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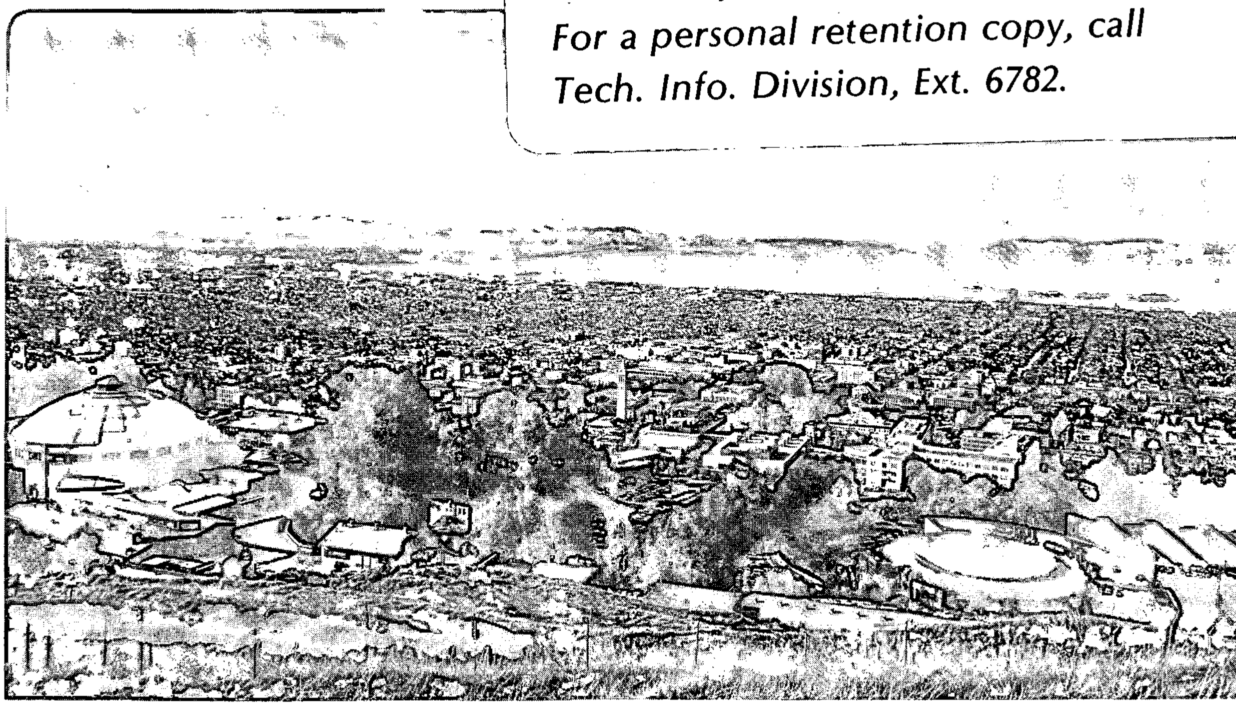

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GEOTHERMAL INJECTION MONITORING WITH D.C. RESISTIVITY METHODS

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ABSTRACT

We consider injection into an idealized geothermal reservoir, assuming that the injected water differs in temperature and salinity from in-place fluids. Changes in formation resistivity resulting from temperature and salinity variations are evaluated, and numerical simulation methods are used to predict effects which would be observed by means of dc resistivity monitoring. The resistivity calculations were performed using a three-dimensional computer code to simulate results from two different resistivity arrays, a dipole-dipole array and a downhole-surface array. Our calculations show that the dipole-dipole method is relatively insensitive to changes due to injection, but downhole-surface measurements are very sensitive. From the simulated downhole-surface measurements a bell-shaped curve for resistivity change is obtained, from which the position of the chemical front may be approximately determined. Resistivity changes from temperature variations are rather small and probably cannot be detected in field measurements. Resistivity measurements are more than twice as sensitive when injected water is more saline than the in-situ reservoir fluid. This suggests that it may be easier to monitor the location of injected water if geothermal brine is reinjected rather than fresher water.

INTRODUCTION

Injection of geothermal wastewater is necessary in many geothermal fields where environmental constraints prohibit surface disposal. Consequently, in recent years theoretical studies and field tests have been reported that address the various beneficial and detrimental aspects of injection. It is established that injection can help to maintain reservoir pressures (Cuellar, 1981) and to increase the ultimate energy recovery from the field (Bodvarsson et al., 1983). However, injection may also increase the likelihood of premature cold-water breakthrough into the production zone (Horne, 1981).

