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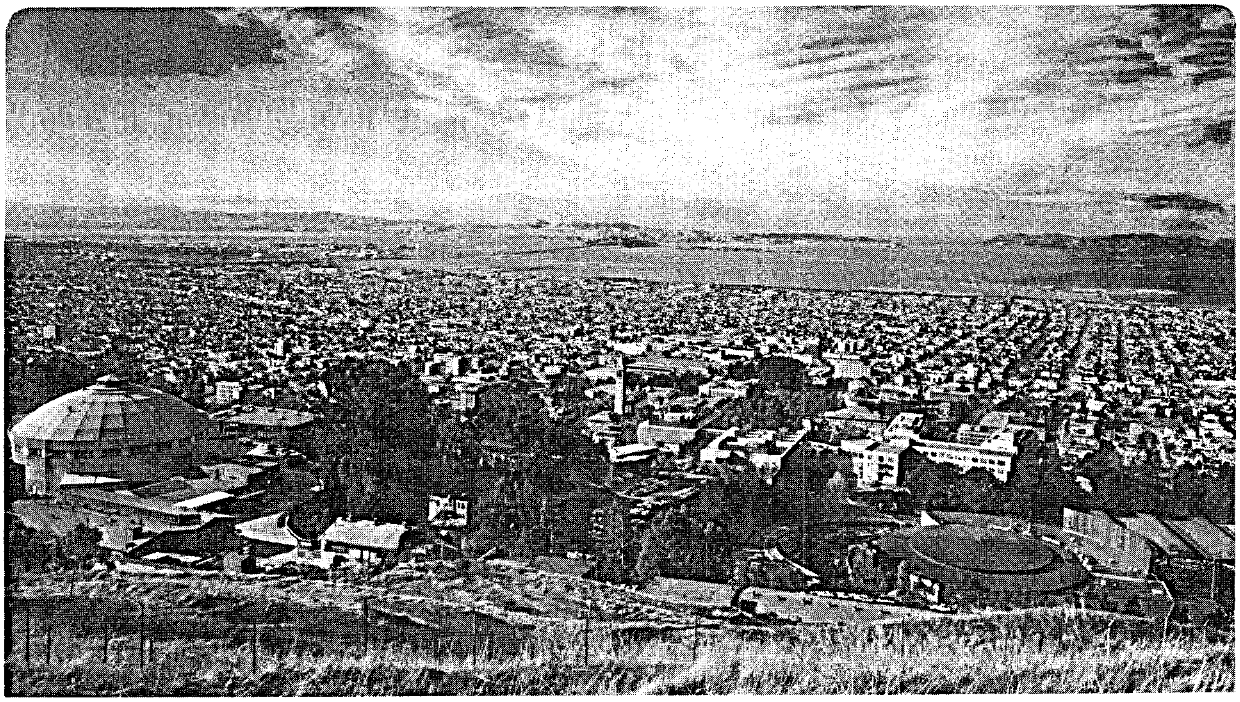

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ABSTRACT

Dipole-dipole resistivity measurements for the combined purposes of reservoir delineation and resistivity monitoring were first made at Cerro Prieto in 1978 and have continued on an annual basis since then. Two 20 km-long dipole-dipole lines with permanently emplaced electronics at 1-km spacings were established over the field area; one of these lines is remeasured annually. Resistivity measurements are taken using a 25 kW generator capable of up to 80A output and a microprocessor-controlled signal-averaging receiver; this high power-low noise system is capable of highly accurate measurements even at large transmitter-receiver separations. Standard error calculations for collected data indicate errors less than 5 percent for all points, but 95 percent confidence intervals show error limits about 2-4 times higher. Data indicate little change of apparent resistivity within the upper 300 m over the field. However, apparent resistivity increases are observed over the producing zone at depths of 1 km and greater. Large zones of decreasing apparent resistivity are observed flanking the zone of increases on both sides.

