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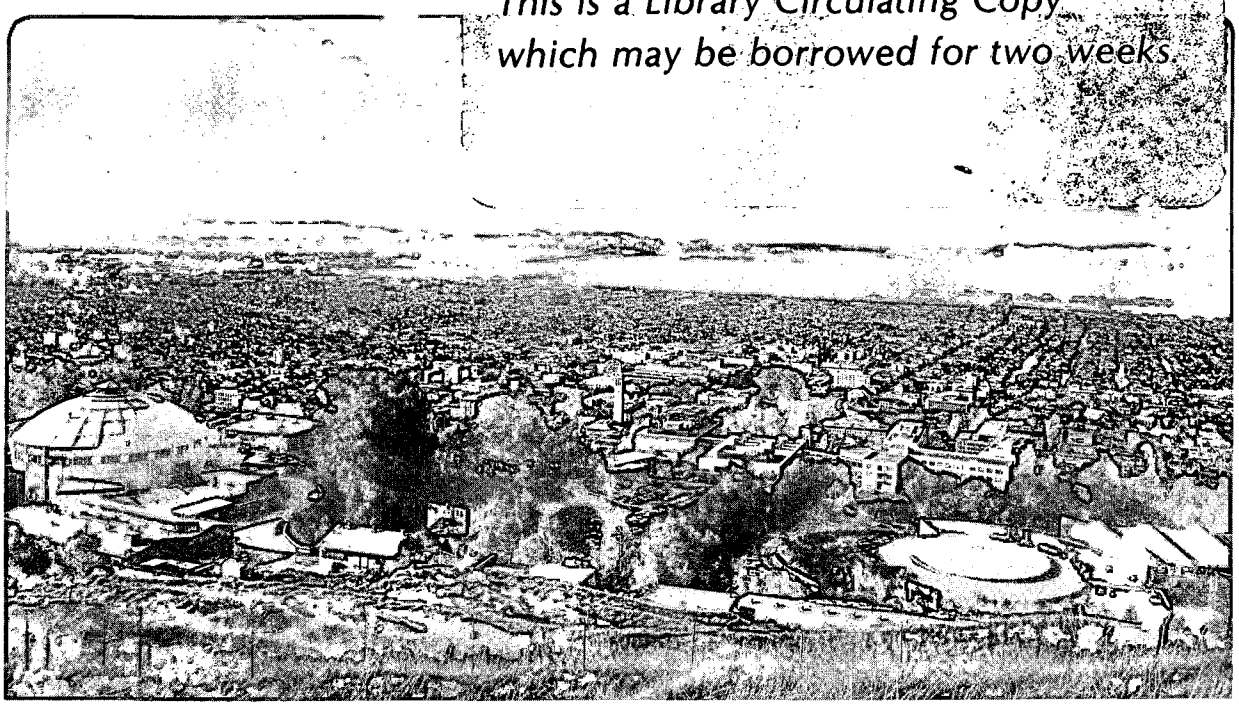

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MONITORING OF HOT WATER PLUME MOVEMENTS IN AN AQUIFER WITH BOREHOLE/SURFACE RESISTIVITY MEASUREMENTS

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ABSTRACT

The present paper proposes the use of surface resistivity measurements coupled with downhole electrodes at aquifer level to provide an economical, continuous monitoring of hot water plume movements. Calculations were performed to show the feasibility of the concept and the expected magnitudes of resistivity measurements for a number of cases.

A three-dimensional resistivity model developed at Berkeley was used to study the change in resistivity due to the introduction and movements of a hot water plume at 80°C in an aquifer 25 m thick and 45 m below the ground surface. The plume is assumed to be 30 m in radius around an injection well. The difference in the storage temperature of 80°C and the initial aquifer temperature of 20°C causes a resistivity contrast of about 2.3 between the hot water plume and the surrounding aquifer region. Potentials were calculated for a three-dimensional resistivity distribution with current injected at the aquifer depth and voltage measurements made on the ground surface. We considered cases where current was injected at a point within the hot water plume as well as outside of the plume (offset case). Three plume distributions were assumed: case 1, the plume forms a constant temperature cylinder centered at the injection well; case 2, the plume forms a cylinder around the well with temperature decreasing with distance from the well; case 3, the aquifer has a variable vertical permeability.

