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GEOPHYSICAL EXPLORATION FOR GEOTHERMAL PROSPECTS WEST OF ALBUQUERQUE NEW MEXICO

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INTRODUCTION

With more than one-third of New Mexico's inhabitants residing in the Albuquerque area, a vast market exists for direct utilization of geothermal heat. Such utilization is prescribed by expectations of low- to moderate-temperature (<150°C) resources at economic depths. Geothermal exploration in the Albuquerque area has concentrated on the western side of the city (fig. 1; for studies on the eastern side of Albuquerque, see Grant, this guidebook). This is an area of anticipated growth where the warmest municipal ground-water temperature (32°C in 360 m deep West Mesa #1, fig. 1) was reported by Bjorklund and Maxwell in 1961. The 32°C reading represents the highest pumped temperature of a city water well despite many recent wells, some drilled near the Albuquerque volcanoes (fig. 1).

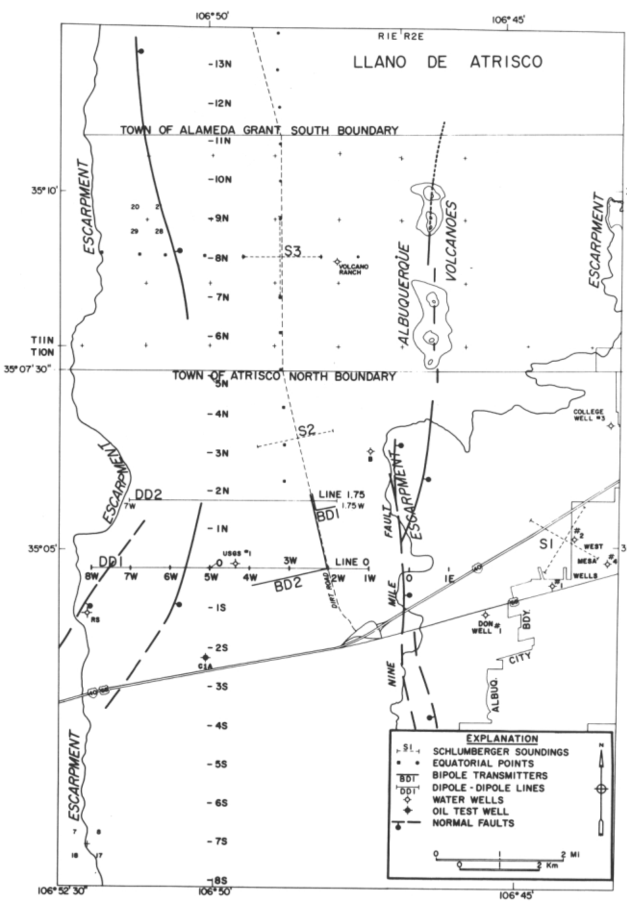

Figure 1. Base map of Llano de Atrisco area west of Albuquerque. RS and B are radar site and Benavides water wells; C1A is Carpenter #1 Atrisco oil test well. Fault locations are based on Kelley (1977).

The Albuquerque volcanoes are a group of fissure-controlled basaltic volcanoes and spatter cones which have been episodically active from about 200,000 to at least 120,000 years before present (Bachman and others, 1975; Machette, 1978; see Machette, this guidebook). They appear to be related to the Nine Mile (County Dump) fault (fig. 1) described by Kelley (1977) and Machette (1978), respectively. The only other mapped faults in the survey area are the unnamed faults west of Nine Mile fault (fig. 1; Kelley, 1977). Machette (1978) detailed 17 m of vertical displacement on the Nine Mile fault in the past 400,000 years. Only 10 m or so of offset was discussed by Kelley (1977) on the faults to the west.

The escarpments on the east and west of Figure I bound the Ceja Mesa of Kelley (1977), also called the Llano de Albuquerque, which extends beyond the study area illustrated in Figure 1 for a total length of 110 km. Parker and Jiracek (1980) have chosen the name Llano de Atrisco for the segment of the mesa encompassed in Figure 1. The northeastern portion of the Llano in Figure 1 is mantled by basaltic lava flows from the Albuquerque volcanoes. Scarps shown on the rest of the map are formed by resistant, carbonate soil horizons developed in post—Santa Fe gravel and eolian sands. Underlying beds of youngest Santa Fe Group sands and gravel are exposed on the erosional scarps. An oil-test well (the Carpenter #1 Atrisco) drilled in 1948 just north of U.S. Highway 66 (fig. 1) in sec. 28.440, T ION, R1E reached 2,027-m depth before leaving the Santa Fe. Bjorklund and Maxwell (1961) describe the bottom 168 m as having penetrated rocks of "Cretaceous (?) age." The well record on file with the New Mexico Oil Conservation Commission is unclear in this regard. As pointed out by Kelley (1977), a projection of the base of exposed Santa Fe in the Rio Puerco valley only 10 km to the west of the well intersects the well at depths of about 450 to 600 m. Consequently, considerable unexposed faulting or increase in easterly dip must exist in the subcrop to the west of the Carpenter #1 Atrisco well. Kelley (1977) has hypothesized that most of the vertical displacement (over 1,600 m) is along the Sand Hill fault about 7.5 km west of the Carpenter #1 Atrisco well. A deeper (5,906 m) oil-test well was drilled in 1981 by Shell Oil Company approximately 2 km west of the northernmost cone of the Albuquerque volcanoes (fig. 1). The lithology of the hole has not been released.

