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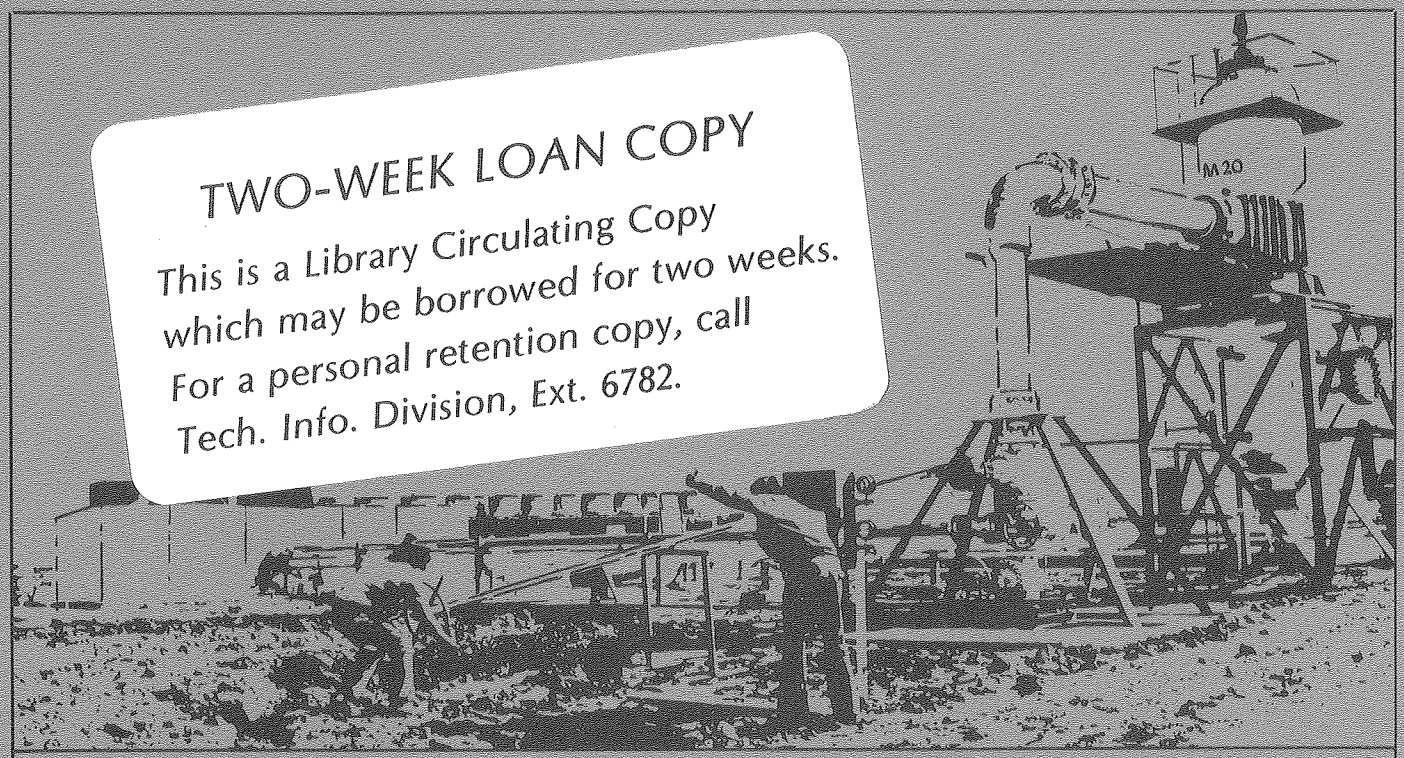

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MAGNETOTELLURIC STUDIES AT CERRO PRIETO

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ABSTRACT

Ten magnetotelluric soundings were made near the production zone at Cerro Prieto, bringing to 17 the number of stations occupied in and around the geothermal field during 1978 and 1979. Results from the first seven soundings were reported elsewhere (Gamble et al., 1979). Data were analyzed in the field using a DEC LSI-11 microcomputer installed in a recording truck. The new soundings provide new information on the geometry of the geothermal system. We find evidence for a narrow resistive zone plunging southeastward, at a shallow angle, from a concealed apex a few hundred meters north of the power plant. This zone comes within about 500 m of the surface and can be traced roughly 5 km to the south. This zone correlates very well with a region of hydrothermal metamorphism, which has been identified by means of detailed studies of cores and cuttings from wells. The three dimensionality of this feature, combined with the influence of the large resistivity contrast between valley sediments and Cucapa Range granites 10 km to the west, makes a rigorous quantitative interpretation impractical. Although such an interpretation awaits further advancements in the techniques of calculating electromagnetic scattering by complex geological structures, the general picture seems clear. A comparison of the subsurface resistivity model with the position of the production zone and with subsurface geology suggests that the heat source lies at depth, roughly 4 km south-southeast of the present power plant.

North of the power plant a two-dimensional interpretation of the magnetotelluric data is possible. A good fit between observed and calculated parameters is obtained for a subsurface model that is consistent with the model derived from dipole-dipole dc resistivity measurements.

INTRODUCTION

To complete magnetotelluric coverage around the Cerro Prieto geothermal field (Gamble et al., 1979), 10 additional stations were occupied during a two-week period in April 1979. Data were obtained using the field system and acquisition procedures developed at U.C. Berkeley and LBL during the last few years. This system uses a remote magnetic field reference for noise suppression, with partial data processing in the field by means of an LSI-11 microcomputer. The purpose of the MT surveys is to determine how well the MT method defines deep geological structure, reservoir boundaries and to supplement subsurface interpretations derived from other geophysical techniques.

DATA ACQUISITION AND ANALYSIS

The sites of the MT soundings performed to date are shown in Figure 1. Stations form three lines: D-D′ located to the north of the plant and trending east-west, E-E′ parallel to D-D′ and through the present production area, and F-F′, also through the field but perpendicular to the other lines and parallel to the geologic strike. The stations along D-D′ were occupied in 1978; the rest in 1979. All soundings were performed using a remote magnetic reference (Gamble, 1978; Gamble et al., 1979a,b).

