Title
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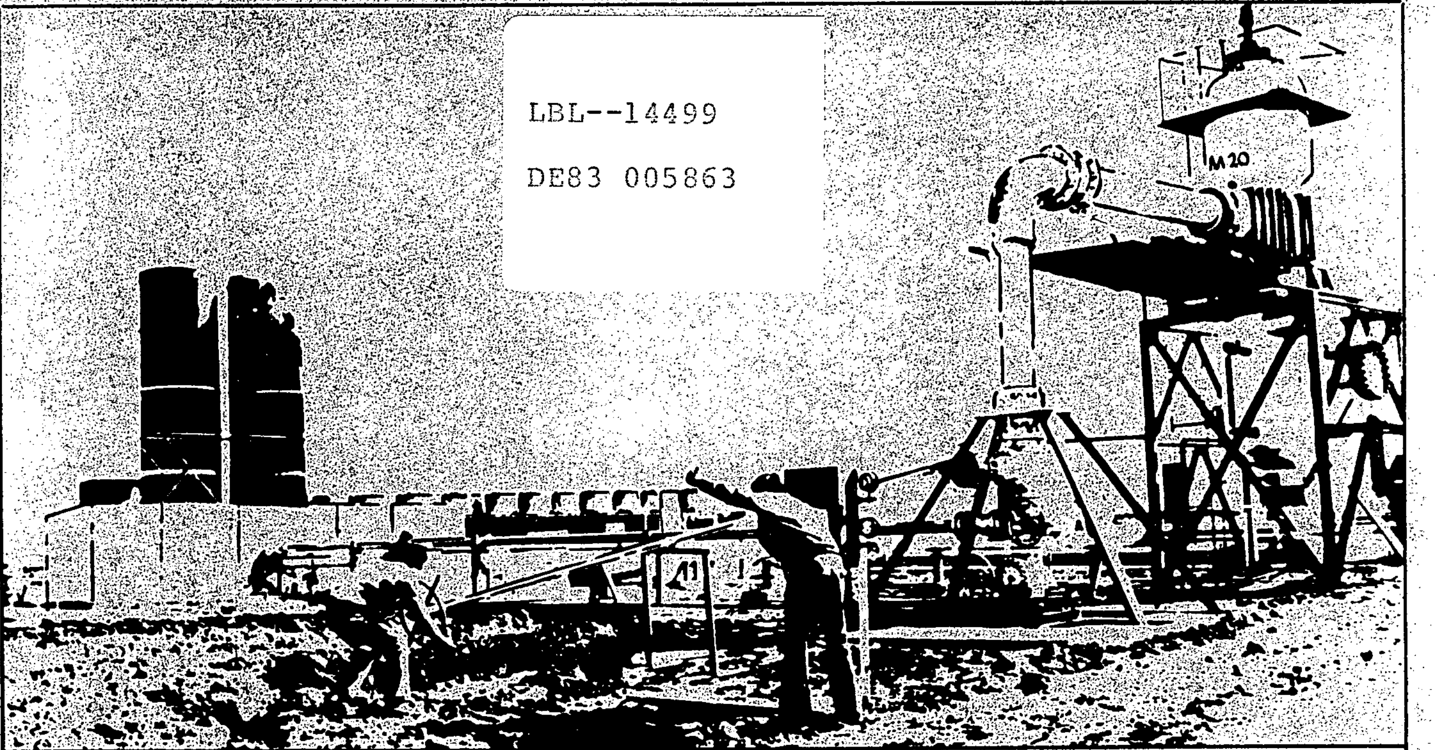
Publication Date
1982-10-01

LBL-14499
CERRO PRIETO-20

MEXICAN-AMERICAN COOPERATIVE PROGRAM AT THE CERRO PRIETO GEOTHERMAL FIELD



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October 1982

A Joint Project of

COMISION FEDERAL DE ELECTRICIDAD
Mèxico

DEPARTMENT OF ENERGY
Division of Geothermal Energy
United States of America

Coordinated by

Coordinadora Ejecutiva
de Cerro Prieto
Apdo. Postal No. 3-636
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Calexico, Ca. 92231

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

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Presented at the 4th Symposium on the Cerro Prieto Geothermal Field Guadalajara, Mexico, August, 1982.

LBL-14499

CP-20

Conf-8208109--1

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INTERPRETATION OF DIPOLE-DIPOLE RESISTIVITY MONITORING DATA AT CERRO PRIETO

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ABSTRACT

Repetitive dipole-dipole resistivity data have been taken on a yearly basis by LBL at Cerro Prieto since 1978. Stations along a single profile line extending from the Cucapá Mountains to the center of the Mexicali Valley and passing over the present production zone have been remeasured with sufficient accuracy to detect subsurface changes in resistivity, some of which are probably related to fluid production. The precision of the most recent measurements (November, 1981) averages about 1 percent. Results from two and one-half years of monitoring indicate a 5 percent annual increase in apparent resistivity over the present production area and decreases in apparent resistivity of the same magnitude in the regions immediately eastward and westward from the production zone.

