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A Heat Injection and Pumping Experiment in a Gravel Aquifer Monitored with Crosshole Electrical Resistivity Tomography

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SUMMARY

Thermal tracing experiments are becoming common in hydrogeology to estimate parameters governing heat transport processes and to study geothermal reservoirs. Electrical resistivity tomography (ERT) has proven its ability to monitor salt tracer tests, but few studies have investigated its performances in thermal tracing experiments. In this study, we monitor the injection and pumping of heated water using crosshole ERT in a panel crossing the main flow direction. Difference inversion time-lapse images clearly show the heterogeneous pattern of resistivity changes, and thus temperature changes, highlighting the existence of preferential flow paths in the aquifer. Comparison of temperature estimates from ERT and direct measurements in boreholes show the ability of ERT to quantify the temperatures in the aquifer and to draw the breakthrough curves of the thermal tracer with a relative accuracy. Such resistivity data may provide important information to improve hydrogeological models. Our study proves that ERT, especially crosshole ERT, is a reliable tool to follow thermal tracing experiments. It also confirms that ERT should be included to in situ techniques to characterize heat transfer in the subsurface and to monitor geothermal resources exploitation.

Introduction

The production of geothermal energy is increasingly growing worldwide. Geothermal energy does not rely only on high temperature and deep systems. Low to very low temperature systems (< 30°C) are relatively abundant in alluvial aquifer for example, with easy access and low implementation costs (Allen and Milenic 2003; Lund 2010).

Parameters governing heat transport processes (mainly heat capacity and thermal conductivity) are necessary to design and exploit properly geothermal energy systems. Electrical resistivity tomography (ERT) may provide spatially and temporally distributed information on temperature distribution during thermal tracing experiments (Hermans et al. 2012a, 2012b). In analogy to salt tracer tests (Ptak et al. 2004), this data may be further use to help calibrating hydrogeological models. Heated water may also be used as a tracer when the injection of salt tracers is prohibited.

Hermans et al. (2012a) have shown during a shallow heat injection and storage experiment in a homogeneous sandy aquifer with no gradient that surface time-lapse ERT sections can be mapped into temperatures using site specific petrophysical relationships. However, those results were influenced by a correction term to account for a difference in electrical conductivity between formation and injection waters.

In this study, we designed a more challenging experiment. Water is extracted in a heterogeneous alluvial gravel aquifer from a pumping well, is heated and reinjected in an injection well located upstream. The test is monitored with time-lapse crosshole electrical resistivity measurements. The results illustrate the ability of ERT to image and quantify temperature changes highlighting preferential flow paths in the aquifer.

Field site and methodology

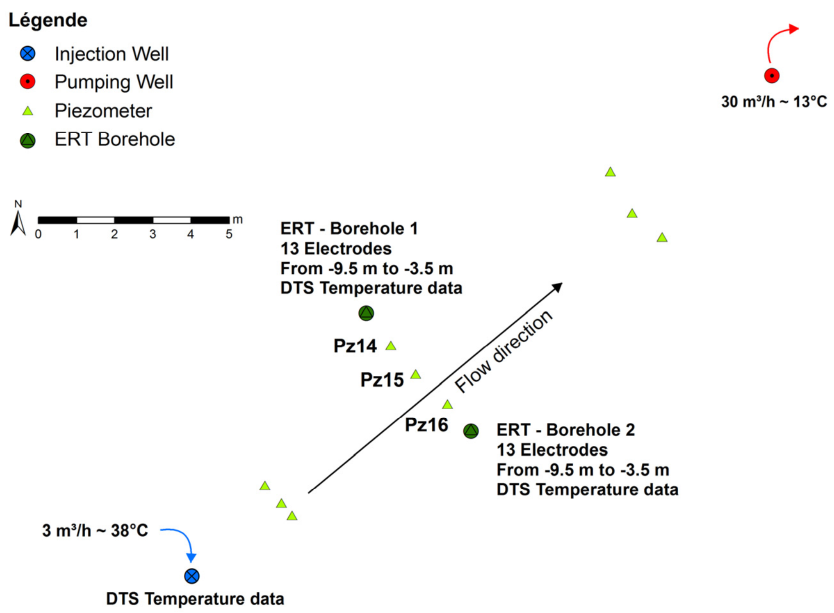

Figure 1 *The study site of Hermalle-sous-Argenteau is equipped with 11 piezometers, one injection well and one pumping well, 2 piezometers were equipped with 13 electrodes every 50 cm for crosshole ERT.*