In 1979 the data were analyzed in the field using the LSI-11 microcomputer. Figure 2 is a block diagram of the field electronics. The referenced signals, consisting of both horizontal magnetic field components, are telemetered to the base station via Sprengnether FM analog telemetry. At the base station, two simultaneous operations are performed on the signals. All signals are sampled at 1 Hz and recorded on a Gould 6000 data logger so that the long period data may be saved for later analysis. Simultaneously, the signals are sent through bandpass Ithaco filters and analyzed via the microcomputer. The sampling rate of the computer could be as high as 6 kHz

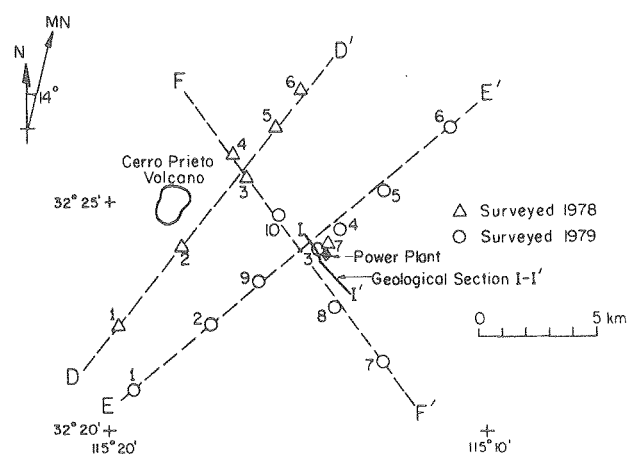

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Figure 1. Location of magnetotelluric stations at Cerro Prieto, Baja California.

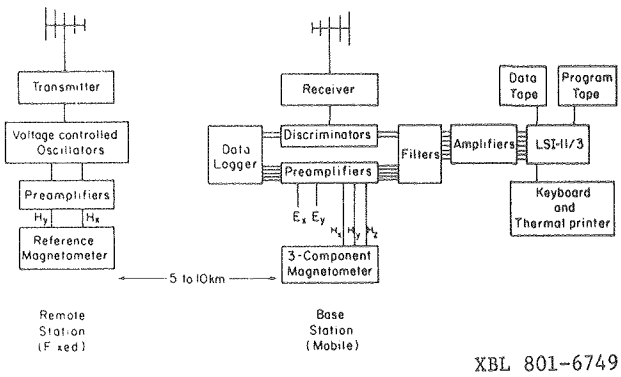

Figure 2. Schematic of the magnetotelluric data acquisition system.

per channel, but the high frequency limit for our system is presently set at 50 Hz by the low-pass filters of the telluric preamplifiers. Numerous difficulties were encountered with the data logger during the 1979 field work so that only the data processed in the field were usable. Thus, the lowest frequency at which results were obtained in 1979 was 0.01 Hz.

The magnetotelluric method provides two complex measures of the electromagnetic response of the earth. The more commonly used one is impedance, Z, which relates the horizontal components of the magnetic field, $\vec{H}$, to the horizontal components of the electric field, $\vec{E}$, by

$$\vec{E}(\omega) = \underset{\approx}{Z}(\omega) \cdot \vec{H}(\omega).$$

The magnitudes of the elements of the 2x2 complex impedance tensor, Z_x are usually presented as apparent resistivities, which are proportional to the squared magnitude of the elements of Z (Gamble et al., 1979a). The second measured response is the tipper, T, which relates H to the vertical component of the magnetic field, H_z, through the relationship

$$H_z(\omega) = T(\omega) \cdot H(\omega).$$

The remote reference method allows one to obtain accurate measurements of Z and T, even when noise is present in both $\vec{E}$ and $\vec{H}$ fields. Using this method we found that about 20% of the measured apparent resistivities have probable errors less than 1% and the root-mean-squared probable error for all the apparent resistivities was about 3%. This is about an order of magnitude better than normally obtained without the use of a reference sensor, and these low errors were achieved despite considerable electrical noise from the power plant and other artificial sources.

After the completion of the survey, data were returned to Berkeley for interpretaton using LBL's CDC-7600 computer. The first step in a quantitative analysis of the results is to find the principal resistivity directions or geologic strike direction. We have developed a program which finds an optimum estimate for the strike direction for a group of stations by minimizing

$$\sum_i [|Z_{xxi}|^2 + |Z_{yyi}|^2] W_i.$$

The summation is over all frequencies and stations under consideration, and W_i is a weighting factor that reflects the statistical confidence of each measurement and the range of penetration of the electromagnetic waves at each frequency. The magnitudes and phases of the apparent resistivity matrix and of the tipper are then plotted in pseudosection form in this fixed coordinate system. The strike was calculated separately for lines D-D′, E-E′, and F-F′ and was found to be 28.4°, 27.9°, and 25.5° west of magnetic north, respectively. We felt that these were sufficiently similar orientations to be treated as identical for the purposes of interpretation.

INTERPRETATION

Currently, magnetotelluric soundings can be inverted to obtain the resistivity of the ground only for the case of a one-dimensional, or layered, earth. Where this condition is satisfied the tipper and the diagonal components of the impedance tensor are zero and the off-diagonal components of the impedance are equal in magnitude and opposite in phase. Station 6, line E-E′, the station farthest from the Cucapas, was the only station for which the results are consistent with a one-dimensional earth over most of the frequency range. We therefore inverted the soundings for this station to obtain a picture of the electrical layering in the Mexicali Valley.

