Time-lapse inversion of ERT monitoring data using variogram-based regularization

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Objectives

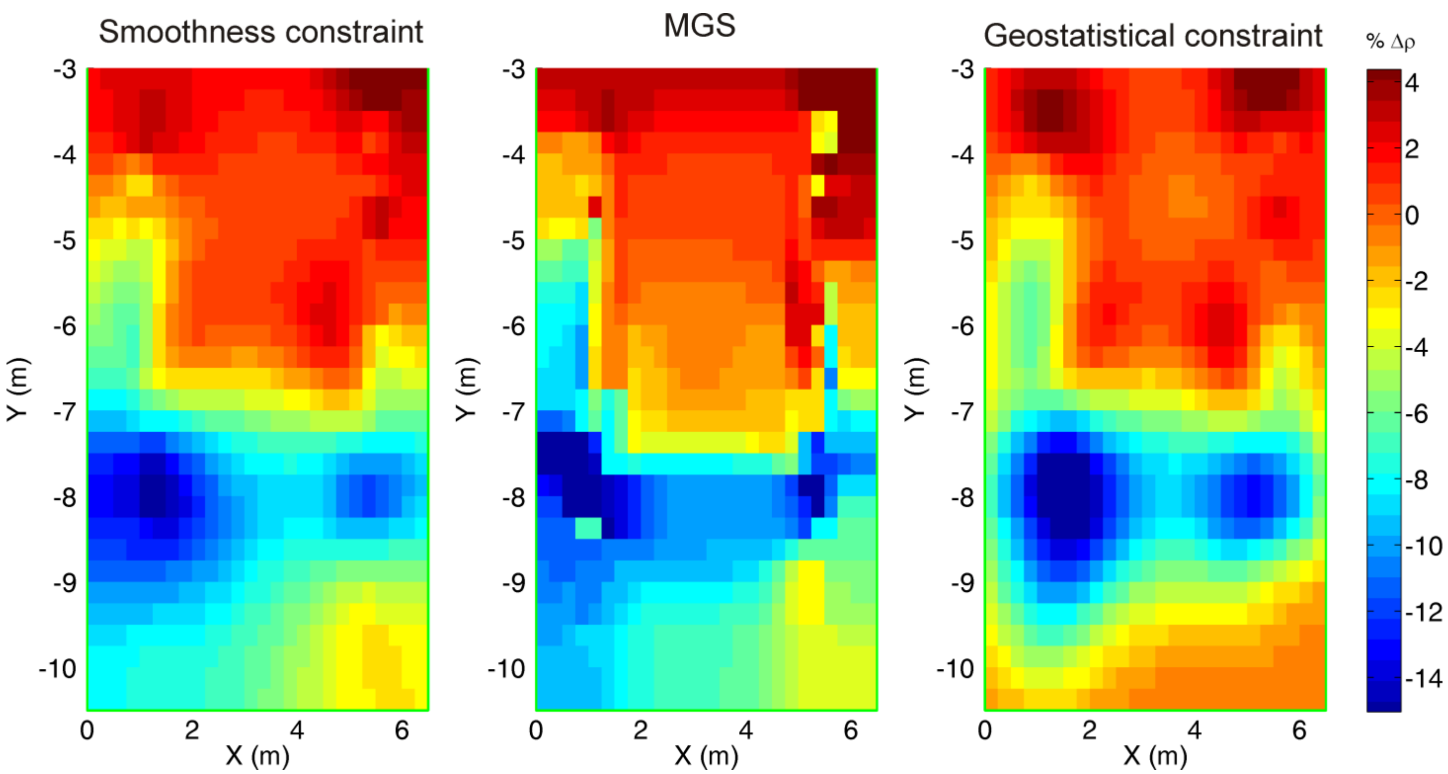
- Recent development in time-lapse inversion:
- time-constraint, 4D inversion (Kim et al., 2009)
- difference inversion (Kemna et al., 2002)

- But few specific studies on the spatial constraint of ERT time-lapse inversion (Fiandaca et al., 2015; Nguyen et al., 2015 for MGS)

- Smoothness constraint is still the standard operator

Objectives

- Smoothness constraint and MGS can be seen as two end-members (sharp and smooth) : need for an intermediate "smoothing"



(Hermans et al., 2014, Energies)

Objective function

We use a difference inversion scheme

$$\phi_{diff}(\mathbf{\Delta m}) = \left\| W_d \left[(\mathbf{d} - \mathbf{d_0}) - (f(\mathbf{m}) - f(\mathbf{m_0})) \right] \right\|^2 + \lambda \left\| C_{\mathbf{\Delta m}}^{-0.5} \mathbf{\Delta m} \right\|^2$$

