Shallow heat injection and storage experiment monitored with electrical resistivity tomography and simulated with heat transport model

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1. Introduction

Groundwater resources are increasingly used around the world as geothermal systems. Understanding physical processes and quantification of parameters determining heat transport in porous media is therefore important. To monitor the geothermal behavior of groundwater systems and to estimate the governing parameters, we mainly rely on borehole observations of the temperature field at a few locations (temperature logs or thermal response tests). In analogy to research in hydrogeophysics, geophysical methods may be useful in order to yield additional information for thermal properties estimation with greater coverage than conventional wells. We report a heat transport study during a shallow heat injection and storage field test. Heated water (about 50°C) was injected for 6 days at the rate of 80 l/h in a 10.5°C aquifer. We monitored the test using surface electrical resistivity tomography and demonstrated its ability to monitor spatially temperature variations. More details about the methodology can be found in [1, 2].

2. Experimental set-up

The site is located on the campus of Ghent University where the aquifer consists of a 4.4m thick sand layer lying on an aquiclude sandy clay formation. The water level lies two meters below the surface. The injection well screen is 90cm thick and is located at the bottom of the aquifer (fig. 1)

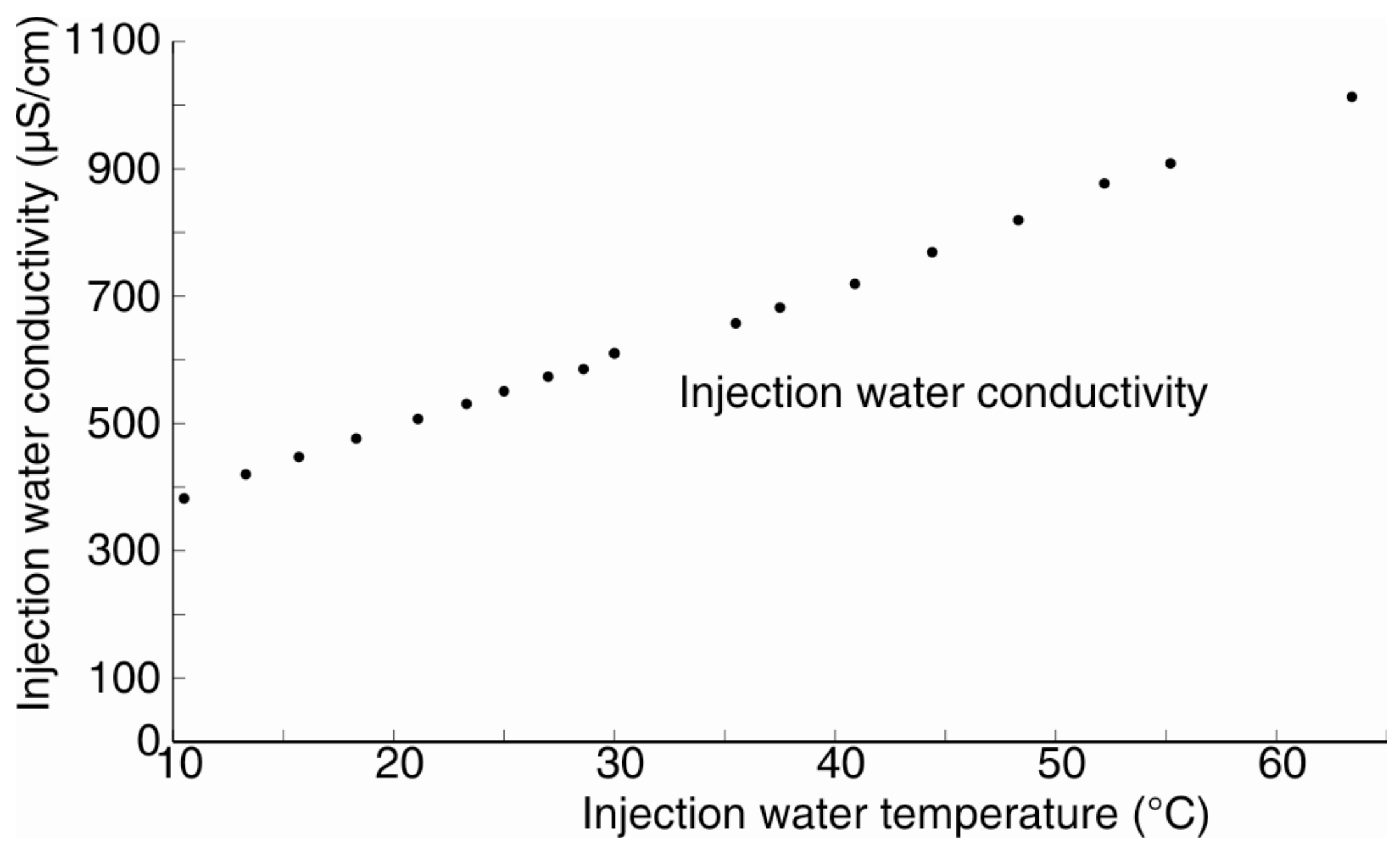

Fig 2. Water electrical conductivity increases linearly with temperature in the range of temperatures of the experiment (10-60°C)