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. An attempt was made to determine whether specific lithologic zones in wellbores show resistivity changes with time by comparing well logs from newly drilled wells with logs from older nearby wells. Results show that lateral resistivity variations within stratigraphic units between closely-spaced wells are sufficient to obscure possible temporal changes.

The area of decreasing resistivity in the eastern part of the field is associated with a steeply dipping conductive body, a zone of higher thermal gradients and an increase in shale thickness in the section. Well log analysis shows that the low resistivity is mostly due to higher temperatures. Decreasing resistivity in this area may be caused by an influx of hotter and more saline brines from depth.

Recent measurements also show a dramatic increase in near-surface resistivity at the western end of the monitored line. This is most likely due to recent changes in local irrigation practices which resulted in a general improvement in groundwater quality.

To investigate the phenomenon of resistivity changes caused by groundwater movement and chemical reactions, we propose the establishment of an additional resistivity line crossing both the new eastern production zone and the present survey line at an angle of 60°. This line would permit the acquisition of baseline data over the future production zone, CPII, and, in conjunction with the present line, would establish a grid of stations which could be used to map subsurface groundwater fronts.

INTRODUCTION

In 1978 Lawrence Berkeley Laboratory (LBL), in coooperation with the Comisión Federal de Electricidad (CFE), began a project of monitoring changes in subsurface resistivity by making dipole-dipole surface resistivity measurements over an area of intense steam and water production at the Cerro Prieto geothermal field (Figure 1). The project goals were to delineate subsurface resistivity structure at Cerro Prieto, including possible reservoir boundaries, and to detect changes in the subsurface resistivity due to continuing fluid extraction. The plan was to establish a permanent array of electrodes one km apart and to repeat the measurements annually as an indirect means for observing changes in the reservoir region due to production. A short summary of some significant results from this project is given below.

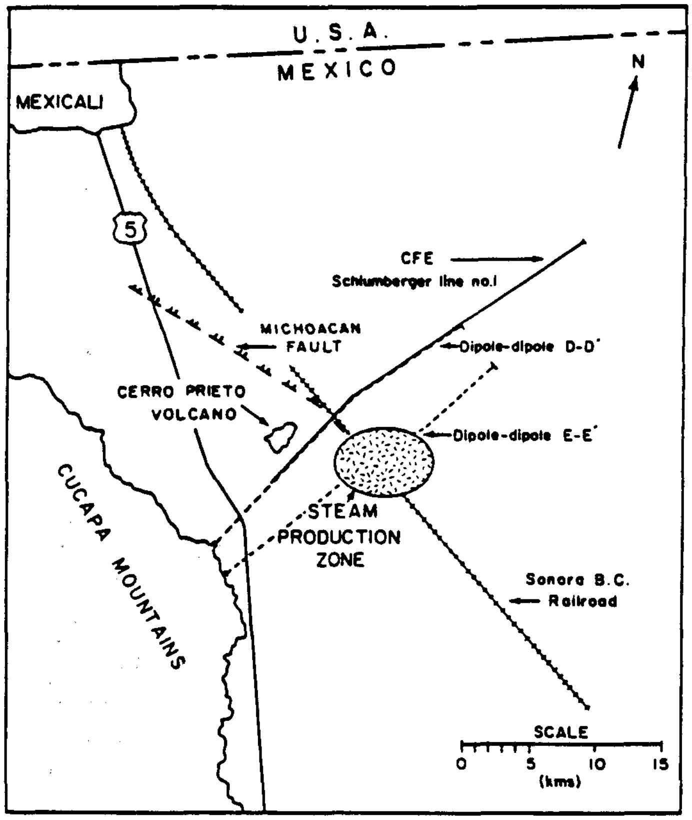

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Figure 1. Location map of the resistivity monitoring lines.

Figure 2 shows the working two-dimensional resistivity model that we derived by fitting field data taken over line E-E′ to data calculated by means of a two-dimensional resistivity modeling program (Wilt and Goldstein, 1979). Figure 3 shows the position of the line in relation to the present well field. Two of the significant characteristics of the resistivity model are the relatively high resisitivity zone (4.0 ohm·m) associated with the reservoir rocks and the steeply dipping (1.5 ohm·m) conductive body located east of the production zone. The high resistivity region surrounding the production intervals can be attributed to reduced porosity, mainly of the shale units, as a result of secondary mineral deposition and hydrothermal metamorphism (Wilt and Goldstein, 1979; Elders et al., 1981). The 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., 1982). During the initial two years of resistivity monitoring, significant apparent resistivity changes were observed that we believe reflect changing subsurface conditions at reservoir depths (Wilt and Goldstein, 1981). Over the production zone, for example, apparent resistivity was increasing at an annual rate of 5 to 10 percent. This change was attributed to (a) an influx of cooler, fresher water replacing the hot brine and (b) possible porosity reduction caused by the precipitation of secondary calcite as the cooler water came into contact with hot rock (Elders et al. 1981; Wilt and Goldstein, 1981). Immediately eastward and westward of the original production area, concurrent decreases in apparent resistivity of the same magnitude were observed. The cause of decreasing resistivity in these areas are more difficult to explain.