The parameter covariance matrix $C_{\Delta m}$ is calculated based on an experimental variogram of the **changes** in the studied parameter (**Δm**)

$$\gamma(h) = C(0) - C(h)$$

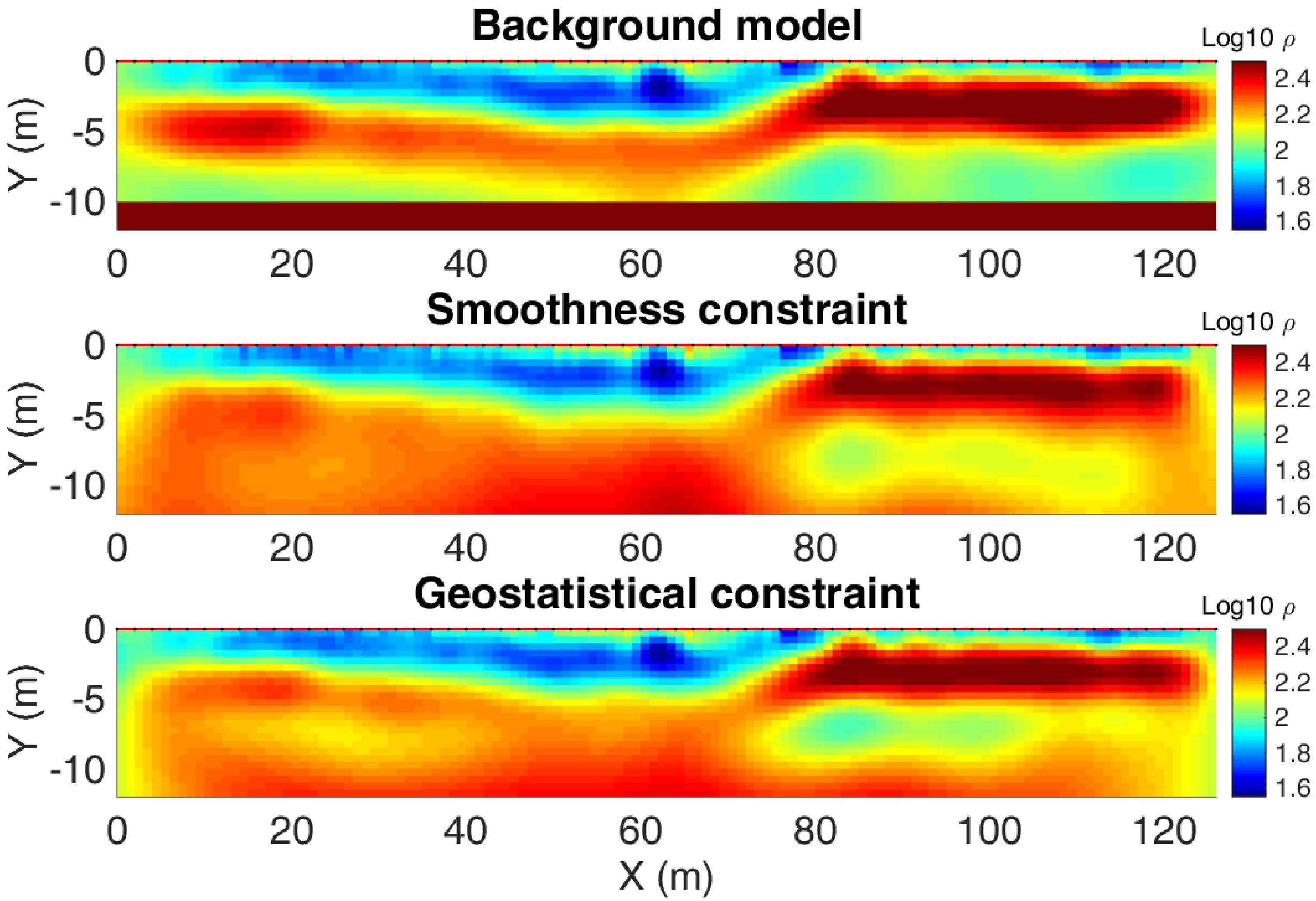
$$\gamma(h) = C(0) \times (1 - e^{-3(\frac{h}{a})^2})$$