To explain the resistivity changes observed, we performed simple two-dimensional reservoir simulations in which cooler, less saline recharge water

enters the reservoir from above through a leaky caprock and laterally through a more permeable vertical boundary. The calculated magnitude of a resistivity change after 3 years of simulated production fits the observed data, but the anomaly shapes differ. We conclude that the rapidly moving hydraulic front produces a salinity change large enough to explain the resistivity increase, but that our recharge assumptions were probably oversimplified. There is geological evidence for hot water recharge ascending into the reservoir from the east.

INTRODUCTION

Beginning in 1978 LBL, in cooperation Comisión Federal de Electricidad (CFE), began making repetitive dipole resistivity measurements over the Cerro Prieto geothermal field (Figure 1). The project goals were to delineate subsurface resistivity features, such as possible reservoir boundaries, and to detect whether changes in subsurface resistivity were occurring due to continuing fluid extraction. A permanent array of electrodes was established one km apart along two lines and the measurements were repeated annually on one line passing directly over the production area.

Figure 2 shows the position of the dipole-dippole line (E-E') in relation to the present well field. When the resistivity surveys began, all of the production was from wells between station 10 and 12. These wells penetrated the "α" reservoir at a depth of 1.4 to 1.6 km and were supplying an average of 2200 tonnes/hr of brine. A small-scale, experimental attempt at reinjection began in 1980. Subsequent to the beginning of the resistivity work, drilling east of the railroad found a deeper reservoir at 2.5 to 3.0 km depth. Production from the deeper reservoir will commence in 1983 when a second power plant is completed.

Figure 3 shows our working two-dimensional resistivity model beneath line E-E' that we derived by fitting field data to results calculated by means of a two-dimensional resistivity modeling program (Wilt and Goldstein, 1979). The resistivity model shown is reasonably consistent with geophysical well logs from newer wells, and thus has not been revised or updated. Two of the more significant features of the subsurface resistivity distribution are the relatively high resistivity zone (4.0 ohm·m) associated with the reservoir rocks and the adjacent steeply dipping (1.5 ohm·m) conductive zone, located east of the production zone. The high resistivity region surrounding the production intervals is 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 zone is associated with high thermal gradients and an increasing thickness of shales in this part of the section (Halfman et al., 1983). After two years of resistivity monitoring, significant changes in apparent resistivity were observed, and we took them to indicate 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 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.

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 square wave periods from 1 to 100 seconds. This power source proved ideal for Cerro Prieto survey since it is easy to move yet powerful enough to provide adequate signals at distant stations. Because of the highly conductive ground, 40-second-period square waves were used to minimize inductive coupling effects.

Signals were observed across four dipoles simultaneously, located end-to-end at integer multiples (n) of 1 to 8 times the 1 km transmitter dipole length. The signals were detected with porous copper-copper sulfate electrodes and then electronically filtered to remove 60 Hz and telluric noise. After amplification, the signals were digitized, decomposed into Fourier components and stacked using a multichannel spectrum analyzer (Morrison et al., 1978). This system was found to be very effective for obtaining high quality data as it was possible to eliminate much of the noise prior to stacking and to reduce the remaining noise by stacking the signals from four dipoles simultaneously.

Two 20-km-long dipole-dipole lines oriented east-west were established in the field area (Figure 1). Line D-D' is outside of the producing field area and was occupied primarily for background information. Line E-E' crosses directly over the production zone and has been remeasured annually. Measurements are taken at 130 points to a maximum n-spacing of 8, which corresponds to a transmitter-receiver separation of 9 km and a maximum depth of penetration of about 3 km. A minimum of 30 square-wave cycles were averaged at each site. For the distant sites, where signals are weakest, more than 200 cycles were averaged. Measurements were often taken during the evening hours and during weekends, when telluric and cultural noise levels were lowest. Almost half of the points were measured twice or more during each annual field session. This was done to estimate repeatability of measurements over a short time interval and to compare short time repeatability with errors estimated from individual data sets.