RECENT RESULTS

The most recent measurements of dipole-dipole resistivity on line E-E′ were made in November 1981. Using newly designed differential amplifiers, we obtained measurements with the lowest error levels to date and in the shortest field time span. The average standard error of 1981 data is 1.1 percent, which is a 25 percent improvement over the best previous data. The project required 12 field days from start to finish, compared to 16 days for past years.

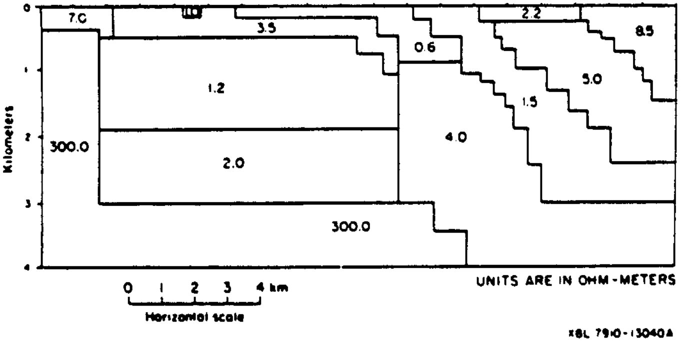

Figure 2. Two-dimensional resistivity model over line E-E′.

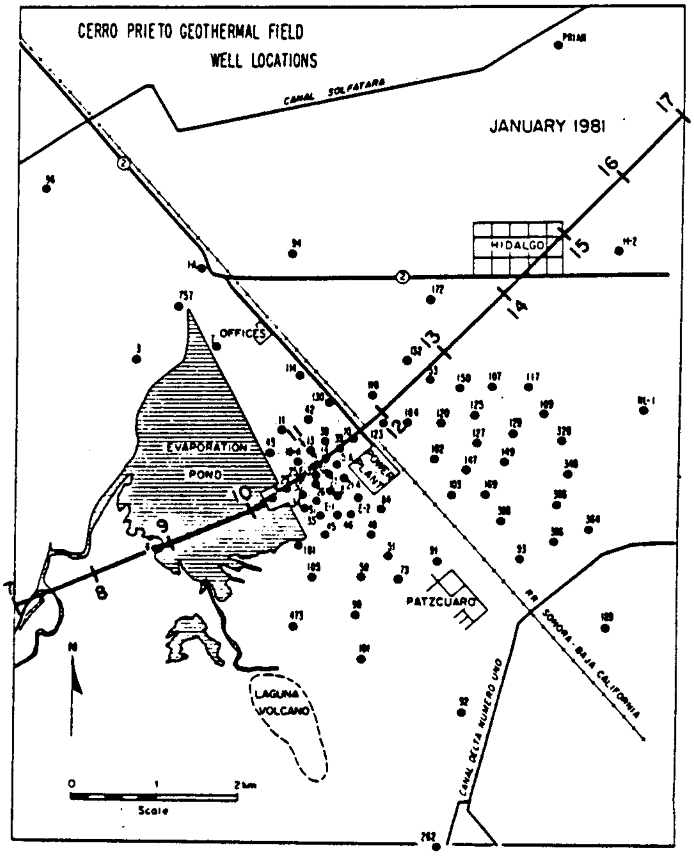

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Figure 3. Station location map for dipole-dipole resistivity line E-E′ in relation to the well field

Figure 4 shows percent standard error for data points taken in 1981. The figure shows very low errors for the smaller electrode separations (n-spacing ≤ 4) and larger errors of 1 to 3 percent for separations out to n=8. Less than 10 percent of these data, however, had standard error larger than 3 percent. This low level of measurement error allows for improved anomaly discrimination and more confidence in the interpretations

Figure 5 shows apparent resistivity changes relative to baseline data taken in 1979 plotted as pseudo-sections for time intervals of 1, 1.5 and 2.5 years after the baseline data taken in 1979.

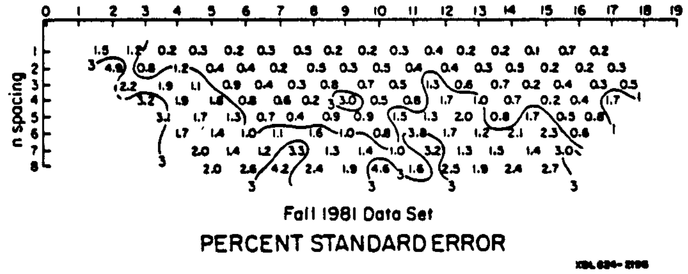

Figure 4. Pseudosection plot of percent standard errors for the Fall 1981 data set.

