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Reliability of ERT-derived Temperature - Insights from Laboratory Measurements

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SUMMARY

We performed laboratory measurements on fully saturated sand samples in the context of deriving reliable temperature from time-lapse electrical resistivity tomography (ERT). The experiment consisted in monitoring an increase of temperature in sand samples with electrical resistivity measurements. We neglected the effect of surface conductivity since experiments showed two orders of magnitude between surface and fluid conductivities. We show that using simple linear relationship between fluid electrical conductivity and temperature alone does not allow reliable temperature estimates. Indeed, chemical analyses highlight the importance of accounting chemical reactions occurring when temperature changes, including dissolution/precipitation processes. We performed two experiments based on typical in-situ conditions. We first simulated the injection of a less conductive tap water and second, the injection of heated formation water. In the second case, minerals solubility decreases and precipitation occurs, leading to an increase of bulk resistivity. This mechanism competes with dissolution of minerals when tap water is injected, since tap water is not in equilibrium with the medium. In any case, further research is needed to fully understand the mechanisms and to develop a fully integrated law to derive better temperature estimates.

Introduction

The production of geothermal energy is increasingly growing worldwide. Low to very low temperature systems ($< 30^{\circ}\text{C}$) are relatively abundant in alluvial aquifers for example, with easy access and low implementation costs for injection and storage of thermal energy (Allen and Milenic 2003; Lund 2010). To study these shallow geothermal reservoirs, thermal tracers are commonly used in hydrogeology to estimate parameters governing heat transport processes.

Classic thermal tests often rely on local and point-based measurements to monitor changes in temperature. In this context, geophysics can bring complementary information which is spatially-distributed and acquired directly from the ground surface. Moreover, methods such as the electrical resistivity tomography (ERT) have proven their efficiency to monitor resistivity changes linked for example to salt tracer tests (see Robert et al. 2012 and references therein). Recently, Hermans et al. (2012a; 2012b) have shown the possibility to derive temperature for the injection phase directly from time-lapse ERT. However, these ERT-derived temperatures were not reliable during the storage phase.

Fluid electrical resistivity and fluid temperature are generally linearly dependent when a small range of temperature is considered (Hayley et al. 2007). However, deriving quantitative temperature variations from electrical resistivity is a difficult task. Many other parameters in addition to fluid resistivity change with temperature, including surface conductivity and viscosity as well as processes such as sorption/desorption and dissolution/precipitation.

The aim of this laboratory study is to understand the global relationship between electrical resistivity and the aforementioned parameters or processes in order (1) to derive the most precise temperature from geoelectrical surveys and (2) to give keys to interpret electrical resistivity changes related to a change in temperature, including associated effects.

Methodology

The experiments of Hermans et al. (2012a; 2012b) were conducted in a sandy aquifer in the campus of the Ghent University. The reader is invited to see the aforementioned references for more details on these shallow geothermal tests monitored with surface ERT. To ensure the reproducibility of the interpretation, we performed our laboratory experiment on sand samples collected on this site.

The experiment consisted in monitoring the electrical resistivity of these saturated sand samples submitted to an increase of temperature, starting at the ambient temperature of 20°C and finishing around 60°C , followed by a decrease of the temperature to the ambient temperature of the room. We used tap water similar to Hermans et al. (2012a; 2012b) to perform the experiment to investigate the difficulty associated with in-situ conditions. However, we also tested formation water directly.

Three columns named I, II, and III were filled with sand samples from the Ghent site. Column I was saturated with tap water and only served for temperature measurements. A temperature probe was introduced in the middle of this column to have the most representative measure. Columns II and III were first saturated with the Ghent formation water. Just before the beginning of the heating process, we replaced formation water by tap water in column III only.

The columns containing the different saturated sand samples have a diameter of 8 cm and a height of 30 cm (Figure 1; left). Current electrodes A and B are connected to bronze porous plates in order to have a homogeneous current inside the column. Potential electrodes M and N are punctual copper electrodes. Electrodes are separated by 10 cm and positioned as a Wenner configuration (M and N are between A and B). Electrodes are connected to an ABEM Terrameter LS to acquire electrical measurements (parameters are given in Table 1). Sand samples were slowly saturated from the bottom to the top thanks to two taps in order to avoid the creation of preferential flow paths.

	Column II	Column III
Water	Formation water	Formation water replaced by tap water
Electrical conductivity (25°C)	1053 $\mu\text{S/cm}$	562 $\mu\text{S/cm}$
Geometrical factor [m]	0.0496	0.0507
Formation factor	2.53	3.34
Surface conductivity Campbell's law	Between 18 and 38 $\mu\text{S/cm}$ $m^f = 2.1\%$	
Current intensity (mA)	1	
Stacking	3 to 6 stacks, with $Q = 0.5\%$ (quality factor)	
Delay time (s)	0.5	
Acquisition time (s)	1	
Resistivity monitoring	Measurements continuously repeated	
Temperature monitoring	Every 30 s	

Table 1 Fluid characteristics and acquisition parameters. Archie's and Campbell's laws parameters were determined experimentally.

