LIGHTNING DOCK KGRA

Setting, Scope and Previous Work

In 1948 attention was first drawn to the geothermal anomaly in the Animas Valley of New Mexico now known as the Lightning Dock KGRA (fig. 27). Lightning Dock Mountain is one of the peaks of the Pyramid Mountains, the range that borders the Animas Valley on the east. Three shallow wells were drilled to provide water for stock in the semi-arid valley in 1948 and 1949. Each well hit steam, boiling water (101.5° C), and rhyolite at a depth of about 27 m. Drilling was halted in the rhyolite at less than 30 m total depth. The hot water is contained in 5 to 10 m of alluvium above the rhyolite (Reeder, 1957). Only one of the wells is still in use - 25.19.7.234 - as a domestic water supply for the family of Tom McCants. Table 5 presents selected chemical analyses of the water from this well.

The wells are nearly 5 km east of State Highway 338, a paved road that runs down the center of the Animas Valley (fig. 27). Valley View Church, 7 km north of Cotton City, is located at the intersection with the private road that leads to McCants' ranch. Lordsburg, the county seat and economic center of Hidalgo County, is roughly 40 km to the northeast via Highway 338 and Interstate Highway 10.

Aside from the Valles Caldera, the Lightning Dock KGRA is the only identified hot-water convection system in New Mexico with an indicated subsurface temperature in excess of 150°C.(Renner and others, 1975). All available geochemical geothermometry is included in table 6.

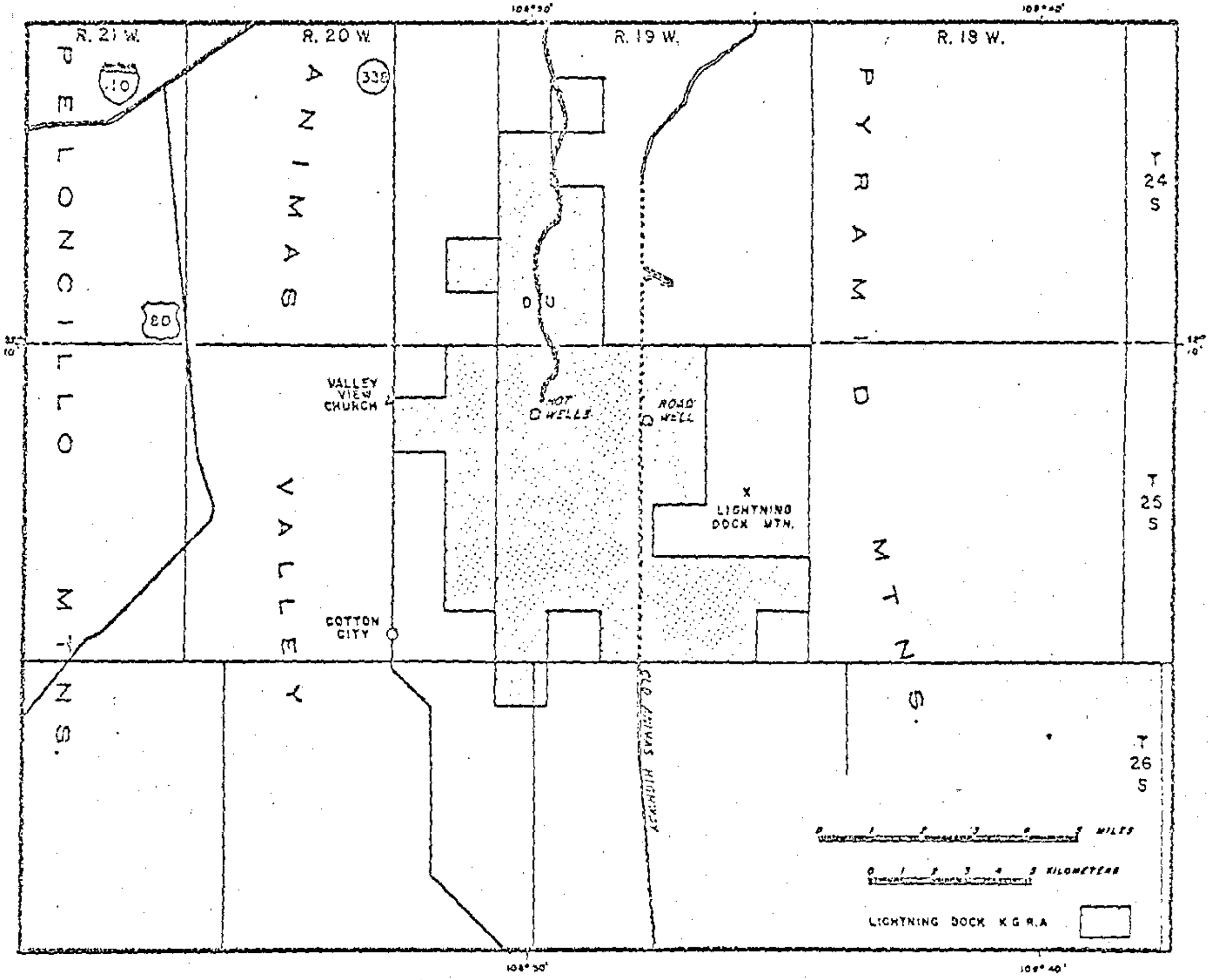


Figure 27. Lightning Dock KGRA study area, showing Holocene fault north of hot wells

TABLE 5

Selected chemical analyses of ground water in the Animas Valley, New Mexico

McCants' Ranch
25.19.7.234

(after Reeder, 1957; and Summers, 1965)

constituent	units	concentration	range
K	mg/l	21.	-
Na	mg/l	364.	-
Ca	mg/l	22.	19. - 24.
Mg	mg/l	1.2	0.7 - 1.5
HCO_3	mg/l	159.	145. - 181.
SO_4	mg/l	476.	459. - 509.
Cl	mg/l	82.	78. - 85.
F	mg/l	11.3	9.9 - 13.
SiO_2	mg/l	138.	135. - 141.
B	ug/l	450.	-
Hardness as $CaCO_3$ (Ca,Mg)	mg/l	58.	52. - 66.
Dissolved solids @ 180°C	mg/l	1105.	1020. - 1160.
Specific conductance	mmhos @ 25°C	1590.	1510. - 1660.

TABLE 6

Selected geochemical geothermometers of ground water in the Animas Valley, New Mexico

Geothermometer	McCants' Ranch 25.19.7.234	Reference
	Estimated temperature	
Na-K-Ca	> 170°C	Swanberg, 1975b
Na-K-Ca	169°C	Renner and others, 1975
SiO_2	> 170°C	Swanberg, 1975b
SiO_2	156°C	Renner and others, 1975
" Various chemical geothermometers"	159-165°C	Lange, 1977

The high temperatures indicated by geothermometry makes the Lightning Dock KGRA attractive for commercial exploration. At least two dozen shallow (100 m) thermal gradient holes have been drilled within the KGRA by several different exploration companies. AMAX Corp. reported heat-flow values in excess of 20 hfu. "The (heat-flow) anomaly extends southward from the area of the hot wells for about 10 km." (Lange, 1977) Of all the geothermal areas in southern New Mexico, the Lightning Dock KGRA is considered the most promising for energy development and has stirred the most interest in industry.

The Animas Valley is in the Basin and Range province of New Mexico. It is an elongated north-south graben flanked by a pair of mountain ranges, the Peloncillo Mountains on the west and the Pyramid Mountains on the east. In the vicinity of the hot wells, the valley is approximately 15 km wide and is conspicuously flat. The hot wells are much closer to the Pyramid Mountains than the Peloncillo Mountains. Gillerman (1956) described the Animas Valley as

> a broad, flat, northward sloping interior basin... Flood waters discharged by the gullies heading in the mountains bordering the valley spread thin sheets across the valley floor and eventually find their way via broad, ill-defined, shallow draws to the playas that occupy the lowest parts of the valley.

Two playas are just north and south, respectively, of Interstate Highway 10. They are remnants of Pleistocene Lake Animas. During the late Pleistocene to early Holocene, the valley was partly covered by the lake. Fleishhower (personal communication, 1976) is presently studying the assorted sills, beaches, and wave-cut terraces associated with the lake. He reported that there are no signs of Lake Animas as far south as the hot wells. The water table in the valley mimics the topographic surface. All ground water flows to the north. In the vicinity of the hot wells, there is a small amount of recharge from the Pyramid Mountains on the east (Reeder, 1957).