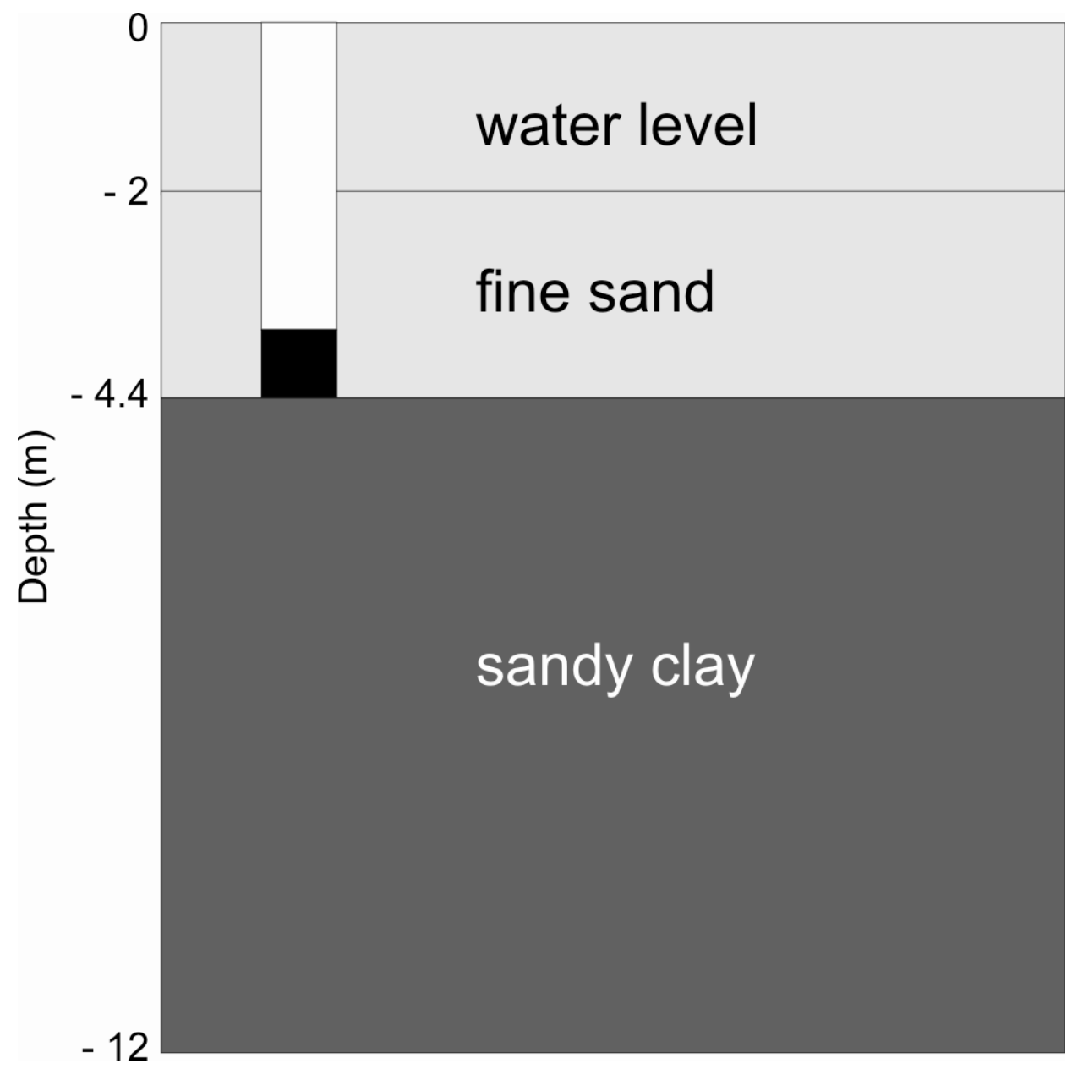

Fig 1. The tested sand aquifer is 2.4m thick

Water conductivity measurements show a linear increase in conductivity with temperature (fig. 2). Using the ratio of bulk resistivities between two time-steps, we can relate ERT-derived bulk resistivity variations to temperature changes in the aquifer.

The experiment was simulated using SEAWAT [3]. The model was calibrated using temperature borehole measurements during the storage phase (fig. 3). ERT measurements permitted to detect leakage above the bentonite seal explaining high temperature in the upper part of the aquifer (between -2 and -3.5 m) during the injection phase.

