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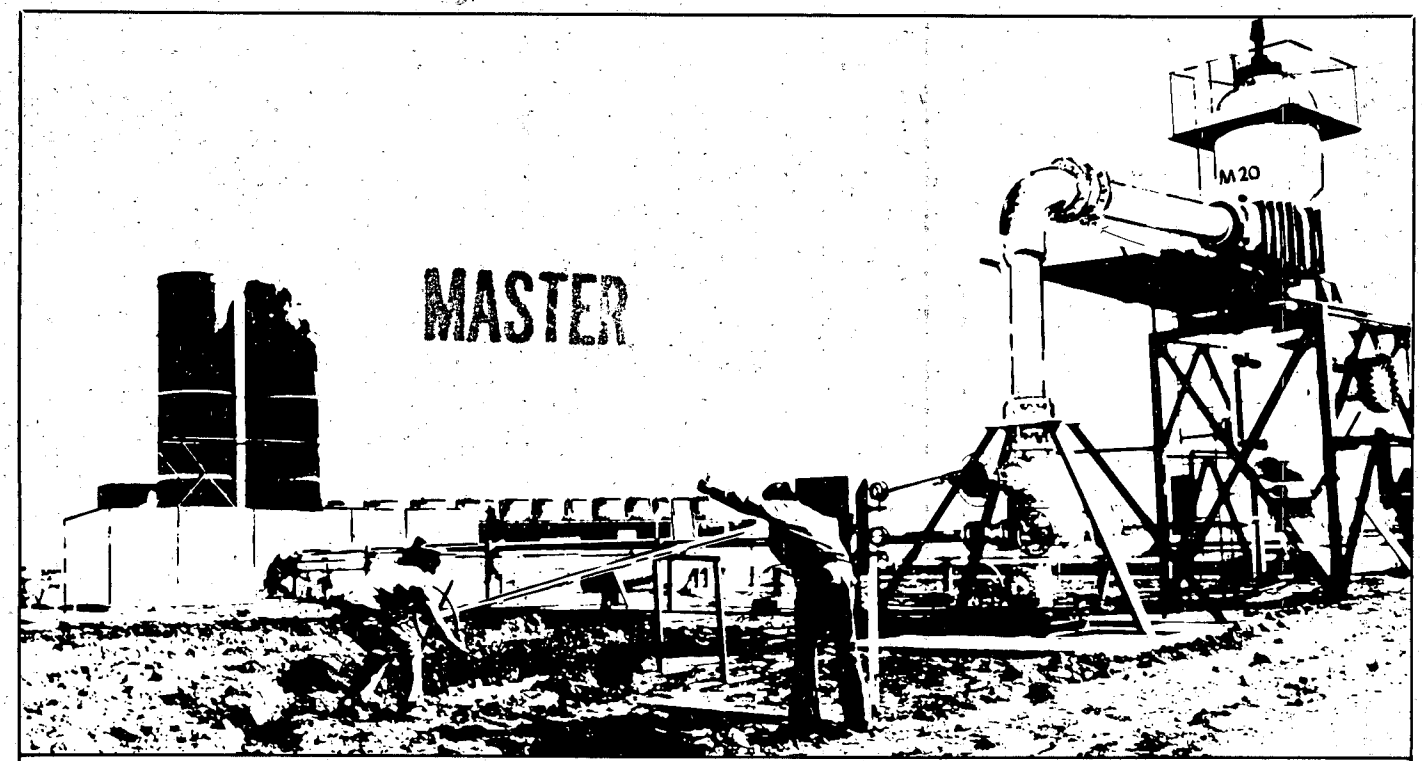
MEXICAN-AMERICAN COOPERATIVE PROGRAM AT THE CERRO PRIETO GEOTHERMAL FIELD



RESISTIVITY MONITORING AT CERRO PRIETO

Michael J. Wilt and Norman E. Goldstein

FEBRUARY 1980

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Coordinadora Ejecutiva
de Cerro Prieto
Apdo. Postal No. 3-636
Mexicali, Bja. Cfa., México
and P. O. Box 248
Calexico, Ca. 92231

Lawrence Berkeley Laboratory
Earth Sciences Division
University of California
Berkeley, California 94720

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ABSTRACT

In 1978 Lawrence Berkeley Laboratory, in cooperation with Comisión Federal de Electricidad, began a program of dipole-dipole resistivity monitoring at the Cerro Prieto geothermal field. Dipole-dipole measurements were first made in 1978, then repeated in 1979: (a) to determine whether the field boundaries could be defined by surface resistivity measurements; and (b) to determine if changes in reservoir conditions due to production may be monitored by surface measurements.

In 1979 data accuracy was improved to where estimated measurement errors were less than 3%. In addition, data coverage on a line over the field was expanded by 40% for greater depth of investigation and more information on the newer, eastern part of the field. Resistivity modeling of the expanded 1979 profile indicates that the resistive body associated with the zone of production (Wilt et al., 1978) dips steeply eastward, and may underlie the eastern part of the field. The model also shows a thin steeply dipping conductor adjacent to the resistive body that may be associated with faulting and fluid movement. Model perturbation studies have shown that small changes associated with cold-water influx, fault zone migrations, and formation of a steam zone would all be detectable with precision dipole-dipole measurements. Telluric profile measurements taken along line E-E′ were found to yield a significant amount of reconnaissance information but are unsuitable for monitoring purposes.