The study site is located in Hermalle-sous-Argenteau, Belgium. It lies in the Meuse River alluvial aquifer. The water table is found at 3.2m depth. The saturated part of the aquifer is composed of coarse gravel and pebbles in a sandy matrix, whose abundance decreases with depth. The bedrock lies at 10 to 10.5m depth. 13 boreholes were drilled on the site to monitor the heated water plume flowing northeast from the injection to the pumping well (Figure 1). The injection well and ERT boreholes (totally screened) were equipped with a fiber optic DTS probe to monitor temperature over the entire thickness of the saturated zone; other piezometers were equipped with divers at 5 and 9 m depth. Formation water was extracted from the pumping well at the rate of 30 m^3/h during the entire test. Its mean temperature was 13°C. Injection took place for 24h, 3 m^3/h of the pumped water was heated using a mobile oil water heater and injected in the injection well at the mean temperature of 38°C.

ERT data were collected about twice a day for five days in two boreholes separated by 4.5m equipped with 13 electrodes (0.5m spacing). We used a combination of bipole-bipole and dipole-dipole configurations (969 measurements). The data were inverted with the code CRTomo using a difference inversion scheme (Kemna 2000). We used reciprocal measurements to assess the error on the data. We derived a linear dependency between error and measured resistance, with an absolute error of 0.002 Ohm and a relative error of 0.5%.

We transformed bulk electrical conductivity changes into water electrical conductivity changes using the ratio of Archie's law between a specific time-step and the background, neglecting electrical surface conductivity. We assumed that all changes in water electrical conductivity were related to temperature variations (e.g., Hermans et al. 2012a). Both assumptions are justified given the conditions of the test (saturated sands and gravels). Water samples were collected to derive the dependence between formation water electrical conductivity σ_T and temperature T (in °C). On the temperature interval 5-40°C, we observed a linear dependence (e.g., Hayley et al. 2007):

$$\frac{\sigma_T}{\sigma_{25}} = m(T-25)+1$$

where σ_{25} is equal to 791 µS/cm and m, the fractional change in electrical conductivity per degree Celcius, is equal to 0.0194.

Results

Figure 2 shows a selection of representative sections, with resistivity changes and corresponding temperature estimates (only in the saturated zone of the alluvial aquifer where Archie's law does not depend on saturation). The initial temperature was set equal to the mean temperature measured in ERT boreholes (13.5°C). In the first hours, no change is observed. The first decrease in resistivity, corresponding to an increase in temperature, is detected after 12h of injection. Then, resistivity continues to decrease, with a maximum decrease of 18% between 25 and 30h. The maximum temperature deduced from ERT is thus about 21°C, corresponding to a difference of 7.5°C compared to the initial temperature. This temperature, however, is 17°C below the temperature of injected water.

During the next days, we slowly move back to the initial state. Resistivity is increasing and temperature decreasing. According to ERT results, temperatures remain above the initial state for 4 days after the end of injection (120 hours after the beginning of the test). However, after 90h, resistivity changes are below -5%. Changes of this magnitude are difficult to interpret, because they may be related to the propagation of noise in inverted sections. However, the noise level on the data is quite low and temperature data in boreholes and piezometers tends to show that temperature is indeed slightly above the initial level.