MONITORING

Figure 5 shows apparent resistivity changes relative to baseline data taken in 1979 plotted as pseudosections for times of 1, 1.5, and 2.5 years after the baseline data were taken. The pseudosections are plotted in units of 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 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.

Within the production zone the apparent resistivities have 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). Chloride concentrations in the water produced by many of the Cerro Prieto wells have decreased over the past 2.5 years (Grant et al., 1981; A. H. Truesdell, 1982, personal communication). Since the amount of chloride dilution is consistent with the observed increase in resistivity, it is likely that dilution is the major cause for the observed resistivity increase.

One of the major questions is how 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 clearly indicate pathways for fluid flow as measurements are (a) heavily volume-averaged and (b) data are limited to one profile. Thus, for example, flow oblique to the line produces changes that cannot be distinguished from movement parallel to the line. 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.

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. 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., 1982). The deeper shales are thought to act as a "leaky" caprock, allowing groundwater to ascend into the α reservoir while maintaining a relatively high thermal gradient.

To help explain the resistivity changes, we performed a series of simple reservoir simulation studies combined with the appropriate resistivity calculations (Goldstein et al, 1982). We considered production from a two-dimensional liquid-dominated reservoir with dimensions and parameters of the Cerro Prieto "α" reservoir, that has been produced continually since 1973. Lateral and downward recharge of colder, less saline waters only was assumed. Calculated apparent resistivities over the reservoir increased on the order of 10 to 20 percent over a 3-year period of simulated production and recharge. The magnitude change was similar to that observed in the field. The numerical simulation showed that the hydraulic front, not the thermal front, was clearly responsible for resistivity changes. It was also apparent from the model studies that the assumed recharge model is not totally correct; that there may be a component of hot water recharge moving upward into the "α" reservoir along the steeply-dipping zone indicated by the 1.5 ohm·m resistivity. This circulation system is consistent with a flow pattern worked out from well log analysis and geologic data by Halfman et al (1982).