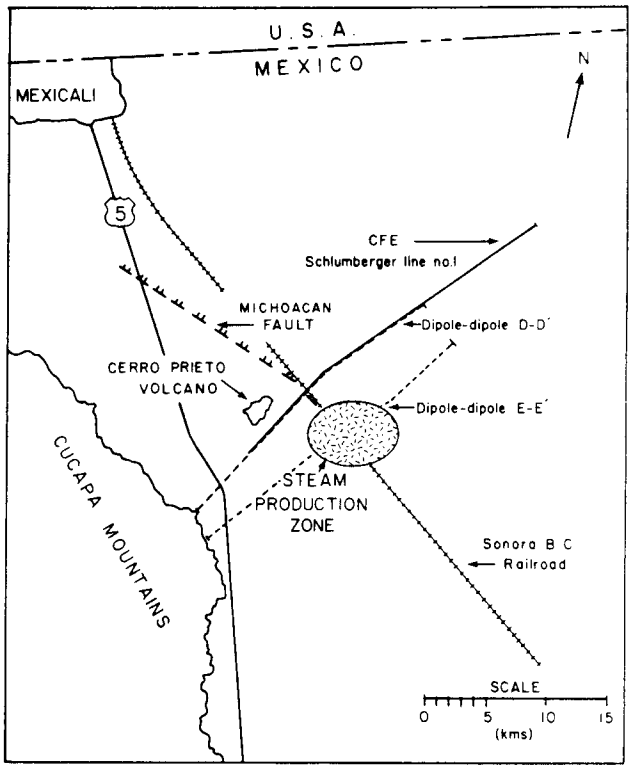

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Figure 1. Project location map, LBL resistivity project.

INTRODUCTION

In 1978 Lawrence Berkeley Laboratory, in cooperation with Comisión Federal de Electricidad, began a program of dipole-dipole resistivity studies at the Cerro Prieto geothermal field. For collecting geophysical data, two east-west survey lines were established; one (E-E′) crossing the central part of the production area near the power plant, and the other (D-D′) about 4 km north of the plant, passing immediately south of the Cerro Prieto volcano (Fig. 1). Dipole-dipole resistivity measurements were then conducted in 1978 and 1979. The utmost care was taken to achieve the best accuracy obtainable with the available instrumentation.

The goals of this project are to construct a resistivity model of the Cerro Prieto region consistent with known geology, and to determine if changes in reservoir conditions due to production (e.g. formation of a vapor zone, changes in porosity at the periphery of the reservoir) may be monitored by means of accurate surface resistivity measurements.

Results of the 1978 survey were presented in an earlier paper (Wilt et al., 1979); a summary of the significant findings is given below.

1. The production region at Cerro Prieto is characterized by a resistivity high relative to the surrounding rocks. Average formation resistivities are 2.0 ohm-m or less, increasing to at least 4.0 ohm-m within the zone. Analyses of well logs and drill cuttings (Elders and Hoagland, 1979) suggest that the increase is primarily due to the formation of reduced porosity zones caused by hydrothermal metamorphism within the reservoir region.

2. Modeling studies showed that resistivity variations with time are theoretically detectable by means of surface dipole-dipole measurements. However, the degree of accuracy needed to observe such variations must be greater than 5%; a better accuracy than we could achieve at large electrode spacings in 1978.

PROGRESS IN 1979

In 1979 line E-E′ was remeasured with 1-km dipoles but with significantly greater accuracy than in 1978, providing better modeling constraints and establishing a reliable baseline for future observations of resistivity changes. The LBL 25-kW motor generator was used as the power source in both years, but greater accuracy was achieved in 1979 because of superior receiver instrumentation, mechanical improvements to the power source, and the experience gained from the previous year. New signal-averaging receivers were used to average 10 cycles of the 40-sec-period square-wave pulse supplied to the ground by the transmitter. At each point of measurement a minimum of 70 cycles were averaged and the mean and standard deviations were computed. The 40-sec period was selected as the best compromise for speed of survey and avoidance of electromagnetic coupling effects. Improvements to the transmitter in 1979--namely a reconditioned engine, new cable, and lower contact resistance at electrodes--allowed us to inject up to 40 A compared with 15 to 25 A in 1978.

In 1979 dipole-dipole measurements were extended 4 km farther eastward and the maximum transmitter receiver separations were increased from N = 6 to N = 8, thereby yielding a greater depth of exploration. In addition telluric profile measurements were made along line E-E′ to test the applicability of this relatively fast and inexpensive method for resolving subsurface structure.

Following data acquisition, the expanded and more accurate results were used to develop an improved two-dimensional resistivity cross-section for line E-E′ (Figs. 2 and 3). New model perturbation studies were performed to identify points of maximum likely interest, such as points where reservoir changes might be most easily recognized, and to examine the magnitude of resistivity change for several possible reservoir changes. An analysis of measurement errors was done with the 1978 and 1979 data and the two sets were compared to see if (a) new measurements (1979) fall within the predicted errors and (b) if data accuracy is sufficient to isolate any changes in reservoir conditions.

Telluric data taken in 1979 were analyzed, and errors were evaluated to determine if it is possible to use this method for resistivity monitoring.

DIPOLE-DIPOLE RESULTS

Dipole-dipole apparent resistivity data taken in 1979 and the accompanying two-dimensional resistivity model are shown in Figure 3. The agreement between calculated apparent resistivities and observed data is good. About 20 trial-and-error iterations were required, however, to reach the model shown, even though the initial model was the final one developed in 1978 (Fig. 2). In general, the 1978 and 1979 models are very similar, although in 1979 the dimension of the pseudosection was increased by 40%. Additional measurement points were needed to provide coverage over the newly discovered eastern part of the field, and to obtain information to greater depths than the 1.5 km obtained in the 1978 survey.