Results indicate that the resistivity anomaly is much greater using the downhole electrode than for surface arrays without a downhole electrode and that the data may be used to roughly characterize the hot water plume and its boundaries. The downhole/ surface measurements are not found to be very sensitive to differences in the plume boundary geometry although a rough determination of the boundary positions is possible. Calculations of resistivity changes as the hot water plume moves away from the downhole electrode show clear characteristic observable variations, thus demonstrating the capability of the method to monitor hot water plume movements in an aquifer.

1. INTRODUCTION

In the storage of hot water in aquifers for later use, it is important to know the position of the hot water plume during the period of storage and retrieval. This is particularly important in aquifers which have a significant regional flow or which are strongly influenced by ground surface conditions such as rainfall and seasonal temperature variations.

In this paper we examine the possibility of mapping a hot water plume in an aquifer using a borehole/surface electrical resistivity method. Using a 3-D dc resistivity computer code, we simulate a three-dimensional aquifer and compare the results of surveys taken before and after hot water injection. In addition to studying the case of a plume moving relative to the downhole electrode, we also consider three different types of plume boundaries to determine the sensitivity of measurements to variations in boundary geometry.

2. RESISTIVITY MODEL

For the resistivity simulation we consider a simple 5-layer resistivity model (Figure 1) with a hot water plume in a sandstone aquifer (layer 4) located at a depth between 45 and 70 m. The porosity of the aquifer is 15%. The hot water temperature is taken to be 80°C, compared with the ambient aquifer temperature of 20°C; the resistivities are then assumed to be 8.6 and 20 ohm-meters, respectively. The detailed resistivity assignments are shown in Figure 1.

The hot water plume is assumed to form a prism buried at a depth between 45 and 70 m.

We consider three types of lateral plume boundaries: (a) abrupt boundary, (b) diffused boundary, and (c) stratified boundary. In each case, the total volume remains fixed at 11,000 m^3. The goal is to determine the sensitivity of the resistivity measurements to the shape of the hot water plume and its boundaries. The abrupt boundary is a case where the hot water does not mix with the native ground water and the aquifer has uniform characteristics. For the diffused boundary, there is heat transfer between the hot water and the native ground water at the boundary. In this case the boundary is assumed to present three subregions that are transitional between the hot and the cold native ground water. With the stratified boundary case the hot water plume spreads in a nonuniform manner because of permeability layering in the aquifer, so that the position of the boundary is a function of depth.

We also considered a case where a regional ground water gradient is incorporated into the model. The position of the downhole current electrode is assumed to be located at progressively larger distances from the center of a sharp-boundary plume, and eventually outside the plume. This corresponds to a case where the hot water mass is being moved by the natural regional flow without changing shape.

3. CALCULATIONS

Resistivity calculations are performed with the three-dimensional finite difference computer code RESIS3D (Dey and Morrison, 1979). With the code, apparent resistivity may be calculated for a variety of surface and downhole arrays over an arbitrary three-dimensional resistivity distribution. Because of computer memory requirements, we limited the mesh to a 51 x 17 x 11 node array. This restricts the complexity of the models used, and limits the amount of detail possible for the simulation. The calculations reported here assume that a downhole current electrode is in a well at a depth of 55 m, within the hot water plume, and potential measurements are made on the surface. The second current electrode is far from the well. Experience has shown that this configuration (also called the mise-a-la-masse method) is much more sensitive than surface arrays to changes in resistivity near the current electrode (Wilt et al., 1983).

