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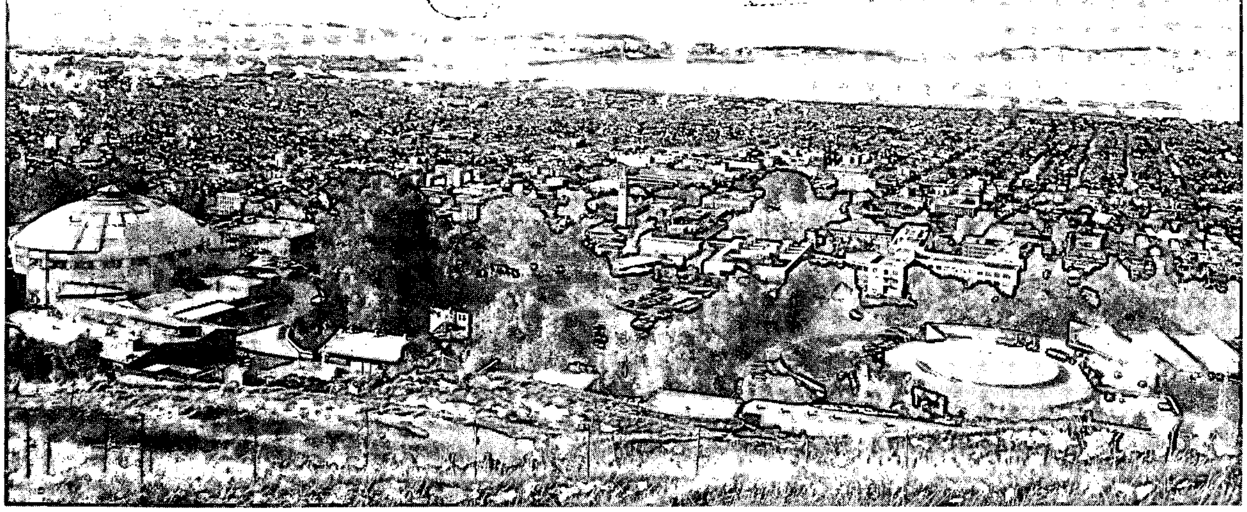

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Two-Dimensional Inversion of Resistivity Monitoring Data from the Cerro Prieto Geothermal Field

by

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ABSTRACT

Two-dimensional iterative, least-squares inversions were performed on dc resistivity data obtained over the Cerro Prieto geothermal field at five successive times during the 1979-1983 period. The data were taken on a 20-km-long control line centered over the production region. Inversions were performed on the apparent resistivities after they were converted to percent changes in apparent resistivity relative to the base year data of 1979. The resulting solutions gave the percent change in resistivity within each of 47 rectangular blocks representing the reservoir and recharge regions. These changes are compared to and found consistent with hydrogeologic and recharge models proposed by other workers on the basis of geophysical well logs, well cuttings, well production, geochemical and reservoir engineering data. The solution support the model of a reservoir that is being recharged mainly by cooler, less saline water, causing changes in both pore fluid resistvity and the extent of boiling near the wells. There may be a component of high-temperature recharge from below and to the east, but flow may be impeded by a two-phase zone. Notwithstanding the various sources of error and uncertainty in the data acquisition and 2-D inversions, repetitive, high precision dc resistivity monitoring seems to be a useful method for assessing reservoir conditions when used in conjunction with production and reservoir engineering data and analyses.

