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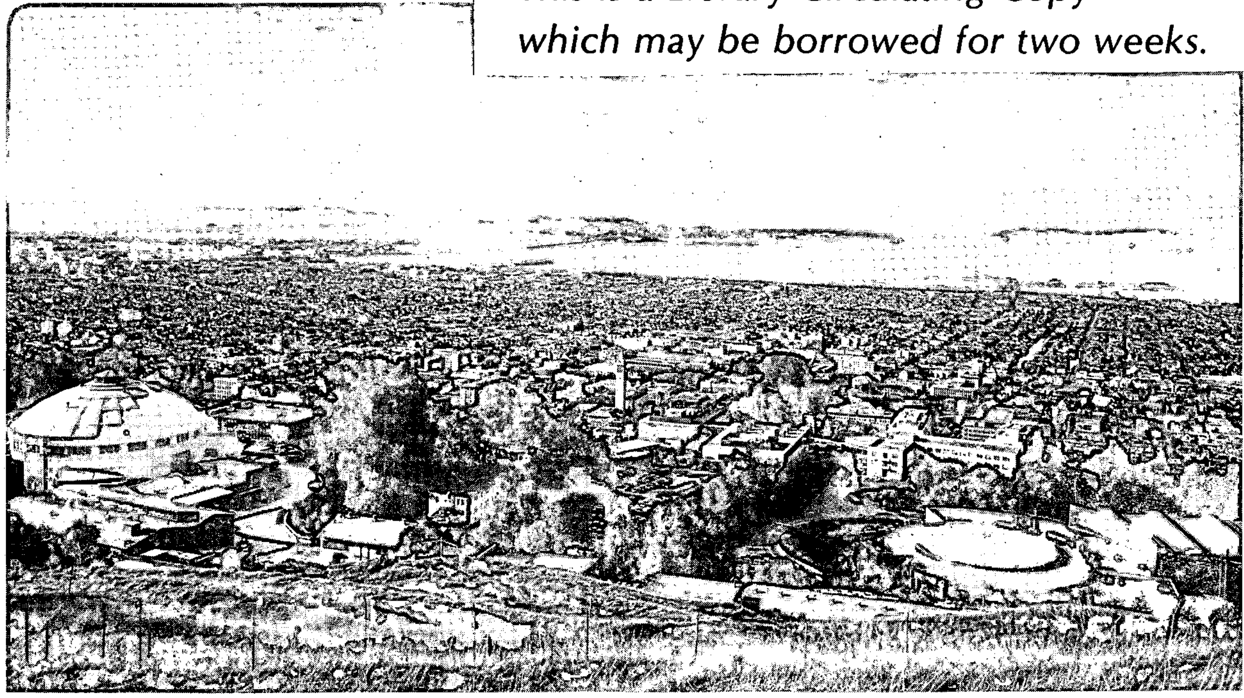

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## Abstract

Three-dimensional resistivity modeling was performed to simulate the changes in resistivity due to the leakage of fluid contaminants into an aquifer. The simulation represents a case where the fluid is introduced into a 25 m aquifer at a depth of 45 m. The contaminant fluid is assumed to be electrically more conductive than the in-situ ground water. Resistivity measurements were simulated using a finite difference algorithm to calculate potentials for an arbitrary three-dimensional resistivity distribution with surface and downhole current and potential electrodes. A downhole/surface array was considered where current was injected at the aquifer depth and voltage measurements were made on the surface. We considered cases where current was injected at a point within the contaminant plume as well as outside of the plume (offset case). We considered three contaminant distributions: case 1, the contaminant plume forms a uniform cylinder centered around the injection well; case 2, the plume forms a nonuniform cylinder around the well where contaminant concentration decreases away from the well; case 3, the aquifer has a variable vertical permeability. 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 contaminant mass and its boundaries. Several cases involving different contaminant boundaries were studied and show 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 downhole current electrode is located ouside of or at the edge of the contaminant, the anomaly size is smaller but the shape allows for good discrimination of the near-side boundary.

