Title

LONG-TERM DIPOLE-DIPOLE RESISTIVITY MONITORING AT THE CERRO PRIETO GEOTHERMAL FIELD

Permalink

https://escholarship.org/uc/item/6630j8rp

Authors

Wilt, M.
Goldstein, N.E.
Sasaki, Y.

Publication Date

1984-04-01

LBL-17644

Lawrence Berkeley Laboratory

UNIVERSITY OF CALIFORNIA

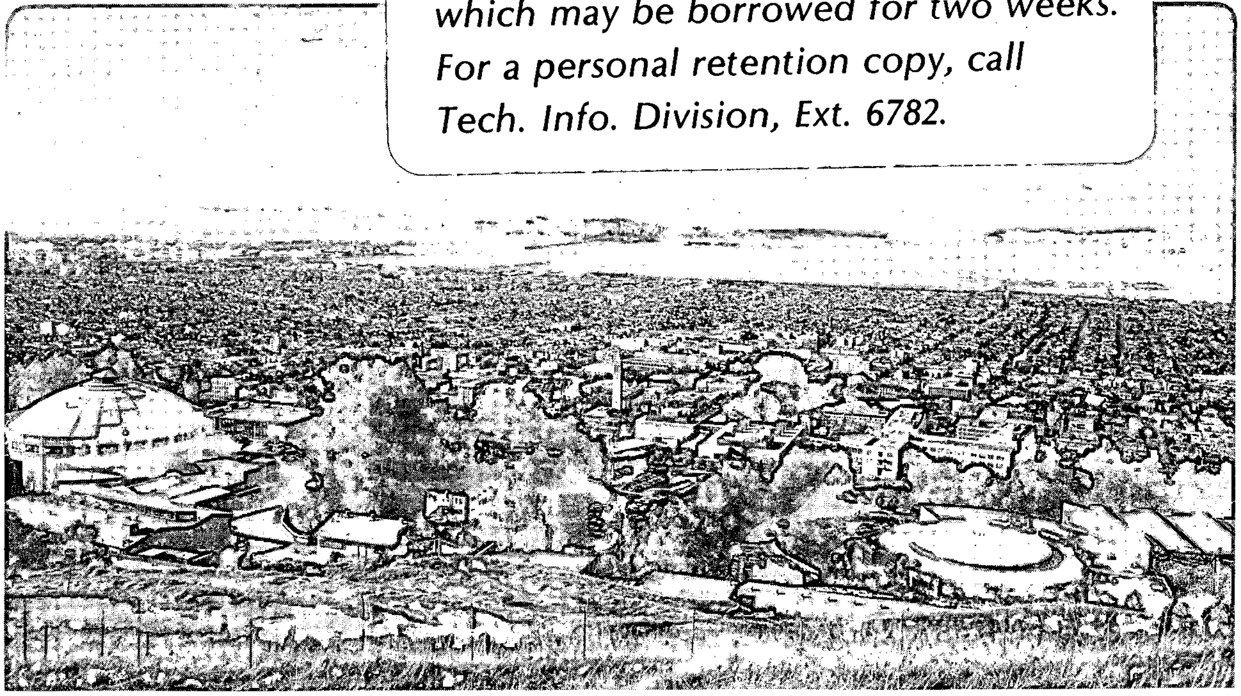
EARTH SCIENCES DIVISION

To be presented at the Geothermal Resources Council 1984 Annual Meeting, Reno, NV, August 26-29, 1984

LONG-TERM DIPOLE-DIPOLE RESISTIVITY MONITORING AT THE CERRO PRIETO GEOTHERMAL FIELD

M. Wilt, N.E. Goldstein, and Y. Sasaki

April 1984



Prepared for the U.S. Department of Energy under Contract DE-AC03-76SF00098

LONG-TERM DIPOLE-DIPOLE RESISTIVITY MONITORING AT THE CERRO PRIETO GEOTHERMAL FIELD

M. Wilt*, N.E. Goldstein†, and Y. Sasaki§

*Engineering Geosciences, University of California, Berkeley, CA
†Earth Sciences Division, Lawrence Berkeley Laboratory, University of California
§Faculty of Engineering, Kyushu University, Kyushu, Japan