INTRODUCTION

Repetitive dc resistivity measurements were made over the Cerro Prieto geothermal field at intervals of 6 to 24 months during the term of the first international agreement between DOE and the Comisión Federal de Electricidad (CFE) to study the Cerro Prieto reservoir (1978-1983). The method of data acquisition and the results of these repetitive measurements have been reported earlier (Wilt and Goldstein, 1984; Wilt et al., 1984). Our initial impressions were that changes observed in the succession of dipole-dipole pseudosections showed (a) increasing resistivity associated with the production zone, (b) possible hot-water recharge from a deeper source to the east, and (c) complex changes in near-surface resistivities due to a combination of factors such as changes in farming and irrigation patterns, infiltration of waste water from the evaporation pond and canals, variations in rainfall, and underflow from the nearby Colorado River. However, these conclusions were based primarily on inspection of the percent changes in the apparent resistivity pseudosections relative to baseline data taken in 1979. Only limited, quantitative analysis of the successive pseudosections was done initially to understand the subsurface processes. For example, we modeled the fluid migration and recharge into the shallow, western "α" reservoir by cooler, less saline waters (Goldstein et al., 1982). By combining 2-D fluid migration and mixing with a 2-D fluid resistivity analysis, we were able to show that the increasing apparent resistivity magnitude associated with the production zone was consistent with a progressive cooling and decline in salinity of the reservoir fluids.

Recently, we have made a more rigorous numerical analysis of the apparent resistivity data, applying iterative, least-squares inversion techniques directly to the percent-change apparent resistivity pseudosections. This paper reports on the results of those calculations, and illustrates both the value of dc resistivity monitoring as a reservoir engineering technique and the uncertainties of the method.

THE RESISTIVITY MODEL

Figure 1 shows the central portion of our control line (E-E') over the well field. During the monitoring time (1979-1983) virtually all of the production came from wells located roughly between electrode points 10 and 12. Fluid production amounted to 36 ± 3 x 10^6 tonnes/y (Mañon, 1984); an average well produced approximately 125 tons/h from a depth of between 1.2 and 1.8 km. Separated brines were sent to a large evaporation pond, and the overflow was carried away via a canal to the Laguna Salada. Only a very small fraction of the brine was reinjected.

During exploitation there has been a slow decline in the temperature of the produced fluids (Fausto et al., 1981) caused by leakage of cooler and probably less saline waters from above (Grant and O'Sullivan, 1982) and from the west (Mercado, 1976; Lippmann and Bodvarsson, 1983). There has also been a steady decline in reservoir pressure during the 1973-1978 period possibly caused by fluid contraction due to cooling. However, further cooling and the presence of CO_2 in the fluids has probably led to boiling near the wells (Lippmann and Bodvarsson, 1983). Because of the high permeability of the system, Grant et al. (1984) doubt that an extensive two-phase zone can develop in the reservoir. Lippmann and Bodvarsson (1983) show, however, that a large two-phase zone may exist to the east of the α reservoir, in the area between electrodes 12 and 13 and at a depth of 1.3 to 1.8 km.

Using what we considered to be a good apparent resistivity data set, taken in 1979, a subsurface resistivity model was calculated by a rather laborious trial-and-error procedure of 2-D forward models (Wilt and Goldstein, 1981). The resulting cross-section (Figure 2) has served as the basis of our subsequent interpretations. Although this model may not be entirely correct, particularly for depths > 2 km, it has been generally substantiated by resistivity logs and other drill hole data (Halfman et al., 1984). The two most important features in this model are:

1. A high resistivity (4 ohm·m) region associated with the production region and attributed to hydrothermal metamorphism and reduced porosity of the shaley units, and
2. A dipping low resistivity (1.5 ohm·m) region flanking the resistive dome on the east, and which has been explained by various authors as due to a zone of recharge along faults or a "sandy gap" in the shaley caprock.

The low resistivities (0.6 ohm·m) at the surface above and to the west of the well-field may be due to a combination of the natural hydrothermal discharge zone (that some believe is fault controlled) and infiltration of saline brines from the evaporation pond and from drainage canals.

APPARENT RESISTIVITY CHANGES

Figure 3 shows the apparent resistivity data plotted as the cumulative percent change 1, 1.5, 2.5 and 4.0 years after the 1979 data were taken. The data are plotted, by convention, at the intersection of the 45° diagonals subtended downward from the midpoint of the current electrodes and the corresponding midpoint of the potential electrodes. In all surveys the electrodes were the same set of buried aluminum plates. Long-term signal-averaging and repeated measurements were used to reduce errors due to telluric noise and cultural noise from farming and geothermal activities. The errors in apparent resistivity due to random noise were estimated to vary between 0.1 and 5%; the errors increasing, as expected, with increasing number of dipole separations (n) between the current and potential dipoles. It can be easily shown that the random error in the cumulative percent change of apparent resistivities to the i-th year,

$$\frac{\rho_a\,(\text{year}_i) - \rho_a\,(\text{base year})}{\rho_a\,(\text{base year})} \times 100, \qquad (1)$$

should be of the order of 0.2 to 10%.