## Introduction

The recent interest in mapping subsurface ground water contaminant fronts with geophysical methods is in response to the growing ground water contamination problem and to federal and state mandates to identify contaminant sources and contaminated sites and to evaluate these sites prior to their clean up. Initial studies have shown that many contaminated sites have distinct geophysical anomalies compared to the surrounding area (Saunders et al., 1984; Gilmer and Hebling, 1984). A wide variety of geophysical techniques including seismic, potential field and electrical methods have been successfully employed to detect the presence of contaminant plumes in ground water (Rodríguez, 1984).

Of all the geophysical techniques available, the electrical methods have had the most widespread use in the detection of ground water contaminant plumes. Many sites have electrical resistivity anomalies that may be directly attributed to the presence of an electrolytic contaminant (Saunders et al., 1984). Presently, the emphasis of field surveys has been on surface electrical techniques. The problem with this approach is that measurements are insensitive to contaminants if they are too deeply buried or if their concentration is low.

In this paper we examine the possibility of mapping ground water contaminant plumes using a borehole/surface electrical resistivity method. Using a 3-D dc resistivity computer code, we simulate a three-dimensional contaminated aquifer and compare the results of surveys taken before and after contamination. In addition, we consider four different types of contaminant boundaries to determine the sensitivity of measurements to variations in boundary geometry.

## Contaminant Model

For the resistivity simulation we consider a simple 5-layer resistivity model with an electrolytic contaminant present in a sandstone aquifer (layer 4) 45-70 m in depth with a porosity of 15% and an initial in-situ water salinity of 600 ppm (Figure 1). Using Archie's law and relations correcting the pore fluid resistivity for pore fluid salinity, we calculate the resistivity of the aquifer. The resistivity of the contaminated zone is calculated assuming a change in electrolyte concentration (assumed to be NaCl) from 600 to 1200 ppm. In Figure 2 the relation between fluid resistivity and dissolved electrolyte is shown for several different electrolytes. The figure indicates that at low salinities typical of shallow ground water systems the change in resistivity due to changes in salinity is quite dramatic. At 800 ppm NaCl a 10% change in pore fluid salinity (i.e., to 880 ppm) produces a 8% change in formation resistivity.

The contaminant mass is assumed to form a prism buried at between 45 and 70 m. We consider three types of plume boundaries: (a) an abrupt boundary, (b) a diffused boundary, and (c) a stratified boundary. In each case, the total volume of contaminant remains fixed at 11,000 $m^3$. For all of these cases it is sought to measure the sensitivity of the resistivity measurements to the shape of the contaminant mass and its boundaries. The abrupt boundary is a case where the contaminant does not mix with the native ground water and the aquifer has uniform characteristics. For the diffused boundary, there is mixing between the contaminant and the native ground water at the boundary. In this case the boundary is assumed to