We use a generalized range to compute the covariance matrix

$$a_\alpha = \frac{a_x a_z}{(a_z^2 \cos^2\alpha + a_x^2 \sin^2\alpha)^{1/2}}$$

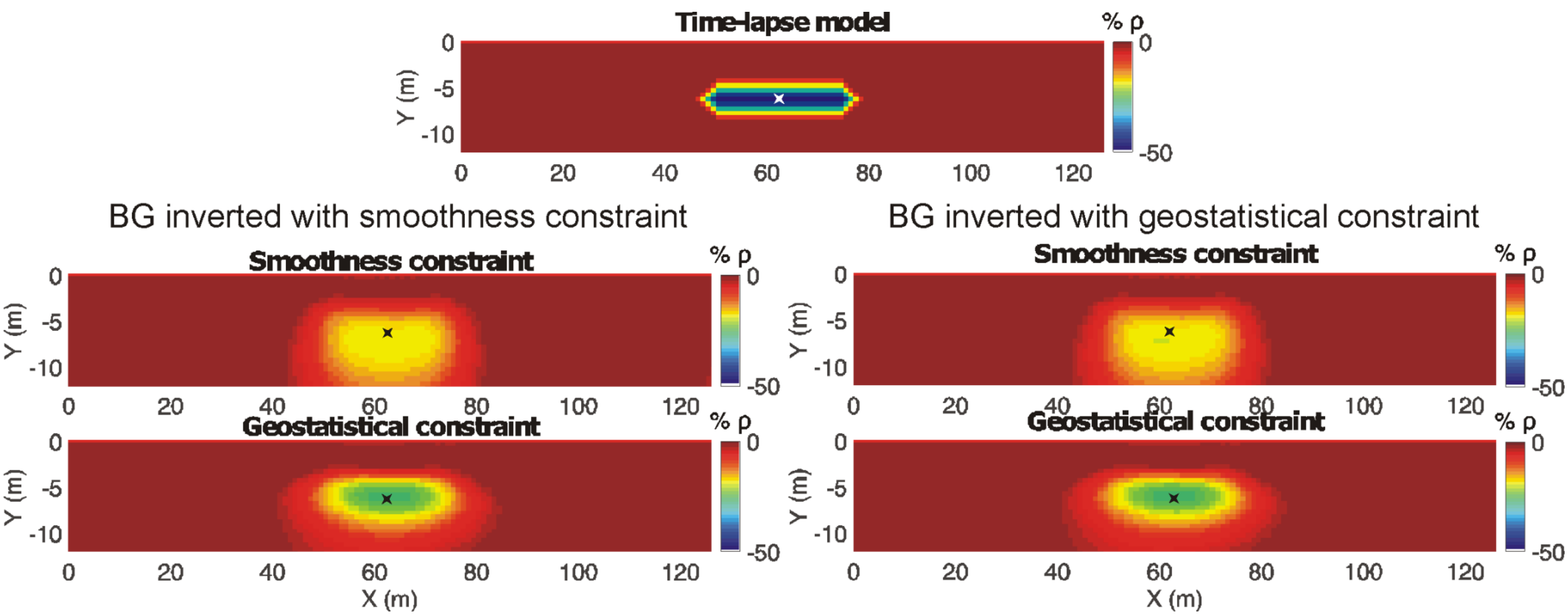
The implementation works for any grid type (topography, irregular grid, etc.)

Synthetic case : background



Synthetic case : time-lapse model

The time-lapse model represents a tracing experiments where we observe gradual spatial changes, corresponding to a limited amount of smoothing.



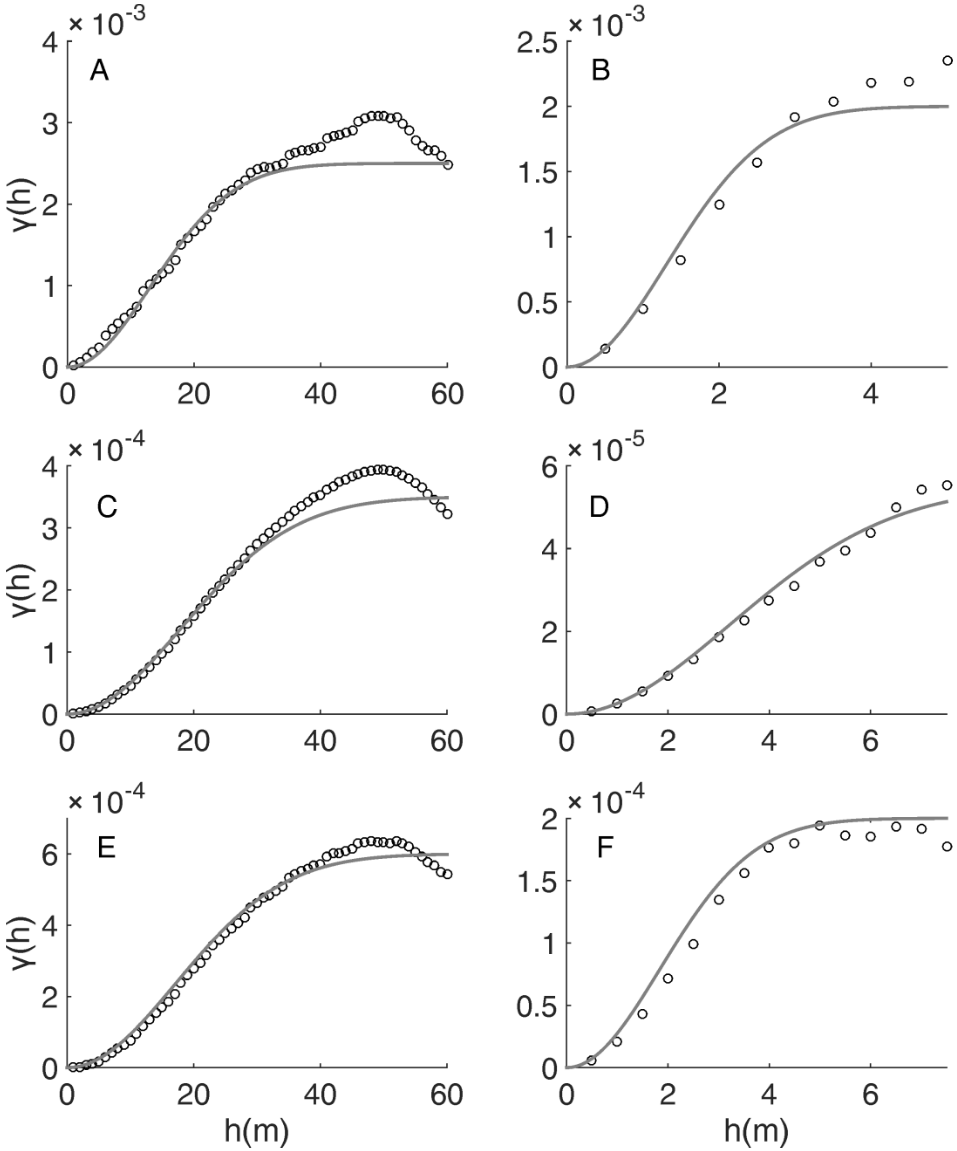
The background inversion has only a limited influence on the time-lapse results