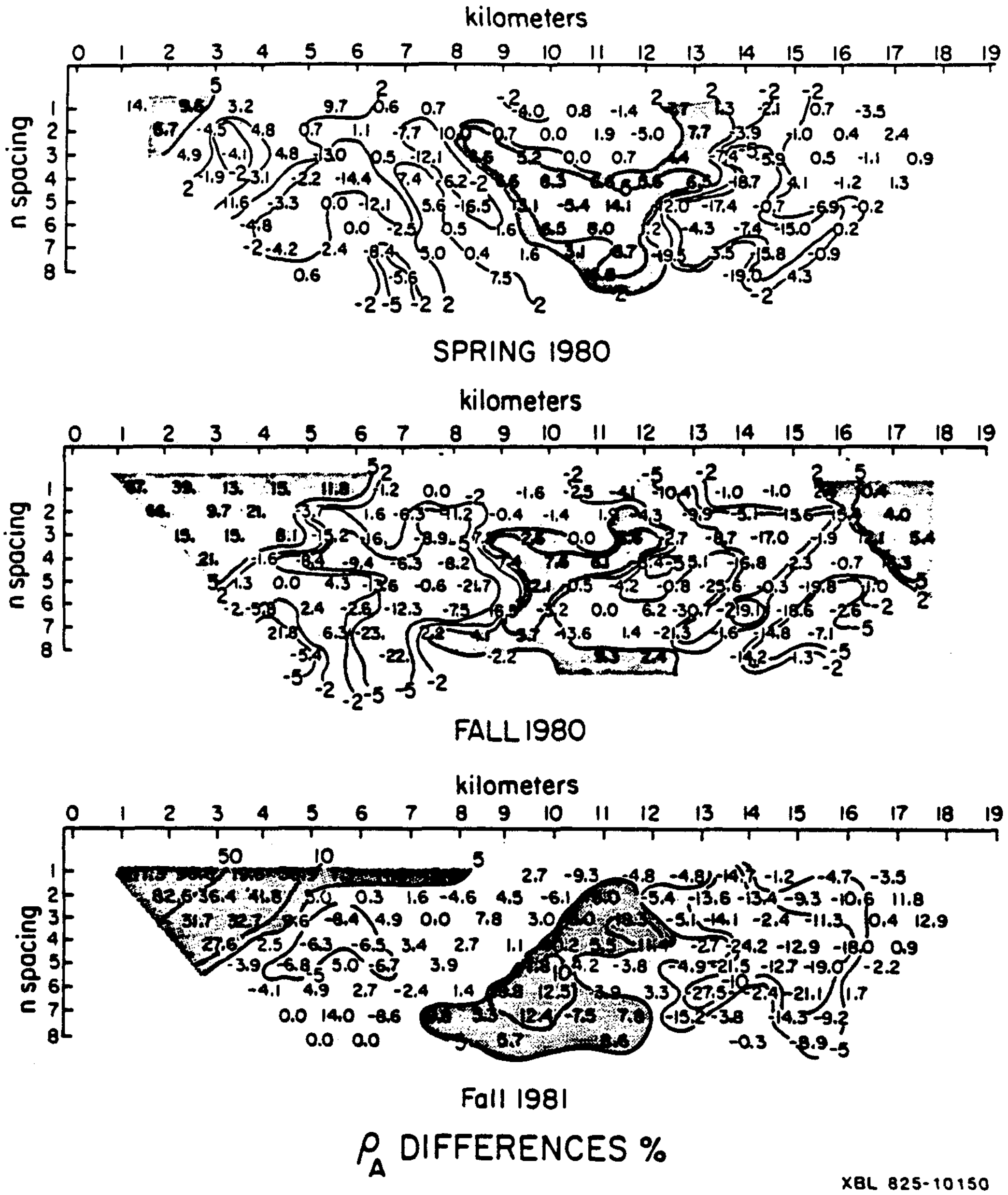

Figure 5. Pseudosection plots of apparent resistivity differences relative to Spring 1979 data set. (a) Spring 1980 (b) Fall 1980, (c) Fall 1981.

The data are plotted as percent change relative to the 1979 data. A similar trend of change is observed for all three plots. Little change is observed for small n-spacings over that part of the line that crosses the production zone; the part of the line adjacent to the Cucapá Mountains, however, shows large changes at small n-spacings, especially in the more recent measurements. This implies that measurements taken at points located over the production field will mainly show the effect of deep changes within the subsurface whereas measurements at points adjacent to the Cucapá's may be dominated by the near-surface effects. The pattern of apparent resistivity difference for n-spacings greater than 2 is remarkably similar on all three plots. All plots show a significant increase in apparent resistivity for points corresponding to the present production zone. They also show a significant decrease in apparent resistivity for points at similar depths but located east of this zone. The changes also seem to be intensifying with time. In the production zone, apparent resistivity seems to be increasing at an annual rate of about 5 percent; to the east of this zone, the annual rate of decrease is perhaps 7 percent.