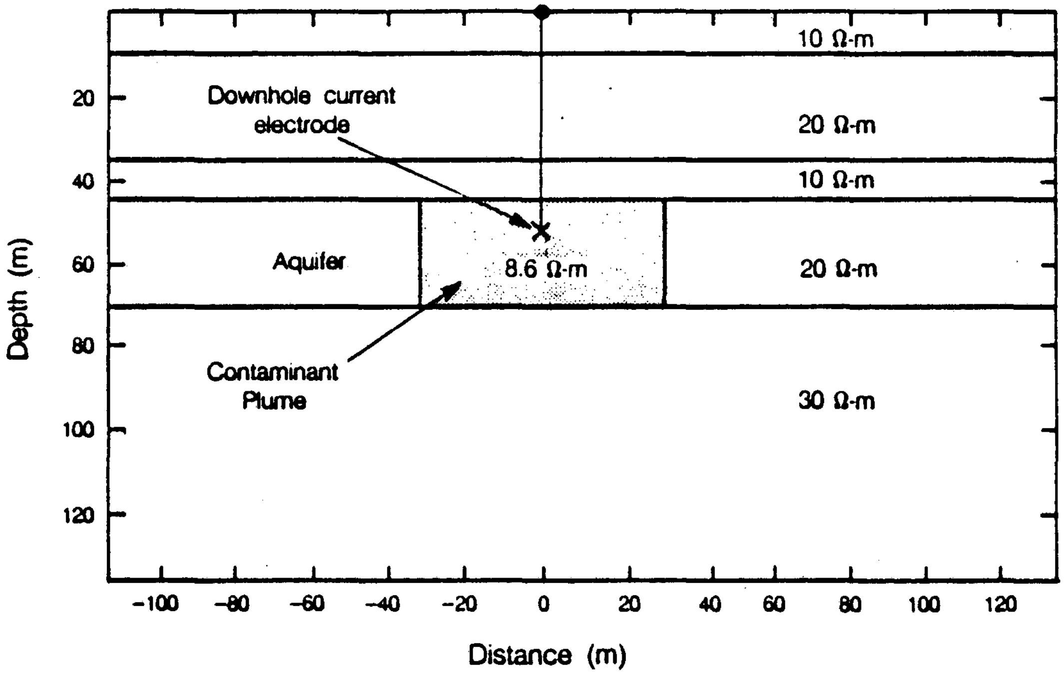


Figure 1. Cross-section of the resistivity distribution for the simulation.

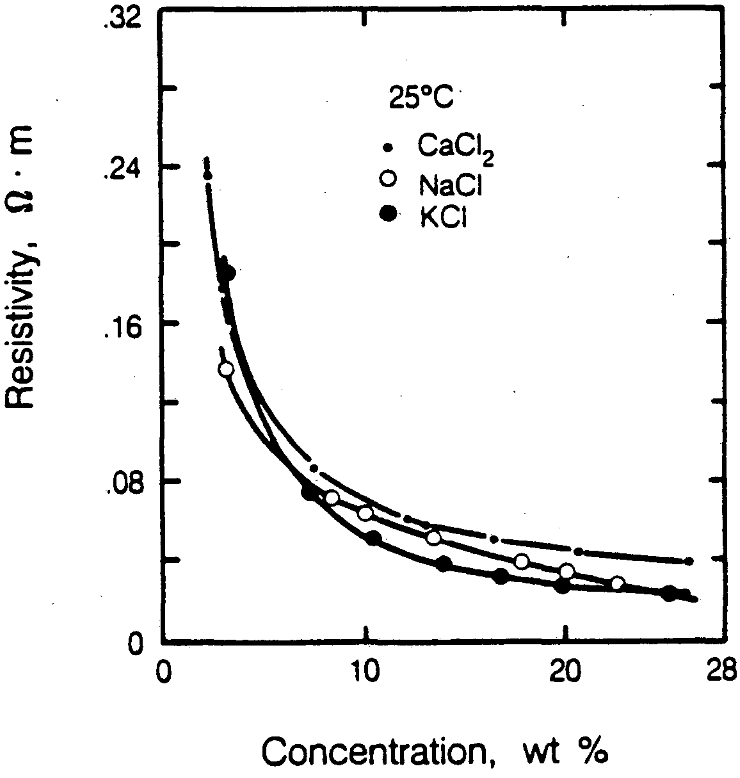


Figure 2. Resistivity variations for different saline aqueous solutions with increasing salt concentration at 25°C (after Ershaghi et al., 1981).

present three subregions that are transitional between the contaminant and the native ground water. With the stratified boundary case the contaminant 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. Based on an abrupt boundary type model the position of the downhole current electrode is assumed to be located at progressively larger distances from the center of the plume, and then outside of the contaminant plume. This corresponds to a case where the contaminant mass is being moved by the natural regional flow without changing shape.

## Resistivity Modeling

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 the 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 contaminant 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).

Calculations are given in percent difference of the total field apparent resistivity of the model considered, compared to baseline measurements of the same model but without the contaminated 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).

## Results

### Central Current Electrode

Figure 3 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 contaminant 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. This compares to a maximum anomaly of about 2% if the entire array were confined to the surface (Wilt et al., 1983). The placement of the current electrode into the contaminated