INVERSION OF THE DATA SETS

Because the apparent resistivities are nonlinear functions of the subsurface resistivity distribution, 2-D inversion is done iteratively. Typically, one must calculate the forward 2-D solution and the partial derivatives of the solution with respect to model parameters at each iteration, which can be an expensive process (Inman, 1975; Hoversten et al., 1982; Sasaki, 1982; Tripp et al., 1984).

For simplicity, we chose a model composed of 47 rectangular blocks, each block with constant but unknown resistivity. As block geometries are prespecified, the resistivities are the only unknown parameters. The block geometry used for the Cerro Prieto data sets was based somewhat on the 2-D model (Fig. 2).

Solutions for block resistivities are little affected by the choice of starting resistivity, but are highly dependent on how one discretizes the mesh into blocks. For this reason, one tries to make the blocks about the same dimensions as the inhomogeneities expected, but for proper resolution of the unknown resistivities the blocks should have dimensions comparable to the electrode separations.

We incorporated the finite difference program for the forward 2-D calculation (Dey and Morrison, 1979) into our inversion algorithm. The potentials at a grid of 113 x 16 nodes is calculated for 21 transmitter positions. The computing time required to determine the resistivities of 47 blocks is approximately 2 minutes on the LBL CDC 7600. It takes 34 CPU seconds for one iteration, 30 percent of which is spent calculating the partial derivatives. The algorithm requires 3 or 4 iterations to converge.

Once the 2-D earth model composed of M blocks with resistivities $\rho_1, \rho_2, \ldots, \rho_m$ is determined, we next estimate the percent change in resistivity for each block for the next set of repetitions. Assuming that the changes in intrinsic resistivity of the blocks are small, then the change in apparent resistivity, $\Delta\rho_a$, at any point on the pseudosection can be approximated by a Taylor series expansion,

$$\Delta\rho_a \approx \sum_{j=1}^{M} \frac{\partial\rho_a}{\partial\rho_j}\,\Delta\rho_j \qquad (2)$$

where $\Delta\rho_a$ is the observed change in apparent resistivity, $\Delta\rho_j$ is the change in resistivity of the j-th block, and $\partial\rho_a/\partial\rho_j$ are the partial derivatives previously calculated for the 2-D inversion. Using the fact that

$$\frac{\partial\ln\rho_a}{\partial\ln\rho_j} = \frac{\rho_j}{\rho_a}\,\frac{\partial\rho_a}{\partial\rho_j}, \qquad (3)$$

we obtain from Eqs. 6 and 7

$$\frac{\Delta\rho_a}{\rho_a} \approx \sum_{j=1}^{M} \frac{\partial\ln\rho_a}{\partial\ln\rho_j}\,\frac{\Delta\rho_j}{\rho_j}. \qquad (4)$$

From Eq. 4 we see that the percent change in apparent resistivity ($\Delta\rho_a/\rho_a \times 100$) can be approximated by a linear combination of the percent change in the intrinsic resistivity of each block ($\Delta\rho_j/\rho_j \times 100$) and the partial derivatives. A least-squares method was used to solve for the unknown parameters $\Delta\rho_j/\rho_j$. Numerical experiments conducted on computed, noise-free data sets show that after three iterations the residual error in the solutions for percent change in block resistivities varies from 1 or 2 percent for shallow blocks in which no change occurred, to 6 to 20 percent in blocks undergoing change of 20 percent resistivity.

DISCUSSION OF RESULTS

The data were inverted twice. The first time we used all the apparent resistivity data collected, making no corrections for random errors in the data points. The results, Figure 4, show the progressive cumulative changes in block resistivity relative to the data set from Fall 1979. The upper number is the percent change in block resistivity, the lower number in parenthesis is the estimated standard deviation of the calculated percent resistivity changes. The standard derivations can be viewed only as a relative measure of statistical significance. The standard deviations are smallest (5-10%) for the shallowest blocks, increasing with depth to >50% for some of the deepest blocks. The standard derivation numbers do not imply that the percent change can be varied by that amount without affecting the forward calculations (Hoversten et al., 1982).