The Peloncillo Mountains consist of Precambrian granite, Paleozoic and early Cretaceous sedimentary rocks, Tertiary intrusive rocks, and late Cretaceous (?) and Tertiary volcanic rock. The late Tertiary fault, or system of faults, which bounds the Peloncillo Mountains horst block can be observed southwest of the study area. In the area of figure 27, it is covered with debris from the range. It is probable that the Paleozoic section exposed in the Peloncillo Mountains is present below the Quaternary sediments what fill the Animas graben. Pennsylvanian rocks are exposed in low isolated hills within the valley, south of the hot wells.

Two field seasons of geologic mapping in the Pyramid Mountains by E. G. Deal (Eastern Kentucky University) and W. E. Elston (University of New Mexico) were completed in 1976. They found the range to be a mid Tertiary caldera complex, informally called the Pyramid Mountains Volcanic Complex. The caldera is asymetrically domed, and is marked by two concentric ring-fracture zones along which rhyolite and latite domes rose to the surface. A thick fill of ash-flow tuff is surrounded by these domes. A sketch map showing the location of the inferred ring-fracture is presented in figure 28. Much of the eastern half of the caldera is observed in the Pyramid Mountains. The Basin and Range faulting that formed the Animas graben must have transected the caldera and dropped its western half into the graben.

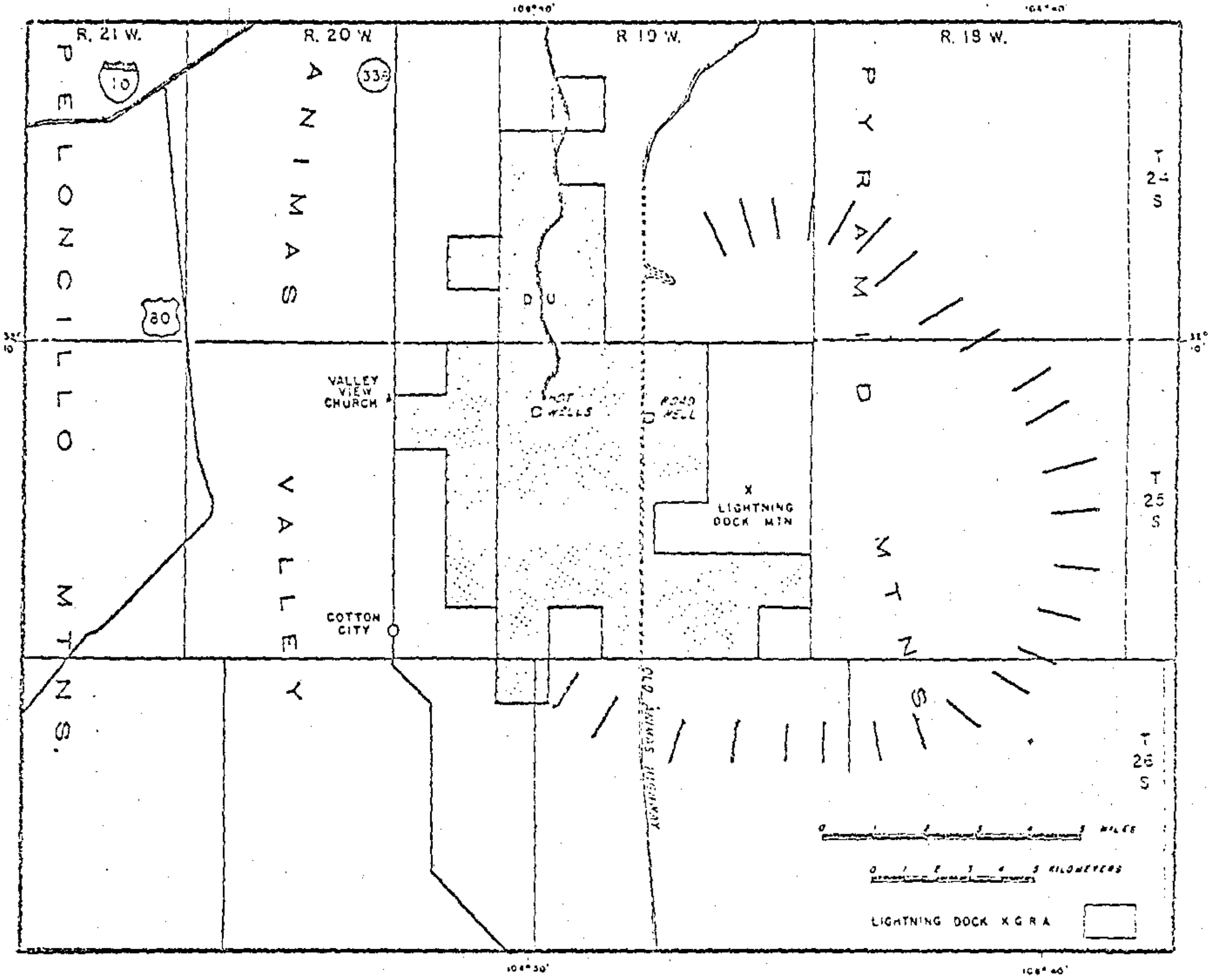


Figure 28. Hachures show inferred ring-fracture zone of Pyramid Mountains Volcanic Complex (after Elston, personal communication, 1977)

Radiometric dates have not been determined for the volcanic rocks of the Pyramid Mountains Volcanic Complex. However, P. E. Damon and associates (University of Arizona) have bracketed the age of the caldera between the Lordsburg stock (55.2 ± 1.2 m.y.) and the Oak Creek Tuff of the Animas Mountains (34.3 ± 0.7 m.y.). The Oak Creek Tuff has tentatively been identified among the units that overlie the Pyramid Mountains Volcanic Complex in the southern end of the Pyramid Mountains (W. E. Elston, personal communication, 1977). This evidence would date the caldera as Eocene to early Oligocene. Even though a caldera this old does not explain the source of the heat for the water at the hot wells, its ring-fracture system may provide a channel for deep circulation of ground water. The coincidence of the vanished western half of an extinct volcano with the geothermal anomaly near the mountains cannot be overlooked.

In the valley itself, a recent fault parallels the Pyramid Mountain front for several kilometers (fig. 27). Its trace vanishes less than 1 km northeast of the hot wells. It probably represents only the most recent episode of continued Basin and Range faulting. Nevertheless, its proximity to the hot wells may indicate that Holocene faulting may in part control the occurrence of the hot water, as suggested by Reeder (1957):

> The proximity of a recent fault to the hot wells and the associated fault zone to the area of abnormally high ground water temperatures are indicators of structural control of the hot water area.

and

> The occurrence of hot water may reflect the upward movement of heat and mineralized hot water along the fault from a deep magmatic source.

Basin and Range faults along the eastern flank of the Animas Valley are sites of hydrothermal manganese and fluorite veins dated at Miocene or younger. The veins extend intermittently from south of the international border to Caprock Mountain, 70 km north of the Lightning Dock KGRA. The veins formed near the present surface and some of them have been observed to grade into black calcite and travertine (Elston, 1965). These veins may be indicators of recent, extensive neogene hydrothermal activity throughout the Animas Valley. The water temperature anomaly at McCant's ranch may be a remnant of a much larger and largely extinct geothermal system.

The simple Bouguer gravity anomaly map of the Lightning Dock KGRA is shown in figure 29. These data cover the valley floor and show the structure of the basement below the valley fill. The survey was conducted by students from New Mexico State University (Preslar, 1976). The steep gravity gradients on the eastern and western margins of the valley north of the hot wells undoubtedly reflect the high angle normal faults that form the Animas graben. On the western side of the valley a fault or system of faults trends north-south, creating a gravity signature typical of the Basin and Range province. On the eastern margin of the figure an unusual pattern emerges. The gravity contour lines bend from a north-south trend to a northeast-southwest trend.