Petrophysical relationships

For clarity, some necessary petrophysical relationships are briefly summarised. Hayley et al. (2007) expressed the linear relationship between fluid electrical conductivity (σ) and temperature (T) (also known as Campbell's law) as:

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

Parameter m is the fractional change in electrical conductivity per degree Celsius (determined here experimentally to 2.1%) and subscripts T and 25 denote temperatures.

The ratio between fluid conductivity and bulk conductivity gives the formation factor (see Table 1 for the values determined experimentally). With the formation factor and Eq. 1, one can derive a change in temperature from any time-lapse resistivity measurement, assuming temperature is responsible of the changes in resistivity.

Calibration

To convert electrical resistances (our measurements) into electrical resistivities (the intrinsic property), we calibrated the geometrical factor of each column experimentally. We filled each column with waters whose electrical resistivity was known and performed measurements. The ratio between the electrical resistivity and the electrical resistance gives the geometrical factor. We took the mean value on three points and the standard deviation value is less than 0.0001 m for each column. Results are given in Table 1.

We experimentally established both the surface conductivity and formation factor for fully saturated Ghent sands (see Table 1). Hermans et al. (2012a) calculated with a semi-empirical relationship based on grain size and surface conductivity of silica grains that surface conductivity of the Ghent sand was three orders of magnitude lower than fluid conductivity. They neglected then the influence of surface conductivity since both fluid conductivity and surface conductivity increase almost equally with temperature (Hayley et al. 2007). Hermans et al. (2012a) found a value 1.2 $\mu\text{S/cm}$ whereas we have a value ranging between 18 and 38 $\mu\text{S/cm}$. Therefore, we are still two orders of magnitude lower than fluid conductivity (see Table 1) and we also neglected surface conductivity.

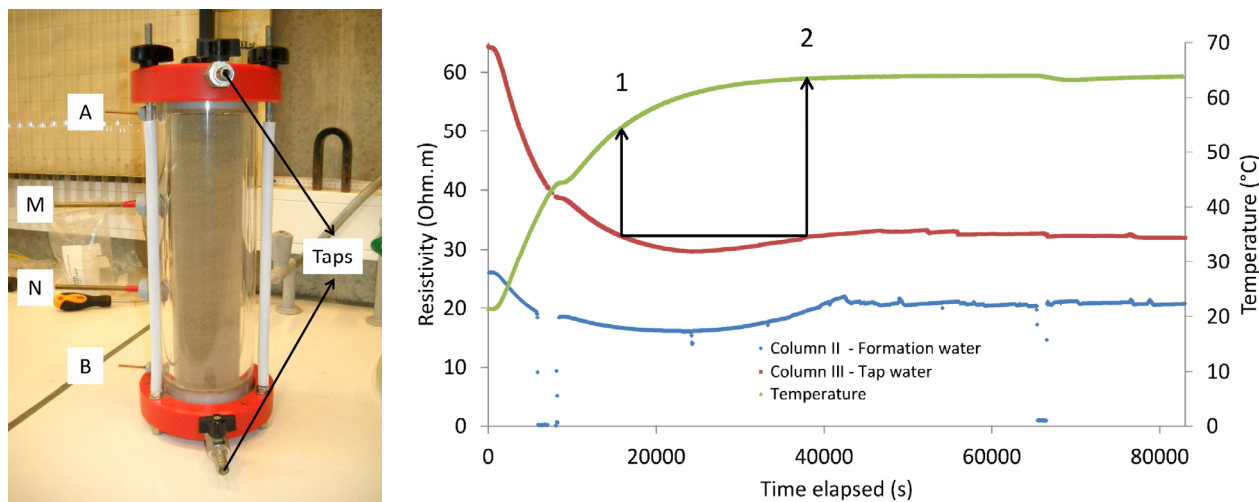


Figure 1 *Left:* columns set up. *Right:* green line: temperature vs. time elapsed; blue line: bulk resistivity measured in column II (sand saturated with its formation water); red line: bulk resistivity measured in column III (same as II but formation water was replaced by tap water just before the commencement of the heating process).

Preliminary results and discussion

Figure 1 (right) shows the increase in temperature with time elapsed and the corresponding changes in bulk electrical resistivity for both columns II and III. As expected, bulk electrical resistivity decreases with increasing temperature for both columns. However, the electrical resistivity does not stabilise at its minimum value but rather increases slightly before reaching the plateau. This means that for a given resistivity (e.g. 32 ohm.m in column III), two different resistivity-derived temperatures (54 and 64°C) are possible according to Eq. 1.