One-dimensional inversions of the apparent resistivity sounding curves for periods up to 30 sec were performed using programs developed by Oldenburg (1979). The models that match the sounding curves for current parallel and perpendicular to the regional strike are shown in Figures 3 and 4, respectively. The resolution

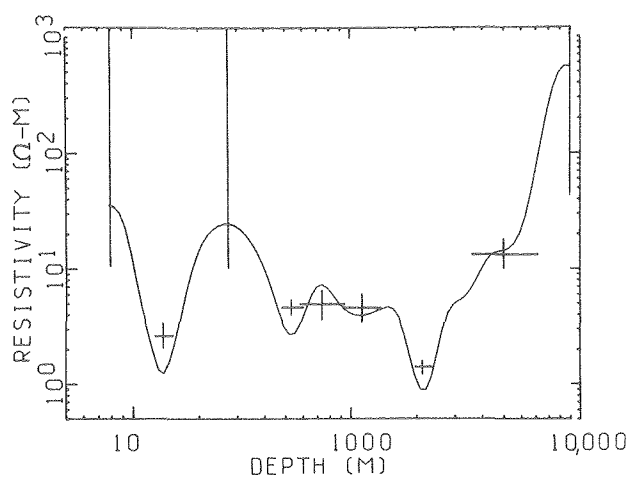

Figure 3. One-dimensional inversion results for station 6, line E-E′; electric field parallel to regional strike (crosses explained in text).

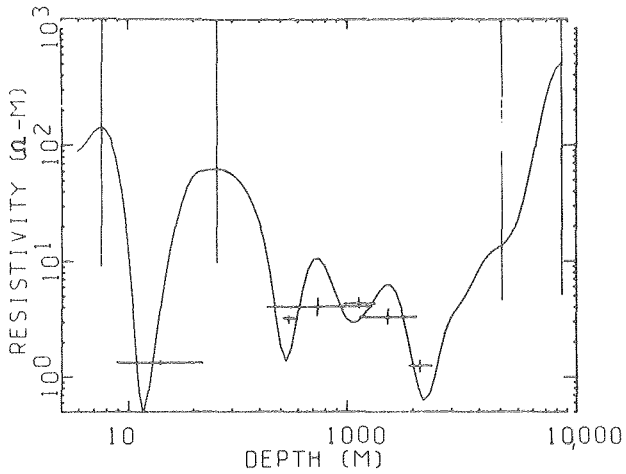

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Figure 4. One-dimensional inversion results for station 6, line E-E′; electric field parallel to regional strike (crosses explained in text).

is defined in the following manner. Weighting functions are formed that have the smallest possible spread in depth around selected depths. Average resistivities are calculated with these weighting functions, and the standard deviations of the average resistivities, due to the statistical uncertainty of the sounding curve measurements, are calculated. Crosses are then drawn at these selected depths and average resistivities so that the vertical line indicates the width of the weighting function at half maximum and the horizontal line indicates the standard deviation of the average resistivity. If it is not possible to form a weighting function whose width is less than the depth under consideration, then only a horizontal line is drawn to show that the resistivity at that depth is not resolved by the measurements. Note that there are two high-resistivity layers near the surface whose resistivities are not resolved. The difficulty in resolving high resistivity layers is inherent in this and other EM techniques because less current will flow in a relatively resistive layer making the sounding curves relatively insensitive to changes in the resistance of such a layer.

Within limits of resolution, the two models are essentially identical. Both show a thin conductive zone of about 1 ohm-m near the surface between relatively resistive layers. The range of resistivities and thicknesses of the resistive layers are slightly larger in Figure 4, but the difference is not large enough to be important. Both models show a general decrease in resistivity with depth, culminating in a well-resolved conductive layer, 0.8 ohm-m, from about 1.9 to 2.4 km depth. A similar picture has been derived from well logs in the general area (D. Lyons, personal communication) and from dipole-dipole resistivity results (Wilt et al., 1979).

It has been suggested that the resistivity variations indicate a transition downward and westward of fresh-water (Colorado River) saturated sediments near the surface to brackish and sea-water-saturated sediments above the basement. Temperature effects are probably important; the deep conductive layer may represent a reservoir of hot, saline fluids. Below this layer resistivities increase, terminating in the resistive basement zone at >5 km. However, between 2.4 and 5 km we see evidence for above-basement layering, possibly altered volcanics and sediments. The deep structure and basement are not well resolved. This is not due to the limitation of the range of frequencies for which the sounding was performed, but rather to the influence of the Cucapa Range, which causes the curves for the two directions of current to diverge at periods longer than 30 sec, thereby invalidating the simplifying assumption that the data can be interpreted by means of horizontal layers only.

Where the earth appears two-dimensional, as along line D-D′, an automatic inversion of the apparent resistivity pseudosections can be made in the sense of finding optimum resistivities for a specified geometrical arrangement of isoresistivity units. Unit boundaries must first be defined, usually from repetitive and tedious forward-model calculations, or from other geological and geophysical data sources (e.g., a dipole-dipole two-dimensional model). Two-dimensional conditions are recognizable because the tipper component in the geologic strike direction is near zero and, in a coordinate system aligned with geologic strike, the diagonal components of the impedance tensor are small. A preliminary resistivity model along line D-D′ was presented earlier (Gamble et al., 1978). After minor changes this model has been refined to yield one giving a much better fit to the observed magnetotelluric responses. The final model is shown in Figure 5. The 41 ohm-m block at the surface at the west end of the line is not meant to represent a distinct geologic unit, rather it is included to compensate for the extra current paths within the Cucapa Range that rise above the

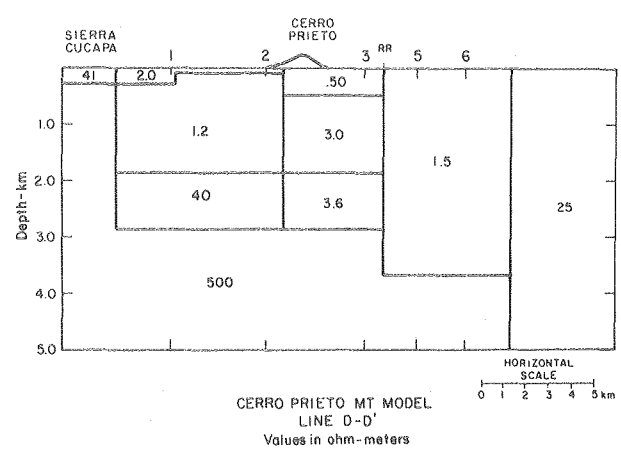

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Figure 5. Two-dimensional interpretation of resistivity fitting the magnetotelluric results at stations along line D-D′.

valley floor. Similarly, the 25 ohm-m block at the eastern end of the line is not meant to indicate that there is a single block extending from the surface to infinite depth. The magnetotelluric data required that there be some relatively high resistivity material beyond the eastern end of the line at indefinite depths and the single block is the simplest way to allow for this.