Analysis of the differences in calculated apparent resistivity between 1978 and 1979 data sets indicates that variations to as much as 25% exist between the two sets (Figs. 2 and 3). Most of this variation is probably due to inaccuracies in the 1978 data set since all deviations fall within the predicted scatter for those points (Wilt et al., 1979). Because of the large scatter, we made no attempt to interpret resistivity changes due to changing reservoir conditions. Standard error for the 1979 data is considerably lower than for 1978 data. However, errors for most data are less than 3% and for all data, less than 10%.

A comparison of the bottom section of figures 2 and 3 show where the 1978 and 1979 resistivity models differ. The important differences include a redefinition of the resistive body within the production zone, a more accurate estimate of the resistivity of the deeper horizons, and some new information over the newer, eastern part of the field.

The newer data indicate that the resistive body, which we associate with the zone of intense hydrothermal alteration and the reservoir units, dips eastward by approximately 30 to 50 degrees, deepening in the region of new production east of the power plant; the dipole-dipole method is not, however, particularly sensitive to the dip of inclined bodies. The data also suggest that this zone is fairly extensive and exists as a flat-lying horizon in the eastern portion of the field. The western boundary of this unit lies about halfway between kilometers 9 and 10, which corresponds to a point about 0.5 km west of well M-9. The bottom of this zone cannot be accurately fixed because of the insensitivity of the model to changes at great depth. For the same reason the position of the basement is not accurately determined; the data do suggest that the basement lies at least 3 and 4 km below the surface, respectively west and east of the power plant. The positions of the step faults shown in Figure 3 are poorly determined.

Adjacent to the resistive unit (Fig. 2) is a thin eastward-dipping conductive body.

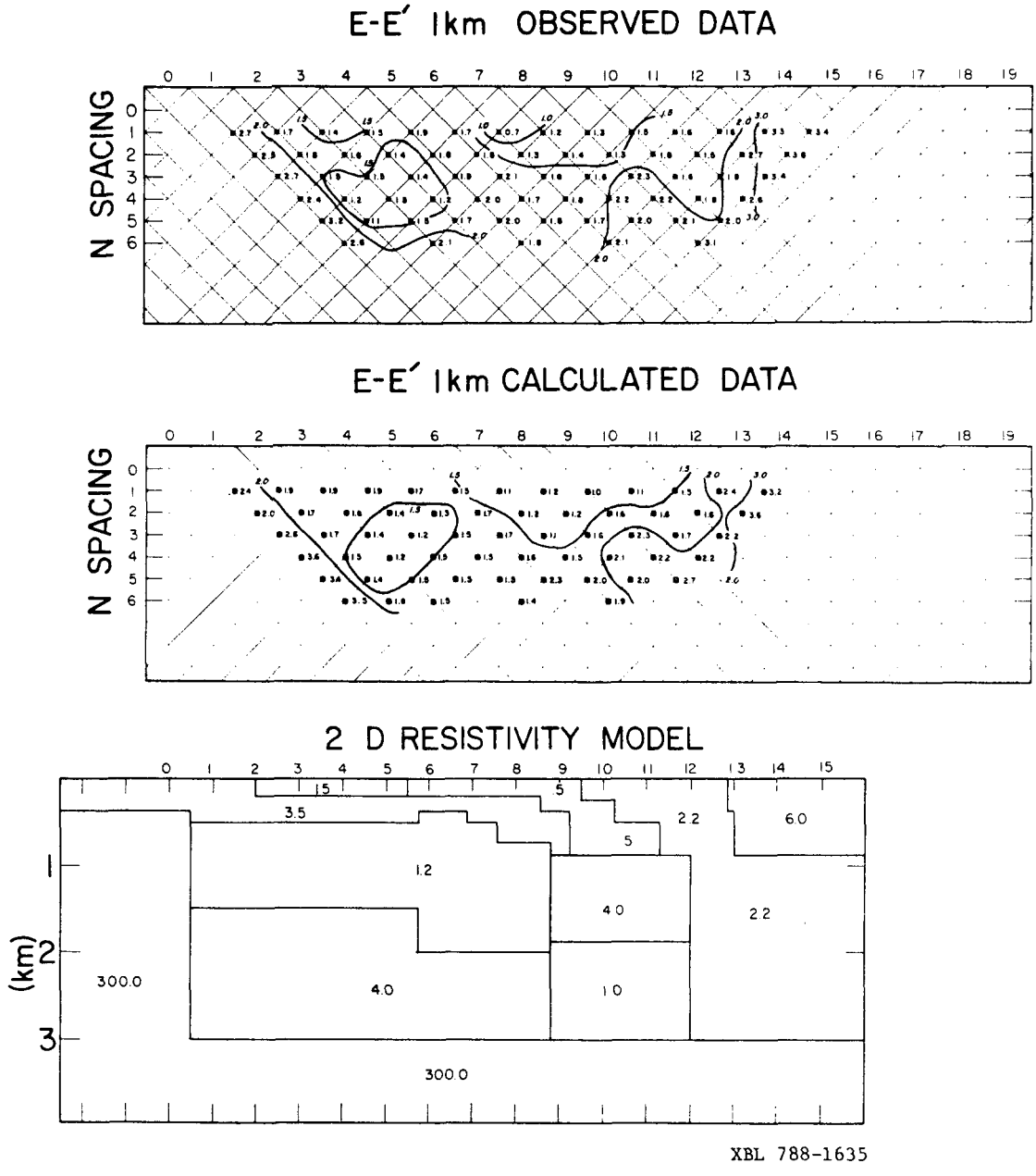

Figure 2. Dipole-dipole apparent resistivity pseudosection for 1-km dipoles along line F-E′, 1978; field data, model-generated data, and two-dimensional resistivity model.