Ranges after inversion

True ranges

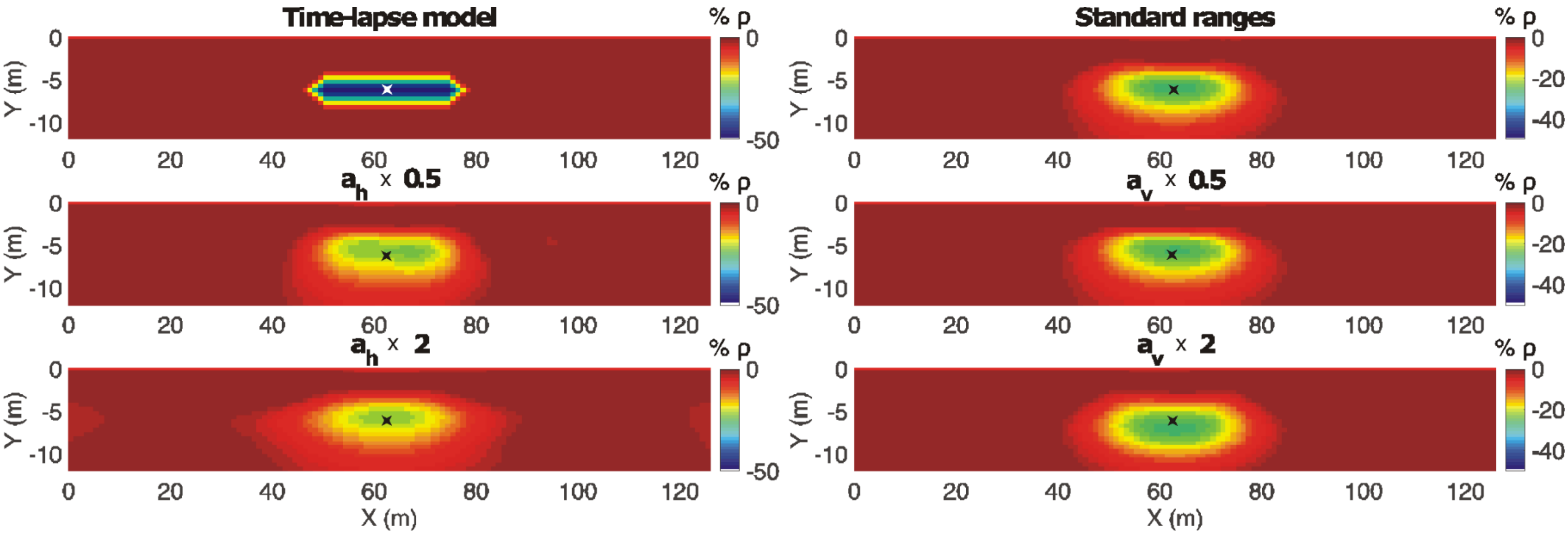
Smoothness constraint

Variogram-based constraint



Synthetic case : effect of the ranges

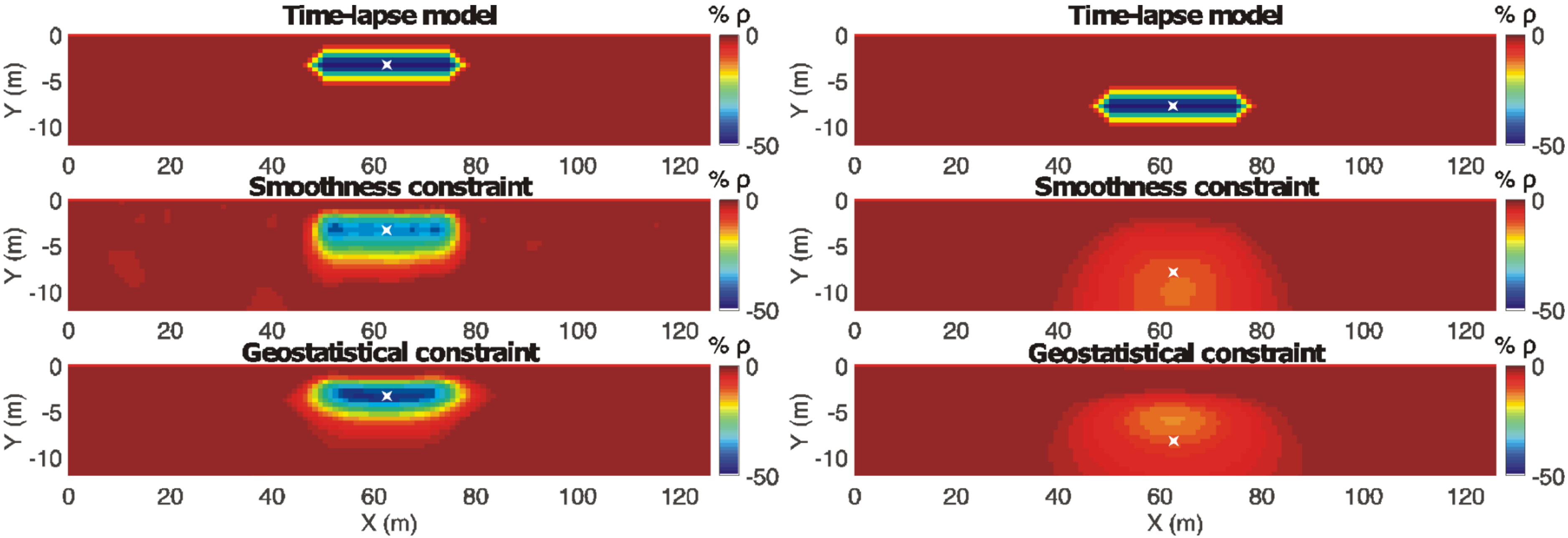
We test the effect of the ranges by dividing or multiplying vertical and horizontal ranges by 2.



The solution is slightly degraded but remains better than the SC

Synthetic case : effect of sensitivity

We test the effect of sensitivity by imaging the same anomaly at different location in the ERT section.



The solution is improved everywhere in the section, in both high and low sensitivity areas

Synthetic case : model misfit

$$MM_{TL} = \sqrt{\frac{\sum_{i=1}^{n}\left(\frac{\log \rho_{TL,i}}{\log \rho_{BG,i}} - \frac{\log \rho_{TL,i}^{*}}{\log \rho_{BG,i}^{*}}\right)^2}{n}}$$

Case	Anomaly	Constraint BG/TL	a_v (m)	a_h (m)	MM_{TL}
1	Middle	SC/SC	/	/	0.030
2	Middle	SC/SCanis	0.1 x a_h	/	0.028
3	Middle	SC/VC	3.2	32	**0.023**
4	Middle	VC/SC	/	/	0.030
5	Middle	VC/VC	3.2	32	**0.023**
6	Middle	SC/VC	3.2	16	0.024
7	Middle	SC/VC	3.2	64	0.025
8	Middle	SC/VC	1.6	32	0.023
9	Middle	SC/VC	6.4	32	0.024
10	Top	SC/SC	/	/	0.019
11	Top	SC/VC	3.2	32	**0.013**
12	Bottom	SC/SC	/	/	0.033
13	Bottom	SC/VC	3.2	32	**0.031**

Synthetic case : Conclusion

- Geostatistical constraint is better than SC
- Even with “wrong” ranges the solution is improved
- All the parts of the section are affected, even if the constraint is mainly useful in low sensitivity zones