The calculated apparent resistivities for this model are compared with the measured apparent resistivities in Figures 6 and 7 for current parallel and perpendicular to strike, respectively. The high resistivity granite of the Cucapa Range beyond the west end of the line affects apparent resistivities all along the line, increasing the apparent resistivities toward the west and at longer periods for the TE mode (Fig. 6), and decreasing apparent resistivities with depth for the TM mode (Fig. 7). Another prominent feature is the low apparent resistivities at Station 3 caused by the low resistivity surface zone (0.5 ohm-m) in the area of the hot springs near the Cerro Prieto volcano. An apparent resistivity for current parallel to geologic strike (Fig. 6) is lower than for the perpendicular direction, indicating a conductor aligned with regional geologic strike. We may be observing the effects of fluid flow in a plane conformable to regional strike, and this could relate to enhanced permeability parallel to the Cerro Prieto fault.

Although the sounding curves are consistent with a 1.7 ohm-m resistivity from 0.5 to 3.0 km depth everywhere beneath stations 3, 5, and 6, we do find a slightly better fit when the resistive 3.0 and 3.6 ohm-m blocks are placed below station 3 as shown in Figure 5. This model seems to suggest a zone of decreased porosity due to hydrothermal alteration bounded on either side by steeply dipping faults; the Cerro Prieto fault on the west end and the Michoacán fault on the east. This model does not unequivocally confirm the suspected basement horst between the two faults because the isoresistivity blocks may be more indicative of hydrothermal over-printing than original lithology. Thick sections of conductive rocks, probably saturated with saline water, bound the resistive zone. Between the Cerro Prieto fault and the range-bounding Cucapa fault, seismic evidence shows a deep trough filled with a shale-sand sequence, possibly marine, that correlates well with the 1.2 ohm-m block. Below this the seismic reflection suggests volcanics above basement (D. Lyons, personal communication) which may be evidenced by the 40 ohm-m zone.

It is interesting to compare the section determined from the magnetotelluric soundings with that derived from the dipole-dipole dc resistivity survey shown in Figure 8 (Wilt et al., 1979). The magnetotelluric soundings along D-D′ obtained reliable results for periods as long as 1000 sec, which corresponds to a depth of penetration of 20 km in 1.5 ohm-m ground, deeper in more resis-

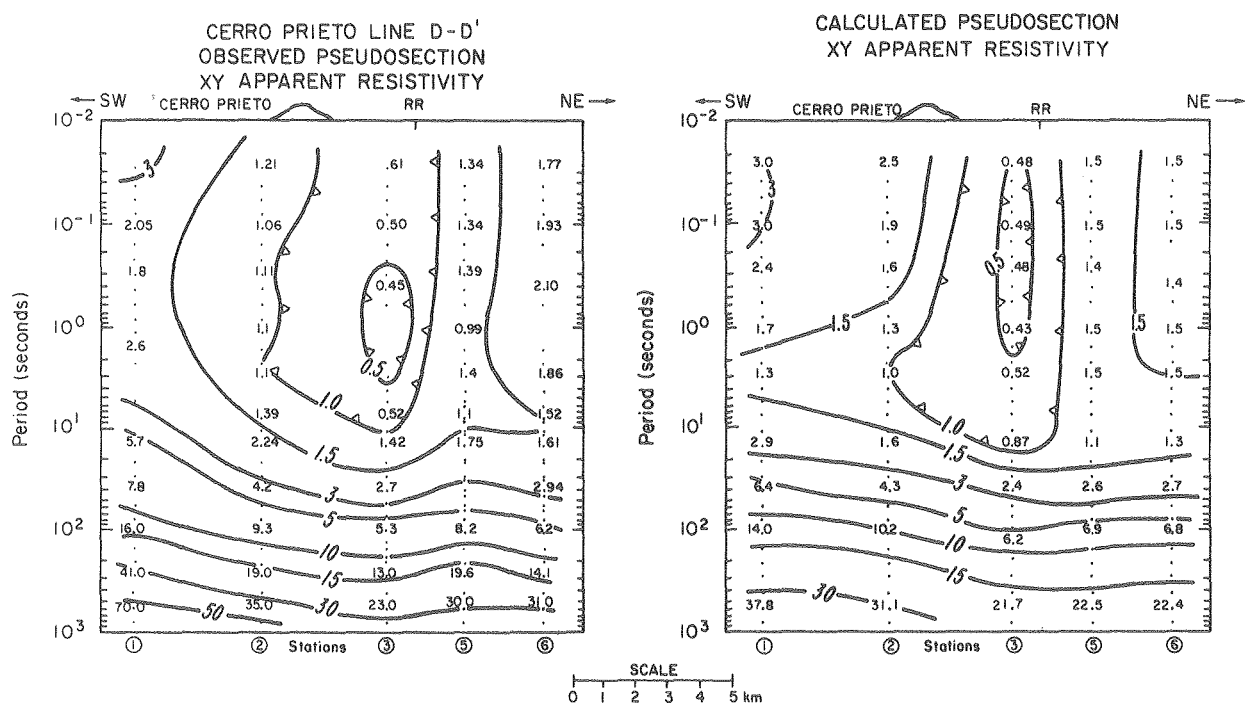

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Figure 6. Observed and calculated apparent resistivity pseudosections, line D-D′, current parallel to geologic strike.