ACKNOWLEDGEMENTS

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FIGURE CAPTIONS

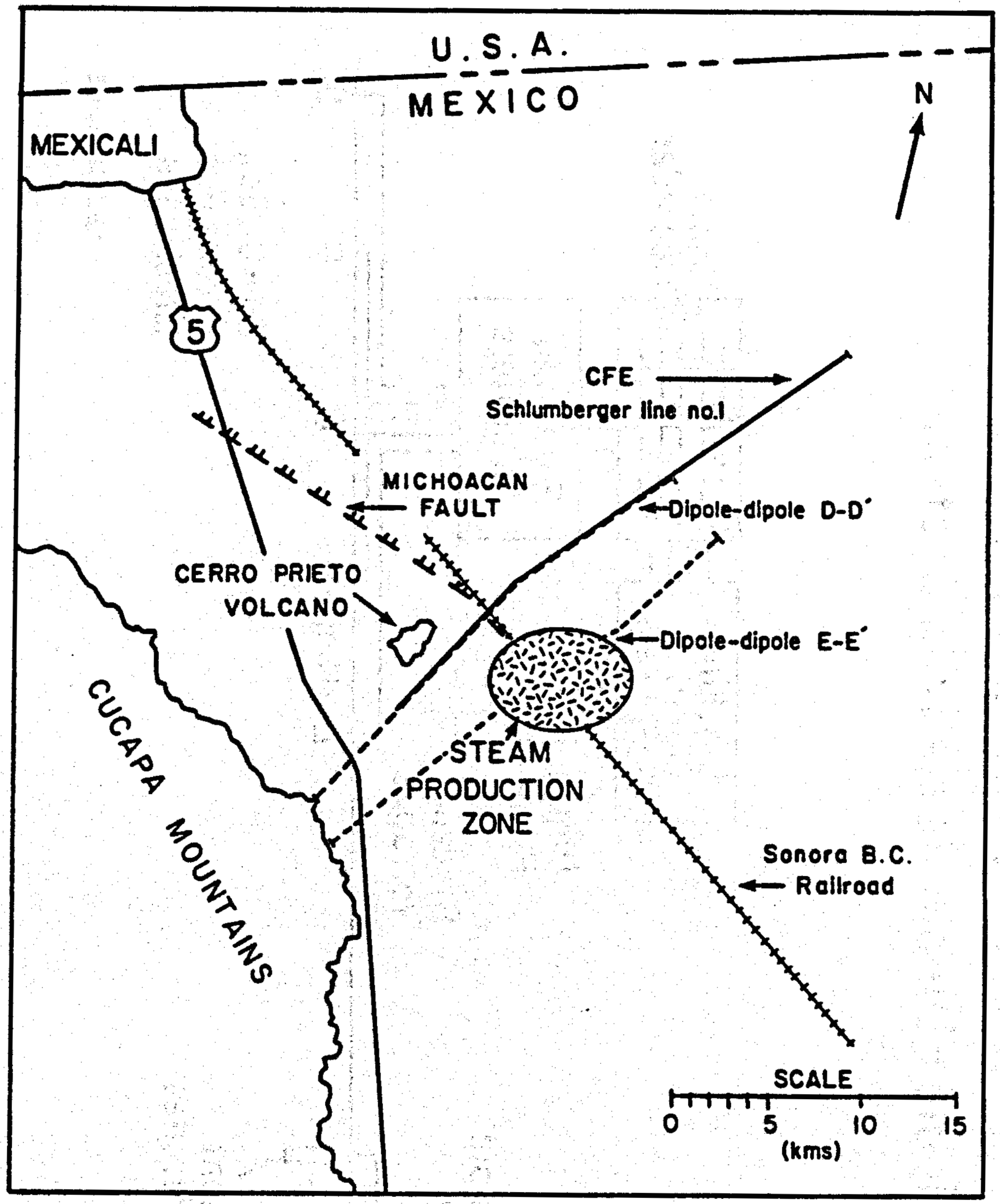
Figure 1. Location map of the resistivity monitoring lines.

Figure 2. Station location map for dipole-dipole resistivity line E-E' in relation to the well field.

Figure 3. Two-dimensional resistivity model over line E-E'.

Figure 4. Schematic diagram of the LBL dipole-dipole resistivity system.