In general, the resistivity associated with the production region exhibits a general increase as noted in the Introduction. There is also a pervasive decrease in resistivity in the deepest blocks, due possibly to broad-scale fluid movement caused by fluid withdrawal from the reservoir. It is perplexing, however, that the largest changes occurred between stations 2 and 6, well away from the production region. These large changes are probably a solution error due to the large progressive increases in shallow resistivity at the west end of the line caused by increased farming and irrigation activities.

Because we were concerned that the calculated percent change resistivities in the deeper blocks of the mesh are strongly affected by abrupt changes caused by near-surface effects such as fresh and saline water infiltration from irrigation canals, brine evaporation ponds and canals, and meteoric water, we decided to smooth the percent change resistivity data sets. Several approaches were considered for weighting or smoothing the data. We finally adopted a moving, three-point weighted operator (0.25, 0.5, 0.25) and applied it to $\Delta\rho_a$'s along each line of constant n. Data at the largest n's were too sparse to smooth, and had to be ignored. Our fear was that the smoothing operation might distort or eliminate critical information. However, as Figure 5 shows, inversions of the smoothed solutions retain most of the essential features of the unsmoothed solutions. Smoothing produced a simpler distribution of resistivity changes and smaller standard deviations. The analysis shows a resistivity increase of approximately 31% occurred by the Fall 1981 for the production region (i.e., the block between electrodes 10 and 12 and at a depth of 1 to 2 km). While this value may seem suspiciously large, changes of this size can be accounted for by small absolute changes in reservoir parameters. Using the Archie's law relationship for the bulk resistivity of partially saturated sediments

$$\rho_R = a\rho_F \, \phi^{-m} \, S^{-1}, \tag{5}$$

where

ρ_R = rock resistivity (ohm·m),
ρ_F = pore fluid resistivity (ohm·m),
ϕ = average porosity of the region under study,
S = average liquid saturation,
a = a constant, and
m = a positive number close to 2,

the fractional change in rock resistivity is

$$\frac{\Delta\rho_R}{\rho_R} \approx \frac{\Delta\rho_F}{\rho_F} - \frac{2\Delta\phi}{\phi} - \frac{\Delta S}{S}. \tag{6}$$

Assuming the brines, initially at a temperature of 260-280°C and with half the salinity of sea water, experienced a slight drop in salinity due to recharge, the brine resistivity could increase from ~.05 ohm·m to ~0.055 ohm·m (Ucok et al., 1980). There might also have been a decrease in bulk porosity of from 0.15 to 0.14 due to water-rock reactions and calcite and/or silica precipitation, and a decrease in liquid saturation due to an expansion of the two-phase zones around the wells. Inserting appropriate values for the estimated changes into Eq. 6, we obtain a change in bulk rock resistivity of

$$\frac{\Delta\rho_R}{\rho_R} \approx \frac{0.005}{0.05} - \frac{2(-0.01)}{0.15} - \frac{(-0.05)}{1.0} = 0.28, \tag{7}$$

which is close to the value obtained from analysis of the dc resistivity data.

It is also extremely interesting that a reversal seems to have occurred in the reservoir region between the Fall of 1981 and the Spring of 1983 when the most recent set of data were obtained (Fig. 6). The percent change in block resistivity associated with production region declines to about +22%, relative to 1979. Alfred Truesdell (1984, personal communication) believes, on the basis of the changing silica content of the produced brines, that the reservoir temperature may have dropped during the 1981-1983 interval to a point below the boiling temperature for that depth, causing a collapse of the two-phase zones. Assuming that there was also a continuing, but slight, decline in salinity during the 1981-1983 period, but no appreciable change in bulk porosity, the fractional change in resistivity can be estimated as

$$\frac{\Delta\rho_R}{\rho_R} \approx \frac{0.006}{0.05} - \frac{2(-0.01)}{0.15} + \frac{0.0}{1.0} = 0.25. \tag{8}$$

Again, we obtain a value in general agreement with results of the resistivity inversion.

