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Preliminary Analysis of the Use of Electrical Resistance Tomography for Injectate Tracking at The Geysers Geothermal Field

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ABSTRACT

Current geochemical and geophysical injectate tracking methods are useful reservoir management techniques but do not track injectate movement quick enough to maximize injection efficiency or avoid negative impacts on nearby steam production wells. A preliminary analysis indicates that two dimensional electrical resistance tomography (ERT) may be useful for imaging plume movement resulting from Geysers/Lake County Effluent Pipeline injectate in near real time.

ERT models comparing an injection plume resistivity of 50 Ohm-m with background resistivities of 10, 100 (typical Geysers greywacke), and 500 Ohm-m (typical Geysers felsite) indicate that liquid plumes can be imaged at depths of 6,000 feet to 8,000 feet or greater for resistivity contrasts of 2 to 1 or greater. Further refinement of the ERT model could be accomplished with more data on porosity in the vicinity of the borehole, resistivity measurements, and reservoir engineering estimates of plume temperature and saturation.

Based on the results of this analysis and previous successes in using ERT to map shallow subsurface steam and water movement in porous media it is likely, but not certain, that ERT will prove to be an additional reservoir management tool to be used in conjunction with additional geochemical, geophysical, and reservoir engineering techniques. A field scale test at The Geysers is required to verify the utility of ERT for injectate tracking.

The goal of this paper is to stimulate discussion among geothermal researchers regarding use of the ERT technique for injectate tracking at The Geysers and get some input on the appropriateness and utility of the assumptions used.

INTRODUCTION

The injection of cold water into vapor dominated reservoirs has been demonstrated to be useful as a means to maintain or increase steam production. Injection derived steam recovery rates of 41% are considered to be successful (Voge, et al., 1994). In order to maximize injection as a reservoir management strategy it would be useful to know what happens to the injectate that is not recovered as injection derived steam.

Tracer and micro earthquake analyses have been successful in reconstructing injectate flow patterns some time after the initiation of injection. The time lag between injection and flow characterization is due to the time it takes to collect, analyze and interpret the data. In the case of tracer interpretations there is also some uncertainty in the areas between wells where samples are collected. Micro earthquake data and interpretation is improving and can show fairly accurately where micro earthquakes have occurred at The Geysers but the exact relationship between injection, micro earthquake source mechanisms, and regional stress is still somewhat problematic (Kirkpatrick et al., 1995). This paper presents the results of a preliminary analysis of ERT as an additional tool for mapping injectate movement in vapor dominated reservoirs.

BRIEF DESCRIPTION OF ERT

Previous studies using ERT to map fluid and steam movement in shallow unsaturated porous media (Ramirez et al., 1993) indicate that there is a reasonable chance that ERT can map injectate paths in vapor dominated geothermal reservoirs. A brief discussion of the ERT technique is presented here. A more detailed description of the ERT technique can be found in Ramirez et al., 1993.

In ERT field applications a series of steel electrodes are coupled or grouted to the borehole wall and connected to surface equipment with insulated cable. Even though this is a very simple configuration, the high temperature installation of these electrodes and cables in geothermal environments may be problematic. Automated equipment is used to apply a known current to any two electrodes and measure the voltage difference between other pairs of electrodes. The process is repeated until the plane between the boreholes is interrogated completely encircling the target area.

The ERT inversion process involves solving both the forward and inverse problems. The forward model uses the finite element method to compute the potential electrical response of a two-dimensional earth due to a three-dimensional source. The inversion and forward modeling procedures are discussed in more detail in Ramirez et al, 1993.

ERT IMAGES OF GEYSERS INJECTATE

ERT images used in this paper are constructed using hypothetical electrical resistivity data from electrodes installed in boreholes as shown in Figures 1 - 3. The injection and observation wells are 1,606 feet apart and assumed to be uncased below 4,000 feet with electrodes every 210 feet from 4,000 to 8,000 feet below land surface.