Abstract

Dipole-dipole resistivity measurements for the combined purposes of reservoir delineation and reservoir monitoring were first made at Cerro Prieto in 1978 and have continued on approximately an annual basis since then. Two 20 km-long dipole-dipole lines with permanently emplaced electrodes at 1-km spacings were established over the field area. Resistivity remeasurements have been made on one line at 6- to 18-month intervals using a 25 kW generator capable of up to 80A output and a microprocessor-controlled signal-averaging receiver. This high-power, low-noise system provides highly accurate measurements even at large transmitter receiver separations. Standard error calculations for collected data indicate errors less than 5% for all points.

Results from four years of monitoring (1979-1983) indicate a 5% average annual increase in apparent resistivity over the present production area, and larger decreases in apparent resistivity in the region to the east. The increase in resistivity in the production zone is most likely due to dilution of reservoir fluids with fresher water, as evidenced by a drop in chloride content of produced waters. The area of decreasing resistivity east of the reservoir is associated with a steeply dipping conductive body, a zone of higher thermal gradients and an increase in shale thickness in the section. Decreasing resistivity in this area may be caused by an influx of high temperature, saline water from depths of 3^+ km through a sandy gap in the shales.

Monitoring data also show that the trend of increasing resistivity associated with the shallow α reservoir has reversed during the 18-month period from fall 1981 to spring 1983 while a resistivity decrease in the region east of the reservoir continues to intensify. On the basis of a continued decline in chloride content of the geothermal brines from the α reservoir due to fresh water recharge, one would expect to observe only increasing resistivities over the main part of the field. The decrease in apparent resistivity may be caused by the disappearance of boiling zones due to a progressive cooling of the reservoir.

Quantitative estimates of resistivity change within a 2-D mesh representing the subsurface were obtained by means of an automatic least-squares optimization code.

Introduction

Beginning in 1978 Lawrence Berkeley Laboratory (LBL), in cooperation with Comisión Federal de Electricidad (CFE), began making repetitive dipole-dipole resistivity measurements over the Cerro Prieto geothermal field (Figure 1). The objectives were to delineate subsurface resistivity structure, such as possible reservoir boundaries, and to detect any changes in subsurface resistivity due to continuing fluid extraction. A permanent array of electrodes was established one km apart along two lines and the measurements were repeated on a nearly annual basis on the line that passes directly over the production area (line E-E′).

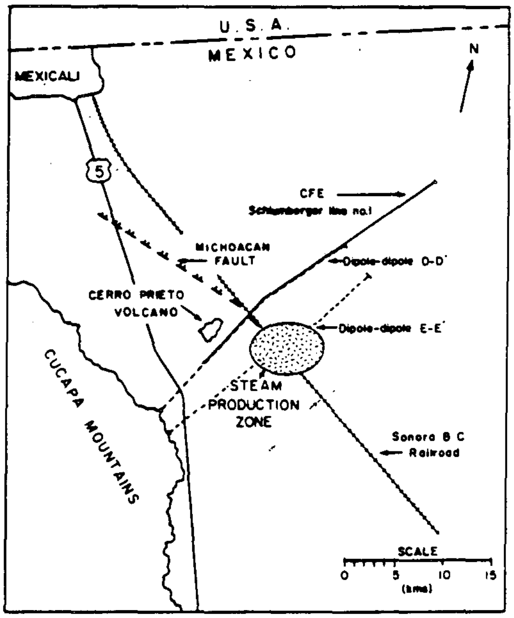


Fig. 1. Location map of the Cerro Prieto geothermal field and dipole-dipole lines D-D′ and E-E′ over the field.

Data Acquisition

A schematic diagram of field system is shown in Figure 2. The 25 kW generator is capable of providing square-wave currents of up to 80 A peak-to-peak into the ground at up to 1200 V for periods from 1 to 100 seconds. This power source is easy to move yet powerful enough to provide adequate signals at distant stations. For the Cerro Prieto surveys 40-second period current was used to minimize inductive coupling effects due to the low resistivity ground.