This 1.5 ohm-m unit contrasts sharply with the 4.0 ohm-m body to the west and the 5.0 ohm-m body to the east. The body is approximately 1.5 km wide and dips eastward at between 30 and 50 degrees to a depth of between 2 and 2.5 km; east of this it appears to be flat lying. Because the dipping portion of this unit corresponds remarkably with the location of the planes of charge proposed by Corwin (1979) on the basis of self-potential measurements, it possibly represents a zone of upward moving hot water that links the deeper eastern aquifers to the shallower production west of the power plant. If this assertion is correct, then changes associated with the deeper production in the east may be reflected in changes in the resistivity of this body. It would then be an excellent target for resistivity monitoring of changes in the newer production region.

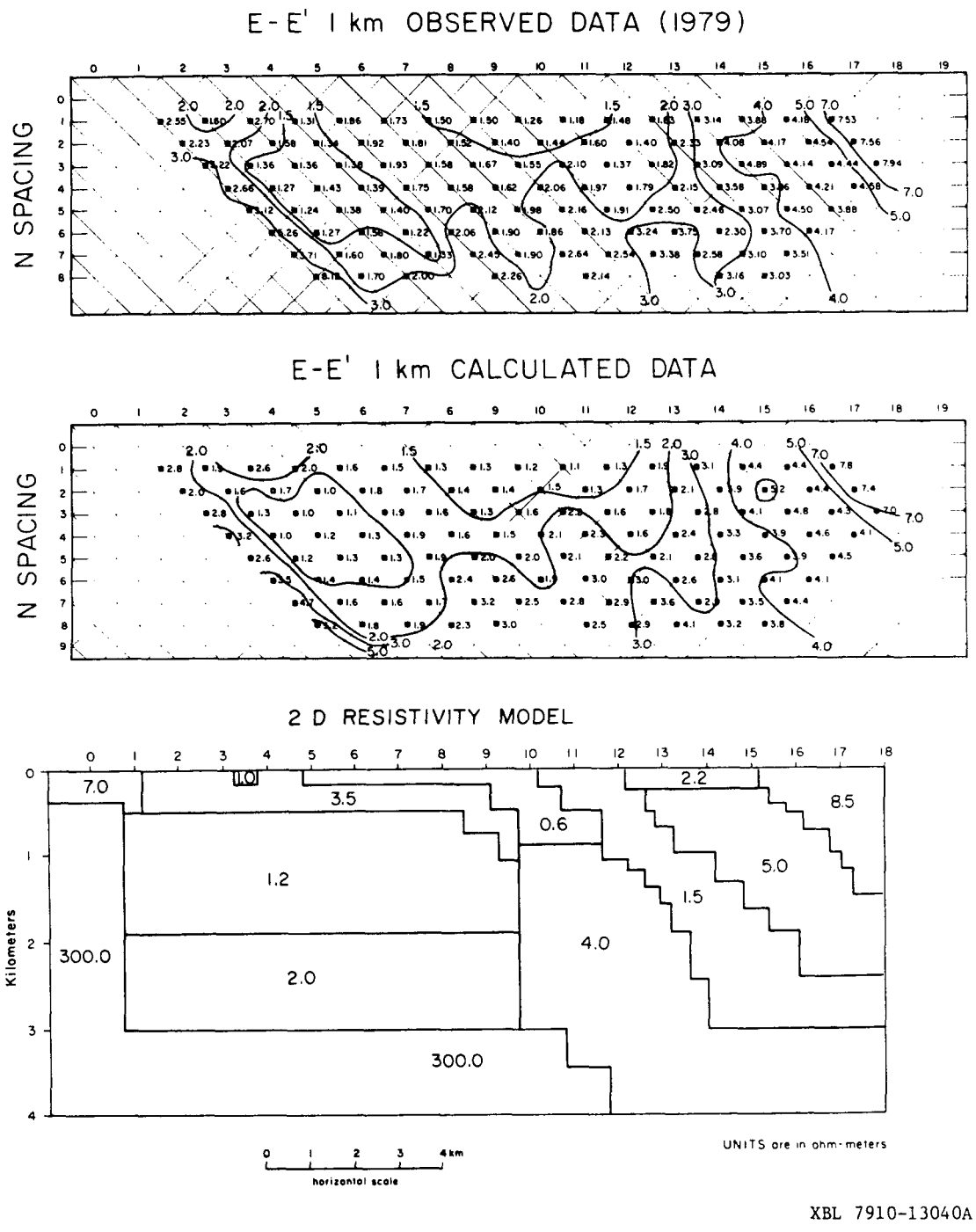

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Figure 3. Dipole-dipole apparent resistivity pseudosection for 1-km dipoles along line E-E', 1979; field data, model-generated data, and two-dimensional resistivity model.

Figure 3 also indicates that east of the power plant the rocks gradually become more resistive than the rocks west of the reservoir, by a factor of 5. These rocks are shown as a series of blocks dipping gently eastward to a depth of about 2 km. The major cause of the increase in resistivity is the transition from brackish pore water to fresher water (Lyons and van de Kamp, 1980). The configuration of these units suggests a transition zone from deltaic waters to more saline sea waters (Lyons and van de Kamp, 1980).