During cold-water injection thermal and chemical fronts will migrate away from the injection wells. A chemical (salinity) front will develop if the salinity of the injected fluids is different from the salinity of the in-situ reservoir fluids. The thermal front will lag considerably behind the chemical front because of heat exchange between the fluids and the reservoir rocks. Proper design and operation of injection systems requires methods for monitoring the locations of the thermal and chemical fronts.

The temperature and salinity difference between the injected and in-situ fluids can result in a significant electrical resistivity contrast in the reservoir. In this paper we examine the possibility of mapping thermal and chemical injection plumes using surface and downhole electrical resistivity methods. Using computer codes, we simulate injection experiments and calculate apparent resistivity for the model before and after each simulation. We evaluate the results to determine how well the reinjection process can be monitored.

<u>Migration of thermal and chemical fronts</u>

To calculate the extent of thermally and chemically swept regions we use a simple model for porous-medium-type reservoirs (Fig. 1). We consider a 400-m thick reservoir beneath a 600-m caprock. We assume that the injection rate is uniform over the thickness of the reservoir, neglecting heat transfer to caprock and bedrock and gravity effects. Furthermore, by assuming piston-like displacement the location of the chemical and thermal fronts are given by (Bodvarsson, 1972):

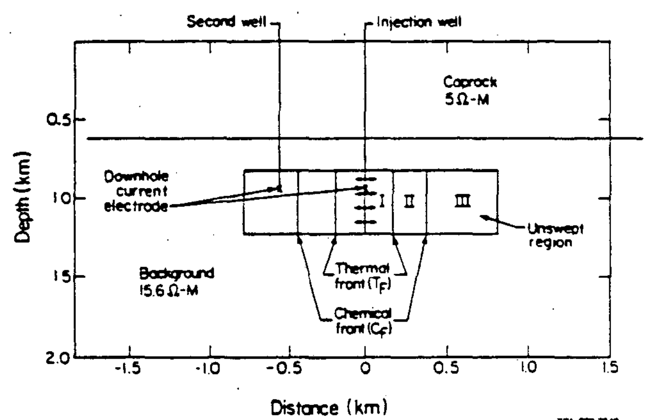

Figure 1. Cross section of the resistivity distribution for injection simulation. Actual reservoir region is a rectangular prism 1.6 km^2 and .4 km thick. Regions I, II, and III represent the thermally swept region, the chemically swept region, and undisturbed parts of the reservoir, respectively.

$$R_c = \left(\frac{qt}{\pi H \phi \rho_w}\right)^{1/2} \qquad (1)$$

$$R_t = \left(\frac{\phi\ \rho_w\ C_w}{\phi\ \rho_w\ C_w + (1-\phi)\rho_r\ C_r}\right)^{1/2} * R_c \qquad (2)$$

In equations (1) and (2) R_c and R_t are the radial distances from the injection well to the chemical and thermal fronts, respectively. Other parameters are as follows:

q is the flowrate (kg/s),
t is the time(s),
H is the reservoir thickness (m),
ϕ is the porosity,
ρ_w is the density of water, (kg/m^3)
C_w is the heat capacity of water, (J/kg·°C)
ρ_r is the density of the rock, and
C_r is the heat capacity of the rock matrix.

We neglect the small effects of density variations of water with temperature and salinity.

Equations (1) and (2) show that in our simple model the extent of thermally and chemically swept regions depends only on the total injected mass, qt, not on the injection rate q or the time t separately. We consider injection of a "small" and a "large" amount of fluid, corresponding to an injection rate of 25 kg/s and 250 kg/s for a 3-year period. For both cases we use a reservoir thickness of 400 m and porosity of 15% (we use standard values for the densities and heat capacities of water and the rock matrix). The thermal and chemical fronts will have advanced 57 and 128 m, respectively, for the "small" injected mass and 180 and 404 m, respectively, for the "large" injected mass.

The model used here for the advancement of thermal and chemical fronts is very simple, especially if one considers that in most geothermal fields fluid flow is controlled by fractures. However we feel that the use of this simple model is justified to obtain an initial assessment of the feasibility of monitoring migration of injected waters with dc resistivity methods.

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 large memory requirement the mesh is limited to a 41 x 12 x 9 node array. This restricts the complexity of the models used, and limits the amount of detail possible for the injection simulation.