Water-table depths in the area of Figure 1 vary from 65 m at West Mesa #4 (our measurement) to 285 m at the former radar site well (Bjorklund and Maxwell, 1961) about 3 km west-northwest of the

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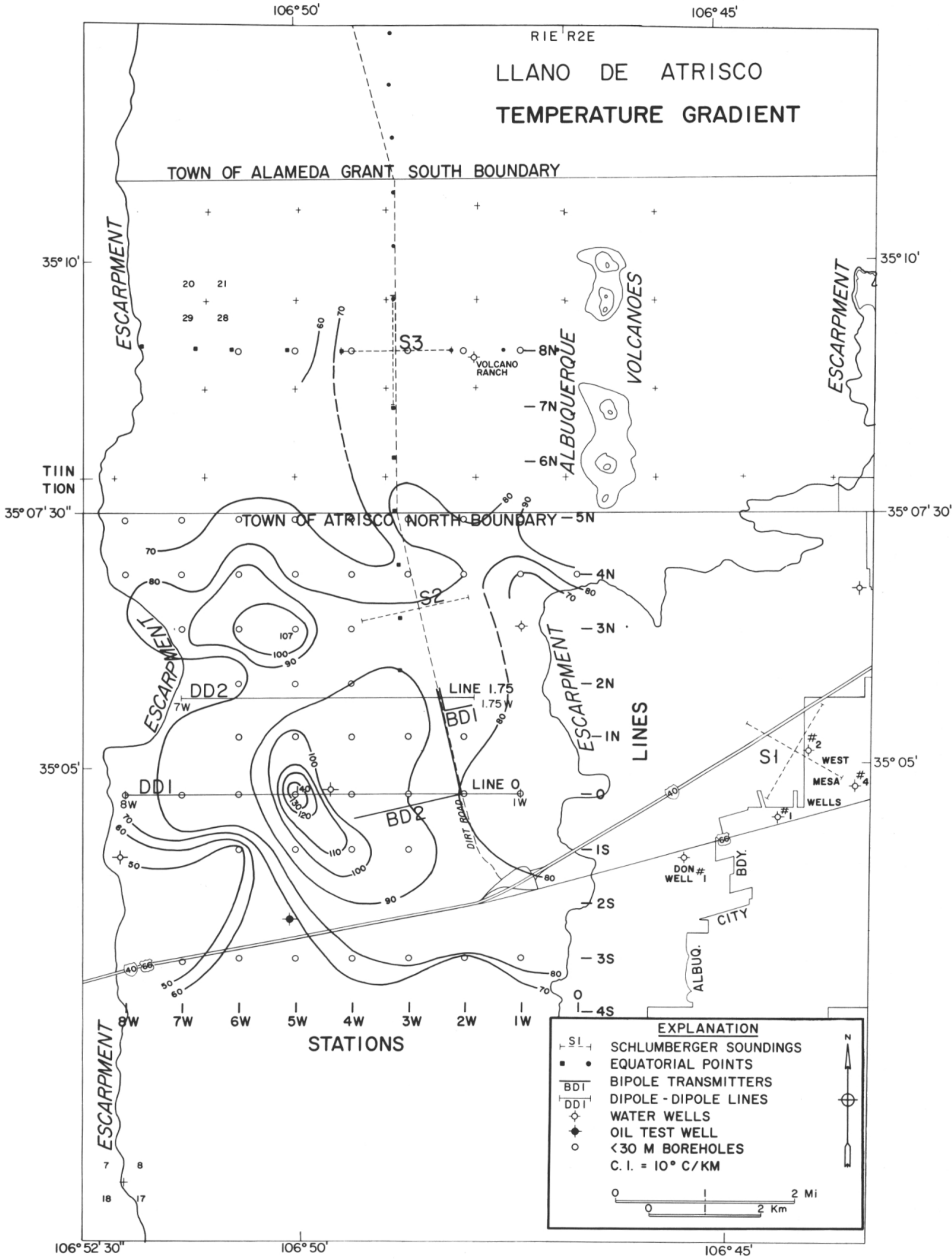

Figure 2. Shallow, temperature-gradient map of Llano de Atrisco. Contours in °C/km.

Carpenter #1 Atrisco well (fig. 1). Probably the most significant aspect of the absolute elevation of the ground-water table beneath the area is a pronounced north-south trough 10-15 km wide approximately centered over the Llano de Atrisco. The trough described by Bjorklund and Maxwell (1961) is about 10 m lower than the Rio Grande 10 km to the east and perhaps 35 m below the water level at the radar-site well. These values are based on very few data (water wells); however, a more recent compilation by the U.S. Geological Survey (D. Wilkins, personal commun., 1981) confirms a considerable hydraulic gradient on the west side of Figure 1 of approximately 10 m/km. This implies significant eastward water movement on the west side of the Llano de Atrisco.

Electrical resistivity investigations in the Albuquerque area consisted first in 1979 of Schlumberger and combined Schlumberger-equatorial soundings at three locations, S 1 , S2, and S3 (fig. 1). The soundings were followed in the same year by bipole-dipole mapping from two orthogonal bipole transmitter pairs BD1 and BD2 (fig. 1). Two dipole-dipole lines DD1 and DD2 (fig. 1) were measured in 1980. Surface magnetic profiles totaling 171 km were occupied in 1980. These followed initial measurements of less than 10 km length made in 1979. Shallow (<30 m) temperature-gradient measurements were made on the Llano de Atrisco during 1979-80. Some anomalously high values (>100°C/km) in the shallow drill holes exposed the need for deep gradient values, particularly below the water-table. One such measurement has been made in a 372-m deep borehole. Data from this U.S. Geological Survey water monitor well #1 (fig. I), drilled in the summer of 1981 by the survey and the City of Albuquerque with our cooperation, are presented herein.

DISCUSSION

Temperature Gradient Survey

Following the discovery of high, shallow temperature gradients (>80°/km in the upper 25 m) on the Llano de Atrisco in 1979 by eight drill holes, 52 additional holes were drilled in 1979-80 in the area. The holes were positioned on a grid of 1-km-spaced lines and stations, e.g., lines 0, 1N, 2N, . . . , 1 S, 2S, . . . ; stations 0, 1W, 2W, 3W, . . . (figs. 1 and 2). Most wells were drilled to 25 m to penetrate below the effect of the annual temperature wave (<10-15 m). Initial results of the 52 holes were presented by Parker and Jiracek (1980); Figure 2 contains contours of these shallow thermal-gradient values after reoccupation of most sites and least-squares fitting of the temperature curves (Jiracek and others, 1982). Most significant (fig. 2) is the high-gradient anomaly, reaching 140°C/km, centered over line 0, station 5W. Figure 3 presents measured shallow, temperature-gradient data from multiple reoccupations of stations 5W and 6W on line 0. Variations in the upper 10 m or so are due to the seasonal dependency of the annual wave. Both the 140°C/km anomaly and a lesser one of I 07°C/km to the north have small areas indicating shallow sources of limited extent.