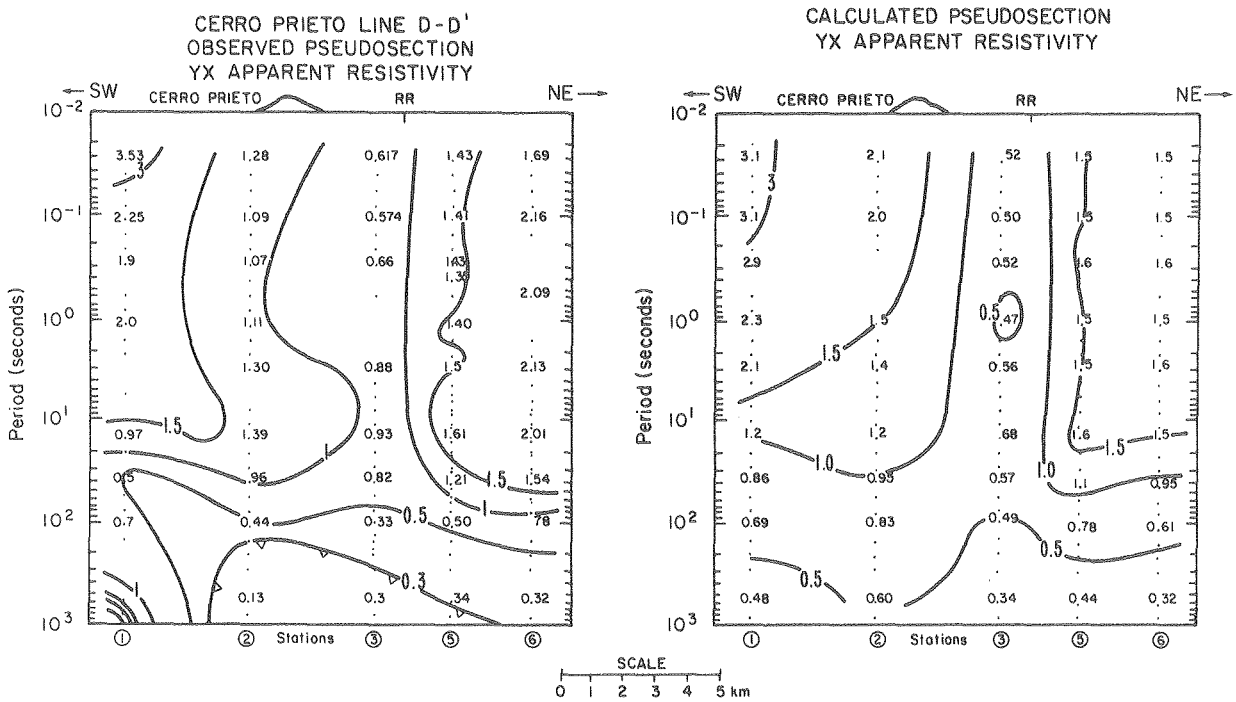

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Figure 7. Observed and calculated apparent resistivity pseudosections, line D-D′, current perpendicular to geologic strike.

tive material. The only substantial disagreements between the two models occur below 2-km depth where dc resistivity interpretation tends to become less reliable because of poorer signal-to-noise ratios and loss of resolving power due to the large electrode separations (Wilt et al., 1979). The 50 ohm-m block at 1.3-km depth in Figure 8 is not consistent with the 3 ohm-m block found at the corresponding position in Figure 6. The 40 and 3.6 ohm-m blocks of Figure 6 indicate that the basement is considerably deeper than indicated by the 300 ohm-m material of Figure 8.

The tipper was not used in the generation of the model of Figure 6 so it is worthwhile to compare the tipper calculated from that model with the measured values as an independent check. The measured and calculated pseudosections are shown in Figure 9. The agreement is excellent, verifying the general reliability of the two-dimensional model.

For lines E-E′ and F-F′ there are marked indications of three dimensionality where the lines cross the production zone. In Figure 10 we present the magnitude of the tipper on line F-F′ for current flow perpendicular to strike; that is, the magnitude of the coefficient that relates the vertical magnetic field to the magnetic field in the strike direction (27° west of magnetic north). If the earth were two-dimensional, then this component of the tipper would be zero. We found it to be nearly zero along line D-D′. We see that, in contrast, the magnitude is very large, reaching a maximum of 1.07 at 1 Hz at station 3, just north of the power plant. This indicates a large lateral variation in resistivity in the north-south direction, and the tipper phase indicates that the resistivity is greater to the south. If the resistivity in this region is roughly 2 ohm-m then the depth of penetration at 1 Hz is approximately 700 m and the maximum lateral resistivity contrast must be at roughly 500-m depth.

Figure 11 is the apparent resistivity pseudosection for the same line (F-F′) and the same current direction (perpendicular to regional geologic strike). The low resistivity near the hot springs at the north end of the line produces a significantly lower apparent resistivity at the higher frequencies there. Toward the southern end of the line there is a clear increase of apparent resistivity with a maximum centered near stations 7 and 8. This indicates a large resistive body whose upper limit is roughly 500 m deep. The presence of this body confirms the large lateral gradient of resistivity indicated by the tipper in Figure 10. The large resistivity of the Cucapa granite presents a barrier to current flow and this tends to depress apparent resistivities at periods longer than 20 sec. Thus we can not easily determine the lower limit of the resistive anomaly.