The process for difference image construction for each Figure involved taking the resistivity distribution from the inversion of the forward model of the injectate plume and performing a pixel by pixel subtraction of the background image. 2% Gaussian noise was added to both the background and injectate plume forward models to demonstrate that the inversion scheme is reasonably robust and will work in an environment with unsystematic geologic or instrumental noise. If the difference images were perfect, the areas outlined in white would exactly equal the difference between the background and injectate plume resistivities. For example in Figure 1 the background image has a nominal (with no noise perfect inversion) resistivity of 100 ohm-m and the injectate plume has a nominal resistivity of 50 ohm-m. The subtraction of the background pixel values from the plume pixel values should result in a difference image pixel resistivity of -50 ohm-m. Difference images can be taken over time to show resistivity changes due to steam or water movement.

Deviations from this value in the difference images represents the net effect of noise added to the forward models for inversion and the effectiveness of the inversion routine.

Derivation of Resistivities Used in this Analysis

Resistivity values of 10 ohm-m, 100 ohm-m and 500 ohm-m were used to represent three different cases of unsaturated or "background" portions of the reservoir. 100 ohm-m was chosen to represent a "typical" Geysers greywacke resistivity at depths of 6,000 to 8,000 feet. The 500 ohm-m value was chosen to represent the resistivity of The Geysers felsite. Although electrical log data is sparse and proprietary, discussions with industry and government workers indicate that these values are reasonable estimates for Geysers greywacke and felsite type reservoir rocks. The 10 ohm-m value for background resistivity was chosen to assess ERT difference image quality when the injectate plume is resistive with respect to background resistivity.

Injectate plume resistivity is estimated to be 50 ohm-m. This estimate is consistent with a background resistivity of 100 ohm-m, greywacke core resistivity (Jeff Roberts, pers. Comm.), core porosity measurements (Gunderson, 1992), the conductivity of Lake County effluent (Mark Dellinger, pers. Comm.), and estimates of temperature and saturation changes with injection based on reservoir engineering models (Preuss and Enedy, 1993). Parameters used for estimating injectate plume resistivity are shown in Table 1.

Estimates based on the parameters in Table 1 tend to support the assumed injectate plume resistivity (50 ohm-m) resulting from the injection of water from The Geysers Lake County Effluent Pipeline into greywacke reservoir rock. Plume resistivities calculated for the Geysers felsite (500 ohm-m) are 270 ohm-m. These are best estimates based on available data and could be improved with additional data, especially in situ resistivity and injection scale reservoir modeling data and porosity estimates. Estimates of the rates at which the saturation and temperature fronts would move is very problematic and requires a serious integrated effort involving reservoir modelers (see Preuss and Enedy, 1993 for example) and other geothermal earth scientists. Indeed, one of the goals of this paper to show how ERT can be used to assist in this effort.

Crude estimates based on injection rates of 600 gpm and 4% porosity indicate that pixels in the difference images would show the effects of injection at rates of between 1 and 40 pixels per day depending on assumed flow (fracture zone) widths (Bob Creed, unpublished data).

Initial background	100 ohm-m
Injectate conductance	405 m mhos/cm
Porosity	0.04
Delta T	40°C
Initial saturation	0.6
Final saturation	0.9
Injectate plume resistivity calculated from background[1]	58 ohm-m
Injectate plume calculated from core data[2]	42 ohm-m
Assumed plume	50 ohm-m

[1] Calculated using Archie's Law and an estimate of the effects of temperature on resistivity (Keller and Frischknecht, 1966).

[2] Calculated resistivity at 4% using core data with initial resistivity of 16 ohm-m at 145°C and 6.5% porosity (Bill Daily, unpublished data).

Table 1. Parameters used to determine injectate plume resistivity.

DISCUSSION AND CONCLUSIONS

Although this analysis was conducted specifically for the case of tracking Lake County Effluent Pipeline injectate tracking at The Geysers, the results may applicable to other vapor dominated fields where similar resistivity contrasts are likely to exist at equal or lesser depths. The black and white results of this analysis are presented in Figures 1,2 and 3. The original color images, which better illustrate the effects of injection on resistivity, may be obtained from the lead author.