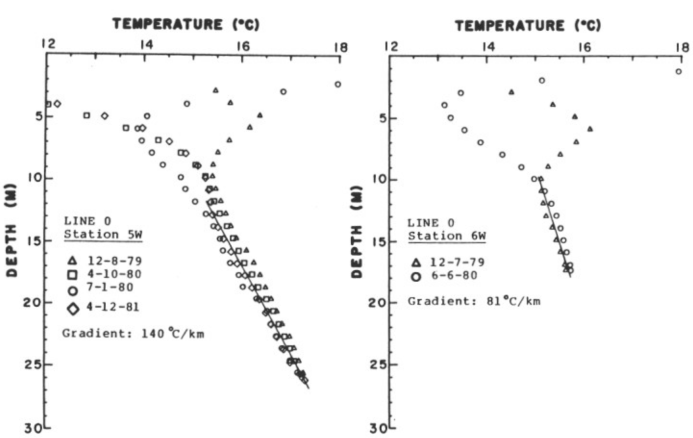

Figure 3. Shallow temperatures measured in test holes located on line 0, stations 5W and 6W.

Resistivity Measurements

Bipole-dipole mapping using the northern segment of BD2 (fig. 4) on the Llano de Atrisco during the summer of 1979 exposed an unusual resistivity ridge of about 25 ohm-m on the west side of the Llano (fig. 4). The uncovering of the near-coincidence of the resistivity ridge in Figure 4 and the maximum subsurface temperature gradient on the Llano de Atrisco (fig. 2) resulted in a more detailed resistivity survey. This dipole-dipole survey was directed at detecting lateral resistivity variations which might explain the association of the resistivity high and the shallow thermal anomaly.

Two dipole-dipole lines were traversed across the Llano de Atrisco during the summer of 1980. One line (DD1 in fig. 1) was run across the temperature gradient peak seen on survey line 0 (fig. 2). The traverse was 8 km long and used dipoles of 250 m; dipole expansions were increased from n= 1 to 7. Another shorter line, 5-km long DD2, was positioned 1.75 km north (fig. 1) to cross a magnetic anomaly discovered during the initial field tests (Parker and Jiracek, 1980).

Figure 5 contains the observed DD1 dipole-dipole results in pseudosection form and the calculated-model results using the finite-difference routine developed by Dey (1976). Although the observed and calculated results show a reasonably high degree of match, one is cautioned regarding the nonuniqueness of the corresponding resistivity model. In the model, the 80 and 20 ohm-m layers above 500 m represent the surficial layers and upper water-saturated zones seen in Schlumberger soundings S2 and S3 (figs. 1 and 7). The 8 ohm-m zone (fig. 5) corresponds to the more conductive, saline waters probed by the soundings. The most significant feature of the DD1 results is a highly resistive zone detected between surface locations 5W and 7W (fig. 5). The modeling suggests a resistive (60 ohm-m) projection between locations 5W and 7W into the shallow sequence and a possible draping of the 8 ohm-m zone over it. Modeling of the DD2 results shown in Figure 6 produced a similar feature which is displaced approximately one kilometer to the west.

Resistive-electrical basement rock, such as the 60 ohm-m blocks modeled in Figures 5 and 6, has not been detected by our measurements elsewhere on the Llano de Atrisco at such shallow depths. For example, Figure 7 presents the combined Schlumberger-equatorial sounding S3 west of the Albuquerque volcanoes centered near station 3W, line 8N (fig. I). The data were modeled using the program developed by Zohdy (1973) to yield the resistivity layering shown with the corresponding fitted curve. The interpreted resistivity decrease at 271 m to 16 ohm-m is in excellent agreement with the measured water-table depth of 266 m at Volcano ranch (fig. 1). There is also a general decrease of resistivity with depth to about 4,300 m. This could result from increased temperature and/or decrease in water quality with depth. This is apparent despite an expected decrease in porosity with depth. Resistive basement (84 ohm-m) at about 4,300-m depth agrees quite well with recent gravity modeling by Birch (1980) which shows Precambrian basement at this location to be about 4,800 m deep. The resistive (60 ohm-m) bedrock modeled on the dipole-dipole lines in Figures 5 and 6 is not expectd to be Precambrian basement but is more likely impermeable Mesozoic strata as discussed later.

Magnetic Survey

A total-field magnetic map of the Llano de Atrisco is presented in Figure 8. An areal coverage of 175 km' was obtained using Geometries