Spatially, we see that the temperature distribution is not uniform. Resistivity changes are higher in the neighbourhood of the first borehole. Changes are also smaller in the middle part of the panel, which is confirmed by divers placed in intermediate boreholes. The thermal tracer also seem to follow a preferential flow path at the bottom part (-8 to -10m) of the aquifer, where hydraulic conductivity is higher due to a smaller sand fraction. Temperature data collected in intermediate boreholes confirms that in the upper part of the aquifer, temperature varies only a little (around 1°C) and more slowly (maximum change after several days).

The ability of ERT to map temperature changes was assessed in ERT boreholes, where DTS temperature data were available with a resolution of 0.5°C for 50 cm spacing (Figure 3A to 3C). In the first borehole, DTS data tend to show an almost constant temperature which is not in accordance neither with ERT results nor with data in piezometers. A possible reason is an intense mixing of water in and around the borehole. In the second borehole, the correspondence is very good, both the trend and the temperatures are globally very well estimated, even if ERT slightly overestimates maximum temperatures.

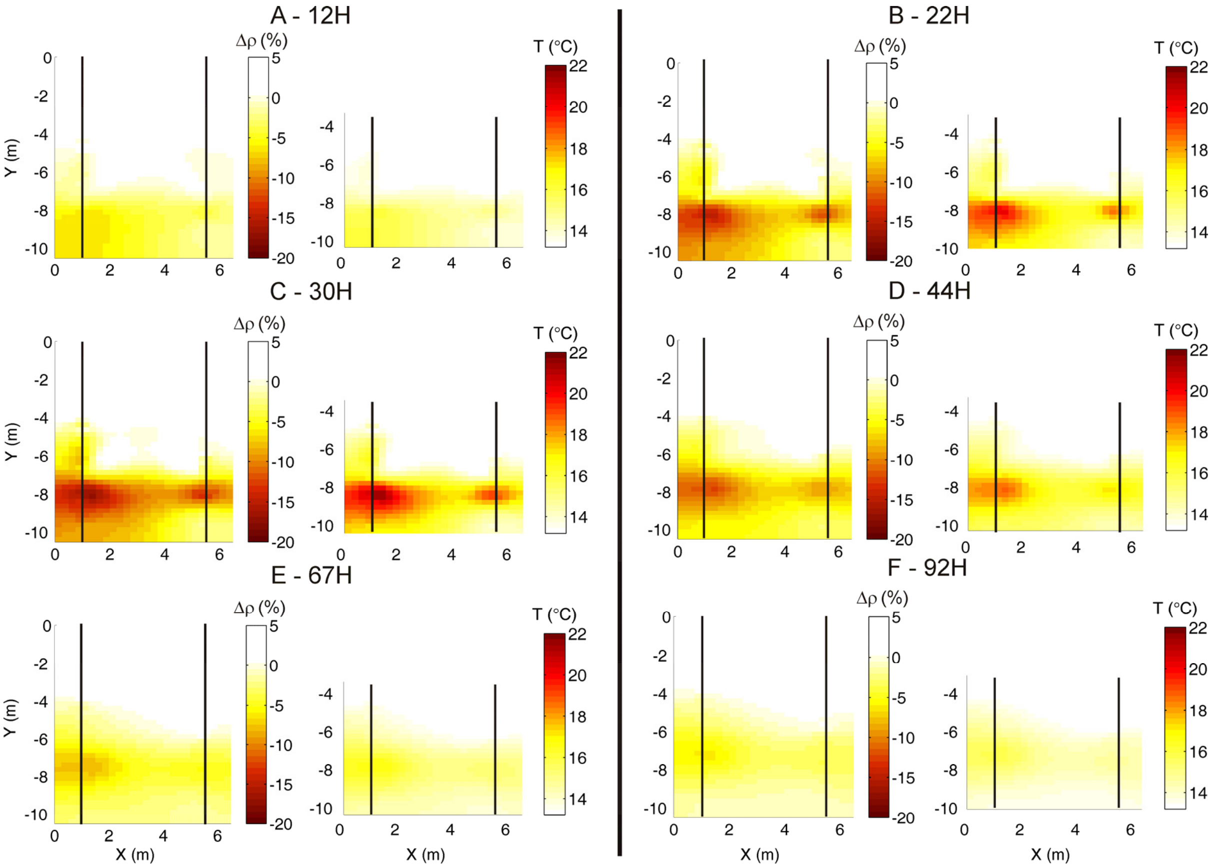

***Figure 2** Difference inversion results of crosshole ERT panel in Hermalle-sous-Argenteau (1st and 3rd columns) with respective temperature estimates (2nd and 4th columns).*