Calculational results are given in percent difference of the total field apparent resistivity for the model considered, compared to baseline measurements for the same model but without the hot water region. The total field apparent resistivity parameter consists of a combination of voltage measurements made parallel with and orthogonal to the profile direction and normalized for separation and current strength (Dey and Morrison, 1979).

4. RESULTS

CENTRAL CURRENT ELECTRODE

Figure 2 is a plot comparing total field apparent resistivity differences for the three cases considered: (a) abrupt boundary, (b) diffused boundary, and (c) stratified boundary. The simulation is for a current electrode in the center of the hot water mass and surface profile measurements made directly over the current electrode.

For each case an inverted bell-shaped curve is obtained with a maximum apparent resistivity difference of about 20%, observed for measurements directly over the current electrode. The calculation is repeated assuming the entire array (including the current electrode) confined to the surface, and the maximum anomaly is found to be about 2%. This is consistent with the results of Wilt et al. (1983). The placement of the current electrode into the hot water region can therefore improve sensitivity by an order of magnitude. We would expect a similar improvement if the potential measurements were also made downhole.

Figure 2 illustrates the effect of the different boundary conditions on the apparent resistivity. For the abrupt boundary (case a) and the stratified boundary (case c) the shape and magnitude of the curve is virtually identical. In a field experiment, it would not be possible to distinguish between these boundaries. For the diffused boundary (case b) the magnitude of the anomaly is smaller and the width of the curve is slightly greater. The anomaly for the diffused boundary is different primarily because the hot water is spread throughout a broader region so the change in resistivity near the current electrode is slightly less.

The approximate position of the hot water boundaries may be estimated by a "half-width" calculation. That is, the plume boundary will be approximately located at a position corresponding to half the maximum anomaly times some constant; for the abrupt boundary cases this constant was found to be 0.5.

OFFSET CURRENT ELECTRODE

When the downhole current electrode is not located in the center of the hot water mass

the resistivity anomaly is no longer symmetrical and the amplitude is smaller. Figure 3 gives percent difference apparent resistivity plots for the abrupt boundary case with the current electrode offset distances from 0 to 67 m from the plume center. As the electrode is moved from the center towards the edge of the hot water several changes are apparent in the observed anomaly. First the peak magnitude of the anomaly is reduced from 20% in the central case to about 3% in the largest offset case. Secondly, the shape of the anomaly changes from an inverted bell curve to an asymmetric anomaly with both negative and positive lobes. For current electrode placements outside the plume, the position of the closer boundary is approximately where the anomaly changes shape (about -40 m). The position of the negative lobe seems to remain fixed at about -10 m regardless of the position of the current electrode.

The asymmetric anomaly pattern is due to current redistribution into the zone of decreased resistivty. The potentials on the near-side boundary are anomalously small because the current is being drawn into the conductive body at the expense of the surrounding medium. The increases in apparent resistivity on the far-side of the contact are due to the increase in current caused by the hot water body.

For the offset case a half-width calculation may be made by averaging the near-side and far-side apparent resistivity differences and adjusting the anomaly to the new level. The half-width calculation indicates a hot water front 43 m from the center which is in reasonable agreement with the true position.

5. SUMMARY AND CONCLUSIONS

In this study a simulation of a downhole/surface resistivity experiment to map a hot water plume was performed using a three-dimensional computer code. A fixed amount of hot water was placed in an aquifer between 45 and 70 m below ground surface and resistivity measurements were made at the surface using a current electrode in the hot water body. Results indicate that the anomaly is much greater using the downhole electrode than for surface arrays and that the data may be used to roughly characterize the hot water mass and its boundaries. Several cases involving different plume boundaries were studied and results indicate that the downhole/surface measurements are not very sensitive to differences in the boundary geometry although a rough determination of the boundary position is possible. For the case where the hot water plume is moving relative to the downhole current electrode until it completely leaves the electrode behind, the anomaly size is smaller but the shape allows for good discrimination of the near-side boundary.