Field case : Heat tracing experiment

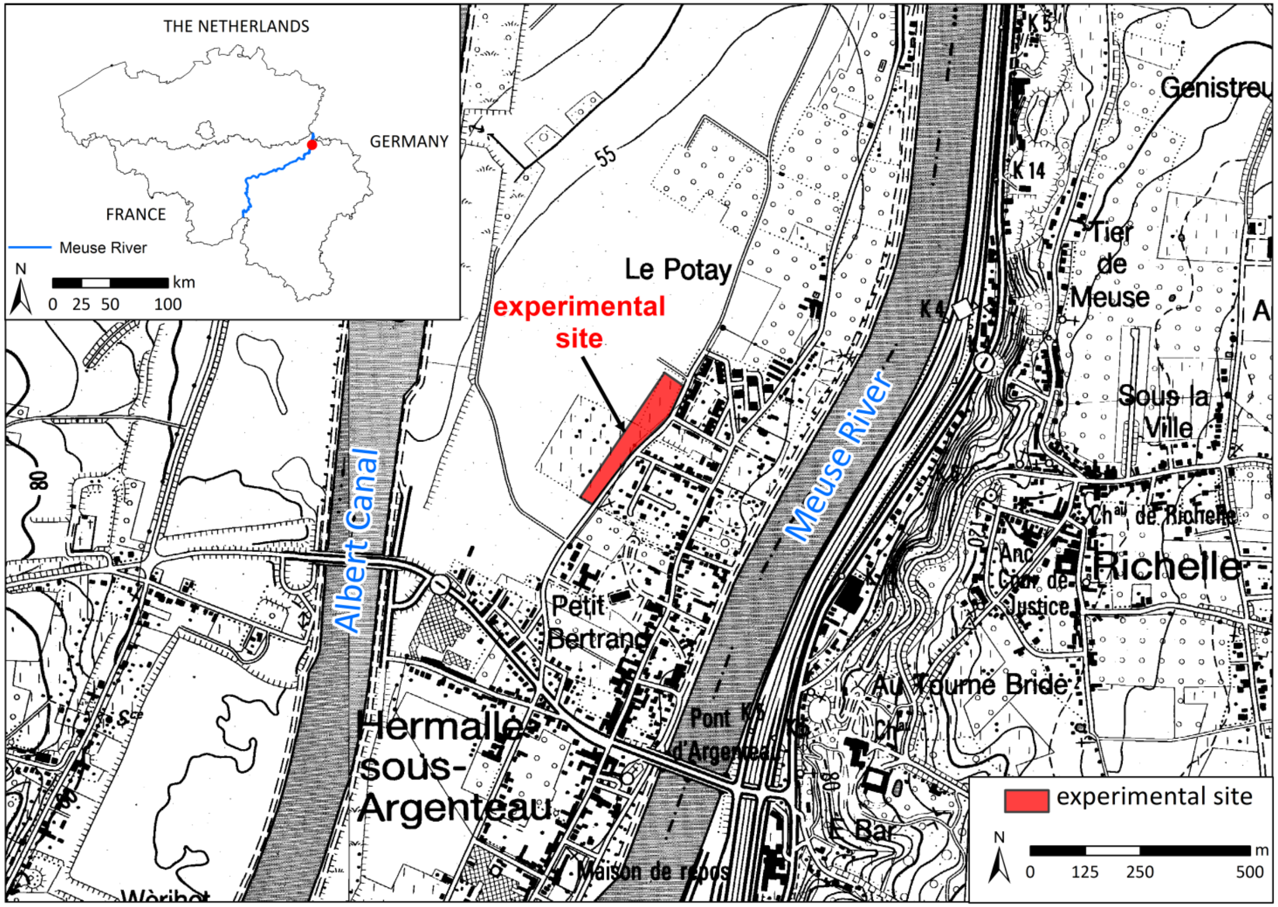
Why using ERT ?

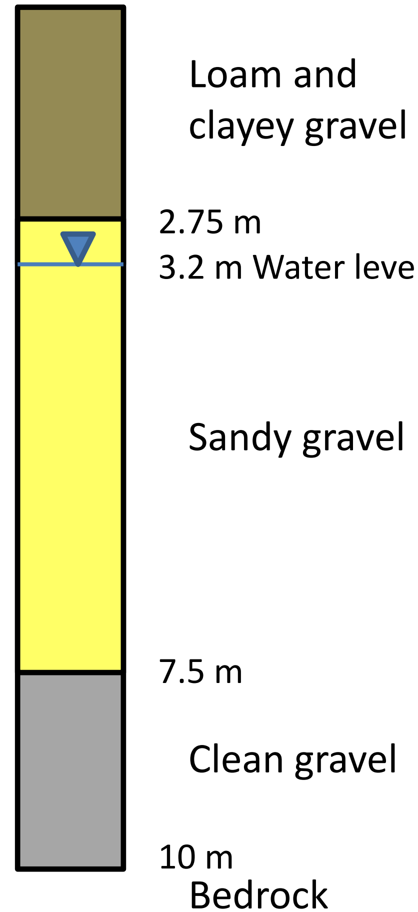
Electrical resistivity varies with **temperature**

Spatio-temporaly distributed information vs point-based measurements like thermal response test or temperature logs