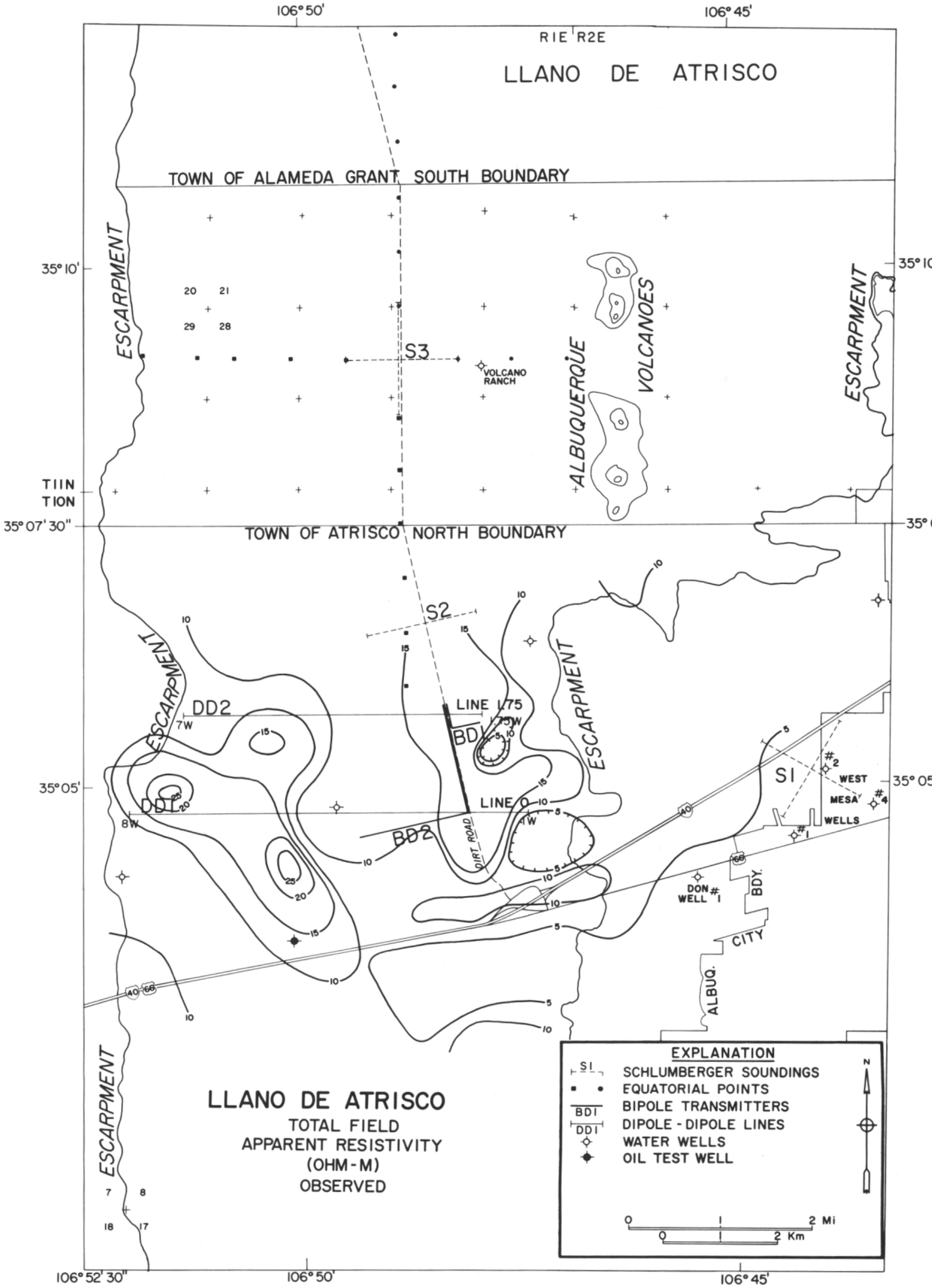

Figure 4. Bipole-dipole total field apparent resistivity map of Llano de Atrisco obtained from ~NS BD2 transmitter.

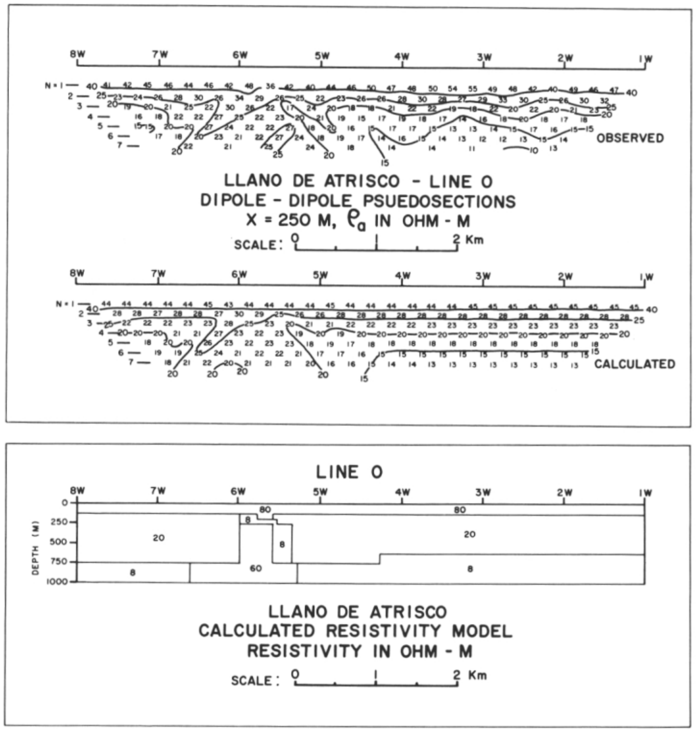

Figure 5. Observed and calculated dipole-dipole pseudosections and calculated resistivity model along line 0 of Llano de Atrisco.

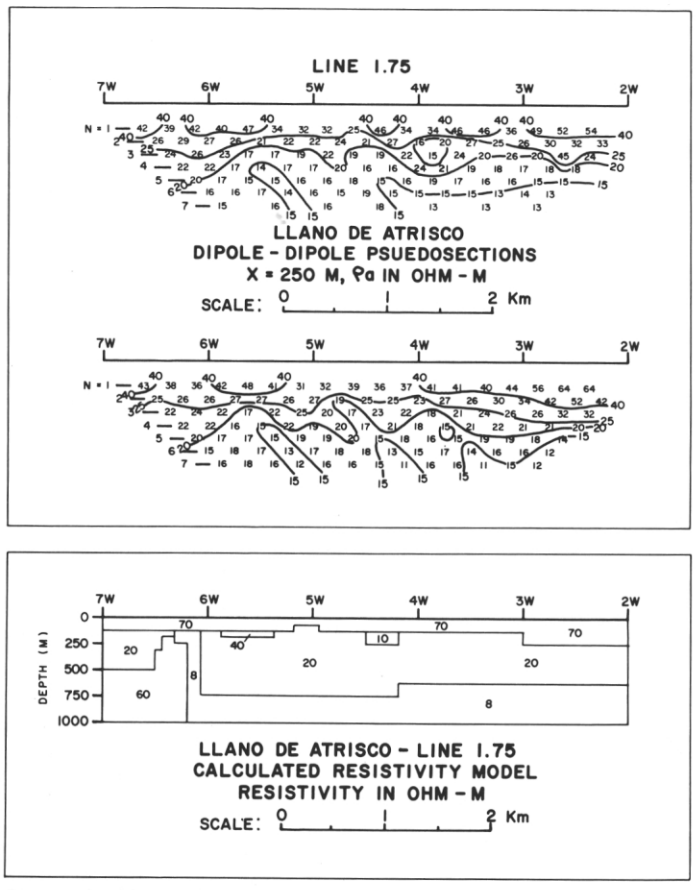

Figure 6. Observed and calculated dipole-dipole pseudosections and calculated resistivity model along line 1.75N of Llano de Atrisco.