Signals are measured simultaneously across four colinear dipoles spaced at integer multiples (n) of 1 to 10 times the 1 km transmitter dipole length. The signals are detected with porous copper-copper sulfate electrodes and then low-pass filtered to remove 60 Hz and telluric noise. After amplification, the signals are digitized, stacked, and decomposed into Fourier components using a multichannel digital signal processor (Morrison et al., 1978). This system is very effective for obtaining high quality data. Measurement error levels for the Cerro Prieto surveys have varied between 0.1 and 5%. The error level rises with increasing dipole separation and levels of cultural and telluric noise.

Resistivity Model

Figure 3 shows the 2-D resistivity model that we derived by trial and error fitting of field data taken over line E-E′ to results calculated by means of a 2-D resistivity modeling program (Wilt and Goldstein, 1981). Figure 4 shows the position of the line in relation to the present well field. Two of the most significant characteristics of the resistivity model are the zone of relatively high resistivity (4.0 ohm-m) associated with the reservoir rocks and the steeply dipping (1.5 ohm-m) low resistivity body located east of the production zone.

The high resistivity region associated with the production zone can be attributed to reduced porosity of the interbedded shale units (Wilt and Goldstein, 1981; Elders et al., 1981). The adjacent steeply dipping conductive body is associated with high thermal gradients and an increasing thickness of shales in this part of the section (Halfman et al., 1984). There also seems to be a "sandy-gap" in the shaley caprock east of the production zone which apparently allows geothermal fluids to ascend into the "α" reservoir which lies at depth of 1.2-1.4 km (Halfman et al., 1984).

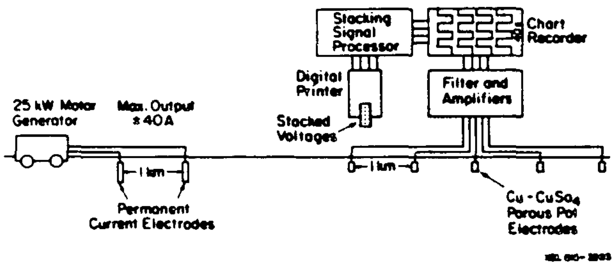


Fig. 2. Schematic diagram of the dipole-dipole data acquisition system.

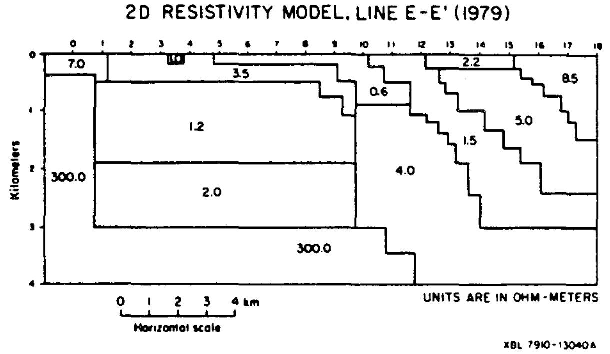


Fig. 3. Two-dimensional subsurface resistivity model for line E-E′, based on the 1979 data set.

Resistivities increase east of the power plant due to the transition from saline to fresher water as one approaches the Colorado River (Lyons and van de Kamp, 1980).