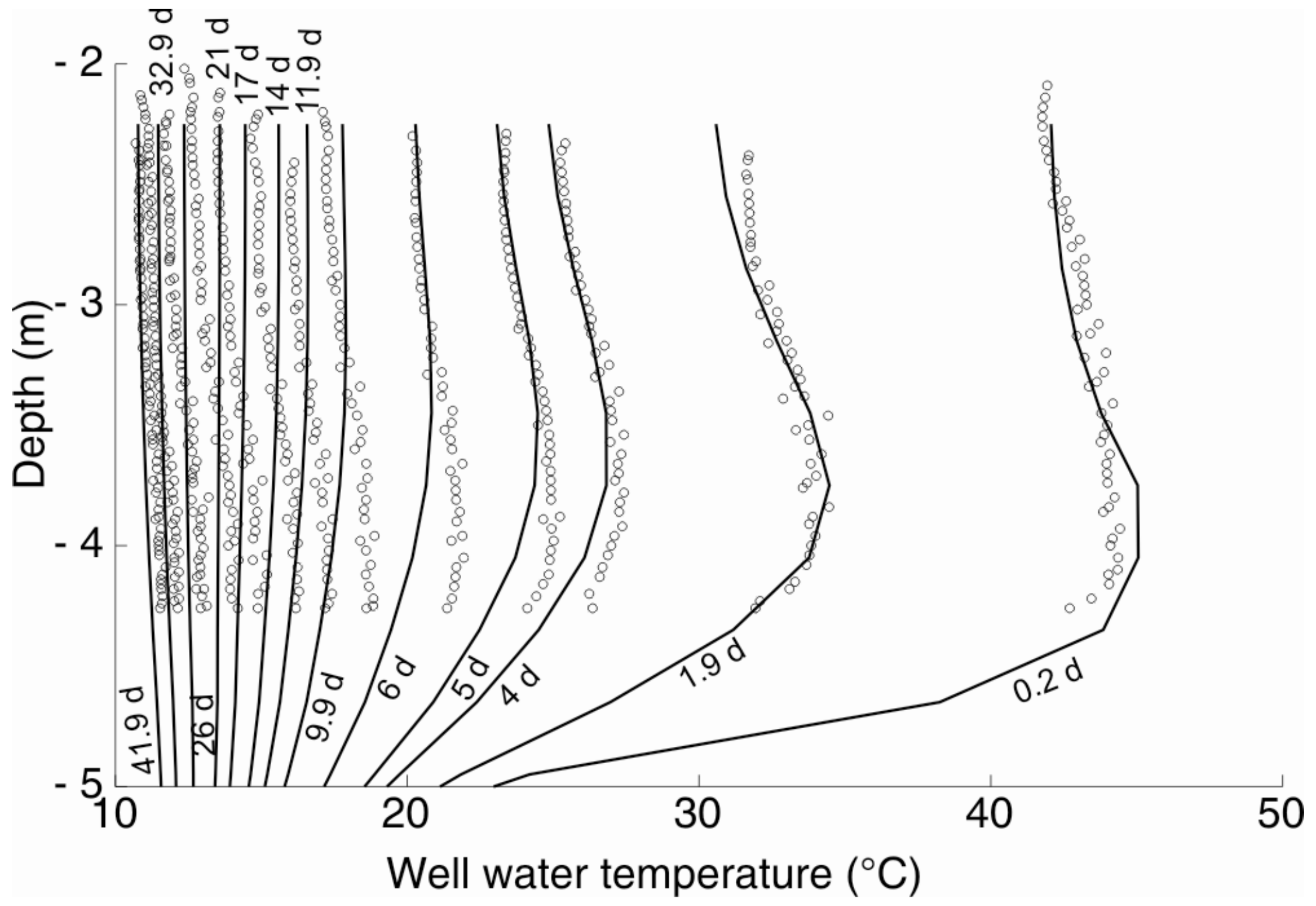

Fig 3. The calibrated model (line) fits well the observed temperature (circles) at the well

3. Injection Phase

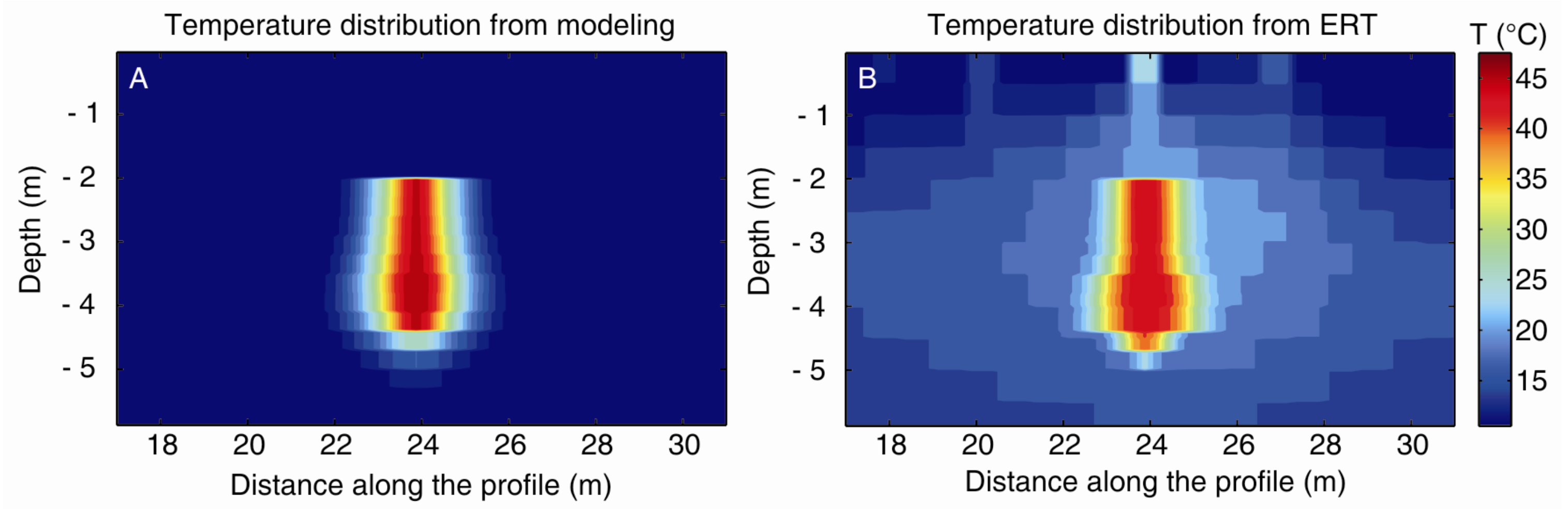

Fig 4. ERT results represent well the modeled T distribution

During the injection phase, ERT was the only way to assess temperature variations, since temperature logs were not available. ERT-derived temperature (fig. 4) are in agreement with the flow and transport model. Smoothing appears due to regularization but the maximum temperature, the position and the thickness of the plume are retrieved consistently with the model simulations [2].

4. Storage phase

During the storage phase (10 days were monitored), temperature logs become difficult to reproduce after 6 days (fig. 3). Fig. 5 shows the ERT-derived temperatures in the aquifer after 8 days of cooling, Fig. 6a shows the comparison with conductivity logs at the position of the well. Fig. 6a shows that surface ERT is able to retrieve the resistivity distribution down to 4 meters (we used a constant distance of 1.8m for the injection dipole and a maximum dipole spacing of 21.6m).