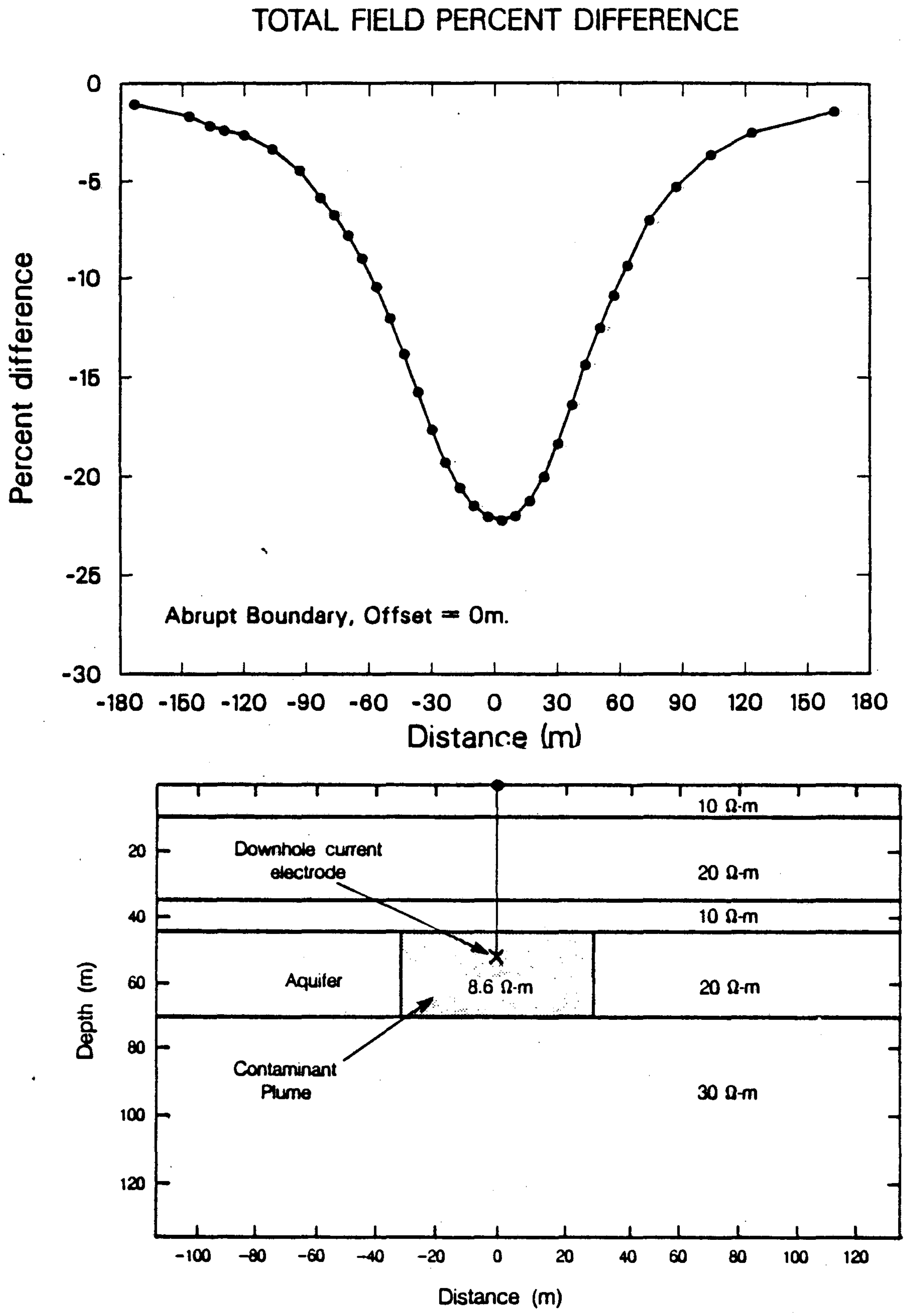