The gravity contour lines are deflected at approximately the location of the western portion of the inferred ring-fracture domes of the Pyramid Mountains Volcanic Complex. This deflection tends to confirm the interpretation that the western portion of the caldera

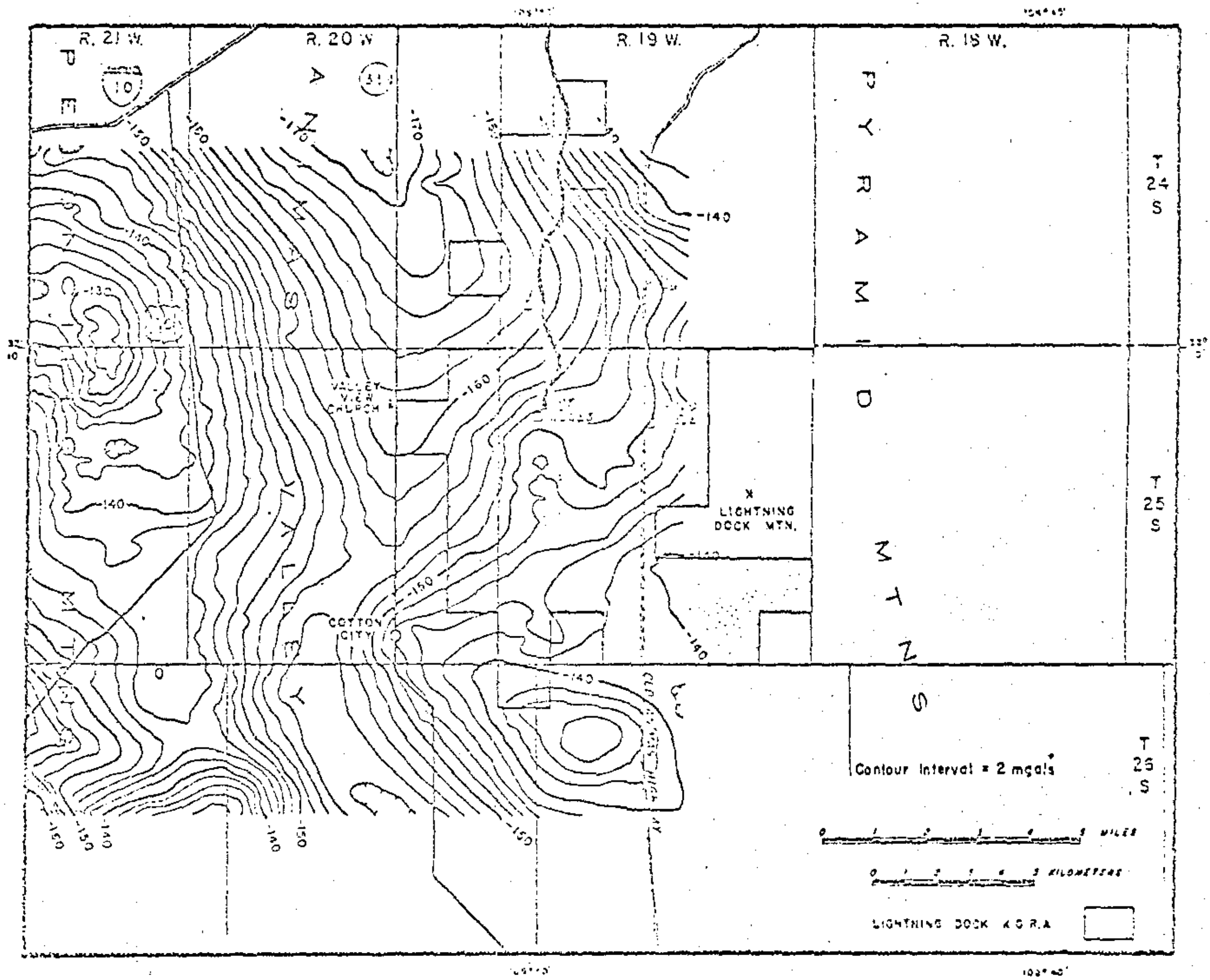


Figure 29. Preliminary simple Bouguer gravity anomaly map - Lightning Dock area, contour interval 2 mGals

has been transected by Basin and Range faulting. The gravity data may also reveal that Basin and Range faults not only transect the caldera but also are in part deflected by it. The hot wells may have been drilled above a zone of deflected Basin and Range faults. The Lightning Dock geothermal anomaly may be structurally controlled by the intersection of a mid Tertiary caldera and deflected, younger (Holocene?) Basin and Range faults.

The thickness of the valley fill can be estimated from the gravity data. Given a reasonable range of density contrasts and the extremes of the gravity data, estimates of the thickness of the valley fill range from 1,600 to 3,200 m. The average estimate is 2,400 m. At the hot wells the gravity displays a local anomaly. Removing a northeast-southwest regional produced a circular residual anomaly with a maximum amplitude of 5 mGals and a half-width of nearly 3 km. A deep-seated dense body could cause the anomaly at the hot wells. A vertical cylinder extending from the surface to 2,400 m, with a radius of 2,000 m, and with a density contrast of .1g/cc could also produce the 5 mGal anomaly (Nettleton, 1942). Silica deposition by convecting thermal fluids may be responsible for the gravity anomaly at the hot wells. It is possible that the large positive anomaly southeast of Cotton City is the sign of a ring-fracture dome buried by the valley fill.

Resistivity Surveys

More than 200 total field apparent resistivity measurements covering more than 125 sq km were completed in 1975 and are shown in figures 30 and 31. Highest observed resistivities exceed 40 ohm-m, the lowest are less than 10 ohm-m. In both figures the observed patterns are complex, but both reveal a salient high resistivity anomaly. An arcuate high resistivity ridge extends from east of Cotton City through the hot wells to the northeastern corner of the figures. The location of this high resistivity ridge is independent of bipole orientation. Therefore, the ridge points to a real structure in the subsurface at this location. It may indicate a simple but abrupt change in the depth to basement caused by Basin and Range faulting. However, a comparison with the probable location of the ring-fracture zone of the Pyramid Mountains Volcanic Complex (fig. 28), and the deflected gravity gradient (fig. 29) suggests that the ridge may be produced by resistive volcanic domes within the ring-fracture zone of the mid Tertiary caldera.

The high resistivity ridge may not be obvious to a reader unfamiliar with total field apparent resistivity maps. It needs to be distinguished from the other complex patterns of figures 30 and 31. For instance, the higher resistivities within 1 km of either bipole reflect the apparent resistivity of only the first tens of meters of dry, calich-rich desert soil.

Figure 30 was generated from the nearly 2 km long, north-south bipole approximately 2 km west of the hot wells. In the northeast