6. ACKNOWLEDGEMENT

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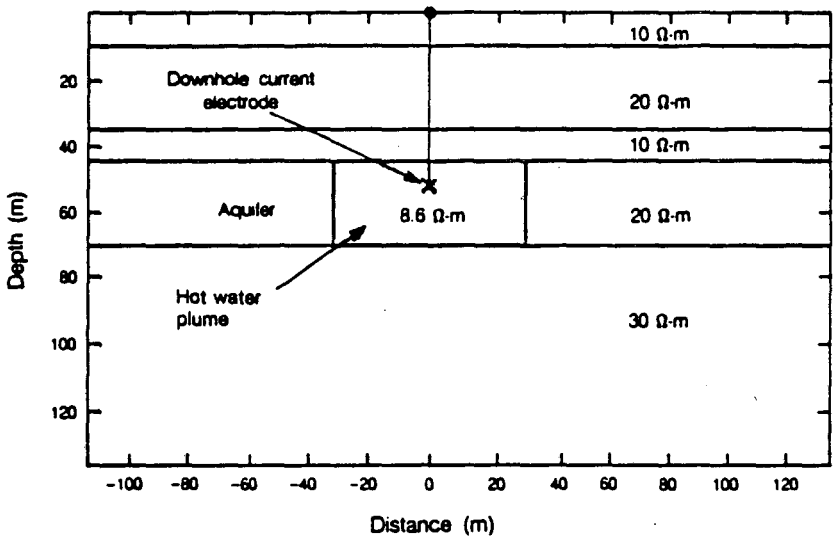

Fig. 1. Vertical cross-section of the resistivity distribution for the simulation.

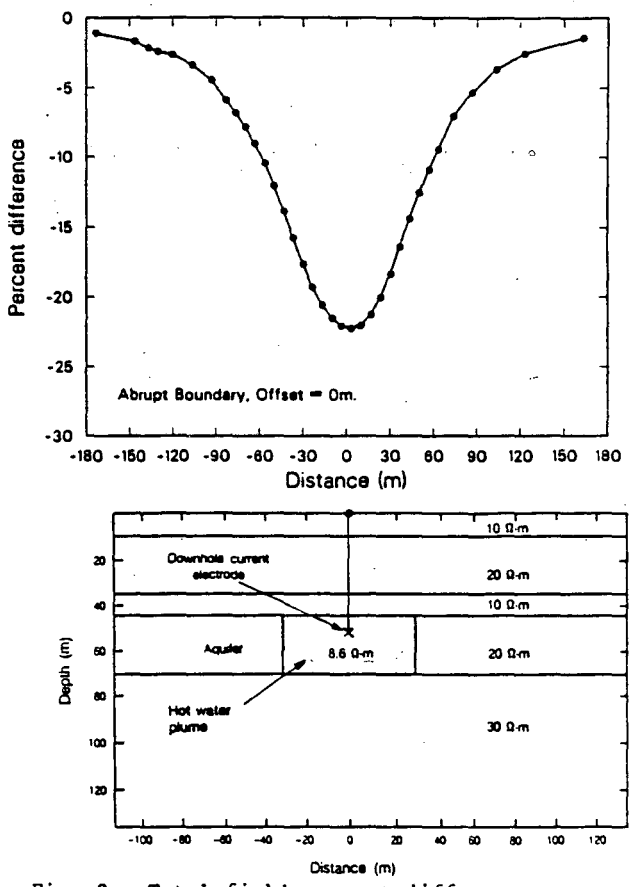

Fig. 2a. Total field percent difference apparent resistivity calculations for the central downhole current electrode with the plume having a sharp boundary.