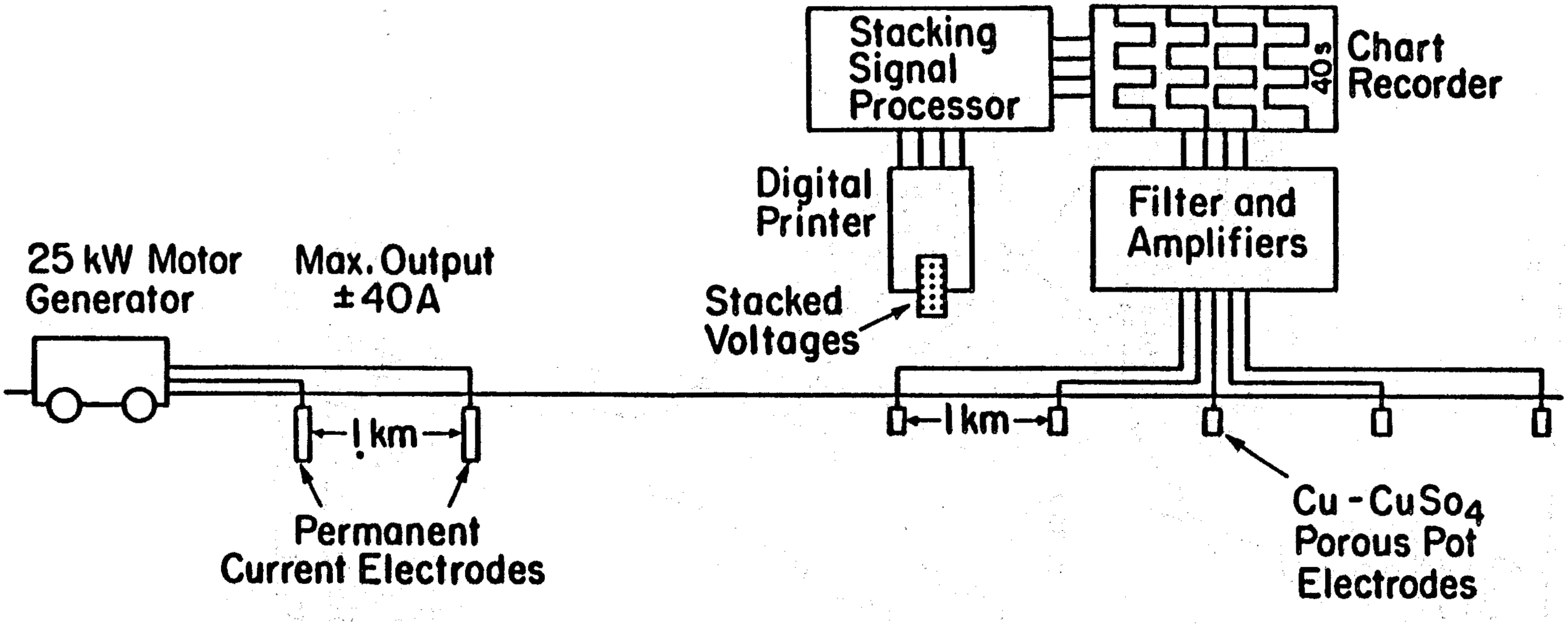
Figure 5. Pseudosection plots of apparent resistivity differences relative to Spring 1979 data set. (a) Spring 1980, (b) Fall 1980, (c) Fall 1981.



LOCATION MAP LBL RESISTIVITY PROJECT, CERRO PRIETO GEOTHERMAL FIELD, BAJA CALIFORNIA, MEXICO.