The model and initial resistivity distribution are given in cross-section Figure 1 and Table 1. The three-dimensional representation of the reservoir region is a rectangular prism 1.6 km x 1.6 km and .4 km thick. The "caprock" and "background" regions are represented by a 600 m layer over an infinite halfspace. The parts of the model affected by injection are designated by Area I for the thermal region, Area II for the swept region and Area III for the nonswept portion of the reservoir. In the injection simulation the first two regions form concentric cylinders. However, because of the rectangular mesh, the regions are approximated by rectangular blocks with the same volume as the cylinders. The error due to this approximation is expected to be small.

The resistivities of the different regions in Figure 1 are calculated from Archie's law and relations correcting the resistivity to the temperature and salinity of pore fluids. We use a porosity of 15 percent, an initial reservoir temperature of 300°C and an initial in-situ reservoir water salinity of 10,000 ppm. For the background region the temperature is 100°C and the salinity 1,000 ppm. The caprock is considered a clay rich layer with a resistivity of 5 ohm-m. Resistivity is corrected for temperature and salinity using the relations of Ershaghi et al. (1981). Model resistivities for regions I, II, and III were adjusted after three years of injection to correspond to the new subsurface fluid and temperature distribution.

Two different resistivity arrays were used in these calculations, a dipole-dipole array and a downhole surface array. The dipole-dipole method is well suited in locating lateral resistivity boundaries and has shown some promise in detecting subsurface changes due to fresh-water intrusion at the Cerro Prieto geothermal field (Wilt and Goldstein, 1981). It also has the advantage of easy deployment and relatively low cost. Downhole-surface arrays may be more sensitive to an injected water plume because of the closeness of the current electrode to the region affected by injection. Downhole-surface measurements may also be more precise because the electrode separations are smaller than in the dipole-dipole case so that errors due to geological noise and weak signal will be less. However, downhole methods are likely to be more expensive and difficult to deploy.

We have considered six cases for this study; the parameters are summarized in Table 1. The various cases were chosen to examine which injection parameters most strongly affect resistivity measurements and which arrays are most sensitive to these parameters.

RESULTS

Dipole-Dipole Array

In Figure 2 a dipole-dipole apparent resistivity pseudosection is given corresponding to the initial conditions before injection started. The dipole spacing is 400 m and measurement is done to an n-spacing of 10. Figures 3 and 4 give pseudosection plots for percent resistivity change after three years due to fresh cold-water injection using rates of 25 kg/s and 250 kg/s.

In both cases the maximum anomaly appears at the edges of the pseudosection. This is a typical anomaly pattern for a dipole-dipole measurement, an artifact of the way the data are plotted. After three years the percent difference pseudosection for the lower injection rate shows a maximum change of about one percent which is comparable to the error level of any practical field measurement (Fig. 3).

TABLE I
Summary of Injection and Resistivity Modeling Parameters

CASE	INJECTION		RESISTIVITY ARRAY	ROCK RESISTIVITIES OF THE THREE REGIONS I	II	III
	Rate	Type				
Base Case	0	No injection 300°C 10,000 ppm	Dipole-Dipole	2.15	2.15	2.15
1	25 kg/s	100°C 1000 ppm (cold fresh water)	Dipole-Dipole	15.6	10.75	2.15
2	250 kg/s	100°C 1000 ppm (cold fresh water)	Dipole-Dipole	15.6	10.75	2.15
3	250 kg/s	100°C 1000 ppm (cold fresh water)	Downhole-surface electrode in injection well	15.6	10.75	2.15
4	250 kg/s	100°C 1000 ppm (cold fresh water)	Downhole-surface electrode in second (offset) well	15.6	10.75	2.15
5	250 kg/s	100°C 10,000 ppm (isochemical)	Downhole-surface electrode in injection well	4.0	2.15	2.15
6	250 kg/s	100°C 15,000 ppm (cold saline water)	Downhole-surface electrode in injection well	1.90	1.07	2.15

Also, only a small number of the measurements seem to be significantly affected by the injection. For the higher injection rate, a maximum apparent resistivity change of about three percent is observed (Fig. 4). Although this is a recognizable change, the accuracy of field measurements would need to be better than .5 percent to recognize an anomaly due to injection. The main reason for the insensitivity of dipole-dipole measurements is that a relatively small volume of rock is affected by the injection compared to the volume of rock sampled by the measurements. For the high rate case the injected water affects a volume of only about five percent of the total sampled by the measurements so that even a large change in resistivity may not be readily observable. Another problem is that less than half of the measurements are affected by the injection so that it would be difficult to accurately determine the affected region based on dipole-dipole results.