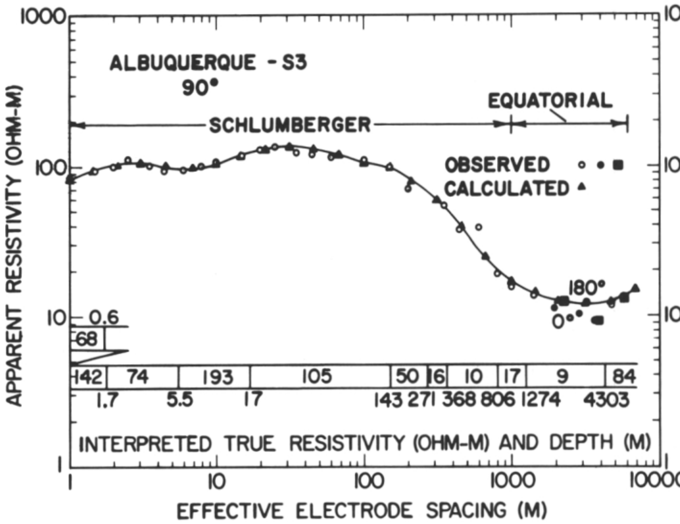

Figure 7. Observed and calculated Schlumberger-equatorial sounding and interpreted layered resistivity model at S3.

G-806 and G-816 proton precession magnetometers. Magnetic measurements were made 100 m apart on the survey lines indicated in Figure 1. Shorter east-west survey lines and some north-south lines were positioned closer than 1 km when deemed necessary for detail. Readings over the surface lava flows of the Albuquerque volcanoes were too erratic for meaningful results.

The two temperature-gradient highs (fig. 2) and nearby magnetic anomalies (fig. 8) disclosed by initial 1979 ground surveys were thought to have a causative relationship (Parker and Jiracek, 1980). Though this may be the case, the very extensive magnetic survey of the Llano during 1980 (fig. 8) has clearly shown that the resistive anomaly in Figures 4, 5, and 6 is nonmagnetic. Furthermore, the dipole-dipole results of DD2 (fig. 6) which cross the highest magnetic anomaly in the entire survey area between stations 3W and 4W on line 1.75N do not measure a corresponding large resistivity high. The highest dipole-dipole resistivity at depth is measured between stations 5W and 6W on DD1 (fig. 5) where the magnetic field is relatively flat (fig. 8).

Three-dimensional modeling of the magnetic patterns in Figure 8 suggests sill-like bodies at shallow depths. Modeling was accomplished using a computer program written following the formulation of Bhattacharyya (1964). The program calculates the total-field magnetic anomaly over a prism-shaped body with vertical sides and flat top and bottom (fig. 9). Any angle of magnetic-polarization vector can be chosen relative to the geomagnetic-field direction, thus allowing for both remanent and induced magnetism.

The relative contributions and directions of remanent and induced magnetism are unknown in the causative bodies producing the anomalies in Figure 8. An igneous body that cooled through the Curie temperature in the last 700,000 years would be expected to have normal remanent polarization. Our modeling has assumed this. More precisely, the total polarization direction has been assumed to be in the direction of the current geomagnetic field in the area, i.e., inclination (I) of 63° and declination (D) of 12.5°E (fig. 9).

The choice of the susceptibility contrast (K) of the anomalous magnetic bodies and the surrounding sedimentary sequence has been made after several considerations as described by Jiracek (1982). The method of Vacquier and others (1951) gave estimates of K = 2,000 x 10_6 and K= 10,000 x 10' (cgs) for the anomalies intersected by survey lines 4N and 1.75N, respectively (fig. 8). However, drill hole cuttings from lava flows of the Albuquerque volcanoes produced susceptibility values