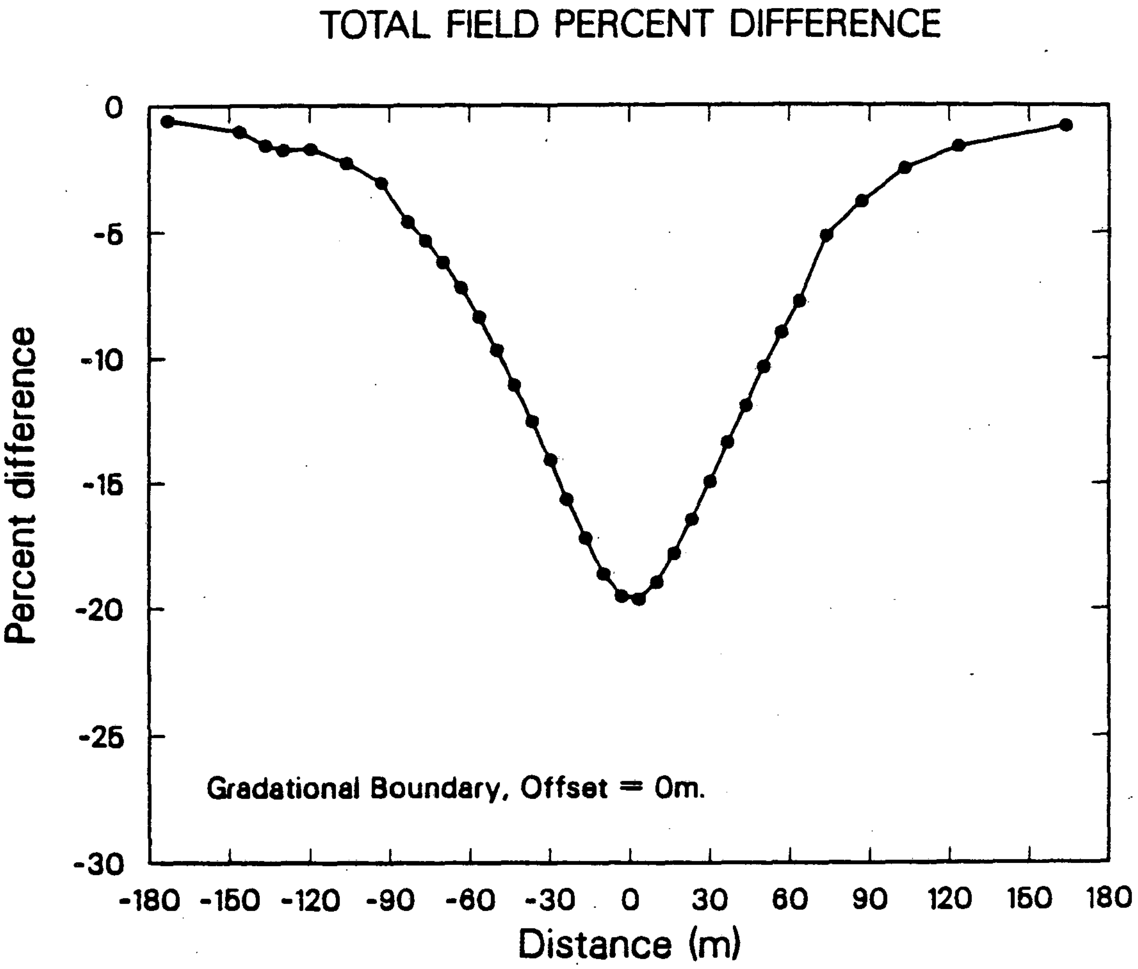