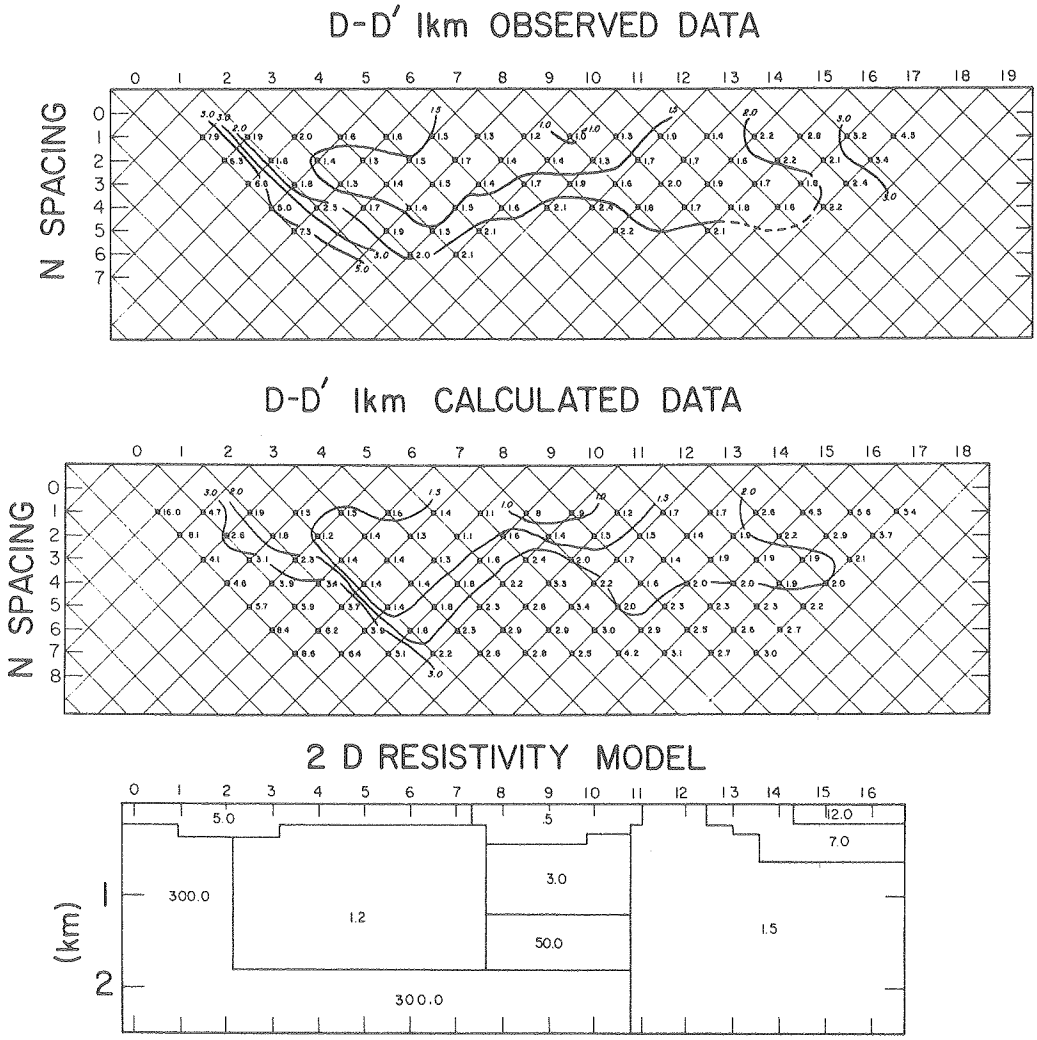

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Figure 8. Dipole-dipole apparent resistivity pseudosection for 1-km dipoles along line D-D'. TOP, field data; MIDDLE, model results; and BOTTOM, two-dimensional model (after Wilt et al., 1979).

Figure 12 shows the apparent resistivity along line E-E′ for current in the regional strike direction. The high resistivity of the Cucapa Range is indicated clearly at station 1, similar to the effect noted for line D-D′ (Fig. 7). The higher surface resistivity at the east end of line E-E′ is also clearly recognizable by the apparent resistivity at the higher frequencies. Note that there is no clear indication of a high resistivity zone in the region of the plant (station 3). This indicates that the resistive region shown in Figures 10 and 11 is either relatively thin or of anisotropic resistivity, which could correspond to a number of alternating conducting and resistive zones.

Even a single forward calculation of the electromagnetic response of such a complex structure is beyond the practical capacity of existing computers and programs. Thus any comprehensive quantitative interpretation of the soundings is impossible. Nonetheless, the qualitative picture is clear and the near-surface resistivities are easily and unambiguously interpretable. The qualitative evaluation we have discussed for Figures 10 to 12 was applied to all 36 pseudosections obtained from these soundings. Figures 13 and 14 show sections of this qualitative picture along lines F-F′ and E-E′, respectively. The 3 ohm-m apparent resistivity of Figure 11 is interpreted as a body of roughly 10 ohm-m intrinsic resistivity. This body presents a large cross section on line F-F′ but is relatively inconspicuous in the perpendicular section (Fig. 14). Again, we cannot distinguish between a single vertical plate and a zone of anisotropic resistivity. We do not yet