The percent change resistivities in the block immediately east of the production region show a rather consistent increase. This may be due to an expansion of a boiling zone predicted by Lippmann and Bodvarsson (1983) from thermal and mass transport modeling of the field in both its natural state and under production during the 1973-1978 period. The decreasing resistivities in other blocks near, and particularly below, the production region are more difficult to explain. Perhaps production has stimulated the upward movement of more saline brines from a deep region in the basin. This is consistent, in part, with the hydrogeological model proposed by Halfman et al. (1984).

CONCLUSIONS

A relatively efficient numerical technique for 2-D resistivity inversion was developed and applied to the percent change pseudosections for the repetitive dipole-dipole measurements made at the Cerro Prieto geothermal field from 1979 to 1983. Both the original and smoothed data sets were inverted, the latter providing a simpler and more easily explained picture of changing resistivities.

The percent resistivity changes associated with the production zone are quantitatively consistent with the changes in brine salinity, reservoir temperature, liquid saturation, and porosity that one might expect from recharge by cooler, less-saline waters. There is also ample evidence both from the resistivity analysis, heat and mass transport modeling (Lippmann and Bodvarsson, 1983) and hydrogeology (Halfman et al., 1984) that the shallow western α reservoir is also recharged, but to a lesser extent, by high temperature brines (355°C) ascending from the east. In both the natural state (pre-production) and during the early phase of exploitation (1973-1978) the hot water flow from the east was estimated to be low due to boiling conditions along the recharge path. The resistivity solutions indicate that in more recent years (1979-1983) this boiling condition has worsened, but the more saline brines may be trying to make their way upward into the α reservoir.

The techniques of repetitive, high-precision resistivity surveying and appropriate data analysis discussed here are potentially valuable for understanding subsurface processes at producing geothermal fields. The sources of measurement error are random electrical noise caused by telluric currents and human activities. Numerical studies show that the residual error of the inversions on noise-free data are of the order of 1 to 20 percent. Errors in the computed solutions can also arise from abrupt changes, spatially and temporally, of surface resistivities, such as changes in farming and irrigation activities, infiltration of brines from the evaporation pond, and seasonal and annual variations in rainfall. We have attempted to smooth the data to reduce the effects of large resistivity changes in the near-surface region. This has given us statistically better solutions, but resolution has been reduced. Finally, the use of a two-dimensional inversion for a three-dimensional problem has undoubtedly led to some inaccuracies.