Relative efficiency proved for salt tracer experiment

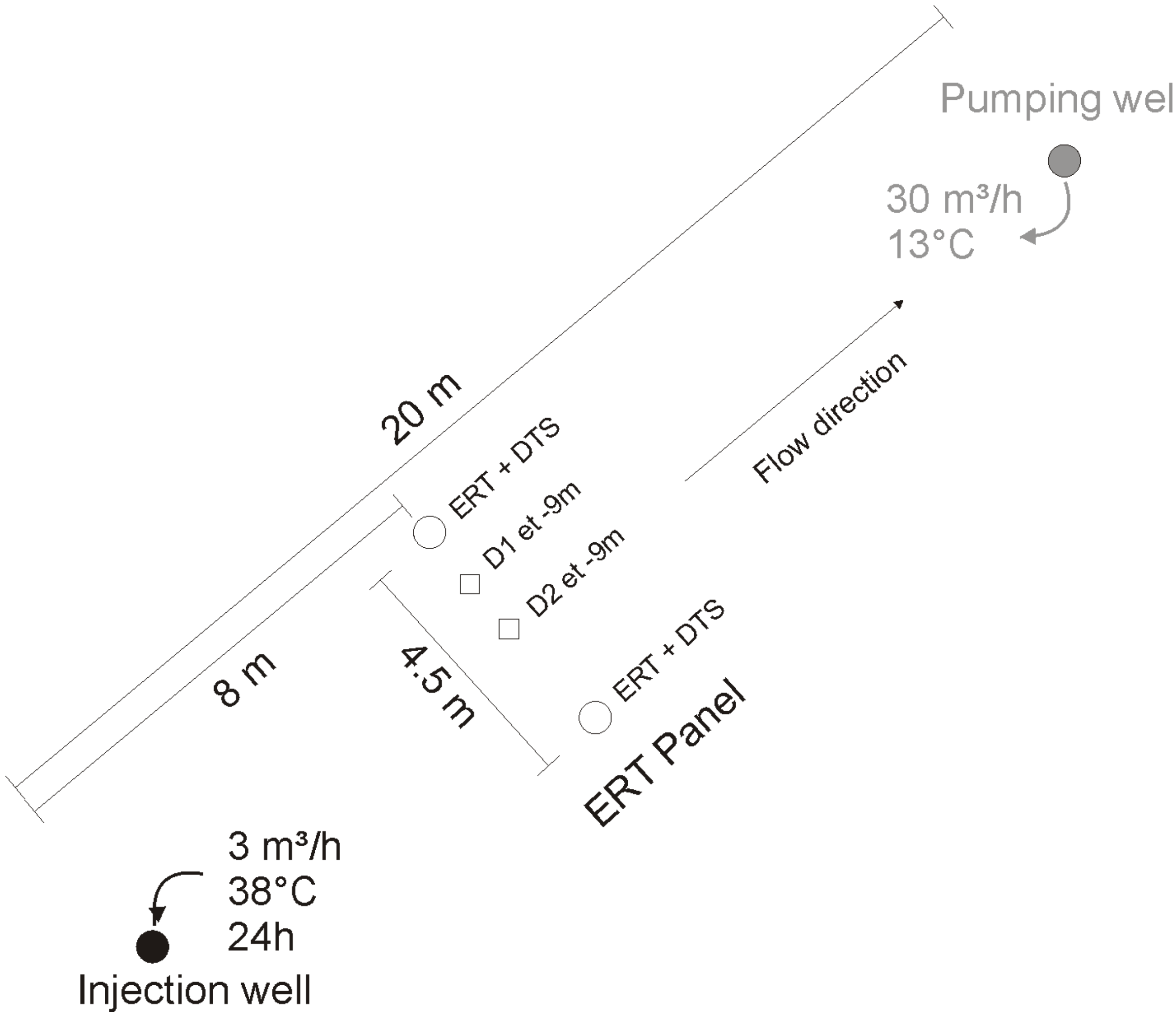
The study site is located in the alluvial aquifer of the Meuse River near Liege (Belgium)