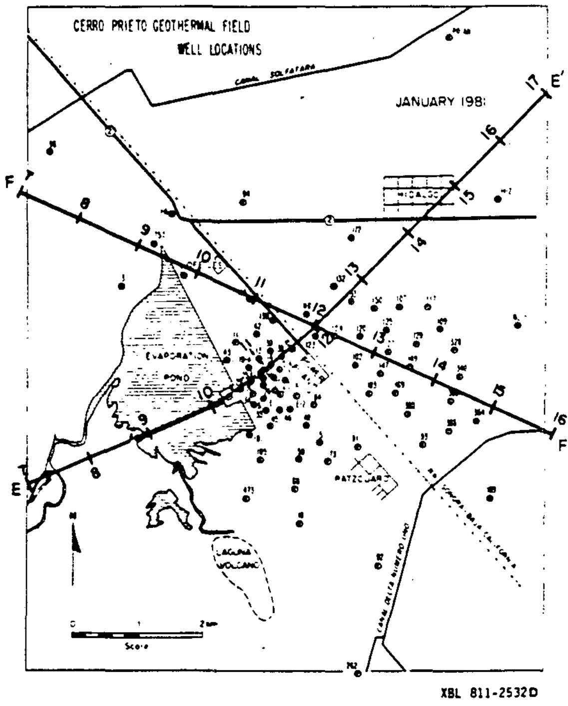
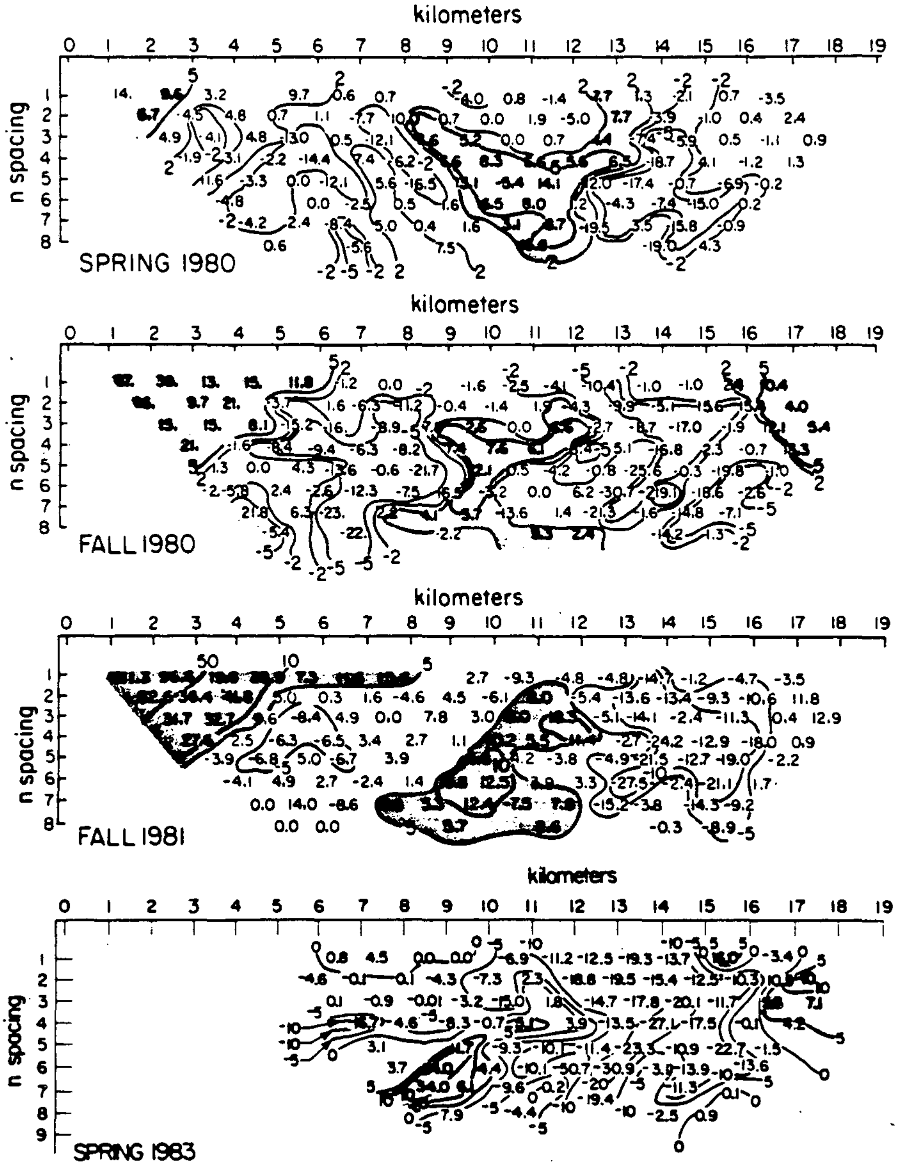


Fig. 4. Detail of dipole-dipole resistivity lines E-E′ (trending NE-SW) and F-F′ (trending NW-SE) in relation to the well locations numbered circles). Not all present wells are shown. The producing wells supplying steam to the first power plant (CP1) are located to the immediate west-southwest of the power plant.