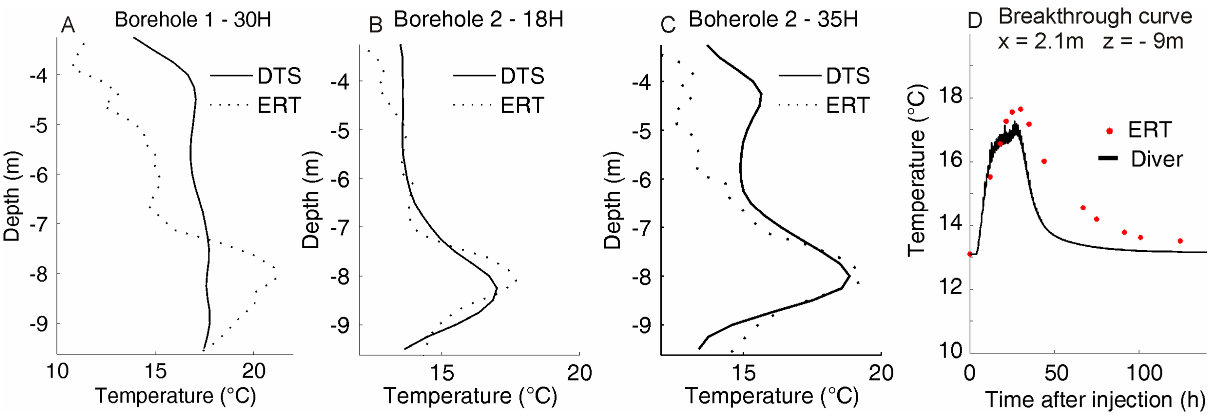

***Figure 3** Comparison between ERT results and DTS temperature (A) in Borehole 1 showing a poor fit and (B and C) in Borehole 2 showing a good fit. (D) Breakthrough curve at Pz14 for ERT and diver measurements, spikes on the diver curve are due to water sampling.*

The breakthrough curves from ERT are very close to the ones measured with divers (Figure 3D). The first part up to the maximum is almost similar. When the temperature is decreasing, ERT tends to overestimate temperature. This might be related to 3D effects in the inversion. Using only ERT to interpret tracer tests would give reliable estimates of advection processes, even if the first arrival and the mode would be determined with a lower time resolution. On the other hand, dispersivity would be overestimated.

Conclusions

Salt tracer tests are common practice in hydrogeology and ERT has already proven to be an efficient tool to follow spatially such experiments. Thermal tracing is also becoming an intensive field of research in hydrogeology, whereas only few experiments were performed to follow heat injection experiments with ERT. In most studies, temperature variations are undesirable artefacts potentially hiding other effects in time-lapse monitoring.

In this experiment, we showed that crosshole ERT was an efficient tool to image temperature patterns during a heat injection and pumping test. The comparison from ERT results with other data confirmed the ability of ERT to derive the spatial distribution of temperature as well as its potential to quantify relatively low temperature changes in the aquifer.

These results have an important and direct implication for the interpretation of tracer tests. Qualitatively, they give an insight on the spatial distribution of the tracer which helps to understand complex behaviour in heterogeneous media. Quantitatively, they provide additional data for calibrating hydrogeological model and deriving (heat) flow and transport parameters.

Our study proves that crosshole ERT is a reliable tool to follow heat tracer test. It also confirms that ERT should be included to in situ techniques to characterize heat transfer in the subsurface and to monitor geothermal resources exploitation.

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