Figure 6 shows apparent resistivity changes over line E-E′ for a one year interval from Fall 1980 to Fall 1981. The pattern of apparent resistivity changes appears very similar to those in Figure 5 over the central and eastern parts of the line but somewhat different for the western part In contrast to Figure 5 Figure 6 shows an increasing resistivity over the western part of the section. This is particularly evident for n-spacings of 1 to 3 where the increase can be as large as 50

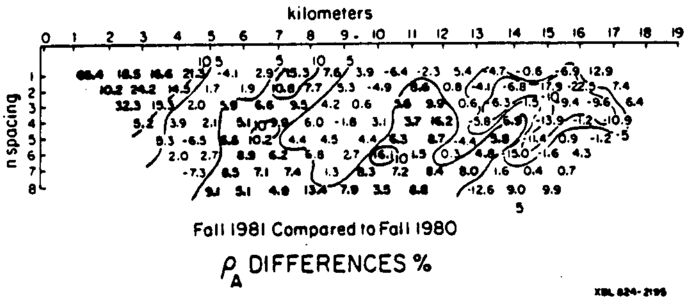

Figure 6. Pseudosection plot of one year apparent resistivity differences over the period Fall 1980 to Fall 1981

percent. The most likely causes of these shallow increases are from changes in the pattern of irrigation. Large near-surface changes would, tend to mask changes occurring deeper in the section but fortunately the irrigated area at the western end of line E-E′ lies sufficiently far from the wellfield as to not obscure resistivity changes in the reservoir.

Although the general pattern of apparent resistivity change over most of line E-E′ appears to be well-established, the local patterns of change may vary greatly. In Figure 7 we display how resistivity has changed at nine data points over the course of the experiment. Six of these points (Figures 7a and 7b) are from the zone of decreasing apparent resistivity east of the present producing zone. The remaining three (Figure 7c) are from the present production zone, where resistivity is increasing. The error bars signify the 95 percent confidence interval. Where data points were repeated during a field session points are plotted adjacent to each other. The three plots in Figure 7a show a steep decline in apparent resistivity over the first 1.5 years followed by little change over the past year. In contrast, the plots in Figure 7b show small increases over the initial 1.5 years but a steep decrease over the past year In a similar fashion, Figure 7c shows apparent resistivity change over time for three points in the production region Again we observe that although all points show resistivity increases with time, the patterns of change vary. These distinctly different patterns of change suggest that the subsurface resistivity in the reservoir region is changing in a fairly complex manner. Although the resistivity changes should be very sensitive to changes in groundwater temperature and salinity, as discussed in the next section, mapping the movement of groundwater fronts would require additional measurements on new lines.

INTERPRETATION AND DISCUSSION

The observed resistivity data will be discussed in relation to the effect of temperature and pore water salinity on typical sediments. Figure 8 (Ershaghi et. al , 1981) indicates that resistivity in the range of 20 to 200°C decreases sharply with increasing temperature but then levels off and may actually increase slightly above 300°C This has some interesting implications at Cerro Prieto. In the reservoir region, for example, where the temperatures exceed 250°C. modest changes in temperature should not be accompanied by changes in resistivity. In the regions adjacent to the reservoir where temperatures are in the range from 20 to 200°C even small changes in temperature may have significant effect on the resistivity. Figure 9 shows how resistivities of aqueous solutions vary with salt type and concentration. For all solutions with concentrations less than 10 percent, there is a sharp decrease in resistivity with an increase in salinity At Cerro Prieto, groundwater salinities are in the range from 0.1 to 3 percent by weight so that small changes in water salinity should have a significant effect on formation resistivity. Other factors, such as porosity and ion exchange capacity of minerals (e.g., clay,