Apparent Resistivity Changes

Figure 5 shows apparent resistivity changes relative to 1979 data, plotted as pseudosections for times of 1, 1.5, 2.5, and 4.0 years after the 1979 data were taken. The pseudosections are plotted in units of percent change relative to the baseline 1979 data. There are similar trends of change observed in all of the plots. Little change is observed for small n-spacings over that part of the line that crosses the production zone; the western end of the line, adjacent to the Cupapá Mountains, however, shows large changes at small n-spacings due to fresher water used to irrigate new farming plots.

Over that part of the profile approximately corresponding to the production zone the apparent resistivities have increased at an average annual rate of about 5%. This is attributed to an influx of fresher groundwater into the α reservoir in response to the drop in pressure caused by fluid production during the 1979-1982 period (Wilt and Goldstein, 1984). In support of this belief, it has been noted that chloride concentrations in the water produced by many of the Cerro Prieto wells have decreased over this time period (Grant et al., 1984; Truesdell et al., 1984). Geochemical data suggest that fresh water enters the system from the sides and from above through a leaky caprock (Grant et al., 1981). The resistivity data do not clearly



XBL 825-10150A

Fig. 5. Apparent resistivity changes along line E-E′, plotted in pseudosection form, relative to the 1979 data set. From top to bottom these pseudosections show the percent change in apparent resistivity 1, 1.5, 2.5, and 4.0 years after the 1979 baseline data were acquired. Areas of dark stipple show resistivity increases greater than 5%. Areas of light stipple show resistivity decreases greater than 5%.

indicate pathways for fluid flow as measurements are (a) heavily volume-averaged and (b) data are limited to one profile.

The zone of decreasing resistivity in the region east of the present production area, between stations 12 and 16, is a major feature in Figure 5, but its cause is not well understood. The 2-D resistivity model (Figure 2) indicates that this region is associated with the eastern flank of the thermal dome which is marked by a steeply dipping, 1.5 ohm-m conductive region. Analysis of temperature measurements and geophysical well logs show that the 1.5 ohm-m zone correlates with an area of high thermal gradients and with thicker shale units in the section (Halfman et al., 1984). To allow for such large scale changes in the subsurface resistivity, major adjustments must be occurring in the groundwater temperature, salinity or both. Some of the change may be explained by noting that farming activity, hence irrigation, ceased in the region in 1981 thus shallow groundwater has likely become more saline and warmer. This predominately affects the small n-spacings of the pseudosections (n=1 and 2) in Figure 5, but decreasing resistivity in the deeper parts of the section suggests changes in the temperature or salinity are occurring at depth. If the percent change pseudosections are examined in sequence from spring 1980 to fall 1982 the area of apparent resistivity decrease appears to intensify and change shape. The -10% contour appears to move upwards and westward with time, suggesting a pulse of hot water ascending into the reservoir region through a sandy gap in the shaley caprock, as proposed by Halfman et al. (1984). About the time of the baseline measurements fluid production was about doubled at Cerro Prieto, and so this pulse may represent a groundwater response to the pressure change due to the increased production. Using some simple reservoir engineering calculations, we estimate that such a pulse would require less than 5 years to move the 2.5 km from east of the reservoir into the production zone (G.S. Bodvarsson, 1984, personal communication).

Figure 6 displays the apparent resistivity changes over the 18-month period of fall 1981 to spring 1983. The recent pattern of change is significantly different from those shown in the earlier pseudosections. It suggests that while the resistivity decline is continuing between stations 13 and 16, a reversal in resistivity change has occurred between stations 9 and 13; i.e., resistivities now seem to be declining within the region of the α reservoir. This reversal is difficult to explain because the continued decline in chloride content of the brines indicates that cooler, fresher groundwaters are recharging the reservoir and these should produce a resistivity increase. One possible explanation, consistent with changes in the silica content of the produced brines, is that the boiling zones in the α reservoir have decreased in size as the reservoir temperature has dropped below the boiling point for that depth (A. Truesdell, 1984, personal communication), and that the increase in liquid saturation has become a significant factor on apparent resistivities.