Downhole-Surface Array

For downhole-surface measurements a current electrode is placed in the injection well at a depth of 900 m (central case) or in another well outside the injection plume at the same depth (offset case). Voltage measurements are made along a profile between closely-spaced surface dipoles. Because of the cylindrical symmetry only one profile per case is needed.

In Figure 5 we have plotted apparent resistivity changes after three years of fresh cold-water injection at the high rate. The figure shows a marked bell-shaped anomaly where the maximum change is more than 70%. The anomaly is almost entirely due to the salinity rather than the temperature contrast. The approximate position of the chemical front 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. In this case this corresponds to 450 m from the well where the actual position is 400 m. Another method of determining the radius is to match the curve to a family of curves for various cylinder radii and heights. Preliminary calculations indicate that the shape of the curve depends mainly on the radius of the cylinder. A change in the resistivity contrast affects only the amplitude of the curve; a change in the reservoir thickness has a similar effect.

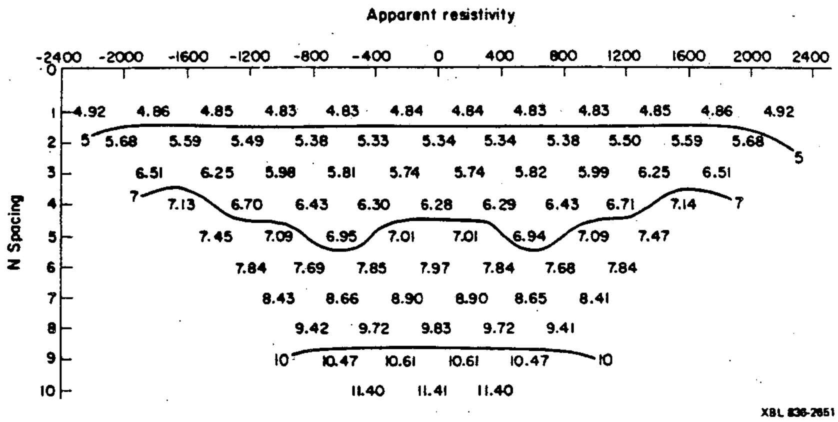

Figure 2. Apparent resistivity pseudosection of resistivity distribution before injection.

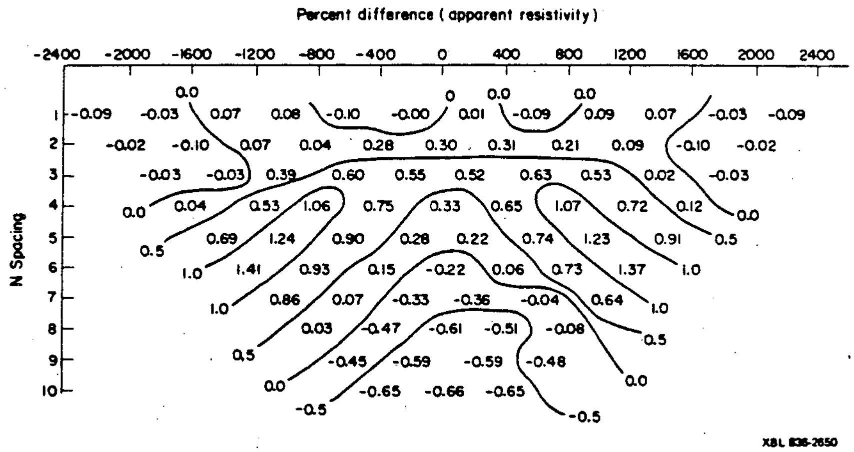

Figure 3. Percent difference pseudosection of apparent resistivity after three years of low-rate injection (compared to initial case).