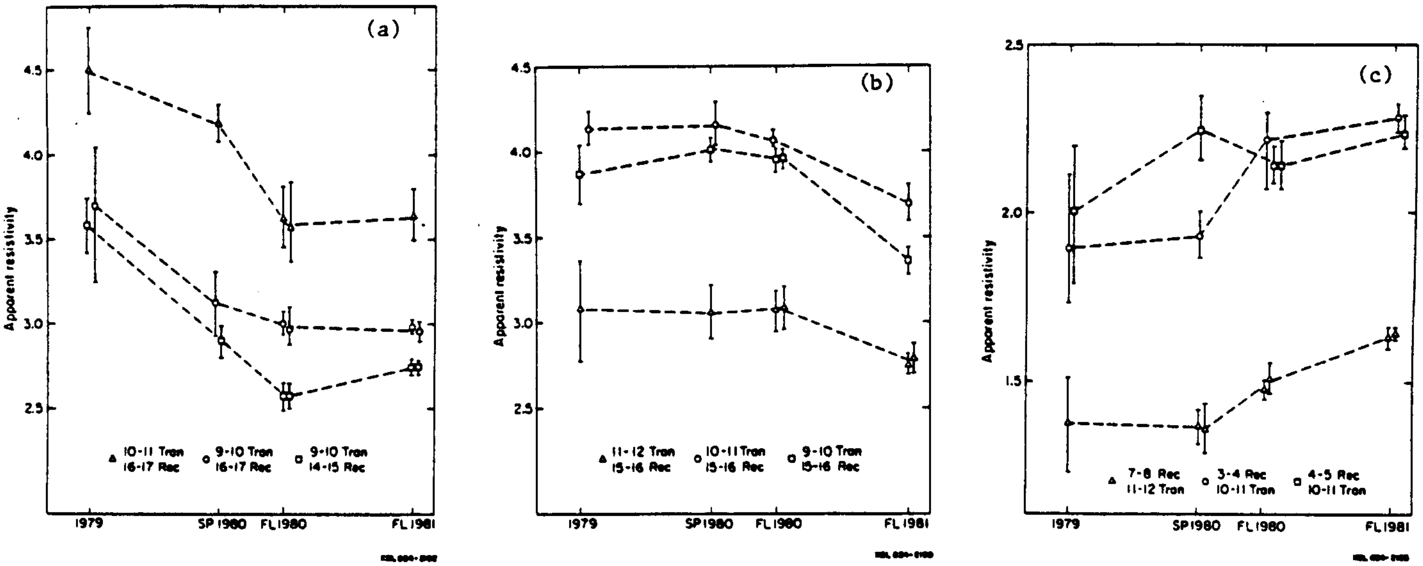

Figure 7 Plot of the apparent resistivity variations for nine selected data points within the reservoir region. Error bars are 95 % confidence limits.
(a) points east of the reservoir with mutual steep decrease,
(b) points east of the reservoir showing resistivity decrease later
(c) points within the reservoir showing resistivity increase.

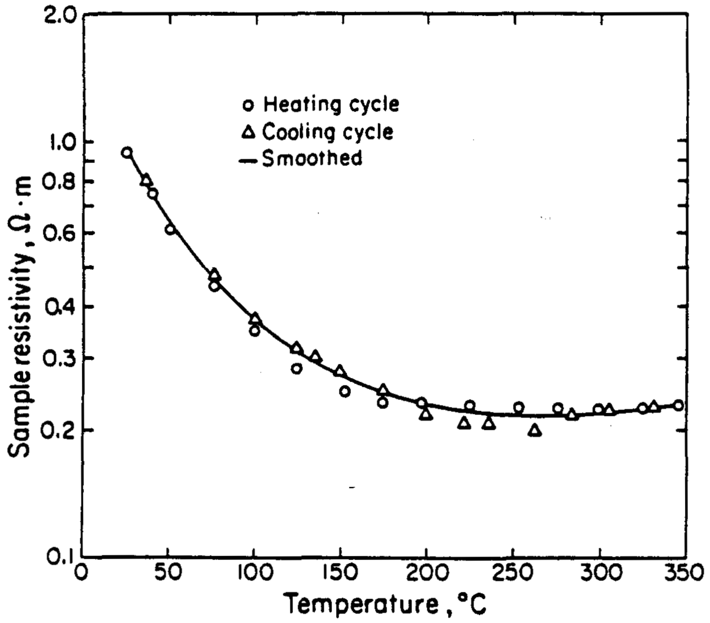

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Figure 8. Resistivity variation with temperature for "typical" water saturated sediments (after Ershaghi et al., 1981).

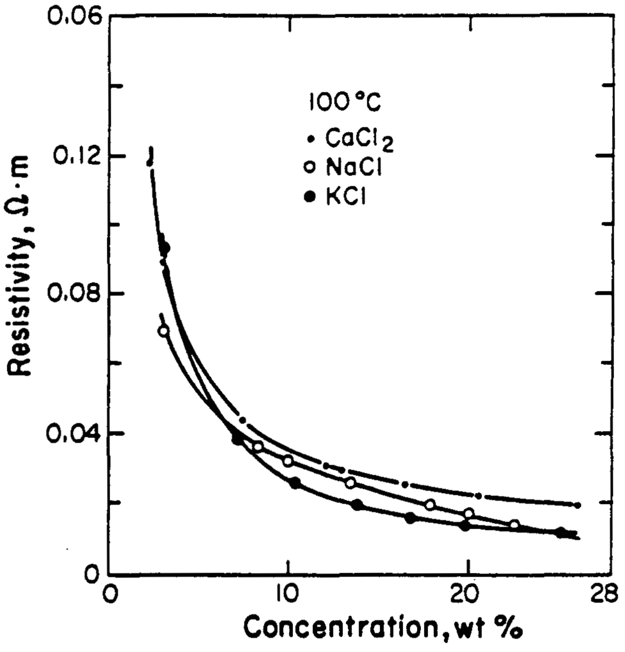

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Figure 9. Resistivity variations for different saline aqueous solutions with increasing salt concentration at 100°C (after Ershaghi et al., 1981).

quartz and zeolites), also influence formation resistivity, but these are believed to be relatively less important as causes of the short-term resistivity changes observed.