Quantitative Estimates of Resistivity Change

It is an unfortunate aspect of the dipole-dipole percent difference pseudosections that they do not clearly reveal from simple examination where resistivity changes are actually occurring and their true magnitude. The pseudosection representation is merely a convention for plotting data, and does not depict the true resistivity distribution. Numerical models show that simple changes in a resistivity model may produce complex changes in the pseudosection (Beyer, 1976). To improve our ability to quantitatively interpret percent change pseudosections we have made some preliminary trials with an automatic 2-D least-squares inversion code (Sasaki, 1982). This code finds, in an iterative fashion, a subsurface distribution of resistivity that yields a pseudosection matching the observed pseudosection. From this we can see how the resistivities in discrete blocks change with time. Resistivity estimates in each block are varied until a point is reached where further changes needed to improve the fit are smaller than some specified amount. The starting model in the inversion is the 2-D model found from a labor-intensive interpretation of the 1979 baseline data (Wilt et al., 1980).

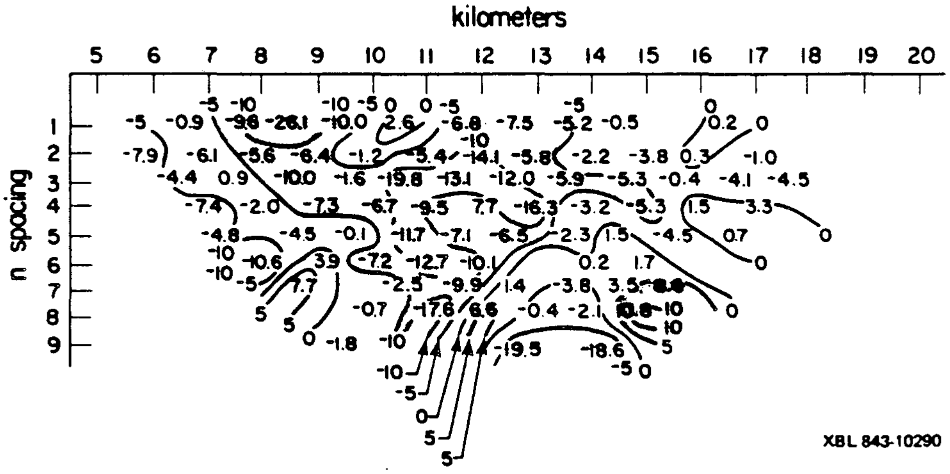
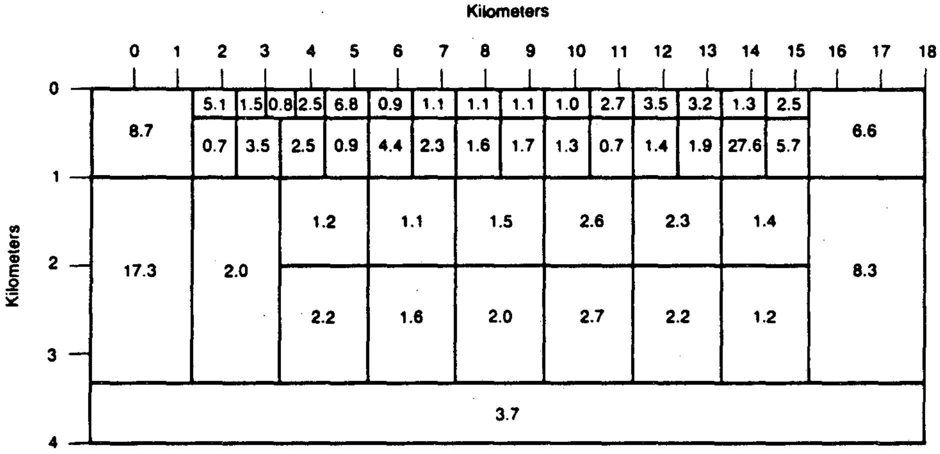