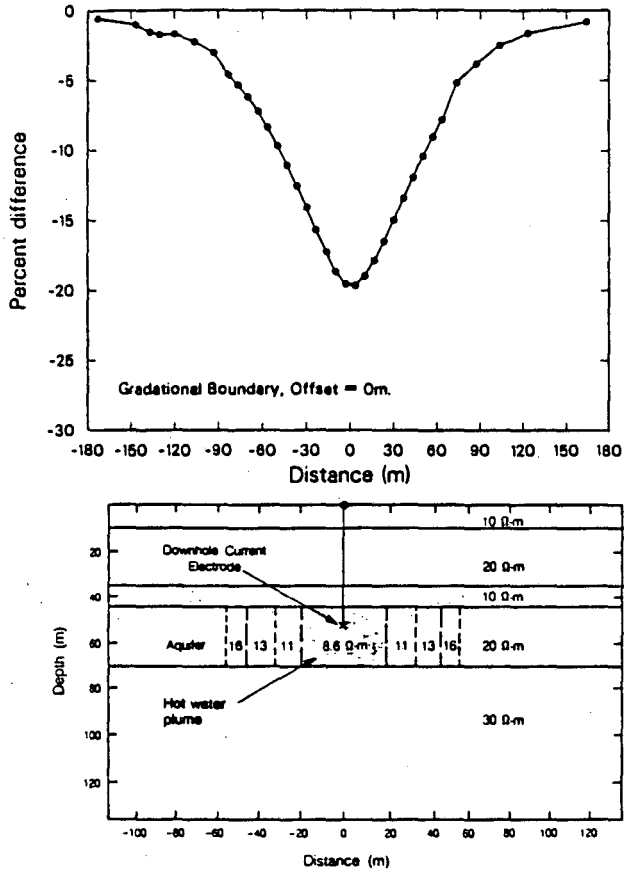

Fig. 2b. Total field percent difference apparent resistivity calculations for the central downhole current electrode with the plume having a diffused boundary.

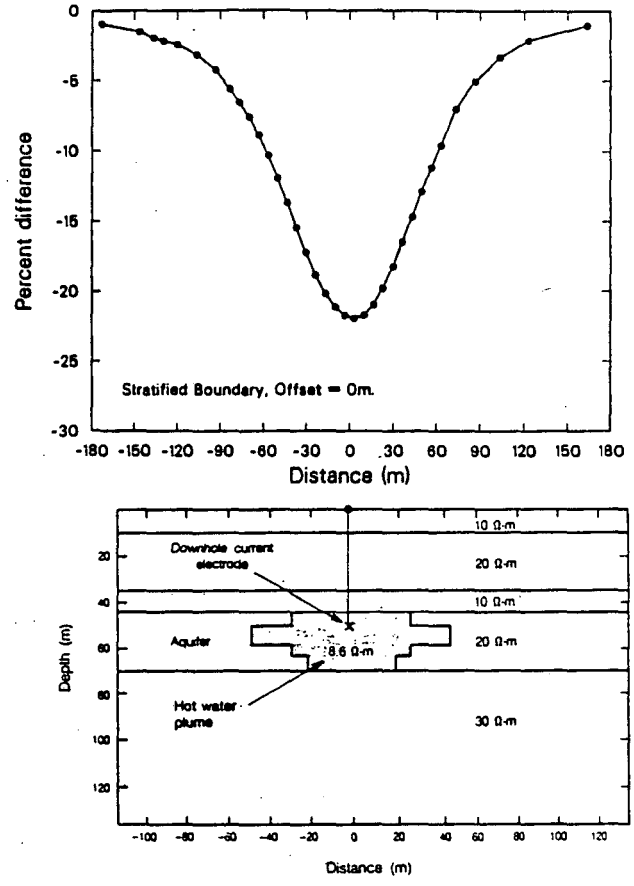

Fig. 2c. Total field percent difference apparent resistivity calculations for the central downhole current electrode with the plume having a stratified boundary.