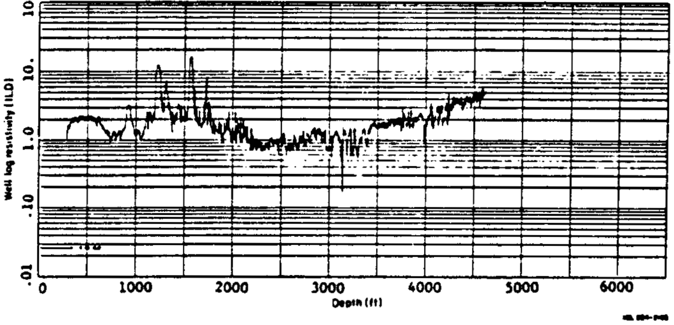
Interpretation of Resistivity Changes

Apparent resistivities have increased dramatically at the western end of line E-E′. Increases of up to 211 percent have been observed over the last 2.5 years, with an average increase of more than 20 percent for the near-surface over the westernmost 4-5 kilometers of the line (Figure 5). Two factors are likely for this overall resistivity increase First, a number of small farming plots have recently been established at this end of the line and the water supplied mainly via irrigation canals is significantly fresher than the native groundwater. A second factor is that groundwater quality as monitored in Mexicali Valley water wells has shown a general improvement over the past several years (B. Terrazas, 1982, personal communication). This improvement is believed due to a greater amount of Colorado River water recharge because of heavier precipitation and run-off in the United States.

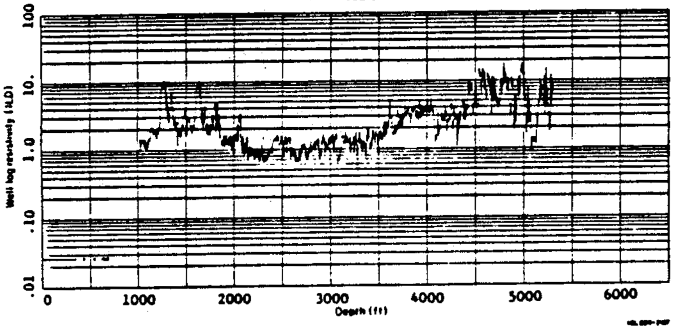
Within the production zone the apparent resistivity has increased at an annual rate of about 5 percent. This has largely been attributed to an influx of fresher groundwater into the system in response to the drop in pressure caused by fluid production (Wilt and Goldstein, 1982). Secondary causes may be the formation of two-phase zones due to local boiling near the wells and porosity reduction due to precipitation of calcium carbonate as cool waters come into contact with hot rock. Chloride concentration in produced water has shown a sharp and continual decrease for many of the Cerro Prieto wells over the past 2.5 years (Grant et al., 1981, A.H. Truesdell, 1982, personal communication). Since the amount of dilution is consistent with the observed increase in resistivity, it is likely that dilution is the major cause for the observed resistivity increase. This brings up the question of how the recharge waters enter the reservoir rocks. 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 indicate a particular pathway for fluid entry, since measurements are limited to one profile. Water entries coming from out of the profile plane therefore cannot be distinguished from movement parallel to the profile. Since groundwater to the north and northeast of the field is considerably less saline (more resistive) than in the reservoir rocks (Grant et al, 1981) it is possible that water may be entering the system from this direction. Clearly, an additional measurement line is needed to establish a direction for subsurface flow.

In an effort to obtain more detailed information on the cause of the resistivity changes in the producing zone, we examined geophysical electric logs for wells in the present well field. The deep induction logs from the recently drilled well E-3 was compared to logs from older nearby wells M-25 and M-29 (Figure 10). These wells are located at the western end of the well field and all lie within a few hundred meters of each other. Self-potential and deep-induction resistivity logs were used in correlating individual lithologic layers between the wells. Techniques used for correlation are described in Halfman et al.,(1982). Although, in general, the individual stratigraphic units correlate very well, initial trials with this technique proved disappointing because the lateral resistivity variations within stratigraphic units were found to be large enough to obscure the observed

(a) WELL M-25



(b) WELL E-3



(c) WELL M-29

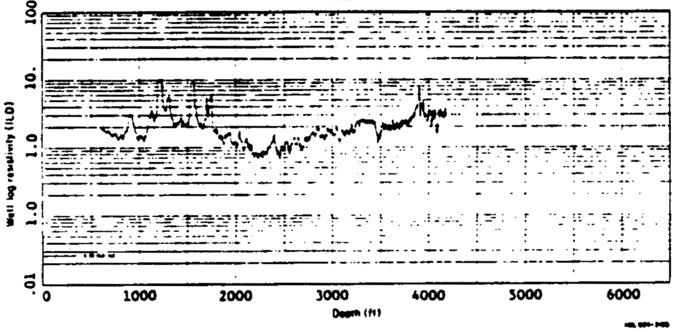


Figure 10. Deep induction and long normal resistivity logs for wells M-25(a), E-3(b) and M-29(c). Well locations were given in Figure 3.

temporal variations. Referring to Figure 10 for example, sand layers at 3500 ft in depth appear higher in resistivity in well E-3 than in M-25 but the same or lower in resistivity than in M-29. The differences may be due to formation damage effects or miscalibration of the logging tool but it is equally likely that the lateral variation of resistivity within the sand is due to mineral, porosity and salinity variations.