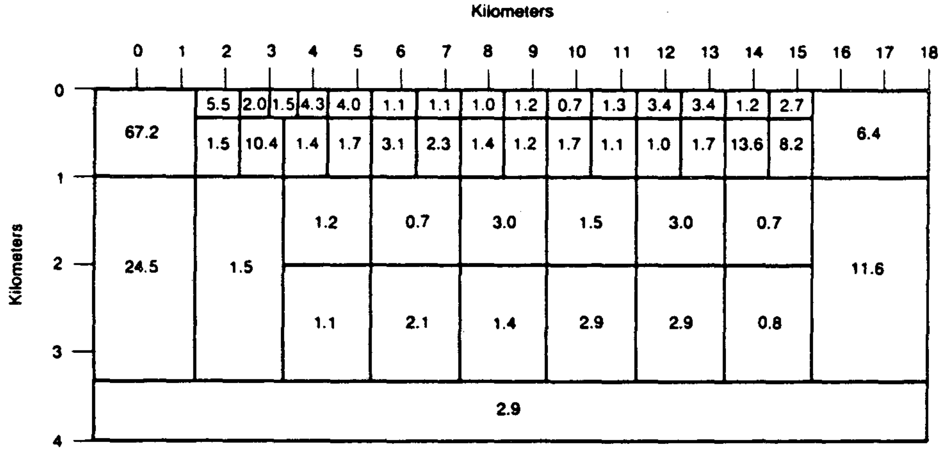
Fig. 6. Apparent resistivity changes for the period of fall 1981 to spring 1983.

The 2-D optimization code uses a finite element algorithm and a slightly different mesh design than we originally used in obtaining the Cerro Prieto resistivity model, hence the model sections appear somewhat different although they are electrically equivalent. The 2-D resistivity model obtained from the optimization procedure for the 1979 data is given in Figure 7. It is very similar to our original 2-D model although there are differences between the two, particularly in the shallow part of the section. Figure 8 is a resistivity model obtained by inverting the fall 1980 data set. Comparing Figures 7 and 8 there are several areas of significant differences. Between stations 13 and 16 at depths between 1 and 3 km the resistivity has decreased by more than 40%. This suggests that profound changes in fluid temperature and salinity are occurring in this region. Since this area corresponds to an area of hot water recharge, as proposed by Elders et al. (1981), Grant et al. (1984) and Halfman et al. (1984), it is possible that the changes are due to increased temperatures and water salinity due to additional hot water recharge. Between stations 11 and 13 a 20% increase in resistivity is observed at depths of between 1 and 3 km. This area corresponds to the present production zone and the magnitude of the change is consistent with changes in fluid chemistry (Grant et al., 1984; Truesdell et al., 1984). Between station 1 and 2 the shallow resistivity has changed dramatically largely because large amounts of fresh water have been used here for irrigation of new farming plots.



XBL 844-9441

Fig. 7. A two-dimensional subsurface resistivity model produced by means of a finite element, automatic least-square iterative technique for the 1979 data set. Compare to Figure 3.



XBL 844-9440

Fig. 8. A two-dimensional subsurface resistivity model for the 1980 data set. Compare block resistivities to those in Figure 7 for a sense of how subsurface resitivities changed during the one-year period 1979-1980.

Ongoing Work

In 1983 baseline measurements were made on a new NW-SE line (F-F′) that crosses E-E′ at an angle of 60 . By having two monitoring lines crossing over the field we will be in a better position to track large scale movements of subsurface fluids. In addition, line F-F′ crosses an area of wells that will supply steam to a new electrical generating plant (Cerro Prieto II), scheduled to start up in late 1984. The new power will more than double installed capacity to a total of 400 MW. Future measurements on this line may indicate how the reservoir is responding to massive changes in fluid withdrawal and recharge.

Summary and Conclusions

Repetitive dipole-dipole resistivity measurements taken during the past 4 years over line E-E′ have revealed a consistent pattern of change over the Cerro Prieto field. A zone of increasing resistivity is related to the present region of fluid withdrawal; zones of decreasing resistivity lie above and flank the region of increase. The resistivity increase is most likely due to the influx of fresher, cooler water into the system to replace the hot brine withdrawn for power production. The resistivity decreases in the eastern part of the field may be due to the upward movement of deep saline water or to local increase in temperature due to upwelling hot waters.