XBL 788-1632

Schematic Diagram of LBL Dipole - Dipole Resistivity System



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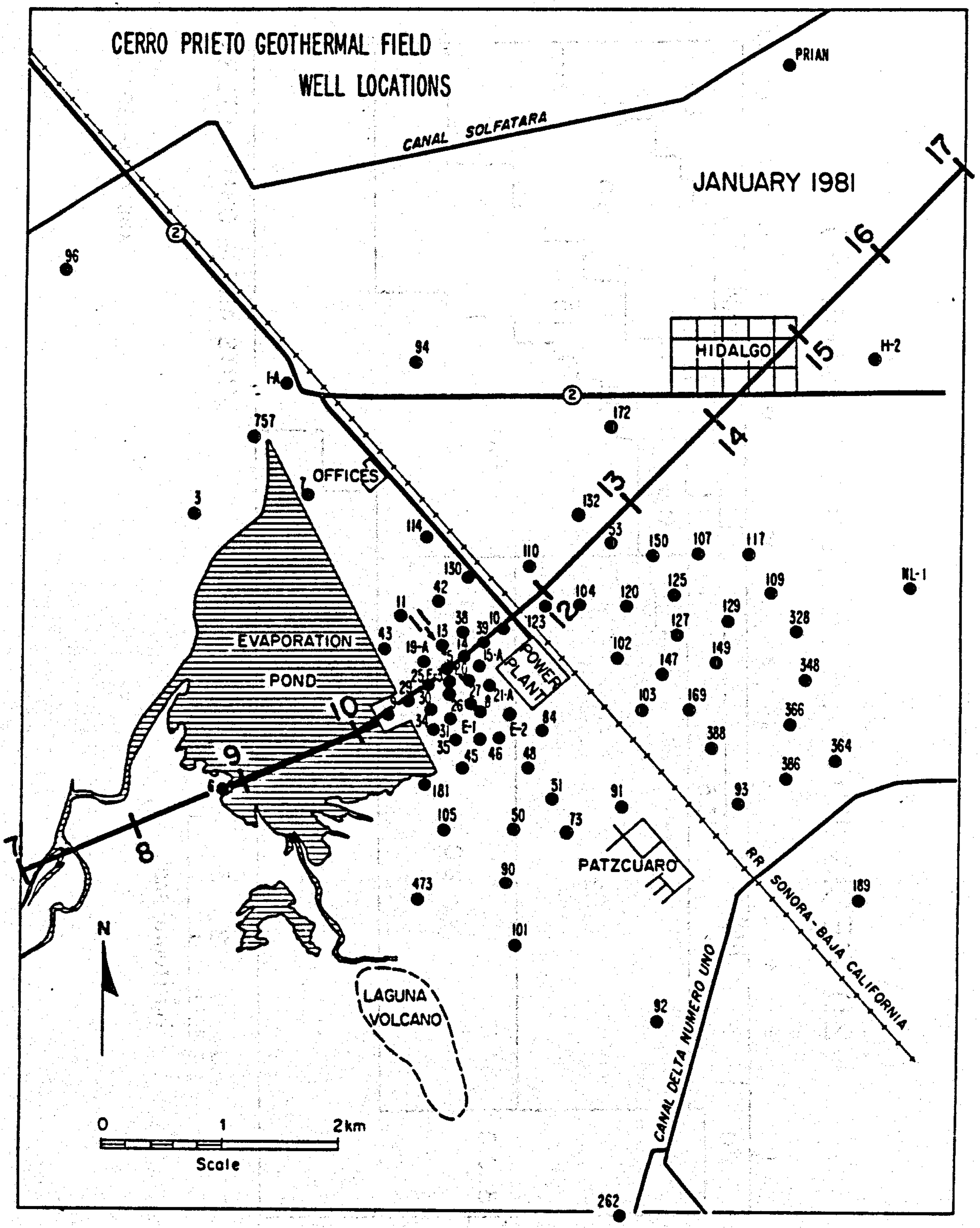