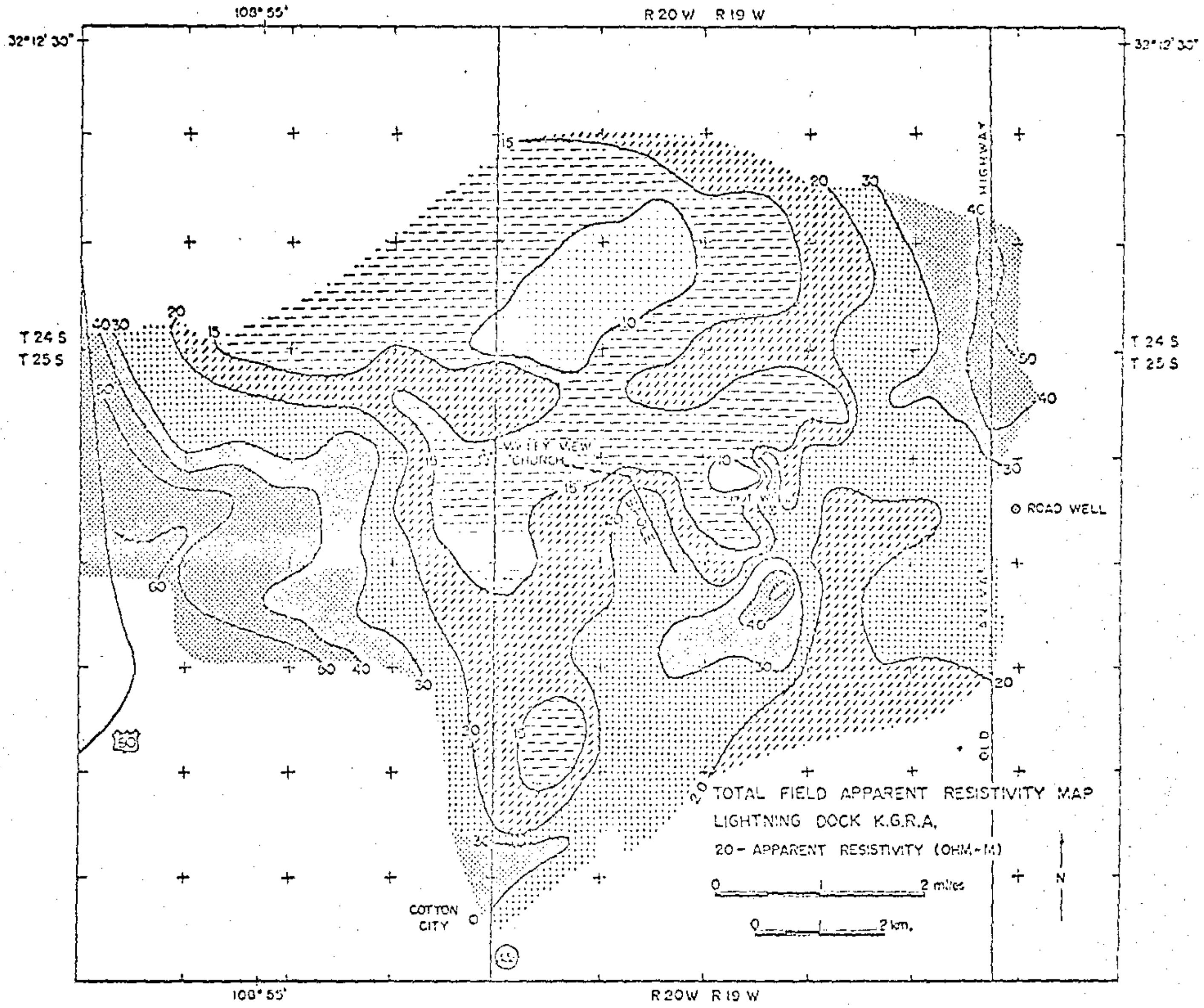


Figure 30. Total field apparent resistivity map, north-south bipole: Lightning Dock KGRA

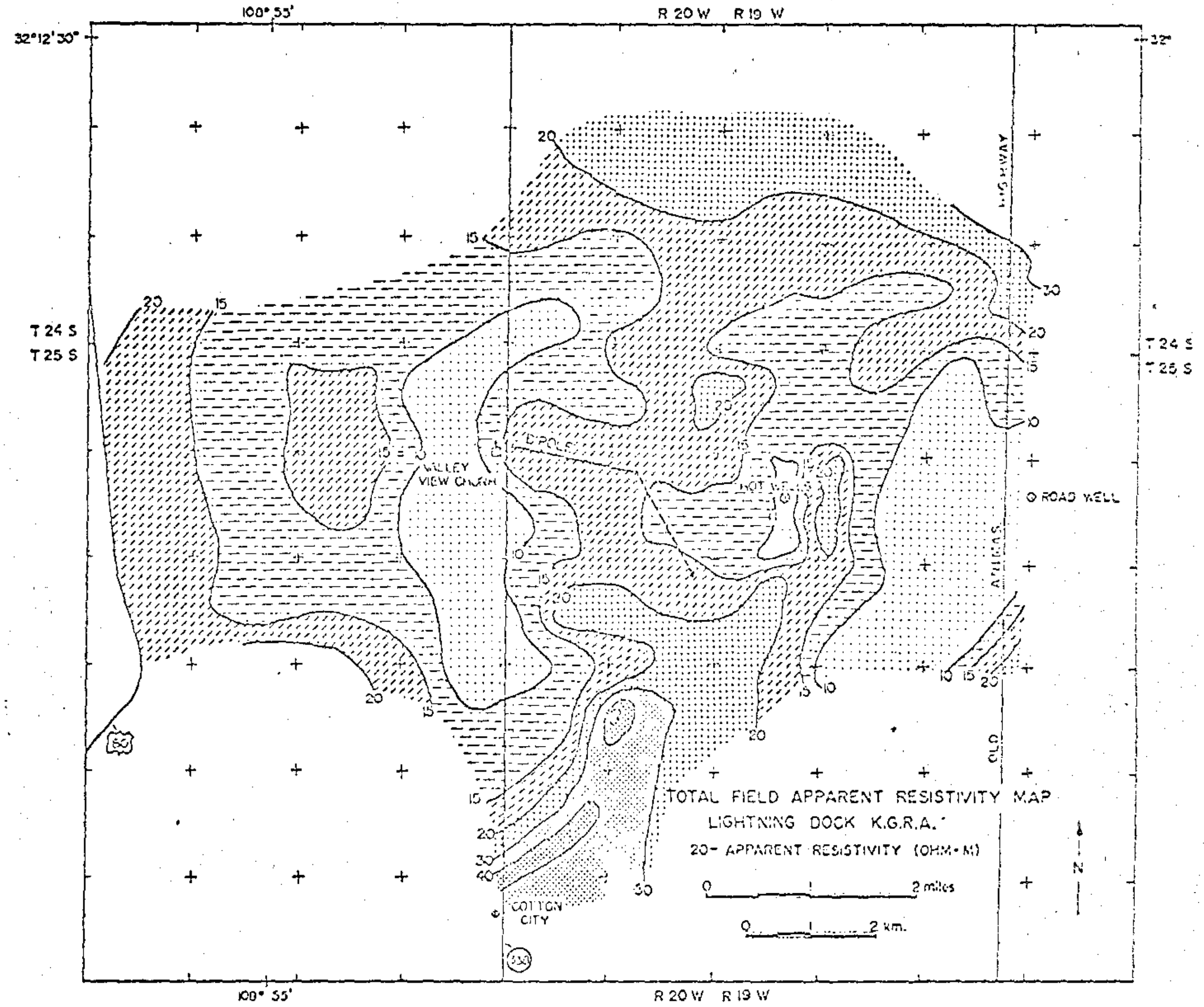


Figure 31. Total field apparent resistivity map, east-west bipole: Lightning Dock KGRA

corner of figure 30, the 50, 40, 30, and part of the 20 ohm-m contours align themselves parallel to the bipole. These high resistivities are undoubtedly due to the proximity of the resistive basement rocks of the Pyramid Mountains. The 40 ohm-m contour line is about 5.5 km away from the bipole; on the other side of the bipole, in the southwest corner of figure 30, the 40 ohm-m contour is also roughly 5.5 km away. There, the 50, 40, 30, and 20 ohm-m contours are also subparallel to the bipole. This region of highest resistivities probably indicates the proximity of more highly resistive basement as well.

A northeast trending 30 ohm-m spur distorts the high resistivity contour lines on the west side of figure 30. However, on the west side of figure 31, there is only an island of much lower apparent resistivity (< 15 ohm-m). At these spacings, the patterns of figure 31 are less sensitive to structures in the basement than are those of figure 30. Evidently, the cause of the spur does not persist to the shallow depth of penetration of figure 31. The spur may therefore be a minor, local deformation in the basement that does not persist to the near-surface. It may be associated with the intrusions in the nearby Peloncillo Mountains.

Values only slightly greater than 20 ohm-m were recorded near the center of the valley broadside to and north of the east-west bipole (fig. 31). The gravity data (fig. 29) suggest that this area is among the deepest parts of the graben. The absence of high resistivities that characterize electrical basement is evidence that the graben is filled with conductive sediments. These sediments may also be responsible for the large regions of low apparent resistivity (< 10 ohm-m) that parallel Highway 338 in the center of the valley south of Valley View Church.

A combined asymmetric Schlumberger and equatorial sounding along the east-west bipole and to the north delineates the electrical properties of the sediments north of the hot wells. Figure 32 plots the observed data and the interpreted geoelectric layering, with values in ohm-m, and depth to layer interfaces in meters. Reeder (1957) showed the depth to ground water in the study area to be on the order of 10 to 20 m. Even allowing for a considerable decline of the water table in the last 20 years. it is probable that the three shallowest layers in the bar graph all represent saturated sediments. If this is so, the 19, 10, and 4 ohm-m layers may indicate a steady increase in the salinity of the ground water to a depth of 466 m, or may indicate greater concentrations of clay with depth. The 27 ohm-m fourth layer may reveal a relatively impermeable, thick, sequence of sediments above the electrical basement. It may also suggest the presence of the Paleozoic section of the Peloncillo Mountains below the valley fill. The estimated depth to basement is 2,288 m. The upper three layers are interpreted to show that heavier, progressively more saline ground waters are collecting above a relatively impermeable interface. The ground water in the Animas Valley appears to become more saline with depth.