MODEL PERTURBATION STUDIES

Figure 4 is an expansion of that portion of the resistivity section corresponding to the region of fluid production; for reference, some well locations are plotted. Dashed lines are plots of metamorphic mineral zonation (Lyons et al., 1980), the first occurrence of the metamorphic mineral epidote (Elders and Hoagland, 1979), and the boundary between unconsolidated and consolidated sediments in the wells (Puente C. and de la Peña L., 1979). The figure demonstrates the association between the above-mentioned resistive body and the occurrence of high temperatures and metamorphic minerals in the production region. It also suggests that changes in the reservoir would be reflected in a relatively restricted part of the resistivity model, or that part associated with the reservoir and its recharge and discharge systems. This limits the "region of interest" to about 60 observation points from the original 133. For these points future observations should be particularly important.

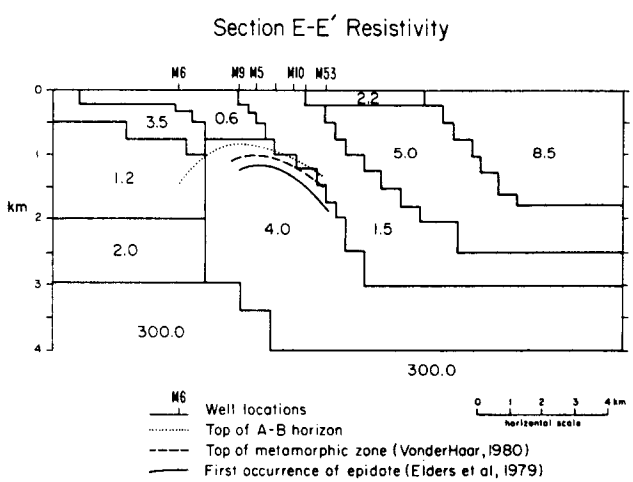

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Figure 4. Expanded version of the two-dimensional resistivity model E-E′. Some well locations are plotted along the top of the figure and positions of various mineralogical and sedimentary horizons, as determined from well cuttings and logs, are plotted below.

To study the effect of certain possible reservoir changes on the apparent resistivity of the 60 points, we have considered the effects from several perturbation models. From these model studies, three cases were selected corresponding to three scenarios of possible reservoir changes (Figs. 5 to 7). At the bottom of each model the percent deviation from the original model is calculated and plotted. Our ability to detect and interpret resistivity changes should then depend on our ability to analyze these plots.

Case 1: Cold Water Intrusion

Recent geochemical studies at Cerro Prieto have found that drawdown in some of the older producing wells is causing colder Colorado River water to move into the producing aquifer to replace produced fluid (Truesdell et al., 1979). Because the fresh river water is replacing more saline reservoir fluid, an increase in resistivity is expected in the producing region and in the rocks above it and to the east.

Figure 4 simulates this change on a fairly large scale. The expansion of the 4 ohm-m zone represents the region that would contain fresher water because of the incursion and thus an increase in the resistivity by a factor of about 2.5. The changes in calculated apparent resistivity are fairly dramatic, up to 20%, and they occur in banded regions. The predominance of high variations for the closer separations suggests that the source of the change is fairly shallow and the banded nature of the plot makes it difficult to confuse such changes with random measurement error. Some points in the plot actually decrease in apparent resistivity even though the only model changes were increases in resistivity. This presents a signature for such a model making it easier to interpret apparent resistivity changes related to this type of reservoir change.

Case 2: Discharge Zone Migration

If the conductive 1.5 ohm-m zone shown in Figure 3 represents a region of upward flowing water, then changes in the resistivity of this zone can be expected as reservoir fluid is produced. One possible change from continuing production is the expansion of the 4.0 resistivity block eastward due to more mineral deposition and the inflow of lower salinity fluid and the subsequent eastward migration of the conductive region. If the conductive region represents a shear zone then this might correspond to an eastward migrating fault zone as the fluid moving through the shear zone deposits minerals and strengthens the rock matrix.

Figure 5 simulates such a case by shifting the eastward boundary of the resistive zone and the adjacent conductive region eastward by 500 m. This model represents a fairly extensive change that might not be expected to occur over a short time interval, but the model is useful for showing