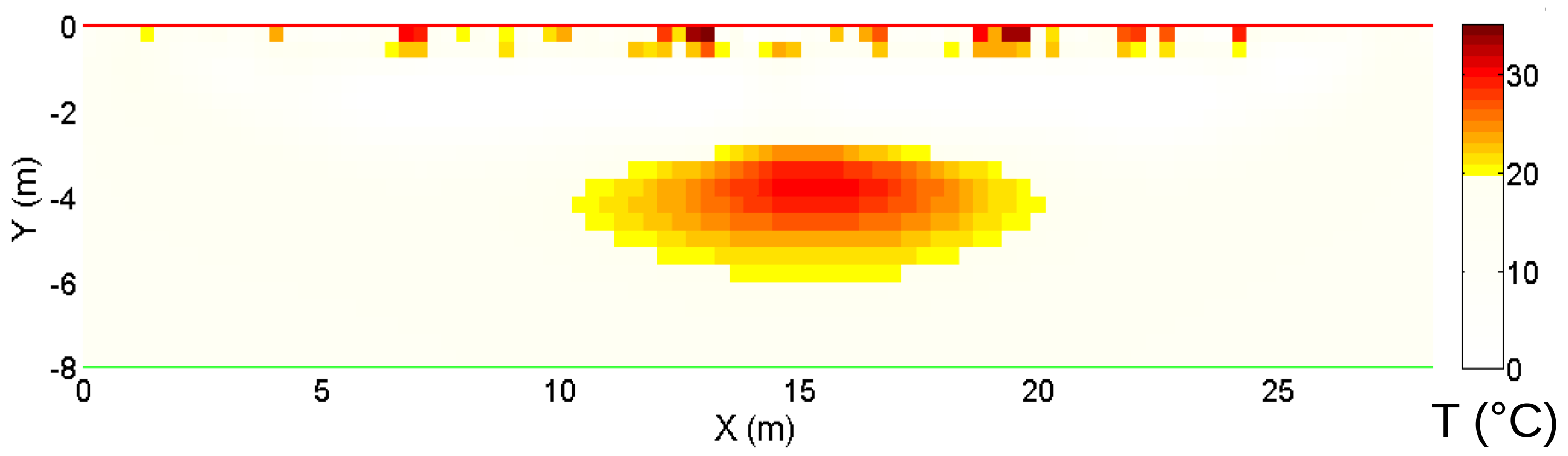

Fig 5. ERT-derived temperature (°C) after 8 days of cooling

5. Storage phase (continued)

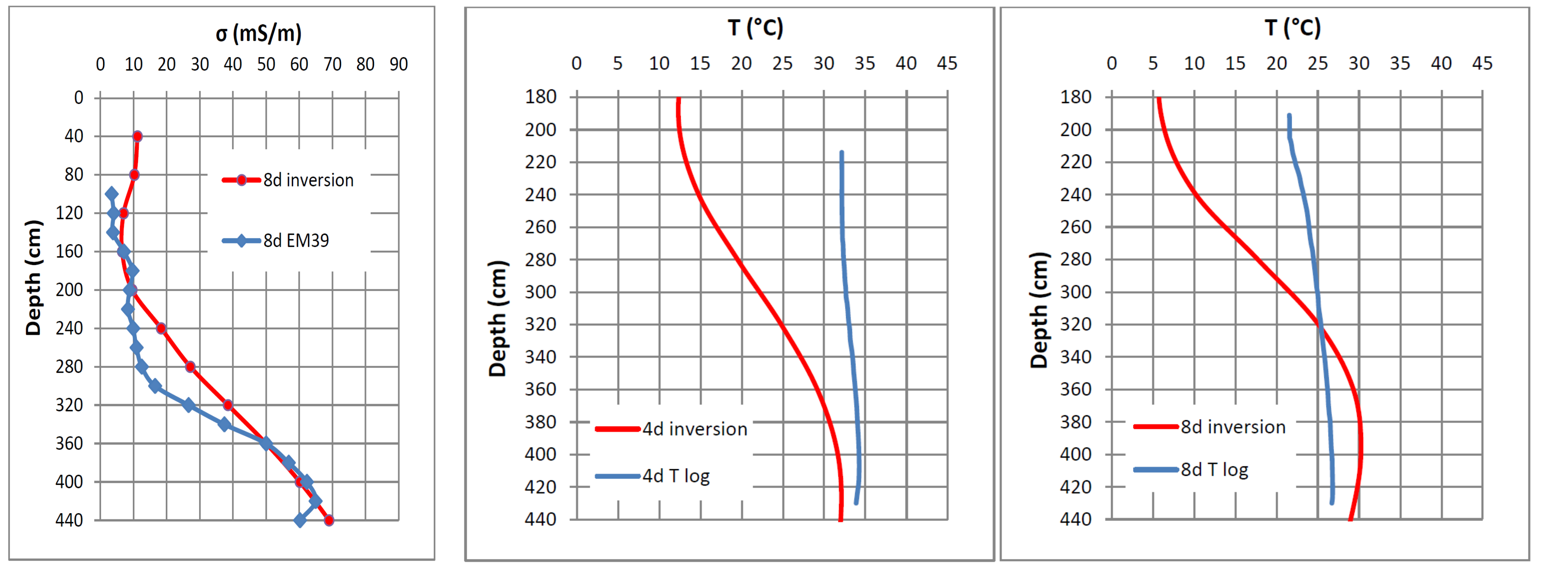

Fig 6. ERT fits well EM39 (a) log but fails to reproduce temperature logs (b)

The comparison between ERT-derived temperatures and temperature logs shows that the fit is poorer than at the end of injection (box 3). We believe that other effects in addition to temperature also impact bulk conductivity. The salinity could increase during the test due to dissolution and cation exchange phenomena related to the change in temperature [e.g. 4].

6. Sensitivity analysis and collinear diagnostic

A sensitivity analysis was performed to determine the most sensitive parameters p_j of the heat flow and transport model by multiplying the calibrated parameters by a factor sf according to $J_{ij} = \frac{T_i(p_j \times sf) - T_i}{\log_{10} sf}$. Then, we calculate $H = J^T J$, the most sensitive parameter being the one with the highest value on the diagonal.

Parameter	Optimal value	99% interval factor
λ_s (W/(m°C))	3	1.38
Θ	0.35	1.77
C_s (J/(kg°C))	710	1.99
α_L (m)	0.2	1.43

Table 1

The most sensitive parameter is the thermal conductivity of the solid λ_s, followed by the porosity Θ, the heat capacity of the solid C_s and the longitudinal dispersivity α_L.

Collinear diagnostic are performed on the model to see which parameter can be derived from the temperature logs using $\mathrm{cov}_p = \sigma^2 (J^T J)^{-1}$. In our cases, we used $\sigma^2 = 1$, so the diagnostic was only dependent of the