Figure 3a. Total field percent difference apparent resistivity calculations for the central downhole current electrode abrupt boundary.



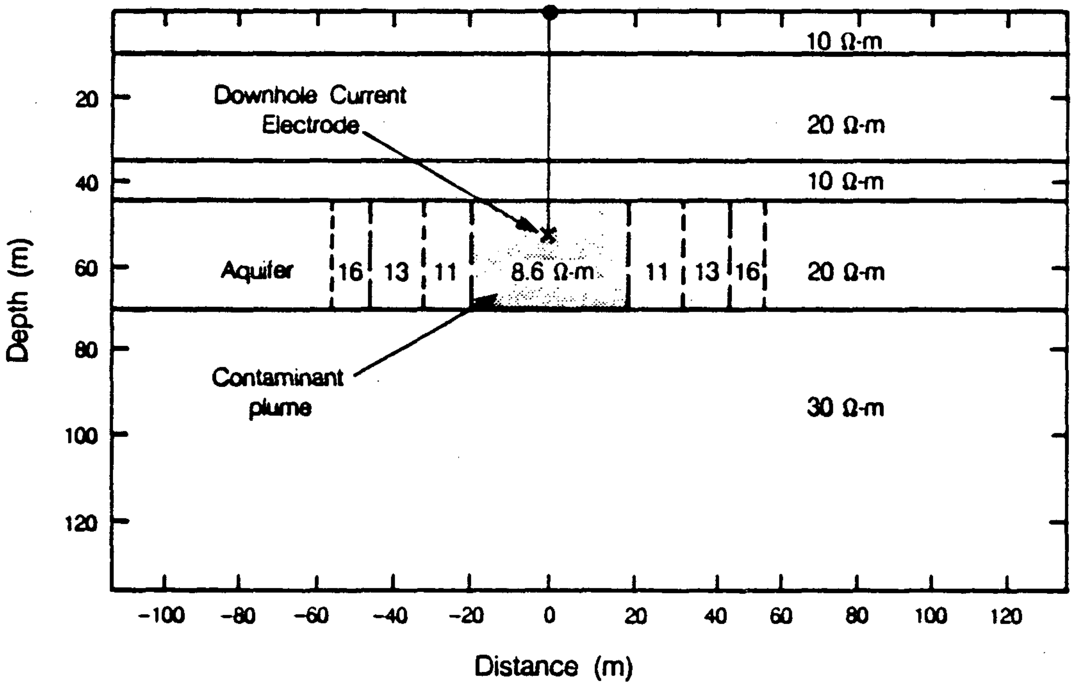


Figure 3b. Total field percent difference apparent resistivity calculations for the central downhole current electrode gradational boundary.