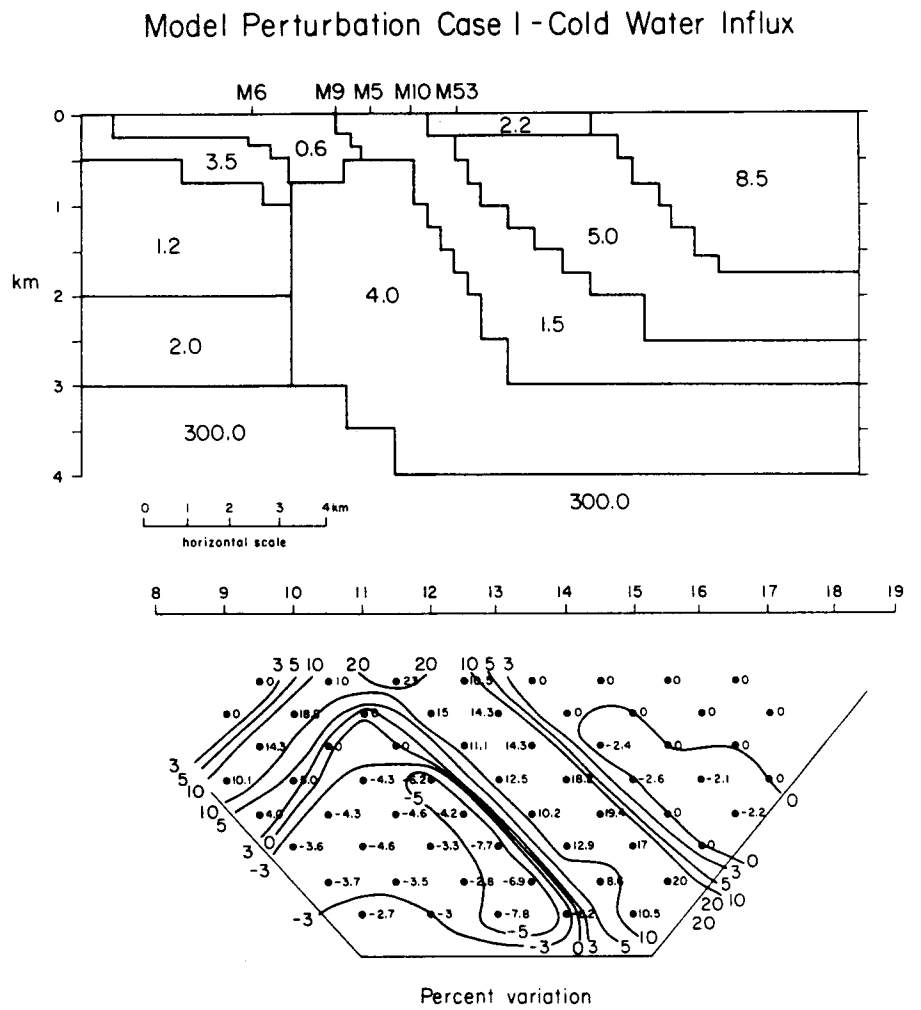

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Figure 5. Model perturbation No. 1, corresponding to the resistivity change due to an influx of colder water into the shallower part of the system.

the effect of resistivity changes along thin linear fractures and establishing a pattern for such bodies. The percent variation of apparent resistivity ranges to 15% and maximum values occur in easternmost located points.

Case 3: Steam Zone Formation

This case simulates the formation of a thin shallow steam zone in the upper part of the reservoir. Formation of such a zone follows from the observation that most of the wells near the power plant now produce a two-phase water-steam mixture, whereas the fluid originally produced was completely liquid (Truesdell et al., 1979). As this process continues the effect might be to reduce permeability because of local boiling and mineral deposition and to deplete the liquid water in the upper parts of the reservoir.

In Figure 6 this situation is simulated by increasing the resistivity by a factor of 2 for a 100-m-thick zone located at the top of the producing region. This represents a relatively minor change in reservoir conditions, but one that might occur over a short time interval.

The plot of percent variation (Figure 6) shows a maximum of 5% deviation due to the model perturbation. These relatively small changes in apparent resistivity should be difficult to observe but they do occur at shallow separations when data accuracy is greatest and they are grouped so it would be easier to separate them from random measurement error.

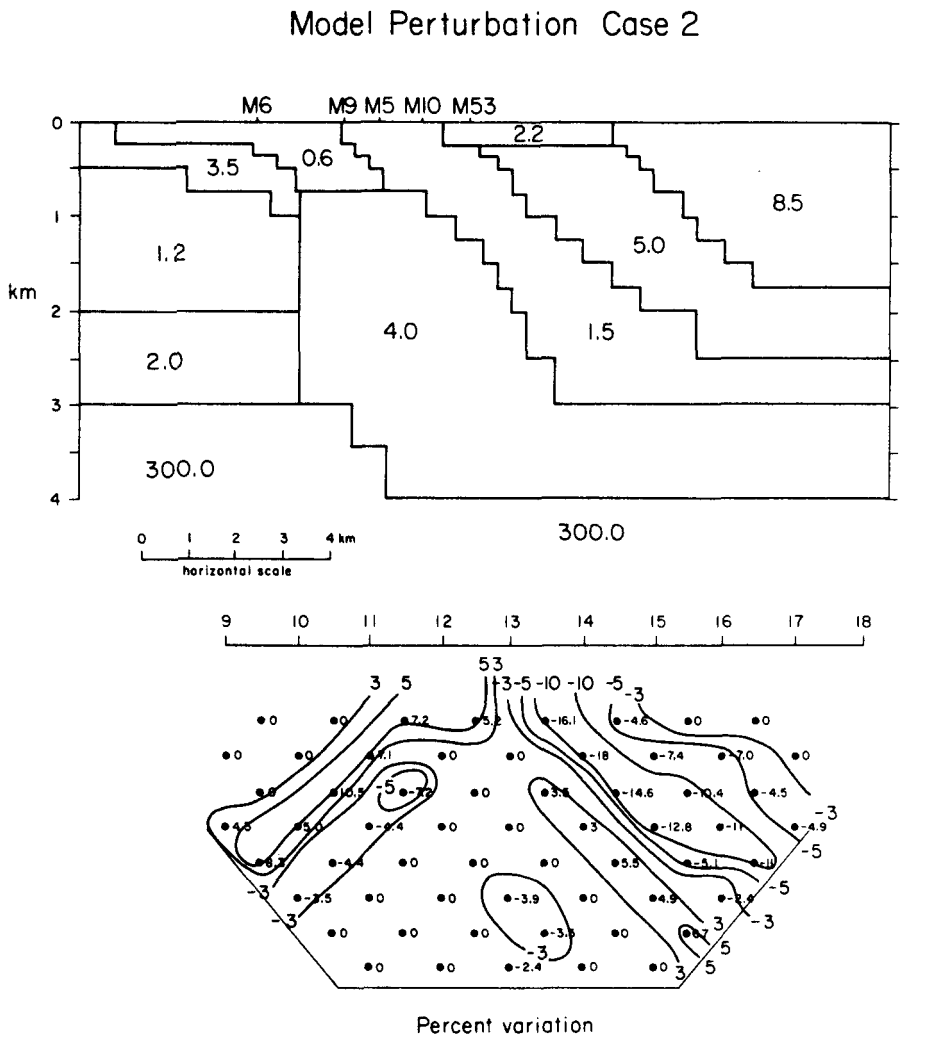

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Figure 6. Model perturbation No. 2, corresponding to the expansion of the 4 ohm-m zone eastward due to reduced temperature and secondary mineral precipitation.