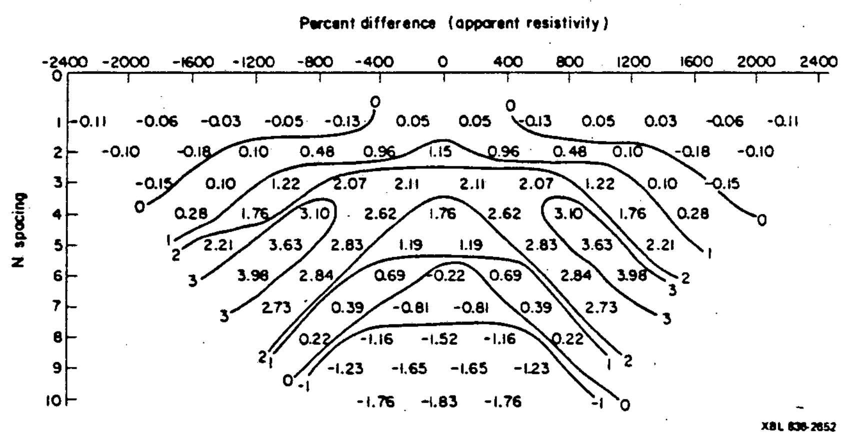

Figure 4. Percent difference pseudosection of apparent resistivity after three years of high-rate injection (compared to initial case).

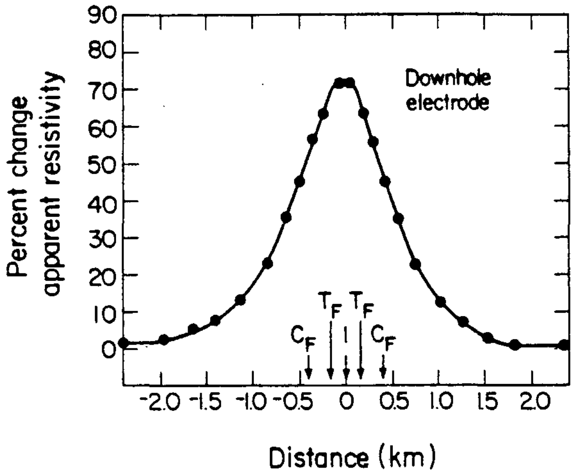

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Figure 5. Percent difference plot for central downhole electrode case after three years of high-rate injection. I is the surface position of the current electrode, T is the surface position of the thermal front, and C is the surface position of the chemical (salinity) front.

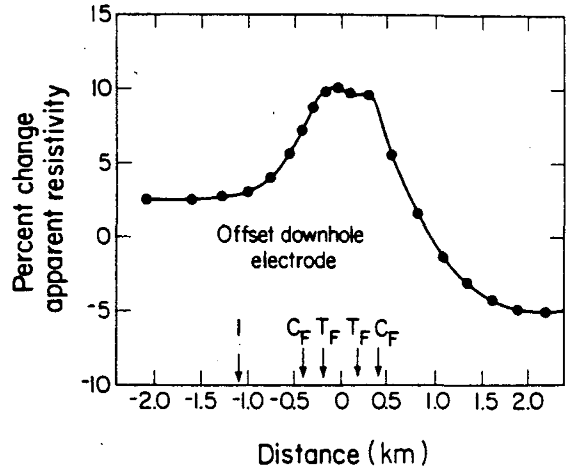

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Figure 6. Percent difference plot for offset downhole injection case after three years of high-rate injection.

Offset Downhole Electrode

Although it is possible to determine the location of the plume under the conditions given above, it may be very difficult to use the injection well to inject current. We have therefore considered a case where current is injected into a well within the reservoir region but at some distance from the injection well (Fig. 1).

For this case the reservoir region was expanded from a 1.6 x 1.6 km^2 region to 3.2 x 3.2 km^2, so that the effects of a nearby boundary would not interfere with injection effects. The current electrode was placed 1066 m from the injection well at a depth of 900 m. In Figure 6 the results after three years of high rate injection are plotted. The figure clearly shows an anomaly in the region where fluid is injected but the magnitude of the anomaly is smaller than that observed in the previous case. The anomaly also has an asymmetric shape, and it is not centered over the injection well but is displaced somewhat away from the injection well. The asymmetric anomaly pattern is the result of subsurface current redistribution around the zone of increased resistivity due to injection. Currents tend to gather at the closer chemical front boundary and disperse at the far boundary. An analogy may be made to fluid flow where fluid streamlines envelop an impermeable object. Some indication of the thermal front may be seen in the irregular shape of the curve at the crest of the anomaly. The effect appears to be too small, however, to be observable in field data.

For the offset case a half-width calculation may be made by averaging the nearside and farside apparent resistivity difference and adjusting the anomaly to the new level. The half-width calculation indicates a chemical front 440 m from the injection well which is in reasonable agreement with the actual value of 404 m.