The 466 m thick sequence of conductive sediments inferred from figure 32 is surely responsible for the large areas of low apparent

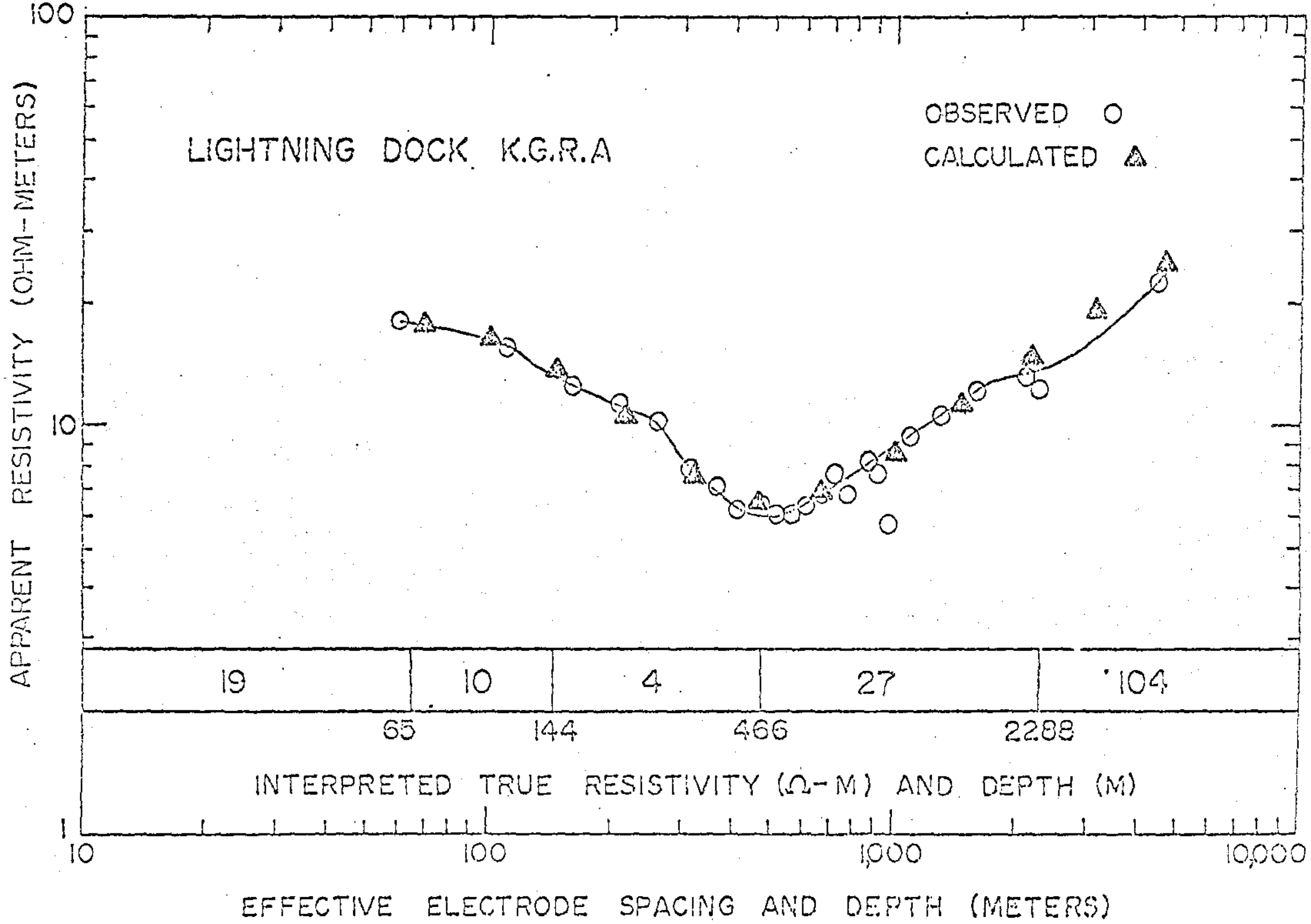


Figure 32. Combined asymmetric Schlumberger and equatorial sounding - Lightning Dock KGRA

loc: 'N of hot wells'

resistivity seen in the total field maps near Valley View Church and to the north. Everywhere north of the bipoles, the observed values in both figures 30 and 31 are less than 30 ohm-m. To the south, apparent resistivities are as great as 50 ohm-m. From this it can only be concluded that the sequence of sediments detected by the resistivity sounding is substantially thinner south of the bipoles. This conclusion is consistent with the gravity data (fig. 29).

Both total field maps show an isolated, closed low resistivity pattern associated with the hot wells. This is to be expected where there is a near surface conductive body of hot, slightly saline water (table 5). The areas of low resistivity are small in both figures, suggesting that the near-surface accumulation of the hot water is small. In figure 30, a small ellipse of low resistivity lies to the northwest of the hot wells. In figure 31, a larger area can be seen directly at the hot well. This difference is probably a function of bipole orientation but it does establish that hot water is present to the west of the hot well.

A shallow (1 to 2 m) ground temperature and temperature gradient survey in the area surrounding the hot wells (fig. 33) reveals that hot water may be present to the north as well. Kintzinger (1956) reported a thermal gradient of $10^{\circ}C/m$ and found an isolated eye of highest temperatures near the southernmost of the hot wells. Further to the south the measured temperatures dropped $10^{\circ}C$ in less than 200 m. To the north the ground temperature remained consistently higher, dropping $10^{\circ}C$ at 2,000 m. The overall pattern of Kintzinger's mapping is a fanlike shape spreading from the hot wells to the north.