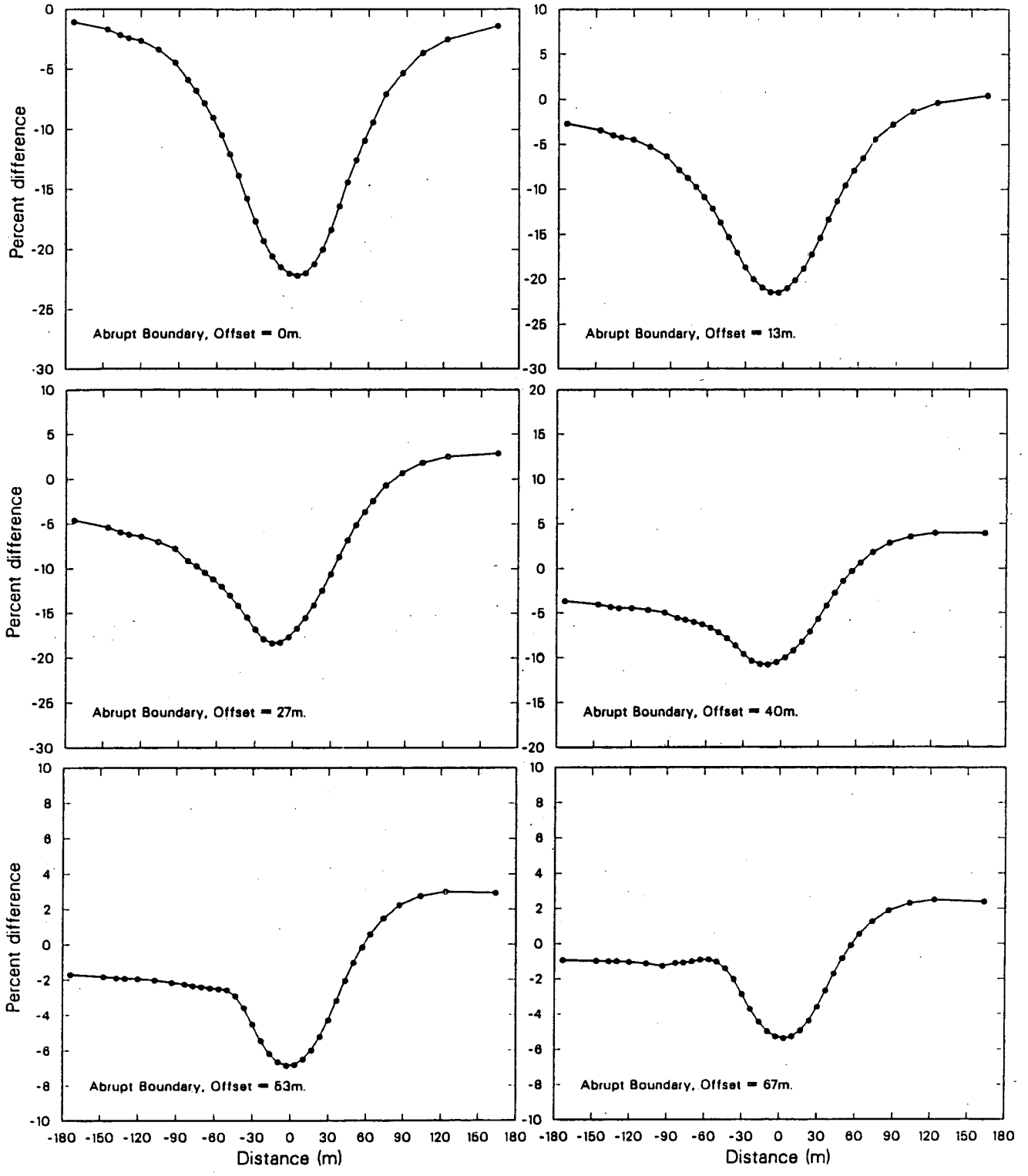

Fig. 3. Total field percent-difference apparent resistivity calculations for the offset downhole current electrode at different offset distances between the electrode and the sharp-boundary plume.

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