Figures 1 - 3 show that there is at least a general correlation between plume geometry and the difference images. Figures 1 and 3 are especially strong in this regard. Figure 1 represents the base case for The Geysers and shows that generally a background to injectate resistivity contrast of 2 to 1 can be imaged at depths of 4,000 to 8,000 feet. Thus, Figure 1 is similar to an image that would result from injection into the Geysers felsite with a plume resistivity of 270 ohm-m and a 500 ohm-m background. Figure 2 is intended to show how a 50 ohm-m plume would be imaged in a less resistive background of 10 ohm-m. Figure 3 shows an image that would result from a 50 ohm-m plume in a 500 ohm-m background and is the highest contrast case considered here. More accurate plume delineation can be expected with more resistivity contrast. The "diffusion" of resistivity about the areas (injection plumes) outlined in white is due to the effects of noise added to the forward models and the instability of the inversion routine.

The case of downward vertical (see (A)) flow reflects the case where fractures with the highest permeability are near vertical such as might be expected in post-Franciscan structures or in the felsite intrusive (Thompson and Gunderson, 1991). Additional data from reservoir engineering (Bodvarsson and Stefanson, 1989 and Preuss, 1994) and micro earthquake analyses (Kirkpatrick et al., 1995) indicate that injectate into The Geysers felsite is likely to flow in a vertical direction. Injection into The Geysers greywacke may also result in vertical flow if sufficient vertical permeability exists to overcome potential flow along sub-horizontal Franciscan faulting. Because the case of vertical flow presents the optimum aspect ratio for imaging between boreholes, it has the greatest potential for being successfully imaged. Case (B) represents horizontal flow and may be an appropriate analog for a condensation zone near the top of the reservoir or where the zone of injection is a subhorizontal fault zone present in Franciscan rocks (Thompson and Gunderson, 1991). Case (C) represents flow along a permeable zone with a dip of 45 degrees. A particularly interesting case can be seen in image (D) in the figures. In this case the plume can be imaged even though it is moving away from the observation well. This is particularly important because it means that a poor choice for an ERT observation well is not fatal with respect to imaging potential. Currently ERT models are being prepared for the three-dimensional case and the case where only a single borehole is available. In the three-dimensional case it may be possible to make quantitative estimates of the direction of injectate movement.

The goal of this paper is to stimulate discussion among geothermal researchers regarding use of the ERT technique for injectate tracking at The Geysers and get some input on the appropriateness and utility of the assumptions used. Comments and suggestions are welcome and should be directed towards the lead author. The results of this analysis seem to indicate that ERT can successfully image Lake County/Geysers Effluent Pipeline injectate but a field scale test at The Geysers is required to fully assess ERT for injectate tracking. Successful reservoir management techniques will require the coordination and integration of diverse suites of data. In the case of injection strategy development, ERT may be a tool that can be used in concert with tracer testing, micro earthquake monitoring, and fine to intermediate scale reservoir models to determine the fate and transport of injected fluids. The advantages of ERT are that images can be acquired in near real time allowing injection strategies to be quickly modified to avoid costly problems like thermal breakthrough or to maximize the return of injection derived steam by identifying optimum injector/producer flow paths.