TELLURIC PROFILE RESULTS

A 12-station telluric profile survey was measured along line E-E′ in an attempt to delineate subsurface structure and to assess the usefulness of this reconnaissance method in resistivity monitoring.

The basis of the technique is the simultaneous measurement of natural electrical fields in two or more adjacent segments of a survey line and analysis of the differences in observed amplitude and phase of the incoming signal. Because the source of these signals is the same, analysis of differences is useful for interpreting differences in geology beneath the measurement points. For a more complete discussion see Yungul et al., 1973.

Figure 7 shows a plot of the amplitude and phase ratios for survey line E-E′. The E-E′ stations correspond to the same ones used for the dipole-dipole pseudosections (Fig. 3). The telluric signals were recorded at a period of 25 sec, which corresponds to a maximum depth of investigation of about 3 km; longer period signals would penetrate deeper, and shorter periods not as deep. The profile then gives a running ratio of the bulk resistivities beneath the line. The method is especially useful in detecting lateral resistivity contrasts since these form barriers to natural horizontal current flow. For this reason and because of the simplicity of this method it was chosen to be tested at Cerro Prieto.

A sample record for station 7 of line E-E′ is shown in Figure 8. The amplitude and phase points are determined from the scattergram and vector plots by selecting the value that corresponds to the outermost cluster of the plotted observed values. This procedure is

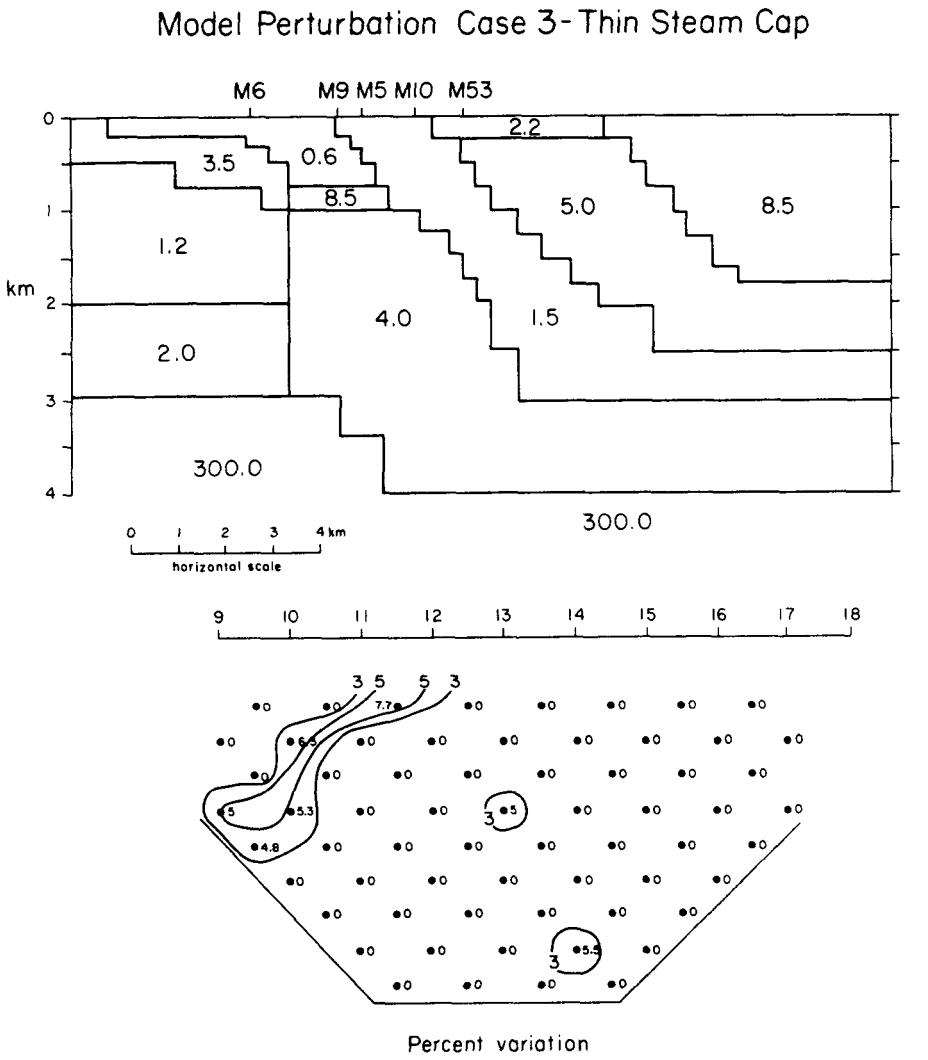

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Figure 7. Model perturbation No. 3, corresponding to the formation of a shallow steam zone.

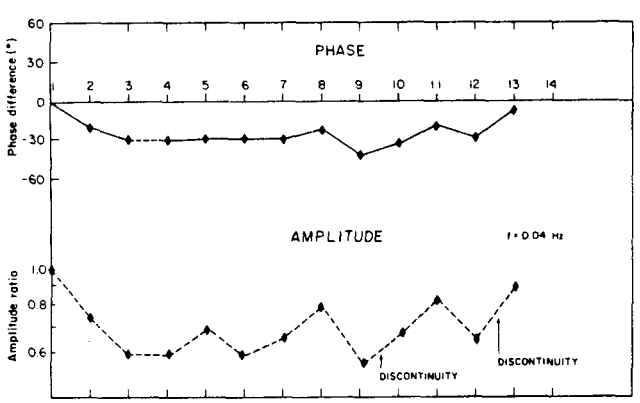

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Figure 8. Plot of amplitude and phase ratios from telluric profile plot E-E′.

followed because a two-dimensional earth energized by electric fields in all directions will yield telluric amplitude ratios with a bimodal distribution; ratios near 1 correspond to geologic strike and the farthest cluster of points correspond to the direction perpendicular to strike. Since the profile was inclined approximately perpendicular to strike, we chose values corresponding to that polarization.