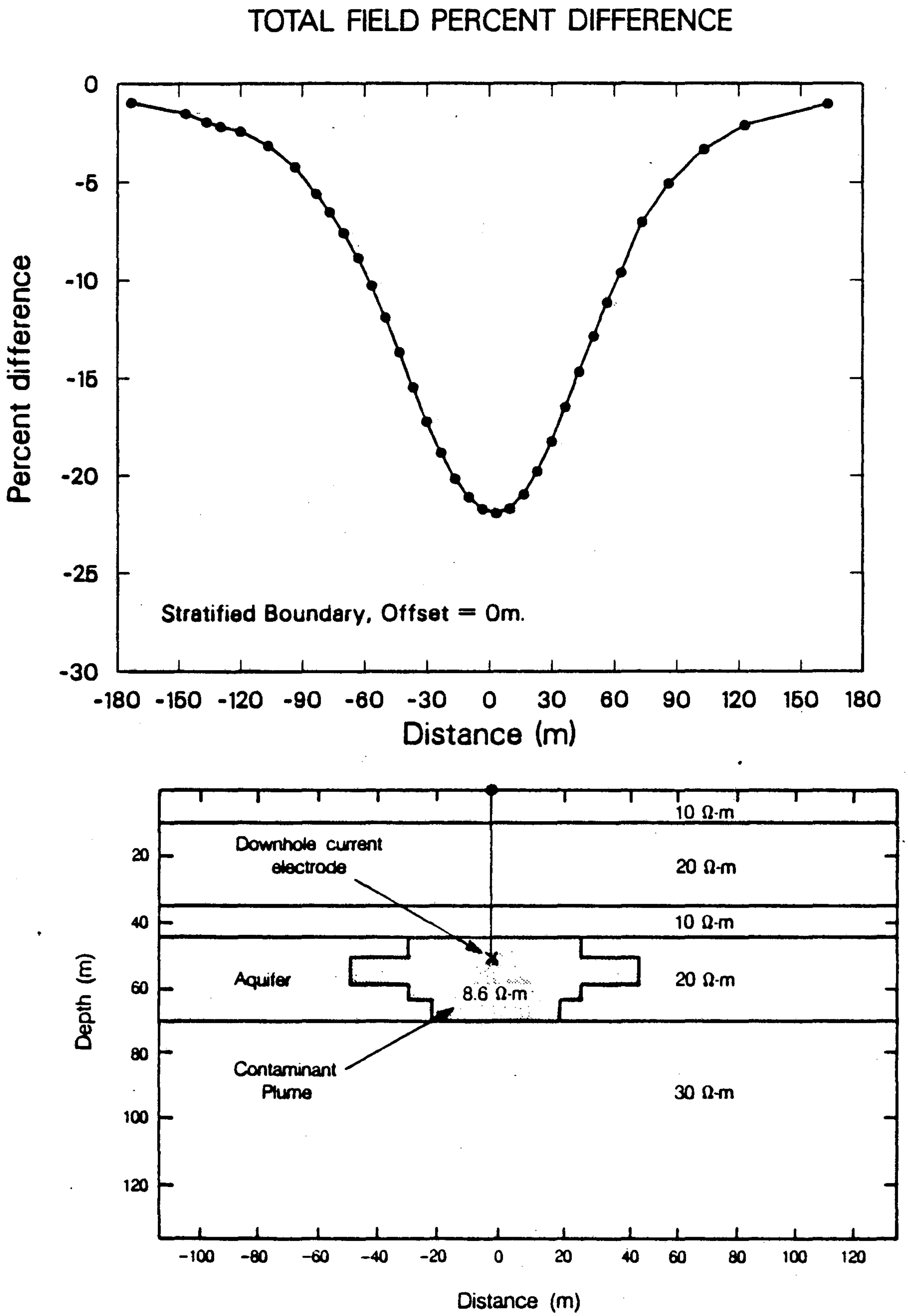


Figure 3c. Total field percent difference apparent resistivity calculations for the central downhole current electrode stratified boundary.

region can therefore improve sensitivity by an order of magnitude. We would expect a similar improvement if the potential measurements would also be made downhole.

Figure 3 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. 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 contaminant is spread throughout a broader region so the change in resistivity near the current electrode is slightly less.

The approximate position of the contaminant 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 .5.

## Offset Current Electrode

When the downhole current electrode is not located in the center of the contaminant mass the anomaly is no longer symmetrical and the amplitude is smaller. Figure 4 gives percent difference apparent resistivity plots for the gradational boundary case with the current electrode offset distances from 0 to 67 m from the contaminant center. As the electrode is moved from the center towards the edge of the contaminant 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 nearside boundary is approximately where the anomaly changes shape, or 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 contaminant 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 contaminant front 43 m from the center which is in reasonable agreement with the true position.