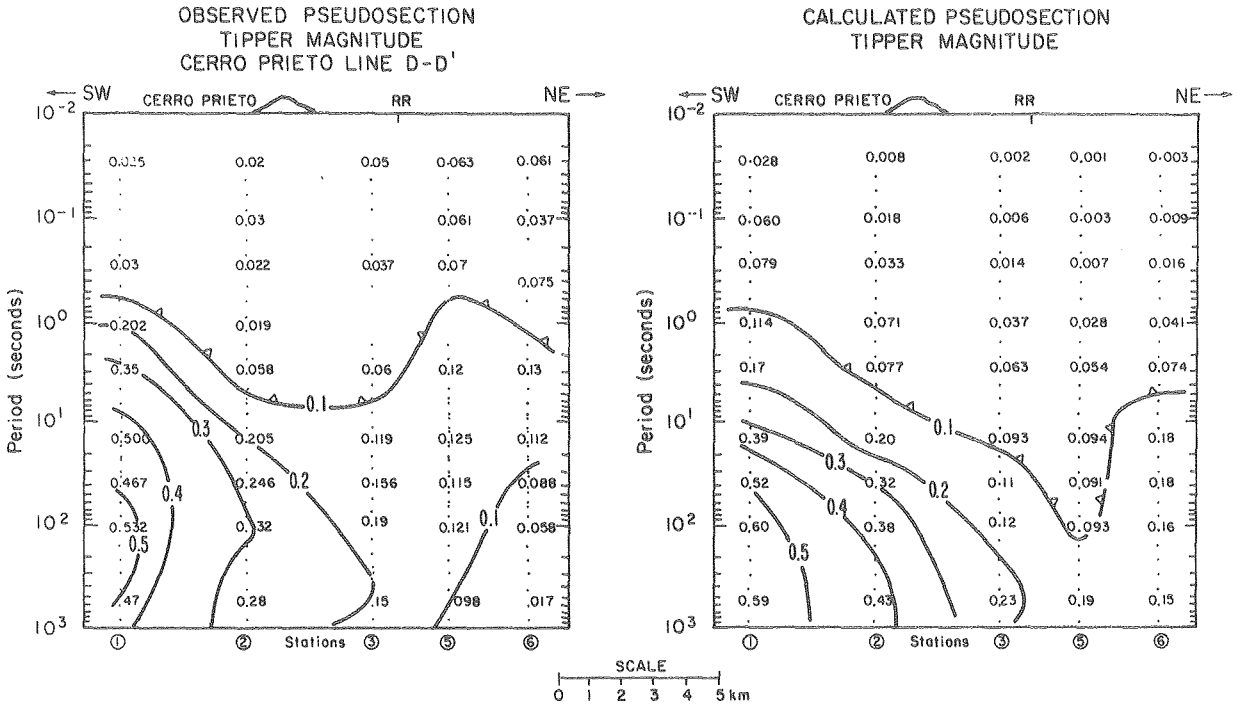

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Figure 9. Observed and calculated tipper magnitude pseudosections, line D-D′, current parallel to strike.

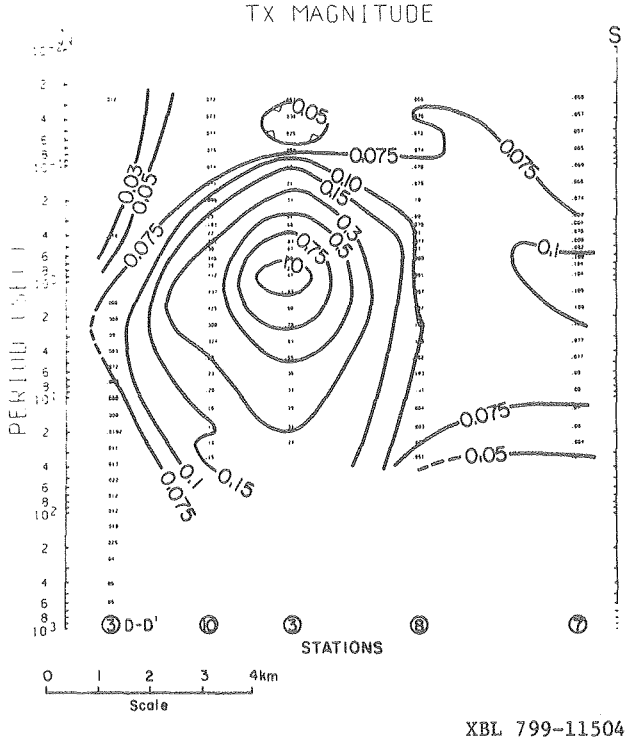

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Figure 10. Observed tipper magnitude for line F-F′, current perpendicular to regional geologic strike.

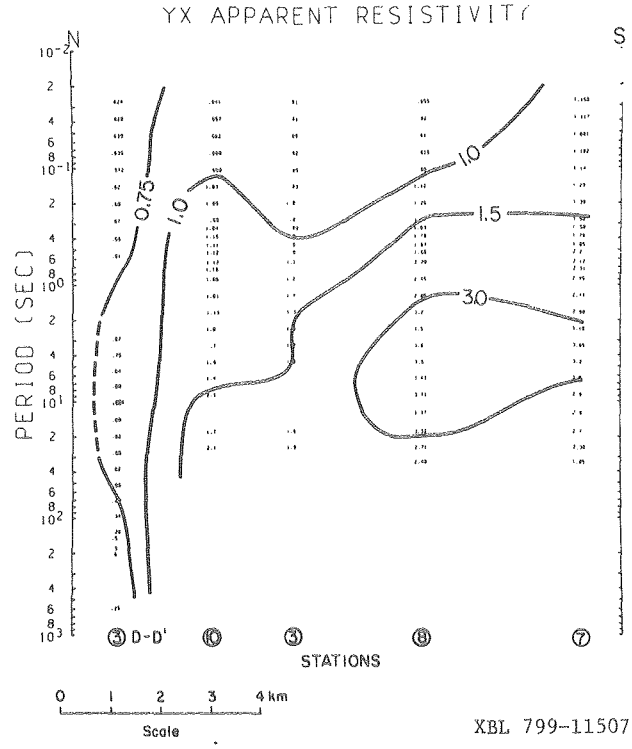

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Figure 11. Apparent resistivity pseudosection along line F-F′, current perpendicular to regional geologic strike.

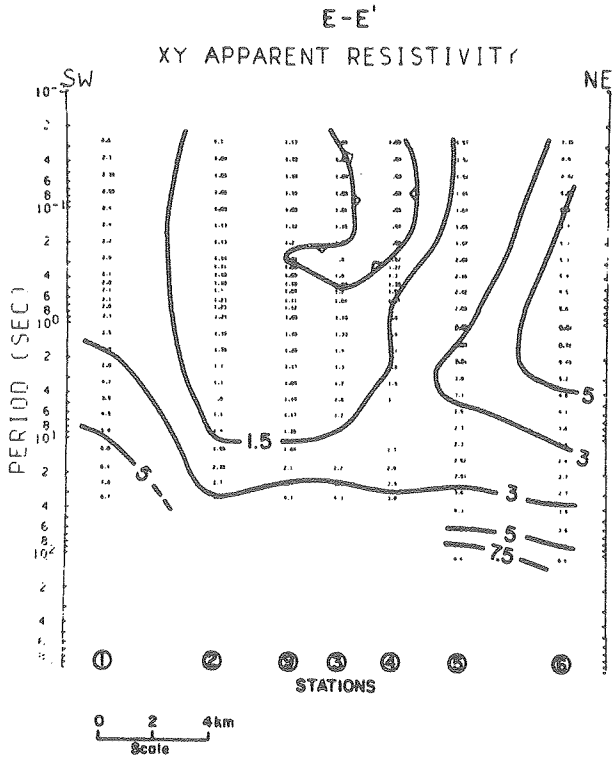

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Figure 12. Apparent resistivity pseudosection along line E-E′, current parallel to regional geologic strike.