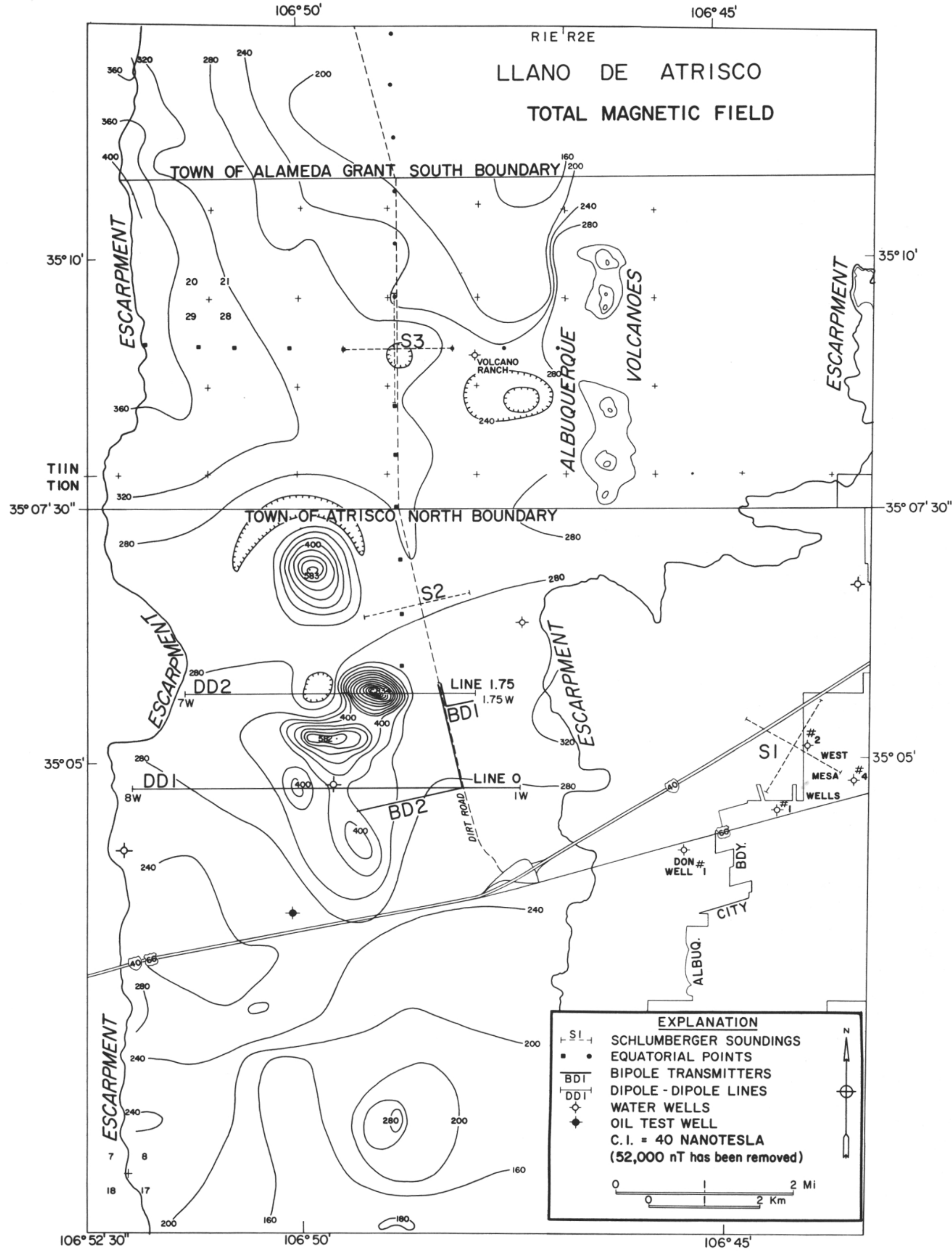

Figure 8. Total magnetic-field map of Llano de Atrisco. Contours in nanoteslas.

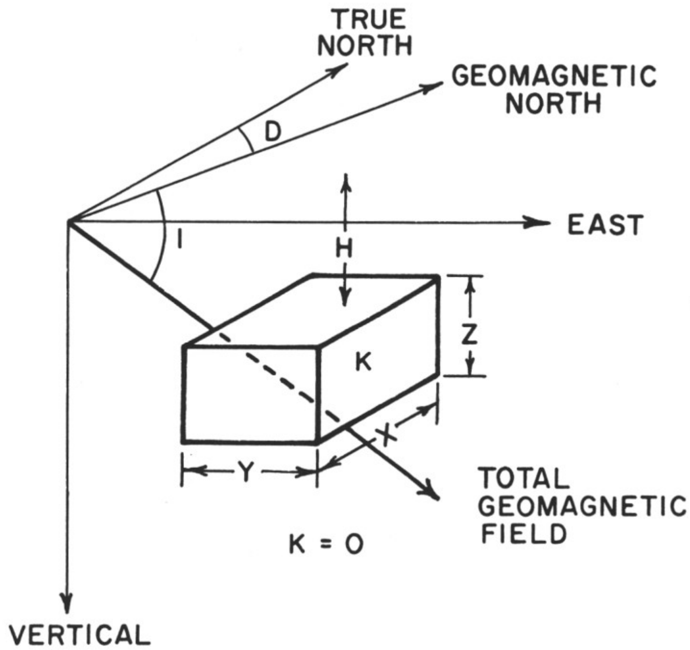

Figure 9. Magnetic prism model.

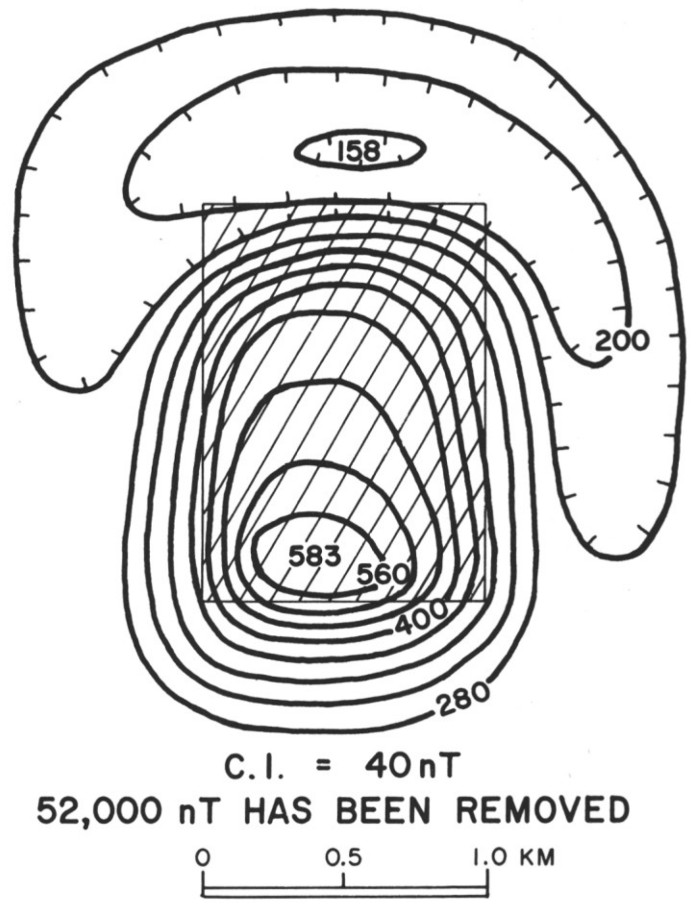

Figure 10. Calculated magnetic anomaly crossed on line 4N of Llano de Atrisco. Hatched area is plan view of prism body.

of less than 700 X 10-6 (cgs). The laboratory measurements do not reflect any remanent component to the magnetic polarization so the difference between the laboratory measurements and the calculations using the field anomalies may approximate the degree of remanence. Consequently, the ratio of remanent to induced magnetization may be a minimum of two and perhaps over thirteen. Basalt samples from near Santa Fe, New Mexico were measured to have ratios between 3.3 and 14.2 (Spiegel and Baldwin, 1963). The highest effective susceptibility measured in these samples was reported to be 9,600 x l0_6 (cgs). This value has been assumed in our modeling as an effective susceptibility, i.e., one that includes combined remanent and induced components in polarization.

An example of the magnetic modeling appears in Figure 10 where the isolated anomaly centered on line 4N (figs. 1 and 8) has been closely matched. The prism body modeled in this case is 1.4 km in north-south extent and 1.0 km east-west. It is at a depth of 275 m and is 87.5 m thick. This is certainly not a unique model; however, the results are consistent with a body that is thin with its top very near the water-table depth. The sharper anomaly on line 1.75N (figs. 1 and 8) is likely shallower, possibly nearer to 200 m depth.