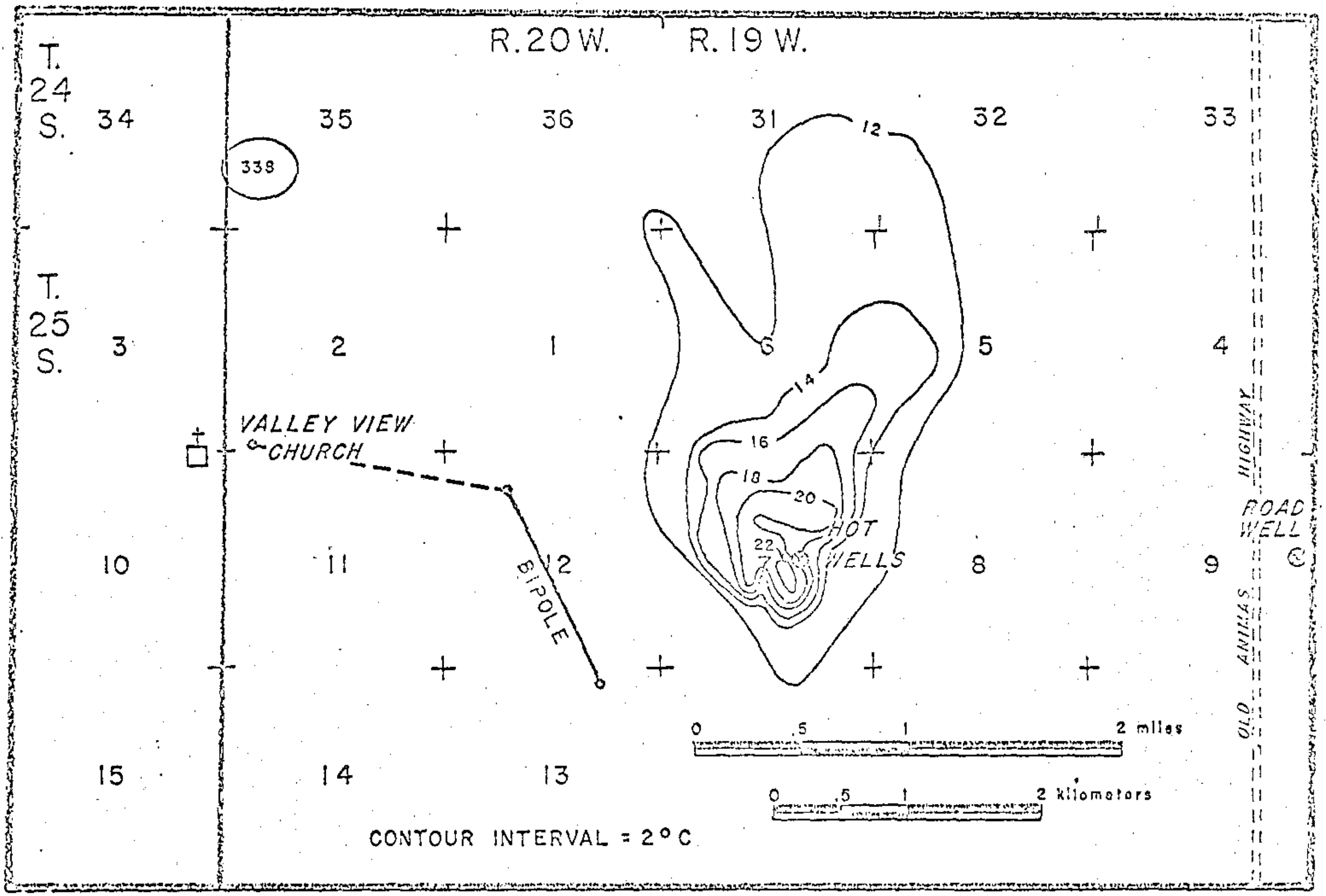


Figure 33. Ground-temperature map, 1 m below surface - Lightning Dock KGRA (after Kintzinger, 1956)

This shape can be explained by data from the ground water study of Reeder (1957). Ground water in the Animas Valley flows from south to north, with local recharge from the flanking mountains. Thermal water meeting low temperature ground water at an isolated location near the hot wells would apread in the pattern of figure 33. Kintzinger's study suggests that the low resistivities (< 15 ohm-m) observed as far as 4 km to the north of the hot wells in figures 30 and 31 may be associated with hot water. The conductive water appears to be present to the west and north of the hot wells and may mask the electrical signature of deeper, more resistive structures.

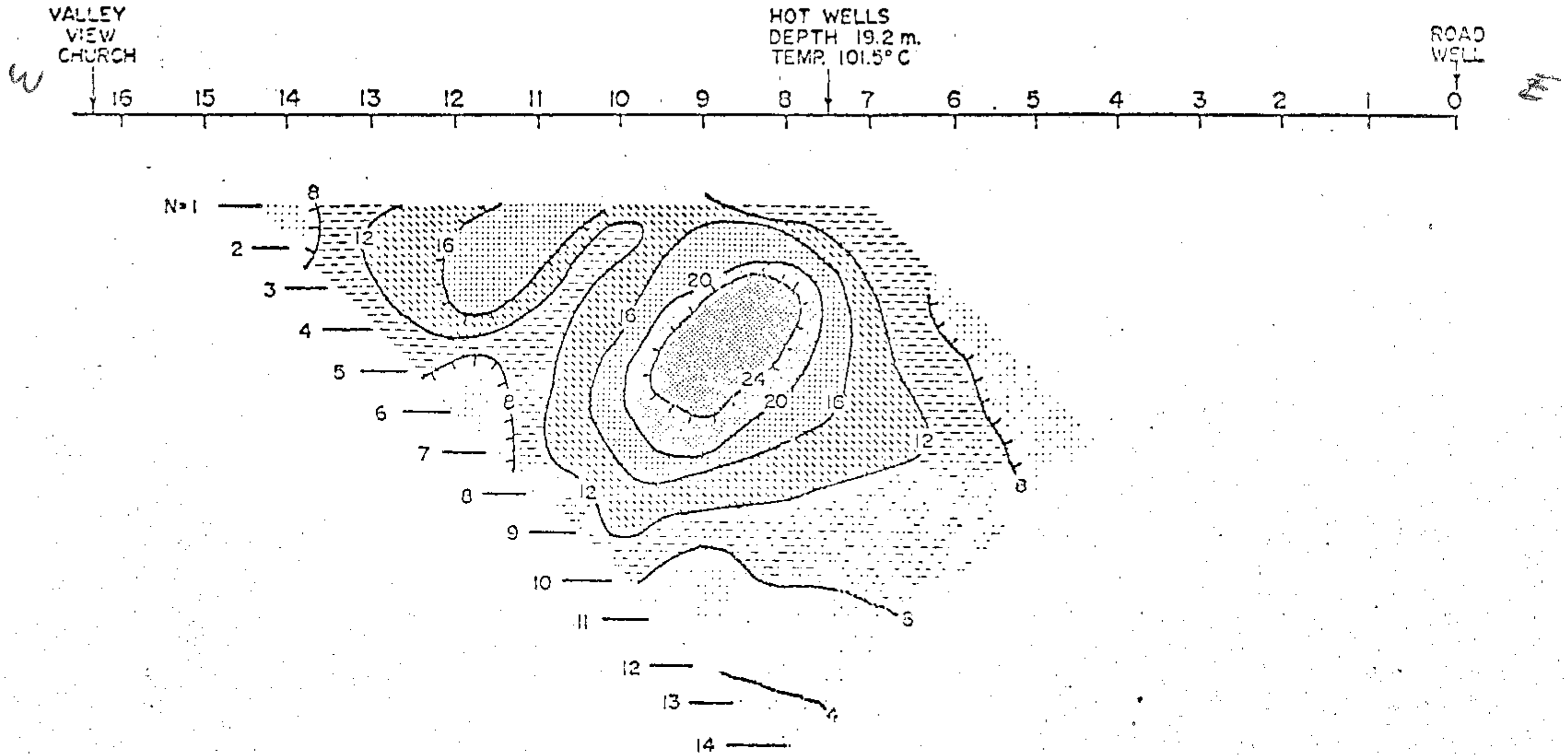
East of Cotton City and south of the bipoles, both total field maps show a large area of resistivities greater than 20 ohm-m. In figure 30 this high resistivity region extends through the hot wells and curves to the northwest. North of Road Well it links with the high resistivities associated with the basement rock of the Pyramid Mountains. In figure 31, the high resistivities continue to the east of the hot wells. They terminate 1 km short of a peninsula of high resistivity that points at the hot wells from the northeast.

This irregular continuity of high resistivities which extend from east of Cotton City through the hot wells to the northeast corner of the maps has been called a high resistivity ridge (Jiracek and Smith, 1976; Lange, 1977). The small anomalies of low resistivity associated with the hot water may be superimposed upon the higher resistivities of the ridge. The agreement between the location of the ridge in figures 30 and 31 suggests that it is the electrical signature of a large structure below the hot wells.

The total field data do not determine the nature of the structure that causes the high resistivity ridge. However, the trend of the ridge continues the curve of the rhyolite and latite domes of the Pyramid Mountains Volcanic Complex (fig. 28). This is interpreted to be evidence for the presence of the caldera below the hot wells. This interpretation coupled to the abrupt termination of the Holocene fault shown by Reeder (1957), suggests that a conduit for the hot water is caused by the intersection of the mid Tertiary caldera by the recent fault.

Figure 34 is a dipole-dipole psudosection generated with both 500 and 1,000 m dipoles. A pseudosection is an electrical cross section with an indefinite vertical scale. The greatest separation of the dipoles was 15 (500 m) dipole lengths. The shorthand for this separation is N=15; N represents one dipole length. The pseudosection extends from Road Well on the east, through the hot wells, and along the east-west bipole of figure 30 to Valley View Church on the west. The east-west bipole spans stations 12 and 16. Recognizable similarities between the total field map (fig. 30) and the pseudosection (fig. 34) give a three dimensional view of geologic structure near the hot wells. The lowest values of apparent resistivity (< 4 ohm-m) appear at the greatest separation; the highest (> 24 ohm-m) in the center of the figure below the hot wells.

Apparent resistivities of less than 12 ohm-m are found on both sides of the pseudosection. These areas were also detected as regions of low resistivity in the total field surveys. The western low



LIGHTNING DOCK K.G.R.A. DIPOLE–DIPOLE PSEUDOSECTION
X=500 m, ρ_a IN OHM-M, C.I.=4 OHM-M

Text: 'composite using 500 & 1000 m dipoles'

Figure 34. Dipole-dipole pseudosection - Lightning Dock KGRA

resistivity region undoubtedly reflects the thick section of saline water saturated sediments near Valley View Church. The area on the east near Road Well may also be a relatively thick sequence of conductive material.