CFE has been reinjecting up to 80 tonnes/hr of untreated brine into a shallow aquifer (800-m depth) via well M-9 since August 1979. This well lies directly on the resistivity line between stations 10 and 11, and small changes in apparent resistivity observed in this area may be the result of reinjection. The pattern of resistivity change shown for n = 1 and n = 2 in Figures 5 and 6 is complicated and we have not yet tried to match the changes by means of numerical simulation

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 two-dimensional 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 that is impacted by cooler, higher resistivity water entering the deltaic sediments from the Colorado River 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, in the western part, with an increased percentage of shale in the section (Halfman et al., 1982). The deeper parts of the shale are thought to act as a "leaky" caprock, allowing groundwater into the system but still maintaining a relatively high thermal gradient.

To illustrate the effect of temperature on the resistivity in this region, Figure 11 shows a deep induction resistivity log from well M-53. This figure shows a smoothed curve of measured resistivity and the corresponding curve after temperature effects were removed. Correcting the resistivity log for temperature nearly eliminates the low resistivity zone between 900 and 1500 m which indicates that the steeply dipping low resistivity zone is predominantly the result of sharply increasing temperatures. Note also that by adjusting the log for temperature, the position of the A/B contact which marks the boundary between unconsolidated and consolidated sediments at Cerro Prieto (Puente C. and de la Peña, 1978) correlates better with increasing resistivity. Since the A/B contact indicates the transition into more consolidated or altered reservoir rocks it is logical that this should also be a zone of increasing resistivity.

Although it is clear from the above that temperature has an important effect on observed resistivity, it is not likely that changing temperature accounts for the bulk of the observed resistivity decrease since this would require a large adjustment in the temperature distribution. It is more

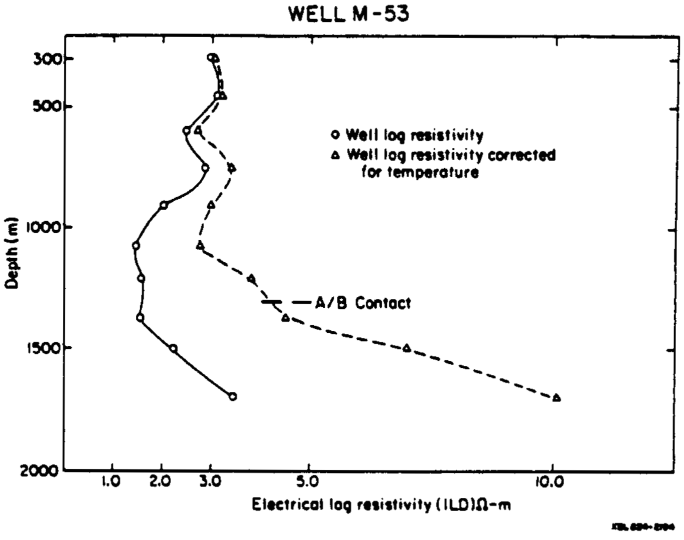


Figure 11 Well log resistivity from well M-53 Plot shows uncorrected resistivity and resistivity corrected for temperature.

likely that much of this change is related to changes in pore fluid salinity. The deeper waters of the Mexicali Valley are known to be quite saline and these waters may move upward and laterally in response to production induced pressure changes (Truesdell, 1982, personal communication). It is possible that decreasing resistivity in the shallower and initially cooler parts of the region are predominantly caused by temperature increases due to upward moving hot waters, for example, through fault zones. On the other hand, resistivity decreases in the hot deeper portions of the region, where temperature effects on resistivity are minor, may be related to an influx of more saline groundwater.

SUMMARY AND CONCLUSIONS

Repetitive dipole-dipole resistivity measurements taken during the past 3 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 easter 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. Reinjection of spent brine may also contribute to resistivity changes near the reinjection well. A sharp increase in resistivity is occurring in the near surface at the western end of the line. This is mainly due to influx of irrigation water for local agriculture and may also be related to a general improvement of groundwater quality in the area. An important aspect to this increase is that it tends to obscure any changes occurring deeper in this part of the section.

Because of the increase in geothermal brine production to serve the new power plants being constructed in the eastern part of the field, it is recommended that an additional resistivity monitoring line be established oblique to line E-E′ and crossing the eastern production area. With this new line resistivity changes due to fluid withdrawal from this region would be measured and the effect of this production on the rest of the system could be assessed. Secondly, using both lines, a more complete picture of resistivity changes would emerge from the additional measurements, thus improving our ability to map the movement of temperature-salinity fronts. Finally, monitoring the water chemistry in available observation wells around the field could provide important clues as to the cause of resistivity changes.

ACKNOWLEDGEMENT

The authors wish to acknowledge the efforts of LBL and CFE field personnel who have helped us throughout this project. Don Lippert, Ray Solbau, Wayne Lee and Bob Davis contributed greatly to the field surveys and the successful aquisition of the high quality resistivity data. The aid of Dr Rubén Zelwer is also appreciated. Sue Halfman provided invaluable assistance with the analysis of well logs. Finally, the personnel at CFE in Mexicali have been of considerable help in providing support for the field project and in helping us interpret the results.

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.

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