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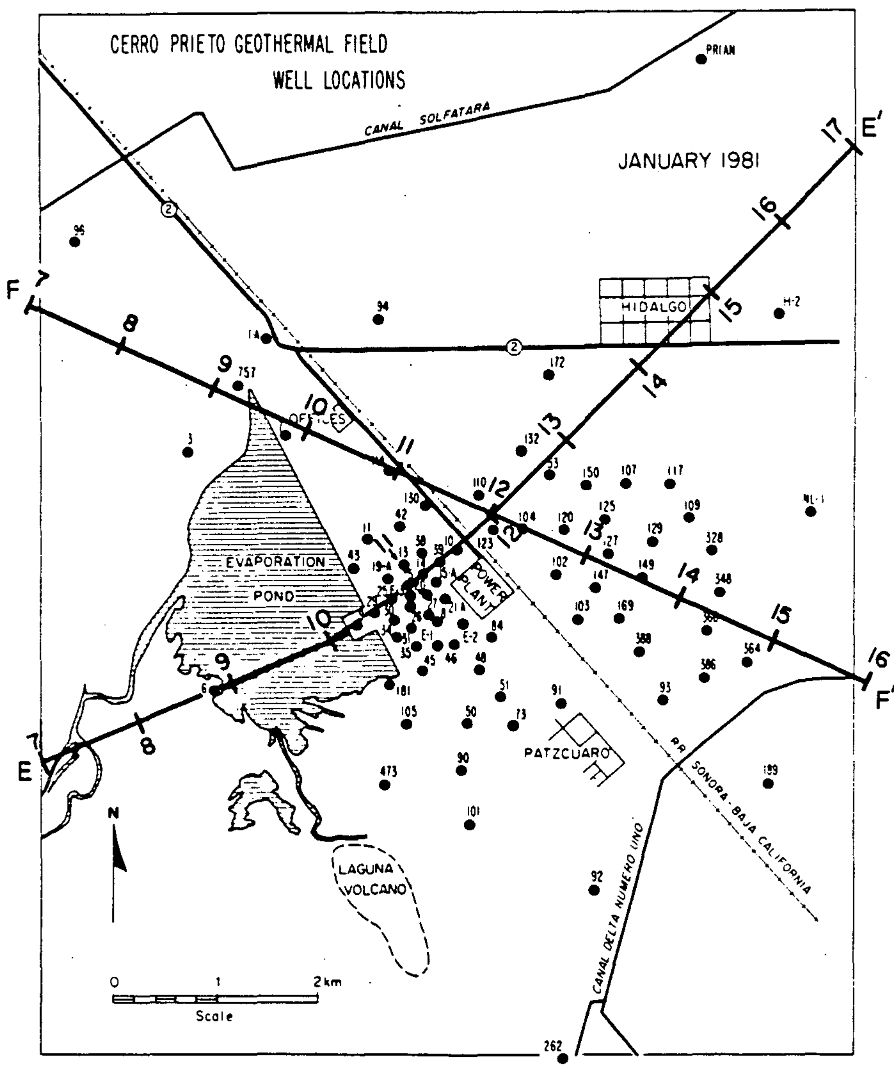

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Fig. 1. Central part of the dipole-dipole resistivity line E-E' over the Cerro Prieto geothermal field. Wells are shown as dark circles, and those producing brine during the 1979-1983 period are mainly between electrode points 10 and 12.

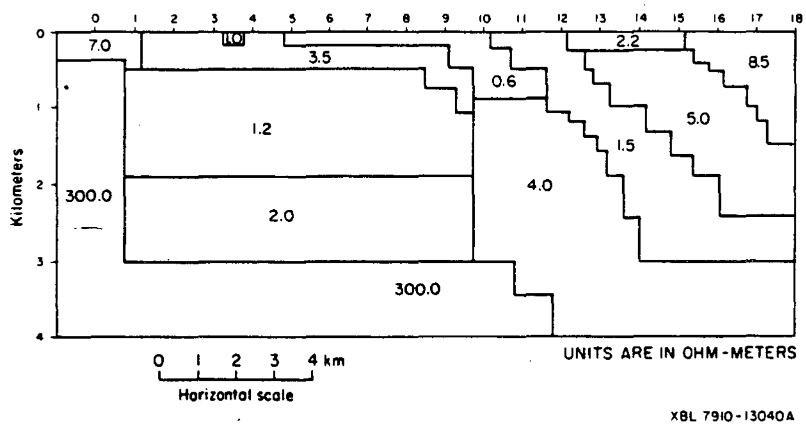


Fig. 2. Two-dimensional resistivity models for line E-E'.