Isochemical Injection

To determine the magnitude of the resistivity anomaly due solely to thermal effects we have considered a case where the injected water has the same salinity as the in-situ water. We consider high-rate injection and a central downhole electrode.

In Figure 7 we plot the percent apparent resistivity change for the isochemical injection case. The bell-shaped anomaly has a maximum amplitude of only about two percent and a half-width of about 200 m, in good agreement with the radius R_t = 180 m of the thermally swept region. If the injected water were 30°C instead of 100°C the maximum resistivity change would be seven percent. The thermal affects seem minor compared to chemical affects for two reasons; first, because heat exchange is occurring between the injected fluid and the rock, the thermally affected region is considerably smaller than the swept region; secondly, the variation of resistivity with temperature is much smaller than the variation with fluid salinity; this is particularly true for temperatures above 100°C.

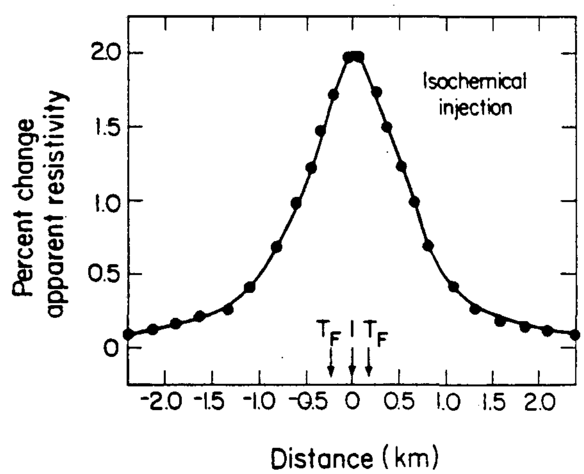

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Figure 7. Percent difference plot for the isochemical downhole injection case after three years of high-rate injection.

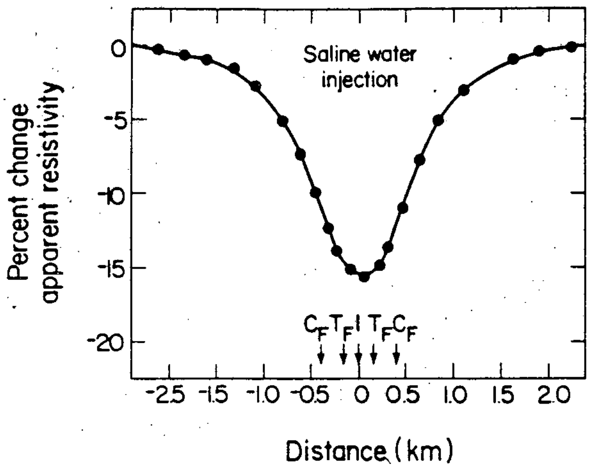

Figure 8. Percent difference plot for the high salinity downhole injection case after three years of high-rate injection.

Saline Water Injection

In the final case considered, the injected water has a temperature of 100°C and is 50 % more saline than in-situ water. This is representative of a case where spent geothermal brine is reinjected into the reservoir. Again a central downhole current electrode is used with high-rate injection.

In Figure 8 a characteristic bell-shaped curve is observed with a half-width of 450 m. The anomaly is negative corresponding to a decrease in resistivity in the injected region. Although the resistivity in the swept region decreased only by about a factor of 2, the maximum anomaly is almost 20 %. This means that the measurement is more sensitive when the injected water is more saline than the in-situ fluid.

CONCLUSIONS

The major conclusions reached by this study are:

1) It is possible to locate the position of injection plumes if the salinity of the injected water differs significantly from in-situ water and a relatively large mass of water is injected.
2) Downhole-surface resistivity arrays can better detect injection plumes than surface measurements.
3) The change in apparent resistivity due to the thermal plume is only one-tenth that of the chemical plume and it may be difficult to locate the thermal fronts if there is a salinity difference between injected and in-situ water.
4) Resistivity measurements are more sensitive when injected water is more saline than when it is less saline than the in-situ water.

Our simulations provide some encouragement for applying dc resistivity methods to monitor injection operations. Actual field cases will likely be far more complex than the idealized models considered in this paper. For example, the reservoir may be fractured, or the injected water may have little resistivity contrast with the reservoir water. Either of these circumstances make the problem more difficult. It appears, however, that the technique shows promise and should be applied to actual field problems.

ACKNOWLEDGMENT

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