There are at least ten volcanic layers listed in the 2,027-m well record from the nearby Carpenter #1 Atrisco (fig. 1); the thickest layer, however, is only 27 m. Resistivity logs of this wildcat oil test record resistivities in excess of 1,000 ohm-m in some volcanic layers and surface-resistivity measurements on flows of the Albuquerque volcanoes by Brandwein (1974) yielded values of 2,850 ohm-m. Such highly resistive layers would be easily detected by surface-resistivity measurements unless they are thin (5_50 m) or contain appreciable interconnected water. All of the above considerations lead us to the conclusion that the resistive ridge detected by bipole-dipole mapping and dipole-dipole sounding-profiling is not due to subsurface volcanics.

CONCLUSIONS

A possible explanation of the resistive ridge and its relation to the thermal anomaly can be derived from a consideration of the gravity patterns (Birch, 1980) over the test area (fig. 11). It is quite obvious from the contours on the west side of the map that a residual gravity anomaly is present. Removal of a reasonable regional gradient yields an approximately 6 mGal north-northwest-trending residual centered roughly over station 5W, line 0. Birch (1980) has computer-modeled an east-west gravity profile passing directly through the Carpenter #1 Atrisco well. He modeled 2.4 g/cm3 (Mesozoic) strata to be upfaulted to within 300 m of the surface only 2.5 km west of the well. This is not nearly as far west as suggested by Kelley (1977). A closed residual gravity anomaly produced by removing the regional trend in Figure 11 would suggest an additional ridge on Birch's upthrown block. Thus, the resistivity ridge in conjunction with the residual-gravity anomaly is consistent with a shallow horst-like structure on the west side of the Llano de Atrisco. Additional detailed gravity measurements would better outline the structure. It is interesting to note that the driller's log of the water well at the radar site (Bjorklund and Maxwell, 1961) terminates with the last entry from 418 to 422 m described as "rock, hard; cut bit."

It is enlightening to compare the various geophysical measurements over the maximum thermal-gradient high on the Llano de Atrisco. These are shown in Figure 12 for the thermal gradient, dipole-dipole pseudosection, and gravity profiles along line 0. The magnetic profile along line 1N, 1 km away, is also included. It is, again, evident that the high resistivity anomaly between stations 5W and 7W is related to the gravity anomaly and is not detecting the magnetic body. This leads to the conclusion that the causative magnetic bodies (probably lava flows) are permeable to water flow and do not act as flow barriers. Furthermore, the gravity and resistivity highs are probably sensing an upthrown block of Cretaceous basement which is relatively impermeable compared to

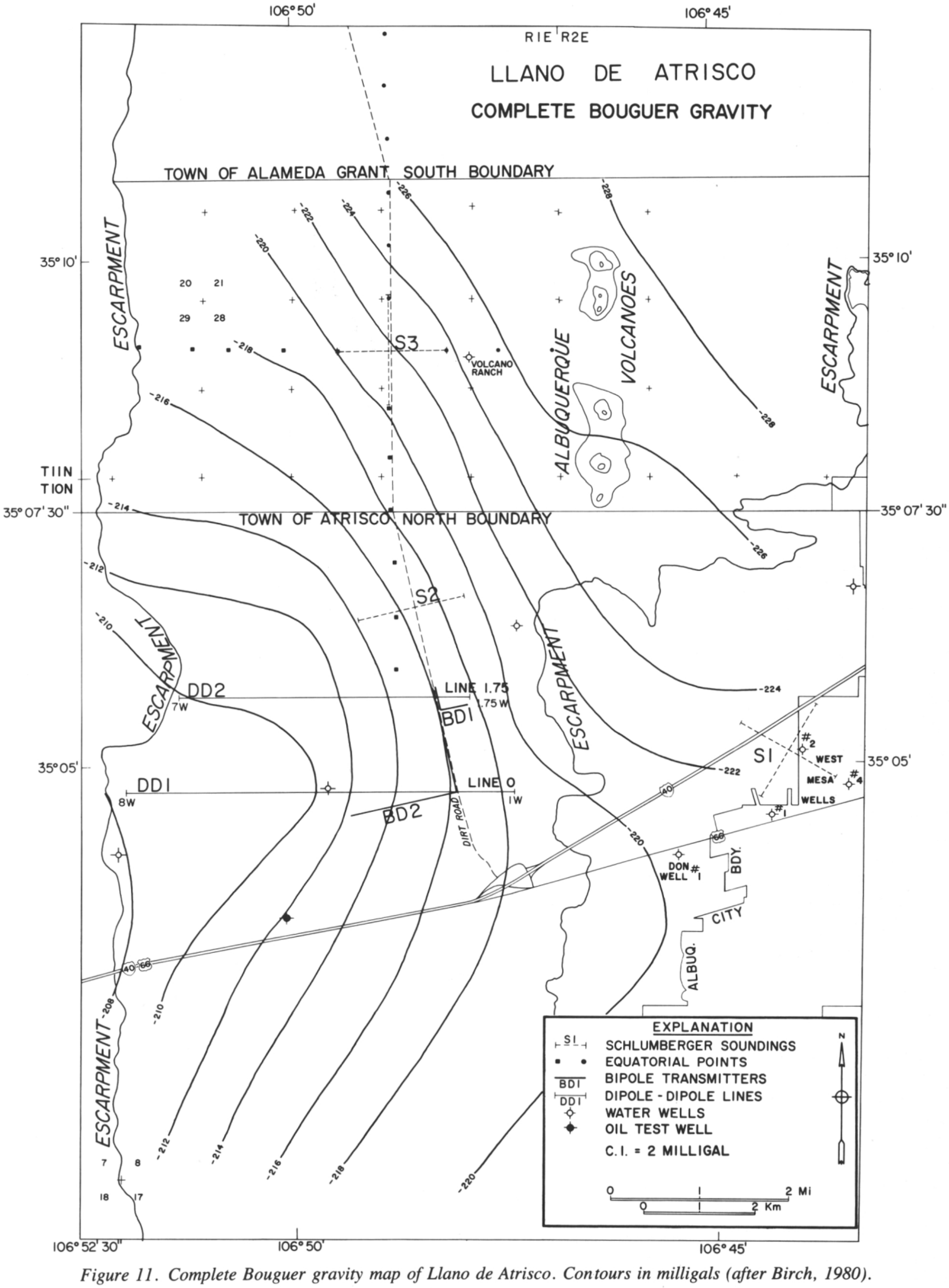

Figure 11. Complete Bouguer gravity map of Llano de Atrisco. Contours in milligals (after Birch, 1980).