sensitivities. The condition numbers of cov_p is very high using all parameters, showing that there is a strong dependency between parameters. If the collinear diagnostic is performed only on the four most sensitive parameters, the condition number decreases to 42 indicating a moderate to high dependency between parameters. This shows that we cannot expect to derive all the parameters for heat transport models only with temperature logs. This was applied (Table 1) to our field data to derive the confidence interval of the parameters [1].

7. Conclusion and perspectives

Surface ERT was able to provide spatio-temporal models of temperatures which can bring important information to derive parameter governing heat transport phenomena, since punctual temperature logs are not always sufficient.

In the future, we will carry out coupled inversion of ERT and temperature logs in order to avoid ERT regularization. It will also be important to investigate in details the change in water composition which could explain an additional variation of water conductivity.

References[1] Vandenbohede et al. 2011. Shallow heat injection and storage experiment: Heat transport simulation and sensitivity analysis, Journal of hydrology, 409, 262-272. [2] Hermans et al. 2011. A shallow geothermal experiment in a sandy aquifer monitored using electrical resistivity tomography, Geophysics, accepted manuscript. [3] Langevin et al. 2007. SEAWAT version 4, USGS. [4] Revil et al. 1998. Electrical conductivity in shaly sands with geophysical applications, Journal of Geophysical Research, 103, 23925-23936.