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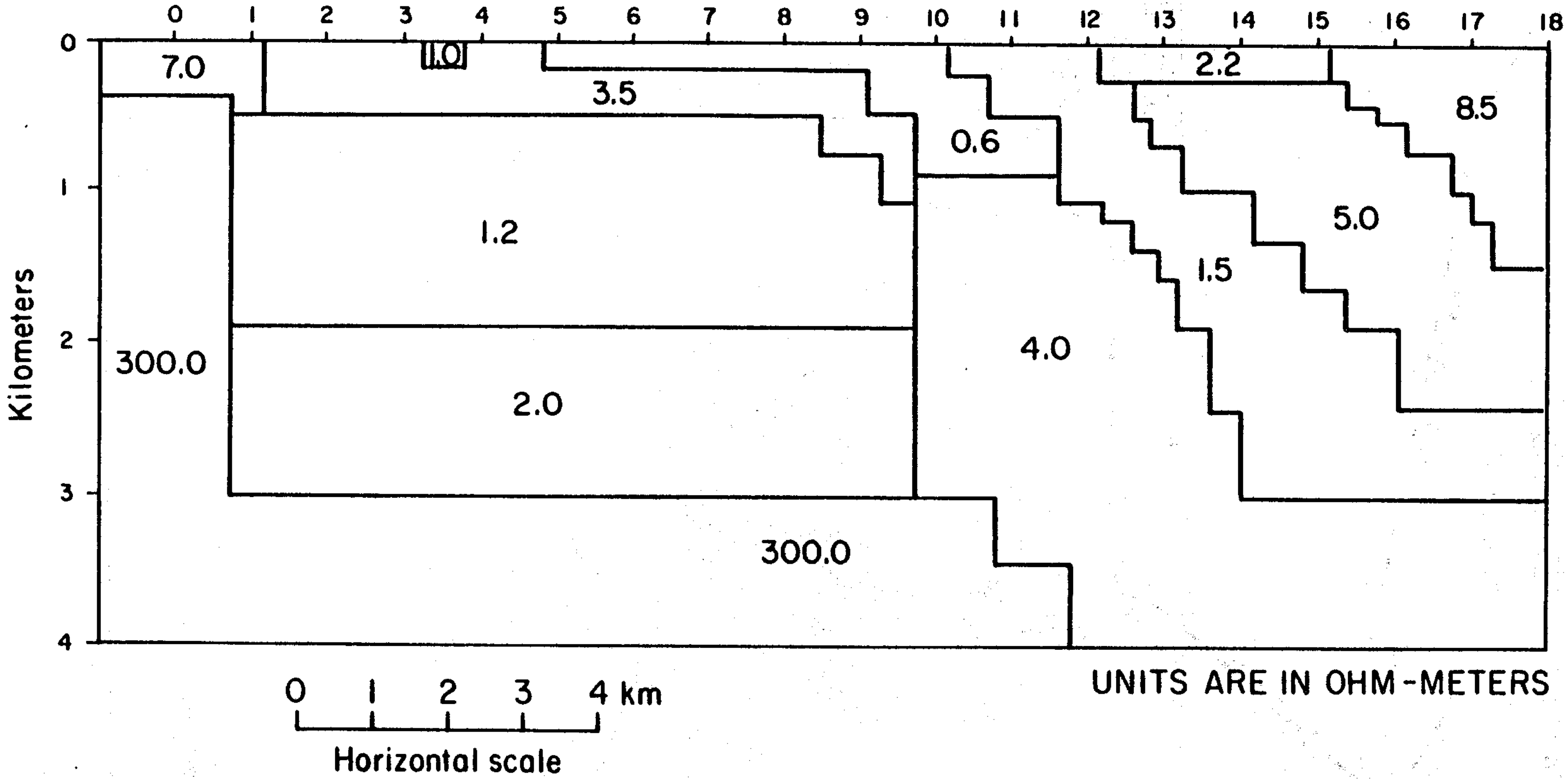
2D RESISTIVITY MODEL, LINE E-E' (1979)