For dipole separations of 10 dipole lengths and greater, N=10, the transmitter dipoles were located near Valley View Church and the receiver dipoles near Road Well; both were in conductive regions. Analyses of the directions of the total field data from the east-west bipole reveal that the electric field direction near Road Well was as much as 76° oblique to the orientations of the receivers. Because of this, only a fraction of the electric field was measured for the distant dipole-dipole soundings. Accordingly, the computed apparent resistivities are low. The low values at the bottom of the pseudosection are, therefore, not indicative of a conductive body at depth. They are the product of the location of the dipoles in the conductive areas and the three dimensional distortion of the electric field. The pseudosection does not contain data relevant to deep structure below approximately N=10.

A large high resistivity bull's-eye below the hot wells dominates the pseudosection and represents a cross section of the high resistivity ridge. There can be no doubt that the same geologic structure is responsible for the bull's-eye in the pseudosection and the ridge in the two total field maps. The shape of the structure can be partially determined by the pattern in the pseudosection. Even though it is obliterated by the 'false anomaly' at the bottom of the pseudosection, this structure appears to become broader with depth. It does not extend to the surface. The 24 and 20 ohm-m contours seem to point to stations 6 and 7. Their pattern suggests that the structure narrows nearer the surface and is nearest the surface just east of the hot wells. These patterns correlate well with the total field maps.

West of the bull's-eye, a distinct, narrow finger of low apparent resistivity (< 12 ohm-m) points at the hot wells. This conductive zone is constricted by the bull's-eye on the east and a smaller area of higher resistivity on the west. It becomes more conductive with depth and may be a conduit for hot water. The inferred conduit is just to the west of the hot wells. This interpretation correlates well with the total field data.

Preliminary results from a computer routine developed by C. M. Swift, Jr. that models dipole-dipole pseudosections are shown in figures 35 and 36. The program takes a two dimensional model of earth resistivities and generates the corresponding theoretical pseudosection. Figure 35 is the computed pseudosection generated from the model of figure 36. The pattern of figure 35 has the same general sense as the observed data in figure 34. However, the fit of the two soundings could be substantially improved. The earth resistivity model (fig. 36) dramatically shows the high resistivity ridge, the flanking sediments, and a 4 ohm-m zone pointing at the hot wells that may be a conduit for hot water. Detailed modeling is beyond the scope of this thesis; more work needs to be done to produce a mathematical model that duplicates the observed data.