The reversal in resistivity change associated with the region of the present shallow production zone suggests that liquid saturation has significantly increased during the fall 1981 to spring 1983 period due to the collapse of boiling zones around the wells.

Initial trials were made with a 2-D automatic least-squares inversion computer program to help locate specific regions where change is occurring and assess the magnitude of the changes. An inversion of monitoring data taken 18 months after the 1979 baseline measurements reveals that within the production zone resistivity had increased by about 20% and at similar depths east of the production zone more than a 80% decrease is observed.

Acknowledgment

The authors wish to acknowledge Don Lippert, Ray Solbau, Wayne Lee and Bob Davis whose efforts in the field contributed greatly to the successful aquisition of the high quality resistivity data. We also wish to thank our colleagues with CFE in Mexicali who have been of considerable help in providing support for the field surveys and data interpretation.

This project is supported by the Assistant Secretary for Conservation and Renewable Energy, Office of Renewable Technology, Division of Geothermal and Hydropower Technologies of the U.S. Department of Energy under Contract No. DE-AC03-76SF00098.

References

Beyer, J.H., 1976. Telluric and dc resistivity techniques applied to the geophysical investigation of Basin and Range geothermal systems, Part II: A numerical model study of the dipole-dipole and Schlumberger resistivity methods: Ph.D. dissertation, U.C. Berkeley. Lawrence Berkeley Laboratory report LBL-6325, 213 p.

Elders, W.A., Williams, A.E., and Hoagland, J.R., 1981. An integrated model for the natural flow regime in the Cerro Prieto geothermal field based upon petrological and isotope geochemical criteria: In Proceedings, Third Symposium on the Cerro Prieto Geothermal Field, Baja California, Mexico, March 1981, Lawrence Berkeley Laboratory report LBL-11967, pp. 102-110.

Grant, M.A., Truesdell, A.H., and A. Mañón M., 1984. Production induced boiling and cold water entry in the Cerro Prieto geothermal reservoir indicated by chemical and physical measurements: Geothermics, v. 13, n. 1/2, pp. 117-140.

Halfman, S.E., Lippmann, M.J., Zelwer, R., and Howard, J.H., 1984. Geologic interpretation of geothermal fluid movement in Cerro Prieto Field, Baja California, Mexico: Am. Assoc. Pet. Geol. Bull., v. 68, pp. 18-30.

Lyons, D.J. and van de Kamp, P.C., 1980. Subsurface geological and geophysical study of the Cerro Prieto geothermal field: Lawrence Berkeley Laboratory report LBL-10540.

Morrison, H.F., Goldstein, N.E., Hoversten, M., Oppliger, G., and Riveros, C., 1978. Description, field and data analysis of a controlled-source EM system (EM-60): Lawrence Berkeley Laboratory report LBL-7088, 150 p.

Sasaki, Y., 1982. Automatic interpretation of induced polarization data over two-dimensional structures: Memoirs from the Faculty of Engineering, Kyushu University, Japan, v. 42, n. 1, pp. 59-70.

Truesdell, A.H., Nehring, N.L., Thompson, J.M., Janik, C.J., and Coplen, T.B., 1984. A review of progress in understanding the fluid geochemistry of the Cerro Prieto geothermal system: Geothermics, v. 13, n. 1/2, pp. 65-74.

Wilt, M.J., Goldstein, N.E., Razo A., M., 1980. LBL resistivity studies at Cerro Prieto: Geothermics, v. 9, n. 1/2, pp. 15-26.

Wilt, M.J. and Goldstein, N.E., 1981. Resistivity monitoring at Cerro Prieto: Geothermics, v. 10, n. 3/4, pp. 183-194.

Wilt, M.J. and Goldstein, N.E., 1984. Interpretation of dipole-dipole resistivity monitoring data at Cerro Prieto: Geothermics, v. 13, n. 1/2, pp. 13-26.

TECHNICAL INFORMATION DEPARTMENT
LAWRENCE BERKELEY LABORATORY
UNIVERSITY OF CALIFORNIA
BERKELEY, CALIFORNIA 94720