Grant Number NSF GI-42835 and New Mexico State Energy Research and Development Grant Number 22.

REFERENCES CITED

Black, B. A., and Hiss, W. L., 1974, Structure and stratigraphy in the vicinity of the Shell Oil Co. Santa Fe Pacific No. 1 test well, southern Sandoval County, New Mexico: *in* New Mexico Geological Society Guidebook, 25th Field Conference, p. 365-370.

Eaton, G., 1973, Statement of Dr. Gordon Eaton, U.S. Geological Survey: *in* Geothermal Resources, hearing before Committee on Interior and Insular Affairs, pt. 1: Washington, U.S. Government Printing Office, p. 86-104.

Furgerson, R. B., and Keller, G. V., 1974, Computed dipole resistivity effects for an earth model with vertical and lateral contrasts in resistivity: Golden, Colorado, Colorado School of Mines.

Inman, R., Jr., Ryu, J., and Ward, S. H., 1973, Resistivity inversion: Geophysics, v. 38, p. 1088-1108.

Jiracek, G. R., 1974, Geophysical studies in the Jemez Mountains Region, New Mexico: *in* New Mexico Geological Society Guidebook, 25th Field Conference, p. 137-144.

Keller, G. V., 1973, Dipole mapping surveys (abs.): Geophysics, v. 38, p. 179.

Keller, G. V., Grose, L. T., and Crewdson, R. A., 1974, The Colorado School of Mines Nevada geothermal study: Conference on Research for the Development of Geothermal Energy Resources, Pasadena, California, Proceedings, NSF-RA-N-74-159, p. 73-84.

Potter, R. M., 1974, Heat flow of the Jemez plateau (abs.): EOS (Am. Geophys. Union Trans.), v. 54, p. 1214.

Satpathy, B. N., 1974, A paradox in apparent resistivity measurements over a ground section with conductive substratum: Geophysics, v. 39, p. 93-94.

Smith, M. C., 1974, Progress of the LASL dry hot rock geothermal energy project: Conference on Research for the Development of Geothermal Energy Resources, Pasadena, California, Proceedings, NSF-RA-N-74-159, p. 207-212.

Smith, R. L., Bailey, R. A., and Ross, C. S., 1961, Structural evolution of the Valles Caldera, New Mexico and its bearing on the emplacement of ring dikes: U.S. Geol. Survey Prof. Paper 424-D, p. 145-149.

——, 1970, Geologic map of the Jemez Mountains, New Mexico: U.S. Geol. Survey Misc. Geol. Inv. Map I-571.

Stanley, W. D., and Jackson, D. B., 1973, A total-field resistivity map of Long Valley, California (abs.): EOS (Am. Geophys. Union Trans.), v. 54, p. 1212.

Trainer, F. W., 1974, Groundwater in the southwestern part of the Jemez Mountains volcanic region, New Mexico: *in* New Mexico Geological Society Guidebook, 25th Field Conference, p. 337-345.

Zohdy, A. A. R., 1970, Geometrical factors of bipole-dipole arrays: U.S. Geol. Survey Bull. 1313-B, p. B1-B26.

——, 1973, Total-field resistivity mapping (abs.): Geophysics, v. 38, p. 1230.