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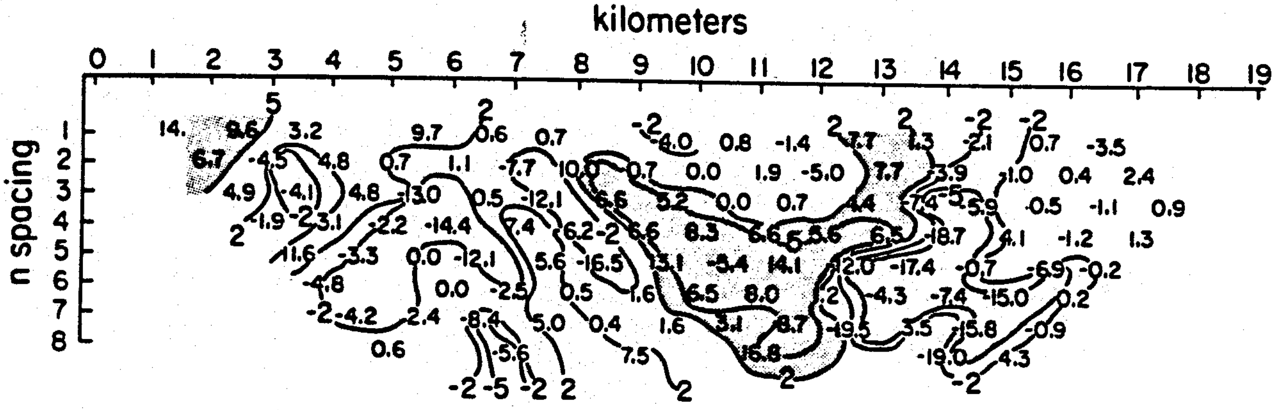
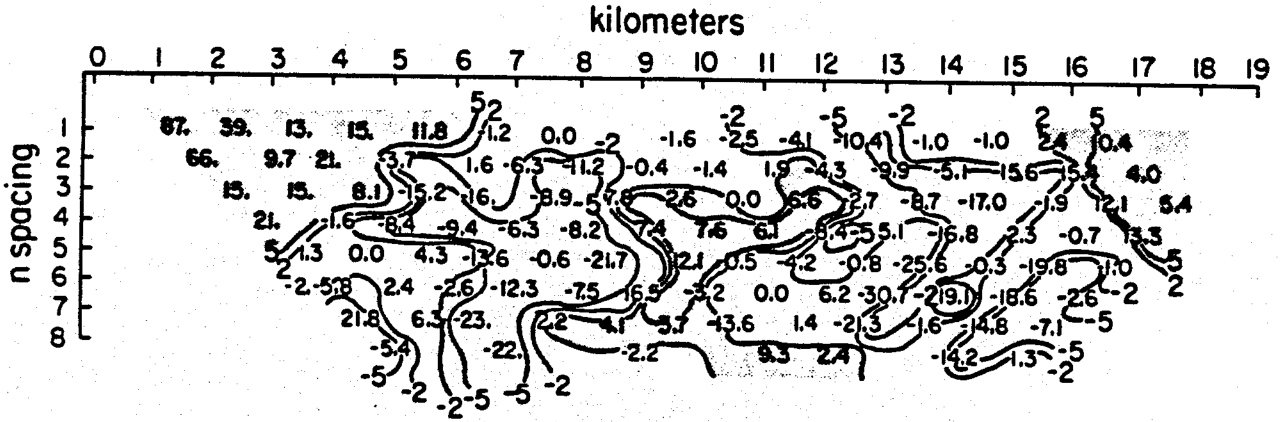
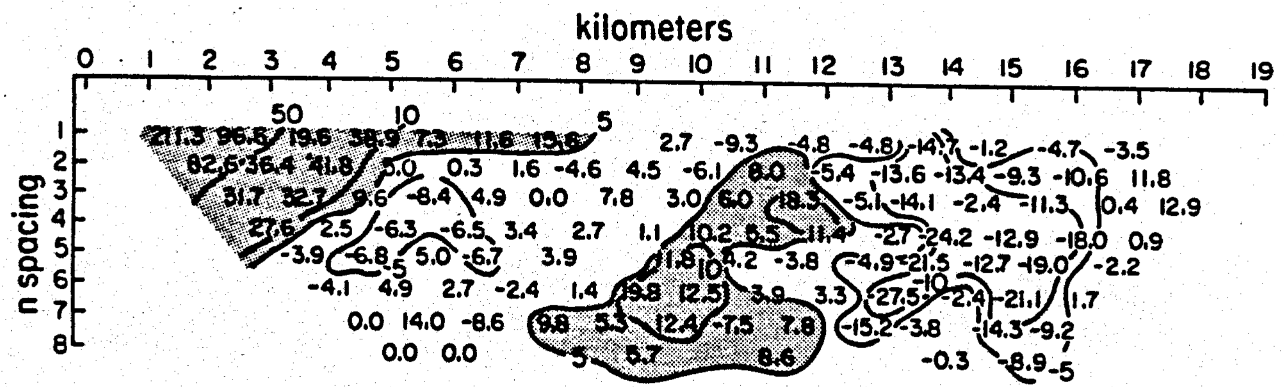


SPRING 1980



FALL 1980



Fall 1981

ρ_A DIFFERENCES %

XBL 825-10150