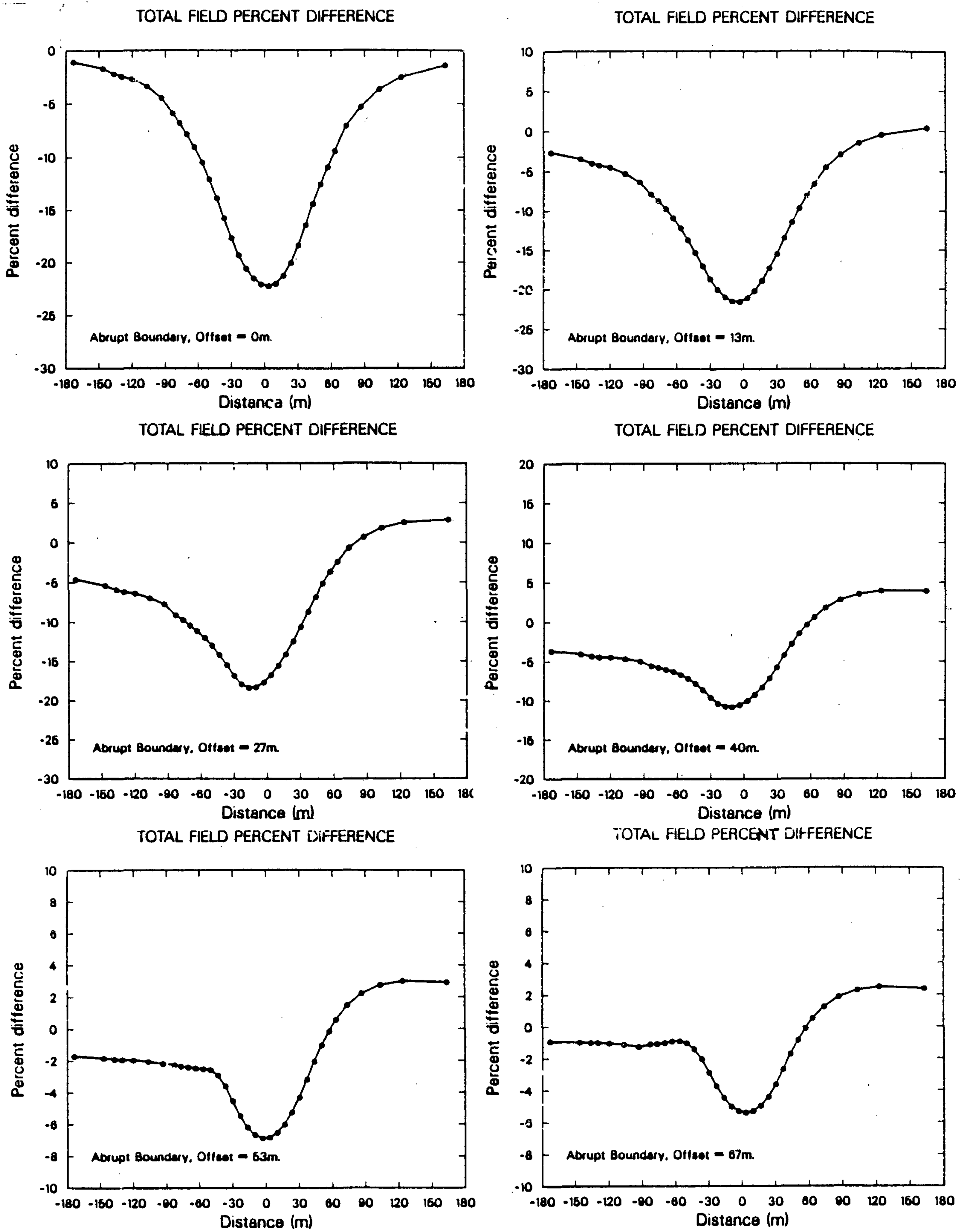


Figure 4. Total field percent difference apparent resistivity calculations for the offset downhole current electrode. Model is using an abrupt boundary (a) offset = 0 m, (b) offset = 13 m, (c) offset = 27 m, (d) offset = 40 m, (e) offset = 53 m, and (f) offset = 67 m.

## Summary and Conclusions

In this study a simulation of a downhole/surface resistivity experiment to map a contaminant plume was performed using a three-dimensional computer code. A fixed amount of contaminant was placed in an aquifer between 45 and 70 m in depth and resistivity measurements were made at the surface using a current electrode in the contaminant 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 contaminant mass and its boundaries. Several cases involving different contaminant boundaries were studied and show 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 downhole current electrode is located ouside of or at the edge of the contaminant plume, the anomaly size is smaller but the shape allows for good discrimination of the near-side boundary.

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## Figure Captions

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## Biographies

Michael Wilt received his B.S. in 1973 and M.S. in 1975 from the University of California, Riverside. He was a staff scientist from 1974 to 1983 at Lawrence Berkeley Laboratory and is currently a graduate student in the Ph.D. program at University of California, Berkeley and a research assistant at Lawrence Berkeley Laboratory. His areas of professional interest include electrical and electromagnetic methods of geophysical exploration with an emphasis on geothermal and ground water studies. He is a member of the Society of Exploration Geophysicists and the Geothermal Resources Council.

Chin Fu Tsang received his Ph.D. in Physics from the University of California, Berkeley in 1969, and is currently a Senior Staff Scientist and the Deputy Group Leader of the Hydrogeology and Reservoir Engineering Group in the Earth Sciences Division of the Lawrence Berkeley laboratory. His research interest ranges from advanced well test methods; flow of fluids through porous and fractured media; non-isothermal reservoir dynamics to coupled thermomechanical, hydrochemical processes in subsurface formations. He has carried out analytical and numerical modeling studies in reinjection into geothermal reservoirs, aquifer thermal energy storage, thermohydraulic phenomena around a nuclear waste geological repository, and contaminant transport in porous-fractured media. He has been the Editor of the International Seasonal Thermal Energy Storage Quarterly Newsletter for the last six years and was one of the Editors for the Journal of Environmental Geology from 1980 to 1984. His recent interests are in ground water contamination studies and coupled thermomechanical hydrochemical processes affecting transport from a nuclear waste repository.

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