An analysis of Figure 8 reveals a problem inherent to this method that limits its value where high accuracy is needed. Even in the absence of noise there is a natural scatter because of random field polarization. This introduces error into the estimation of ratios. This error may be significantly larger than the precision necessary for accurate monitoring. Another problem with this method is that the depth to the source of perturbations is difficult

to determine because the measurement is done at only one frequency.

An analysis of Figure 9 reveals some of the features of the Cerro Prieto field detectable with telluric profile measurements. The steep decline in the first several measurements indicates the effect of the Cucapa range (located 2 km west of station 1) first. A discontinuity is evident between stations 9 and 10. This corresponds to the western boundary of the geothermal field and correlates well with the location determined from a detailed interpretation of dipole-dipole results. The problem with measurements taken with 1-km dipoles, however, is that the resolution of lateral features is no better than the dipole length. Therefore, it is impossible to tell exactly where discontinuities occur unless the dipoles are made small. Another discontinuity is evident between stations 12 and 13. This correlates well with the area of steep decline of the resistive body interpreted with dipole-dipole data and may relate to a zone of faulting.

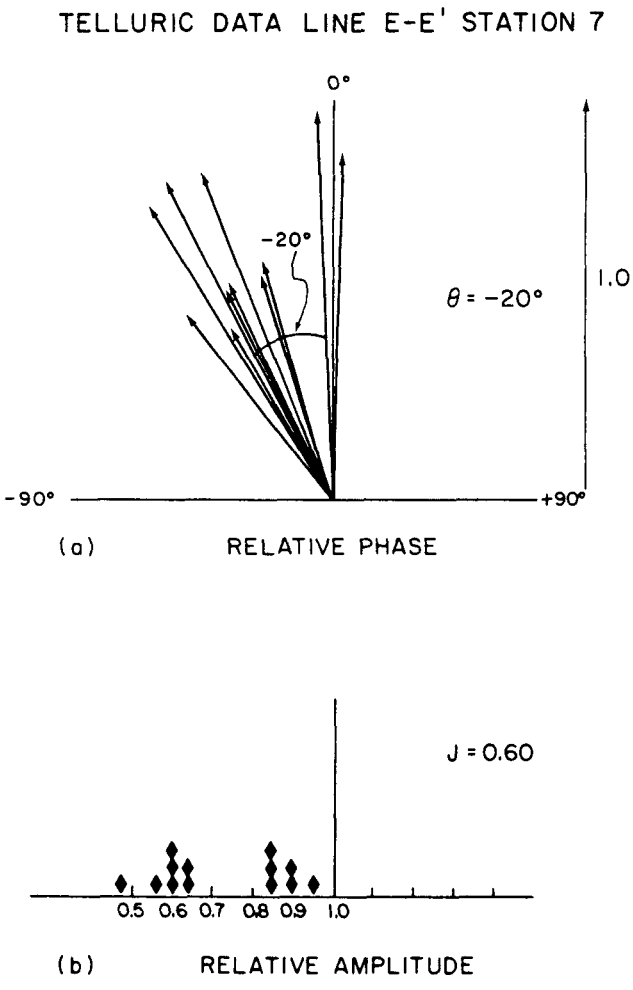

Figure 9. Scattergram and vector plot from a typical telluric profile station. Plotted points correspond to individual measurements.

The telluric measurements suggest a slight increase and resistivity over the reservoir region, but since several faults are crossed by the widely spaced stations the lateral effects cannot be totally separated from the vertical. In general the phase changes closely follow the amplitude changes giving more creedence to the interpretation but not supplying any new information.

Since the profile was measured in two days by two people and very little equipment was necessary, the amount of reconnaissance information obtainable is significant. It does not seem likely, however, that this method is well suited for resistivity monitoring.

CONCLUSIONS

The following is a summary of some of our findings:

1. The dipole-dipole data-gathering technique was improved in 1979 to where estimated measurement errors are less than 3% for most points. This is sufficient accuracy to observe small scale changes in resistivity that may occur over short time intervals.

2. Resistivity modeling of the expanded 1979 profile has better defined the resistivity structure of the eastern part of the field. The models suggest that the resistive body associated with the producing zone dips eastward at 30 to 50 degrees to a depth of greater than 2.0 km. A narrow, steeply dipping conductive zone lies immediately east of the resistive body and may be associated with a zone of recharge or faulting.

3. The resistivity modeling suggests a deep source of fluid in the eastern part of the field. There is also some evidence of a connection between the older, shallower and the newer, deeper production.

4. Model perturbation studies show that apparent resistivity changes due to model variations normally run as banded or grouped areas of anomalous apparent resistivities. The signature of such models may allow detection and identification of changes in the presence of noise. The study also helped define an "area of interest" of 60 measurement points particularly associated with changes in the reservoir formation.

5. Interpretation of telluric profile measurements done over line E-E′ yields a significant amount of reconnaissance information about the field. Because of inherent measurement uncertainty however, the method seems unsuitable for monitoring purposes.

ACKNOWLEDGMENTS

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