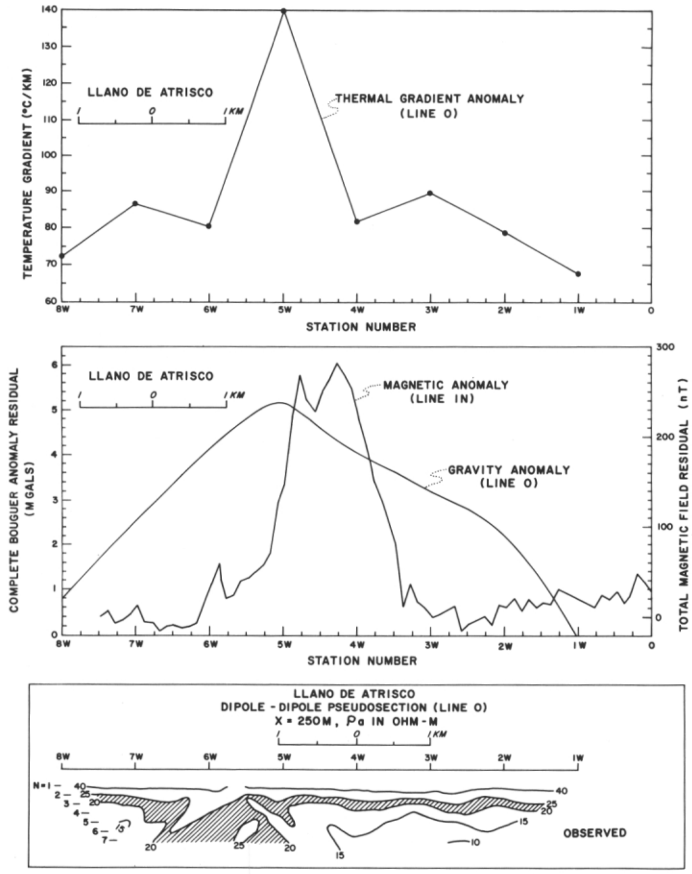

Figure 12. Profiles of shallow thermal-gradient, magnetic, gravity, and resistivity surveys on Llano de Atrisco.

the overlying Santa Fe beds. Minimum depth to the contact may be 200-250 m based on dipole-dipole modeling (figs. 5 and 6).

The possibility that a buried ridge rises to about 250 m of the surface on the west side of the Llano de Atrisco suggests an explanation for the hydrothermal anomaly there which is the forced ground-water convection model described by Morgan and Dagget (1981) and Morgan and others (1981). In this model, heated ground water from depth is brought closer to the surface by flow over subsurface constrictions or barriers. The proposed buried ridge would be such a barrier. The large west-to-east hydraulic gradient in this area, discussed earlier, could be the driving mechanism for this heat-transfer hypothesis. Since this area of the Llano de Atrisco has mapped faults (fig. 1) which are presumably deep-seated (Kelley, 1977), we cannot rule out the possibility that all or a portion of the temperature anomaly is due to deep thermal convection. The alternate explanation of forced convection would lead to a lower maximum temperature at depth since it is limited by the maximum depth of water circulation (Morgan and others, 1981).

An alternative explanation for the high, shallow temperature-gradient anomalies mapped in Figure 2 is that they do not reflect deep conditions but are reflecting only shallow-material variations. Parker (work in progress) has found strong statistical correlations between temperature gradients, surface temperatures, and thermal diffusivity which measures the materials' ability to transmit heat. Consequently, varying amounts of eolian sand, caliche, and gravels may result in varying depths of penetration of the annual-temperature wave. The effect is to alter the temperature gradient predicted by least squares regression in an area of constant heat flow. Deep drilling by the U.S. Geological Survey in the area suggests that the high gradients found near-surface may not reflect a high temperature source at depth.

Temperature measurements of the U.S. Geological Survey water monitoring well #1 near line 0, station 4.3W (figs. 1 and 2) have yielded a bottom-hole temperature of 34°C at 372 m depth. The temperature gradient below the water table (265 m) was reported (D. Wilkins, personal commun., 1981) to be a linear 30°C/km. Although these temperature measurements exceed those at similar depths elsewhere in the Albuquerque area (Jiracek and others, 1982), they are not particularly encouraging for geothermal exploitation. Our measurements of ten deep water wells on the west side of Albuquerque with depths from 110 m to over 440 m have yielded only two locations where temperatures over 30°C were encountered. The College #3 well (fig. 1) has a temperature at 372 m depth very nearly equal to that measured at the U.S. Geological Survey hole. A gradient of approximately 30°C/km was measured to a total depth of 445 m. Almost 32°C was measured at just 20 m depth in the only West Mesa well accessible for our measurements (West Mesa #4, fig. 1). This anomalous temperature was due to distortion from active pumping of the well prior to our measurements. Here, warm water pumped from depth greatly enhanced the temperature in the upper portion of the well. We were unable to obtain an equilibrium gradient in this well but obviously deep temperatures are greater than or equal to 32°C. The well was drilled to 436 m.

The U.S. Geological Survey water monitoring well was positioned in the vicinity of our line 0, station 4.3W because of the possible geothermal significance. Positioning of the hole to the west of station 5W (at about line 0, station 5.5W) appeared to be a better geothermal choice based on resistivity modeling (fig. 5). However, the site drilled was more readily accessible.

It is interesting to note that the well record of the nearby Carpenter #1 Atrisco well (figs. I and 2) lists zones of "large volumes of water" at depths of 671, 899, and 1,003 m. Extrapolation of the temperature gradient from the U.S. Geological Survey well leads to expected temperatures of 43, 50, and 53°C at these depths, respectively.

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Early construction at Nob Hill. Note early smog in background (Albuquerque Museum Photoarchives).