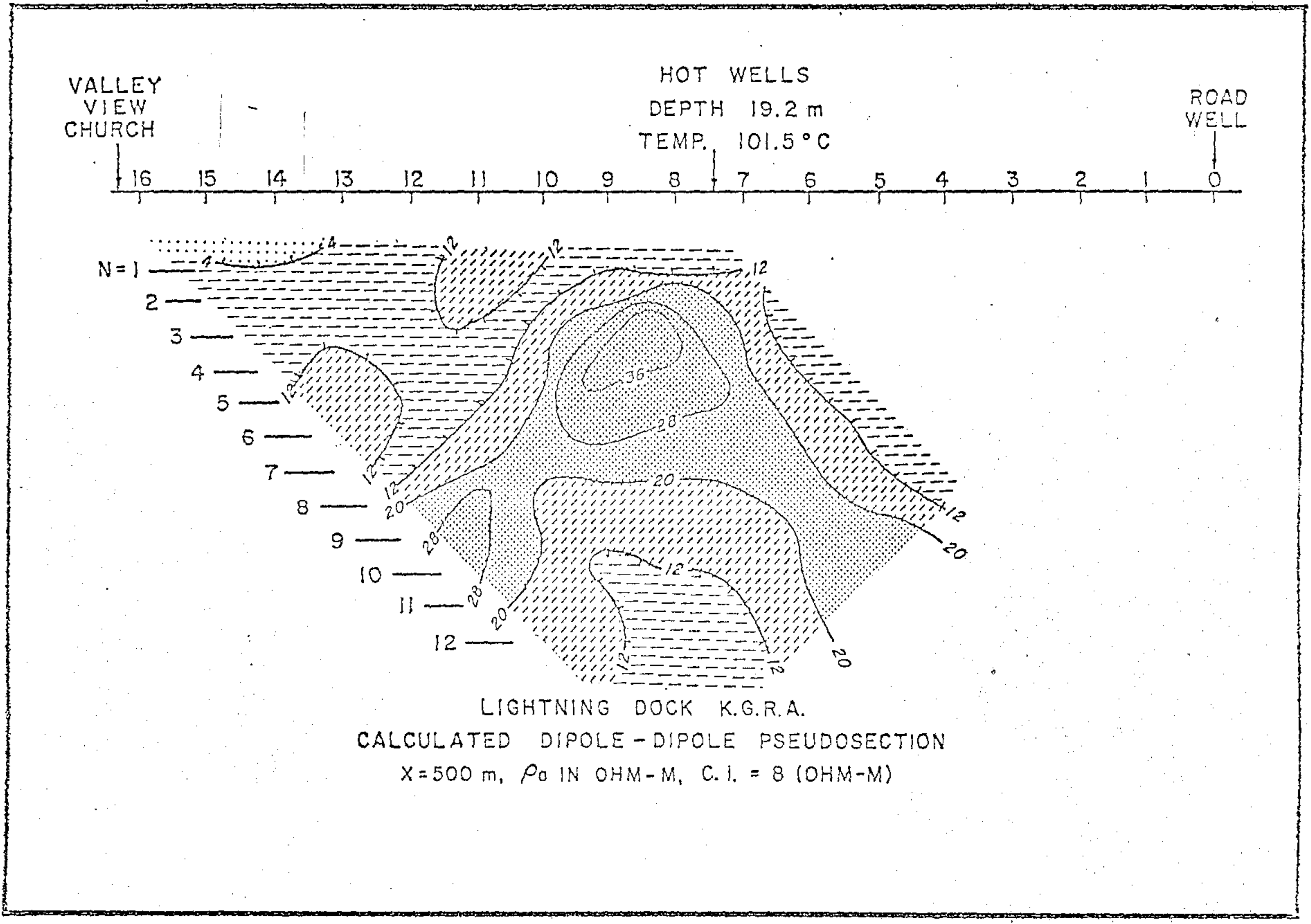


Figure 35. Calculated dipole-dipole pseudosection - Lightning Dock KGRA

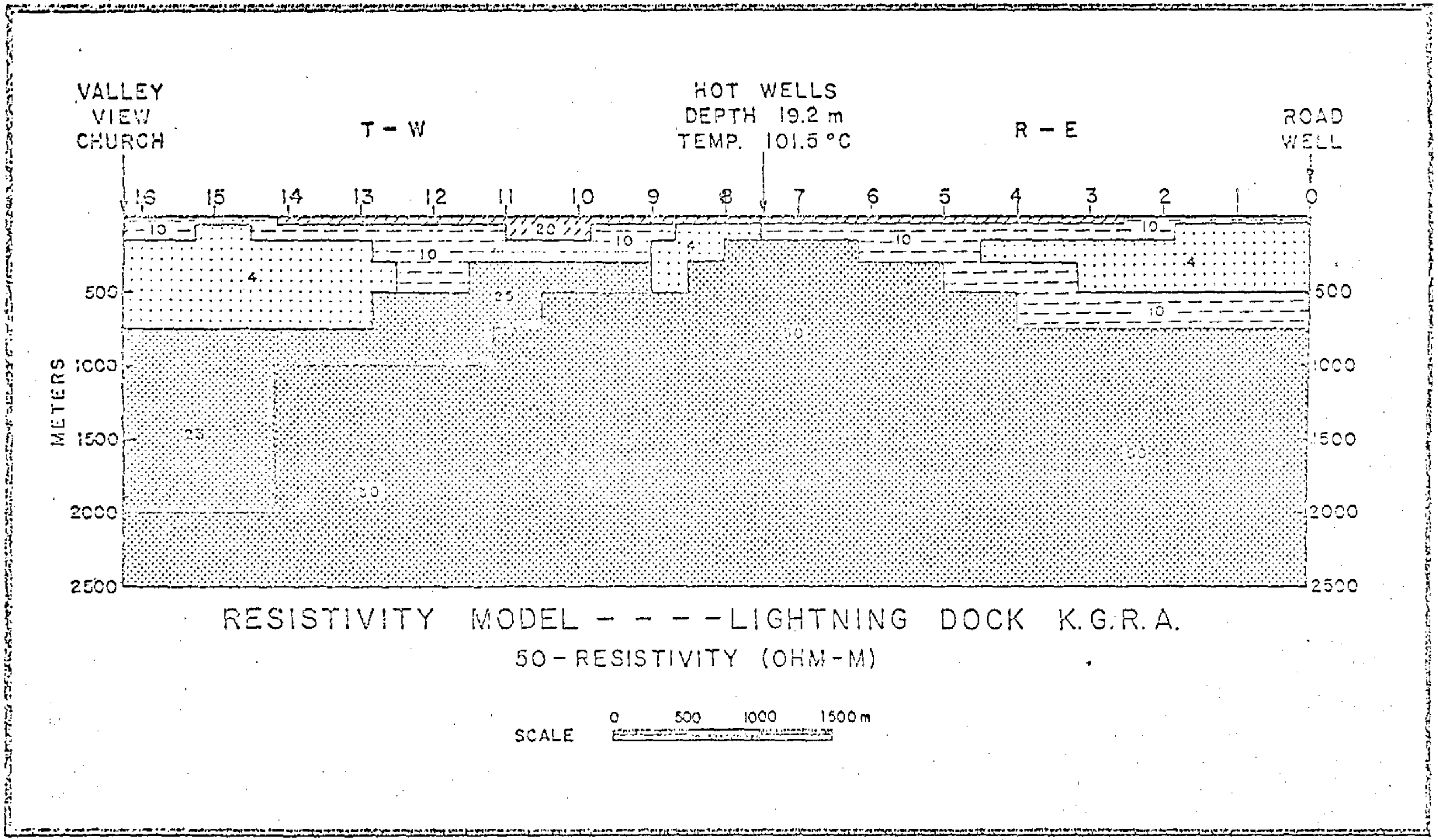


Figure 36. Resistivity model for figure 35

Work in Progress

Data collection during the second field season at Lightning Dock KGRA was hampered by floods. Total field surveys south of the areas of figures 30 and 31 were not attempted. Such surveys could define whether or not the high resistivity ridge curves southeast to join full-circle with the inferred location of the ring-fracture of the Pyramid Mountains Volcanic Complex. The data that were obtained are presented in figure 37. This figure shows the correlation of all the available geophysical information along the east half of the dipole-dipole pseudosection. The telluric profiling technique indicates the presence of a resistive structure below the hot wells. Gravity shows a positive anomaly in the same area. A self-potential survey reveals a negative anomaly over the hot wells - the meaning of this result is obscure. Preliminary results of a limited magnetotelluric survey (not shown) indicates that the high resistivities below the hot wells are underlain at a depth of about 5 - 10 km by a conductive layer. All the data show that there is some kind of highly resistive or dense structure below the hot wells.

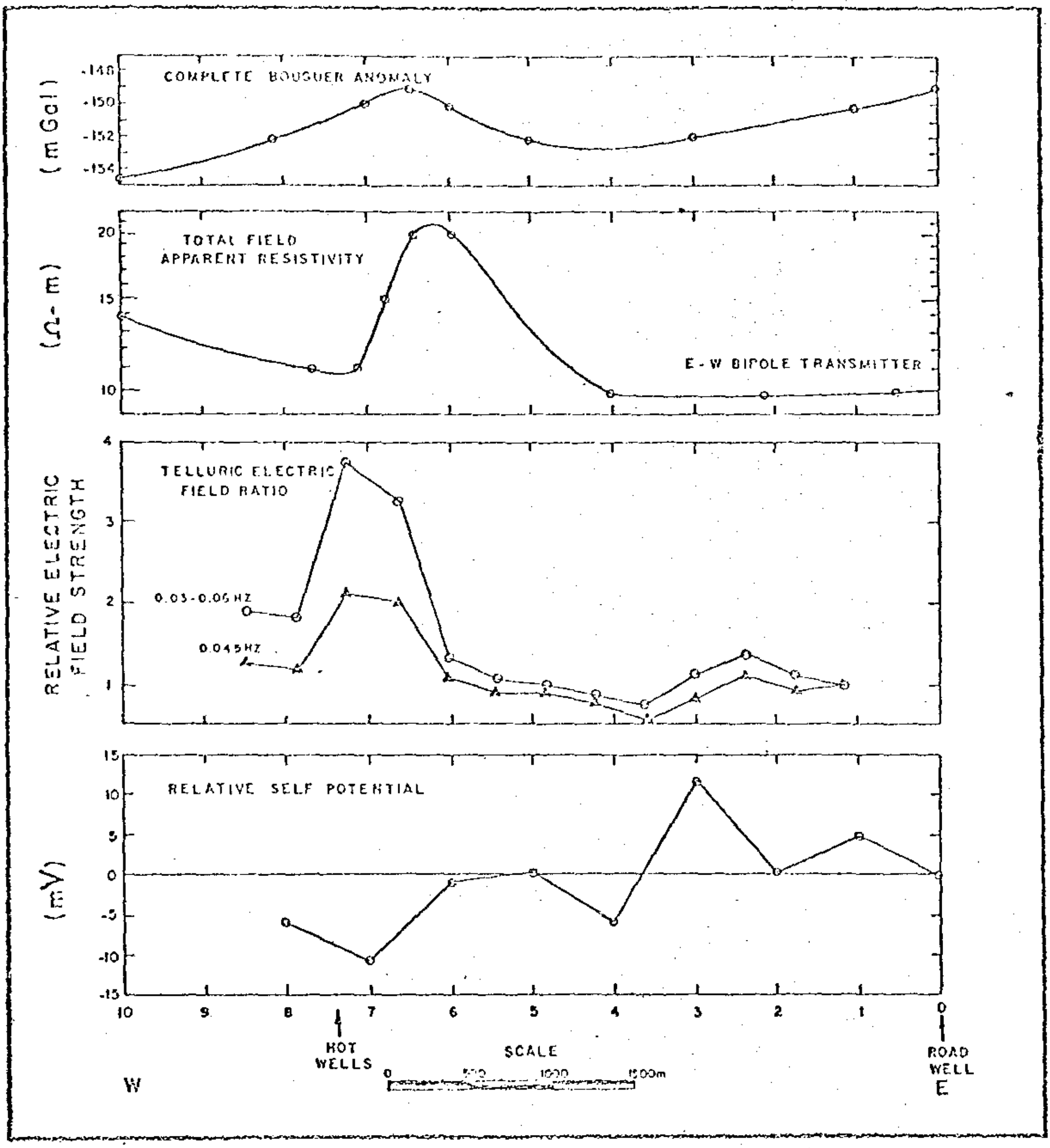


Figure 37. Comparison of various geophysical parameters along the eastern half of the dipole-dipole pseudosection - Lightning Dock KGRA

Conclusion

The electrical surveys at the Lightning Dock KGRA detected a high resistivity ridge both in plan-view and cross section. No positive identification of the ridge is possible, but all available geologic evidence suggests that the ridge may be associated with volcanic domes of the Pyramid Mountains Volcanic Complex. A low resistivity zone is associated with the high resistivity ridge and may be a conduit for hot water. The inferred conduit may be controlled by the intersection of recent Basin and Range faults and the ring-fracture zone of the mid Tertiary caldera.

SUMMARY

It appears that the Radium Springs and Lightning Dock geothermal resources areas are products of superimposed episodes of tectonism. Both occur where Miocene and younger Basin and Range faults intersect Oligocene and older structures. At Radium Springs KGRA, a Laramide anticline may be a reservoir for the hot water. At Lightning Dock KGRA, a caldera complex may provide a conduit for deeply circulating ground water. At both areas, Basin and Range faults are near the hot springs or wells.

The electrical resistivity experiments defined thermal aquifers at all three areas and associated structures at Radium Springs and Lightning Dock KGRAs. Continued work is needed at Las Alturas Estates to determine the extent of the aquifer and the structure(s) than control(s) it.

These experiments did not attempt to fathom the source of the heat for the hot water. Magnetotelluric surveys are more appropriate for the required depth of sensing. Delineating the heat source, if possible, may be the logical next step towards a more complete evaluation of these geothermal resource areas.