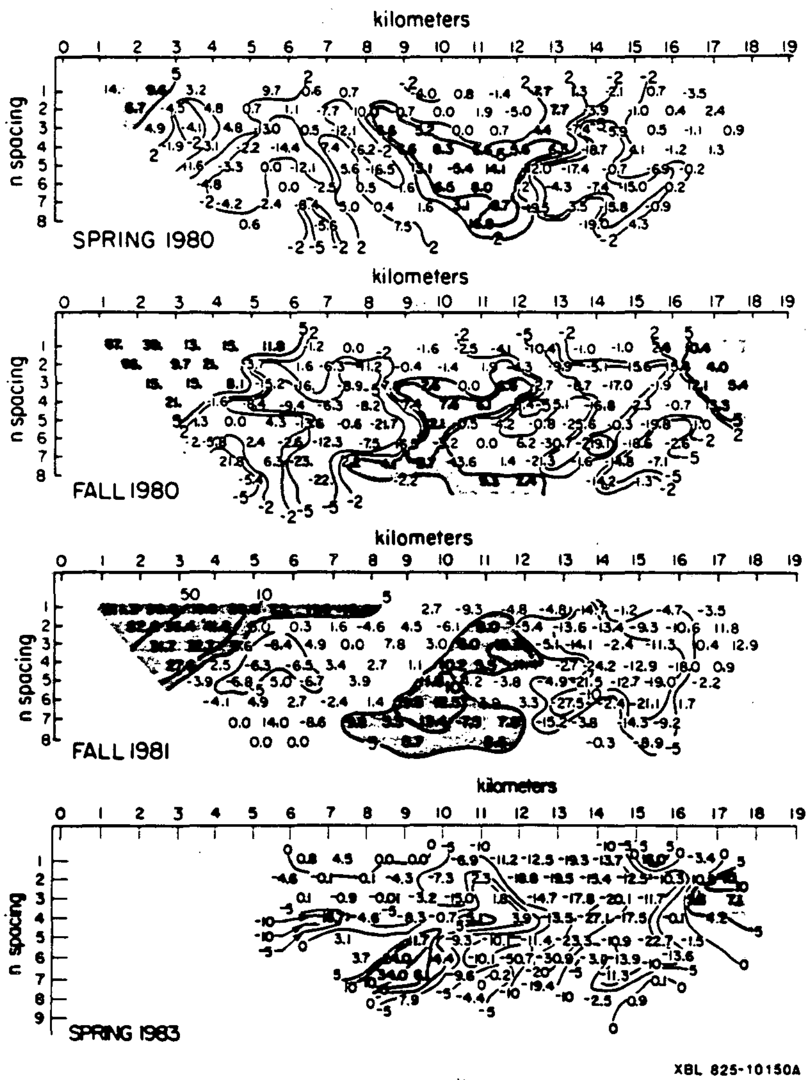
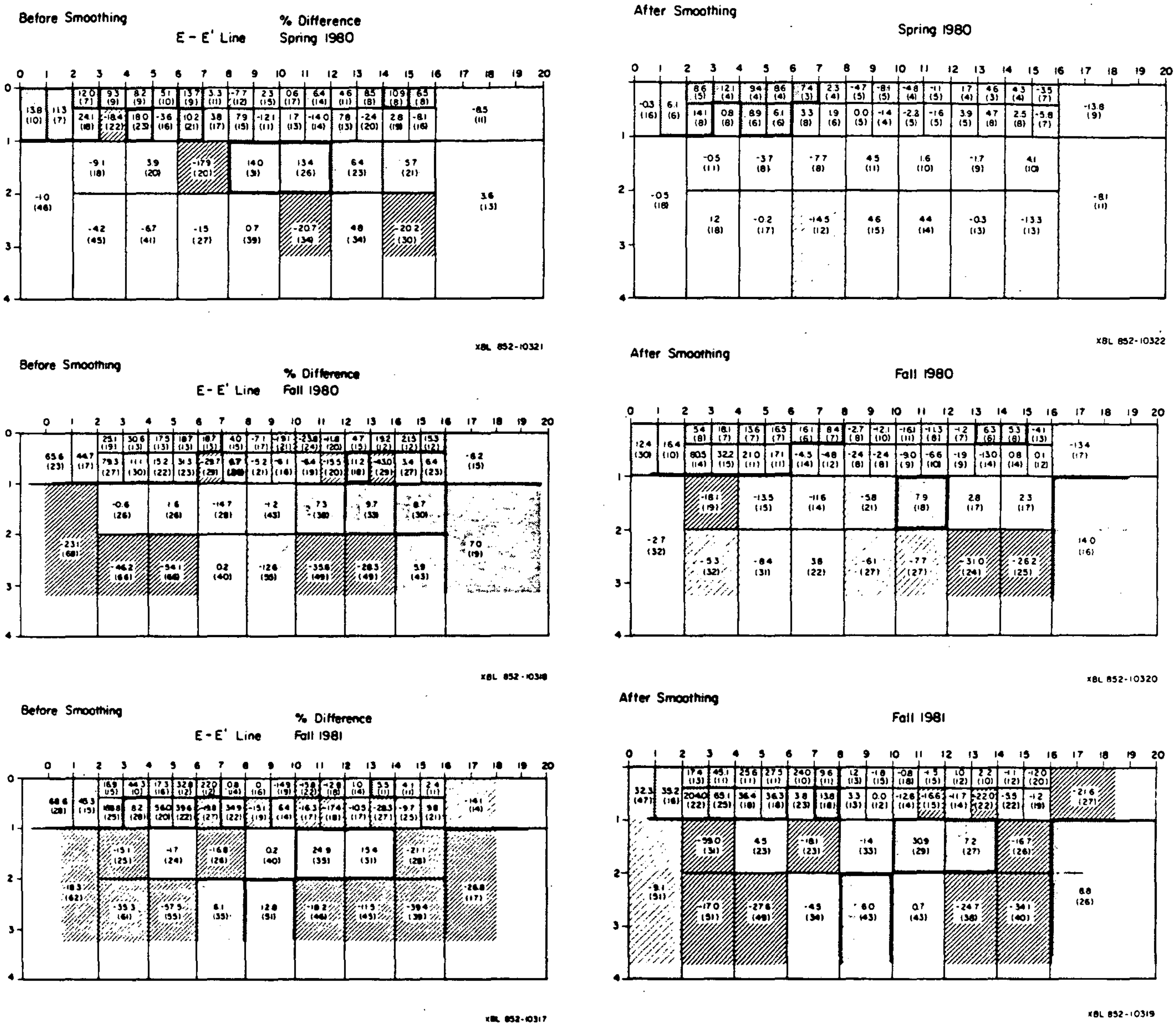