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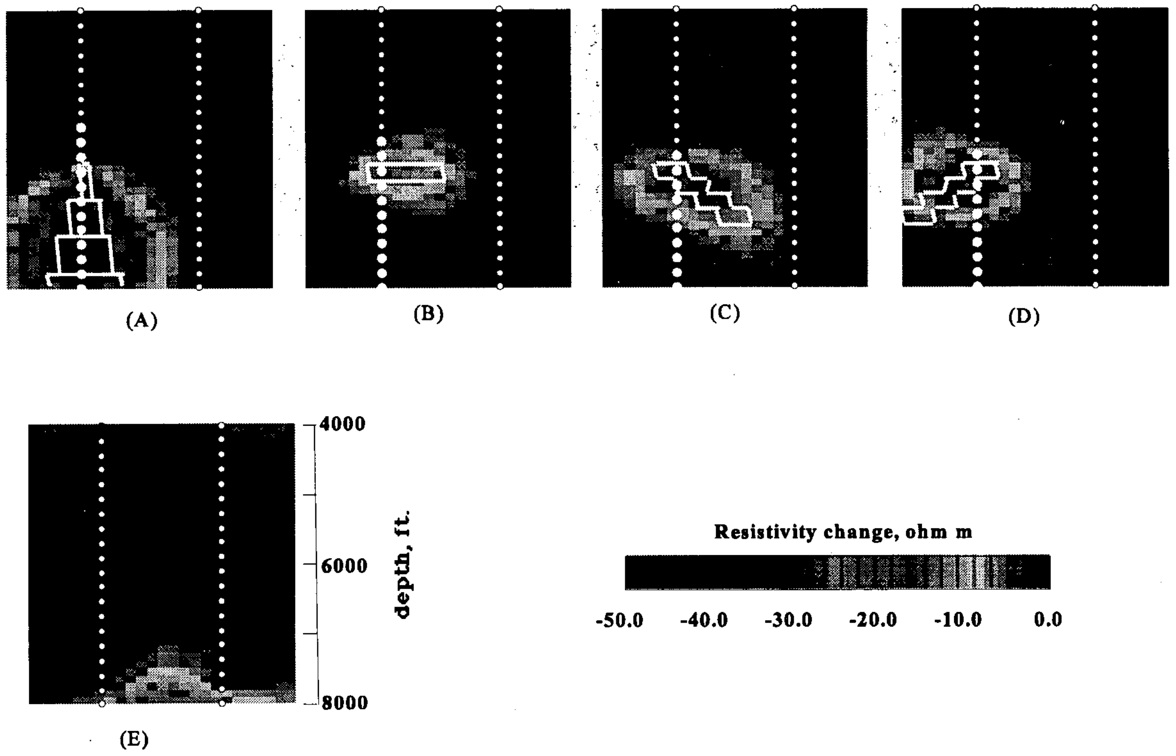

Figure 1. ERT images for 100 ohm-m background with a 50 ohm-m injectate plume resistivity outlined in white. Vertical and horizontal scales are the same. The white dots represent electrodes spaced 210 feet apart. Image A represents vertical flow, B horizontal flow, C represents flow with a 45 degree dip and D shows flow away from the observation well. E is the preinjection baseline or background image with 2% Gaussian noise added before inversion. Images A through D are difference images (see text).