Figure 2 shows the bulk electrical resistivity versus the measured temperature (blue curve) and the expected relationship using Eq. 1 and the estimated formation factor (green curve). The top of Figure 2 is for column III (tap water) whereas the bottom is related to column II (formation water). The experimental curve (blue) diverges from the theoretical one, in both cases (tap or formation water), highlighting again the poor reliability of ERT-derived temperature in some cases.

Two mechanisms explain the divergence. First, when temperature increases too much, the solubility of some minerals decreases (e.g. calcium carbonates precipitate). This results in a decrease of fluid conductivity and thus, an increase of bulk resistivity. This is highlighted by Figure 2 (bottom) which corresponds to column II (formation water in equilibrium with Ghent sands). Indeed, when temperature increases, the experimental bulk resistivity diverges (almost totally after 60°C).

The second mechanism occurs only in column III (formation water replaced by a less conductive tap water). Since tap water is not in equilibrium with Ghent sands, since this water is less conductive than formation water, the medium must equilibrate and minerals are dissolved. This is corroborated by chemical analyses of water samples taken at the beginning and at the end of the experiment. This means that fluid conductivity increases and thus, bulk resistivity decreases. The first mechanism also plays a role and both mechanisms will compete.

Further investigations are needed to fully understand all mechanisms and to develop a methodology to derive quantitative temperature from resistivity measurements. Here, we highlighted the danger of deriving temperature without accounting chemical reactions occurring when temperature changes. The next step will be to take these reactions into account (based on available chemical analyses) to develop an integrated law allowing a better temperature estimate with ERT.

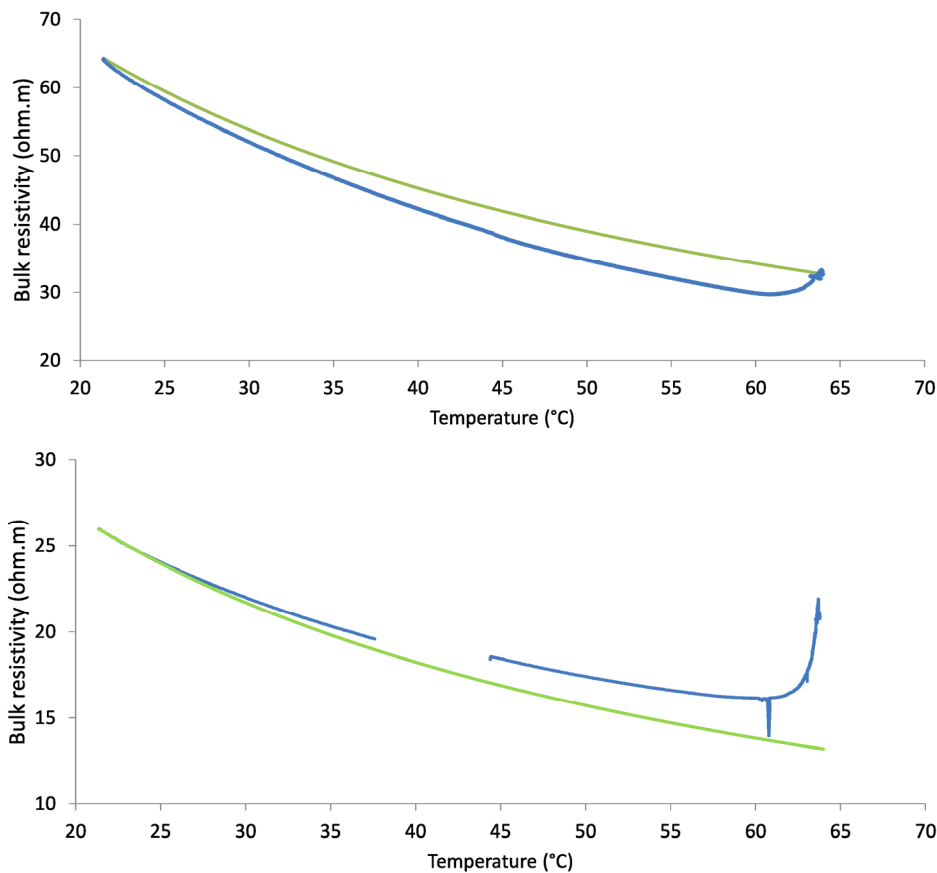


Figure 2 Green lines: bulk resistivity vs. temperature relationship based on Eq. 1 and the estimated formation factor (Table 1); blue lines: bulk resistivity measured in column III (top) and column II (bottom). The experimental curve diverges from the theoretical one, inducing poor reliability of ERT-derived temperature.

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