Fig. 3. Apparent resistivity pseudosections plotted as the percent change in apparent resistivity relative to the 1979 data set. Areas of dark stipple show increases >5%; areas of light stipple show decreases >5%.



Figs. 4-5. 2-D resistivity inversion results of repetitive dipole-dipole surveys for both the unsmoothed and smoothed data sets. Solutions are the percent change in block resistivity relative to base year 1979. Numbers in parenthesis are the calculated standard deviations expressed as percent of the estimated percent change. Horizontal and vertical units are km; vertical exaggeration is 2X.

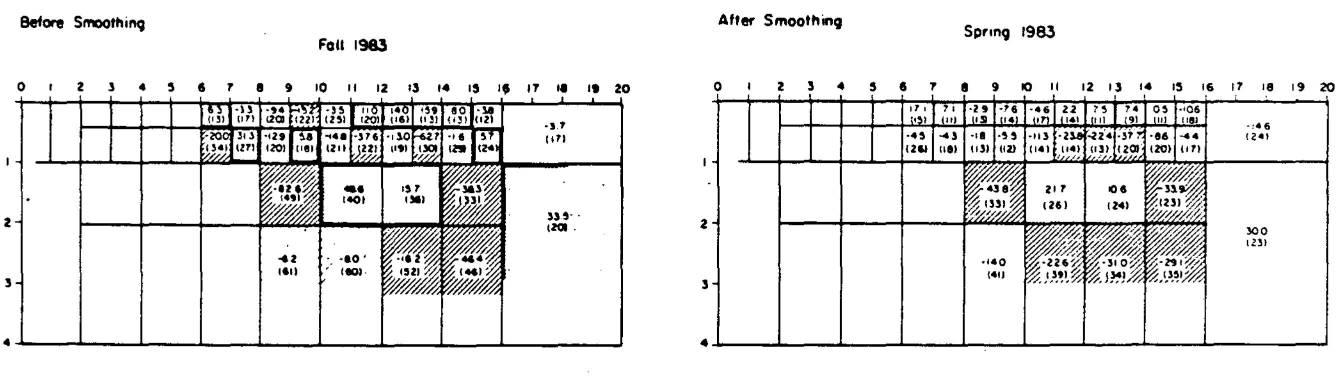


Fig. 6. 2-D resistivity inversion results of dipole-dipole surveys made in 1983. See Figs. 4-5 for full caption.