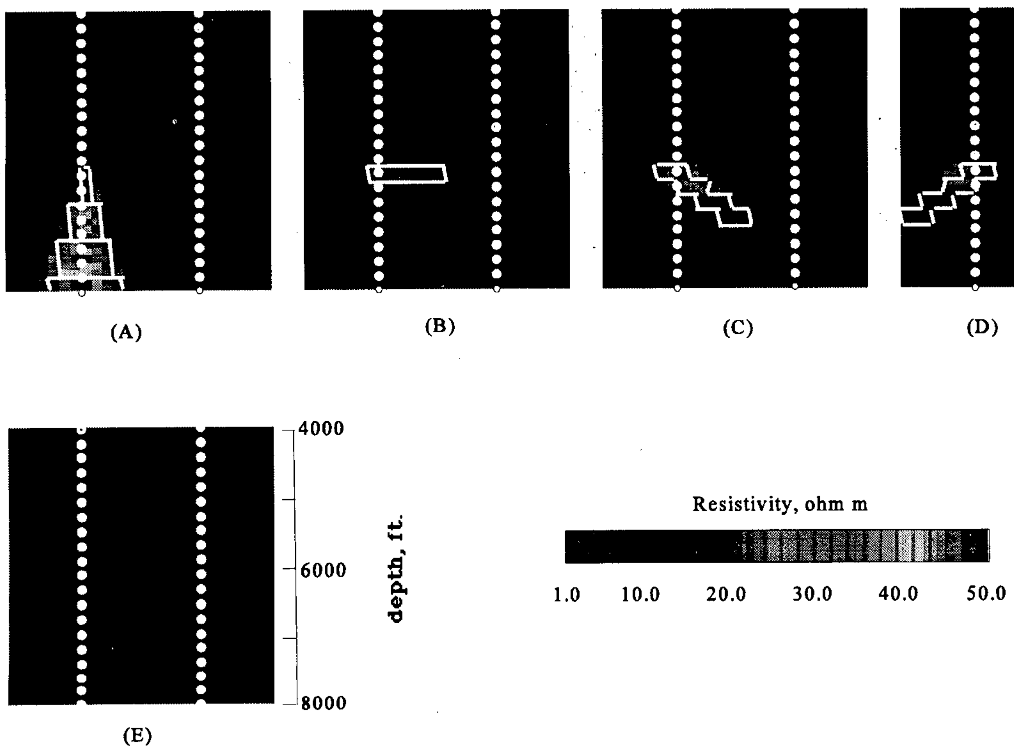

Figure 2. Same as Figure 1 with a background resistivity of 10 ohm-m.

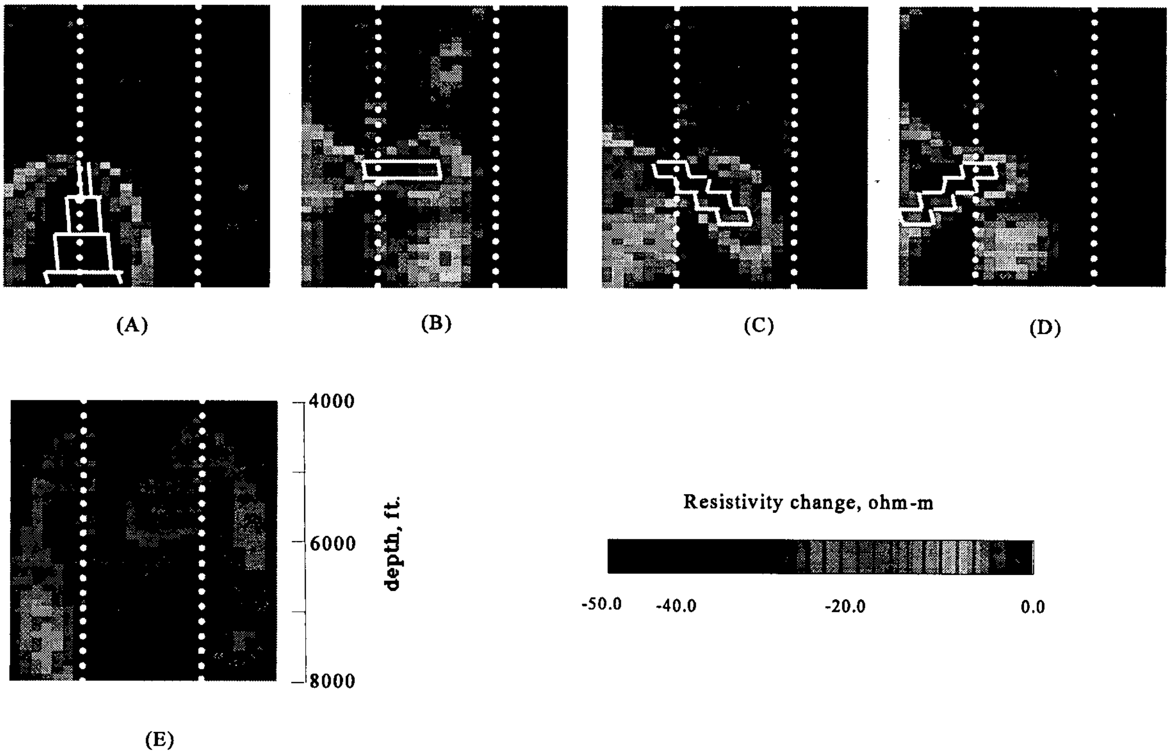

Figure 3. Same as Figure 1 with a background resistivity of 500 ohm-m.