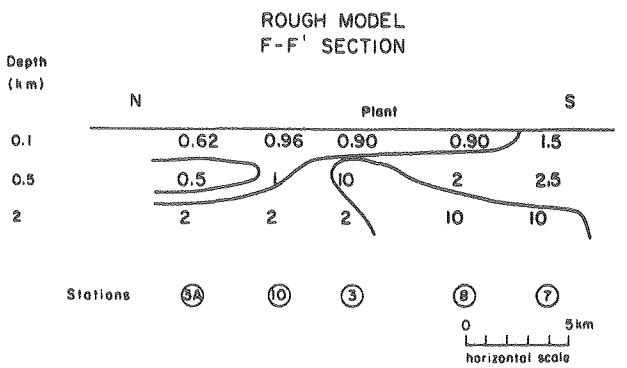

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Figure 13. Semiquantitative estimate of subsurface resistivity distribution along line F-F′, vertical scale logarithmic.

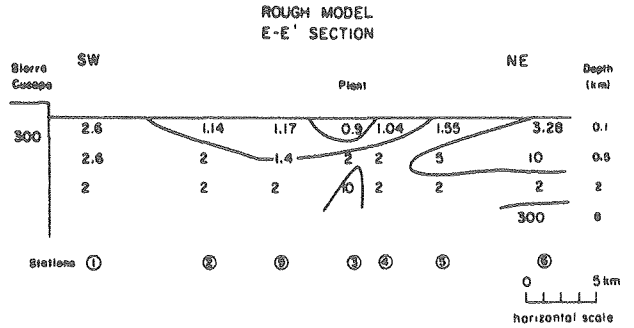

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Figure 14. Semiquantitative estimate of subsurface resistivity distribution along line E-E′, vertical scale logarithmic.

have any soundings distributed over the width of the body in the direction perpendicular to strike that might help us determine its width.

We developed this resistivity model without knowledge of the subsurface geology logs. Therefore, it is important to compare the model to known features of the geothermal field. Figure 15 shows the production zones in wells along line I-I′ of Puente C. and de la Peña, L. (1979), which is subparallel to line F-F′. The boundary of the resistive anomaly from Figure 13 is drawn as a cross-hatched line. As can be seen, the high resistivity zone closely correlates with the approximate halo of hydrothermal alteration (Elders et al., 1979). and the A/B lithologic contact (Puente C. and de la Peña L., 1979).

This resistivity structure suggests a hydrology of the geothermal field in which the water is heated at depth to the south-southeast of the current production zone. The water ascends along north-northwest parallel fractures in a zone of faulting parallel to the regional strike. Where the temperatures exceed 200°C, significant hydrothermal metamorphism occurs, reducing the gross porosity by secondary mineral growth, blocking conduction paths, and increasing formation resistivity to as much as 10 ohm-m. Within 500 m of the surface the waters cool to the point where metamorphism does not occur, but the saline, hot waters cause a reduction of the resistivity to about 0.5 ohm-m in a long thin surface discharge area north of the power plant.

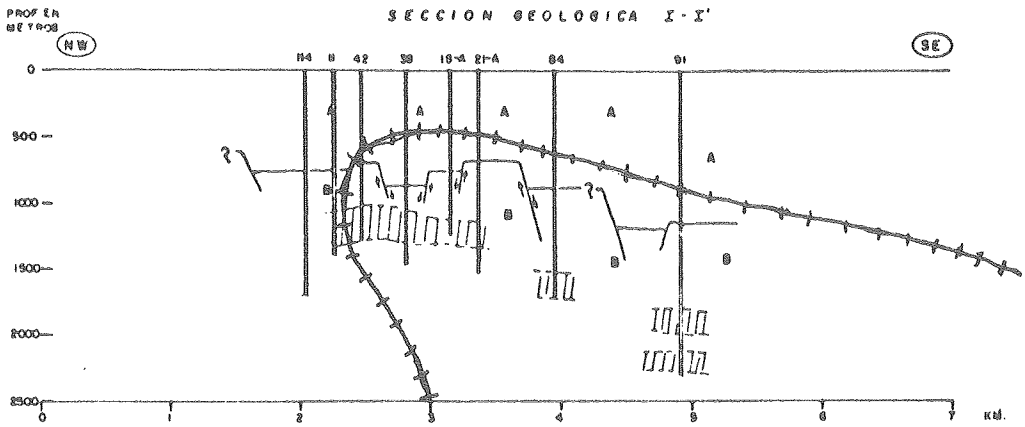

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Figure 15. Approximate relationship between the dipping resistive zone and sub-surface geology.

CONCLUSIONS

The MT survey of 1979 produced the first referenced magnetotelluric data processed in the field. The LSI-11 proved to be a field-worthy instrument and the availability of the information from the referenced measurements in the field was invaluable in insuring the collection of satisfactory data.

Although limited portions of the data can be inverted to yield one- or two-dimensional models, the structure in the region of the production zone is too complex for quantitative interpretation. Nevertheless, the qualitative picture is clear: the current production zone is associated with a significant resistive anomaly.

The shape of the resistive anomaly and a consideration of the geology of the region suggest a deep source of heat approximately 4 km to the south-southeast of the present geothermal power plant. We suggest further measurements to define the extent of the resistive anomaly and to investigate the possibility of other extensions of the geothermal field from this apparent source.

ACKNOWLEDGMENTS

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