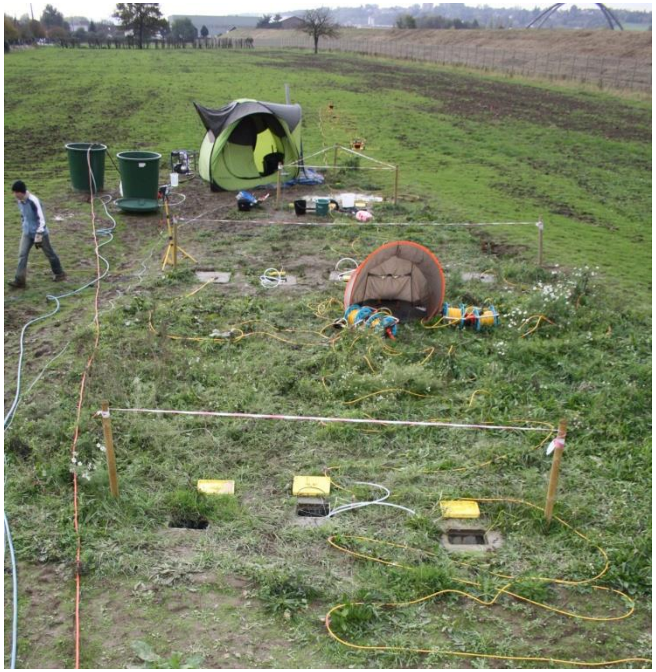




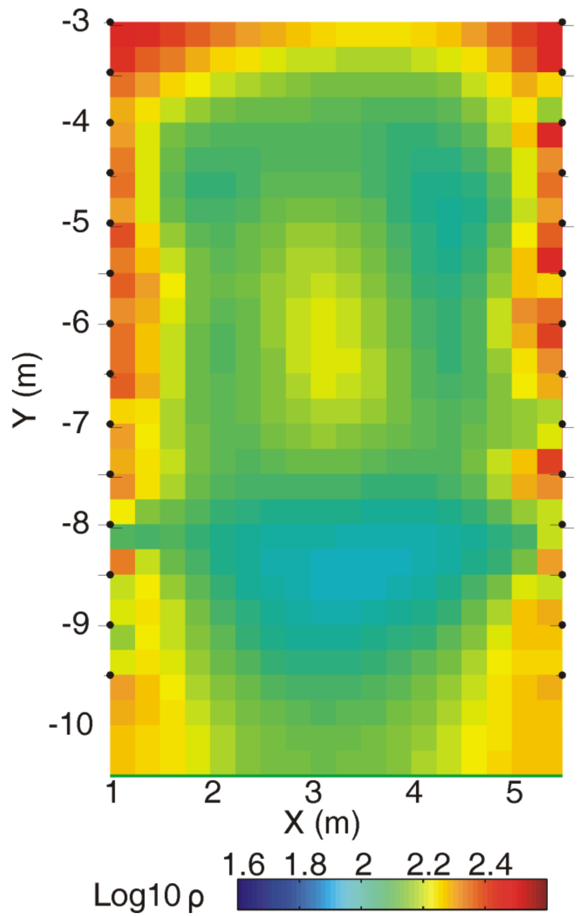
Lithological surveys have shown that below surface loams, the saturated part of the aquifer is composed of sandy gravel and clean gravel

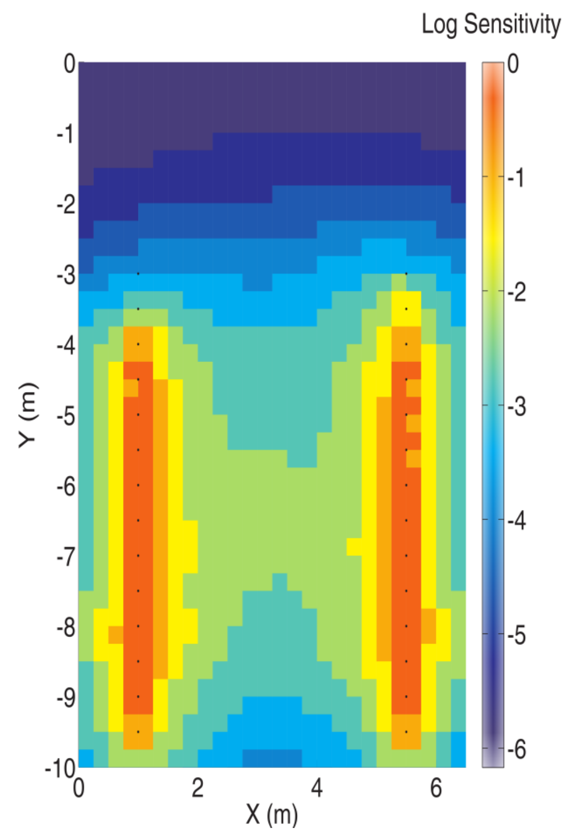
The study site is equipped with several control piezometers, 1 injection well and 1 pumping well.





The background image shows heterogeneities in the resistivity distribution with values between 100 and 200 Ohm.m

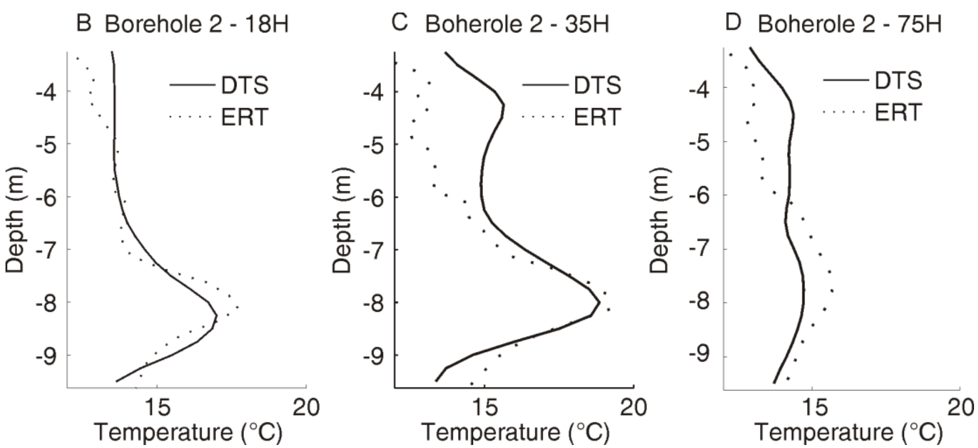


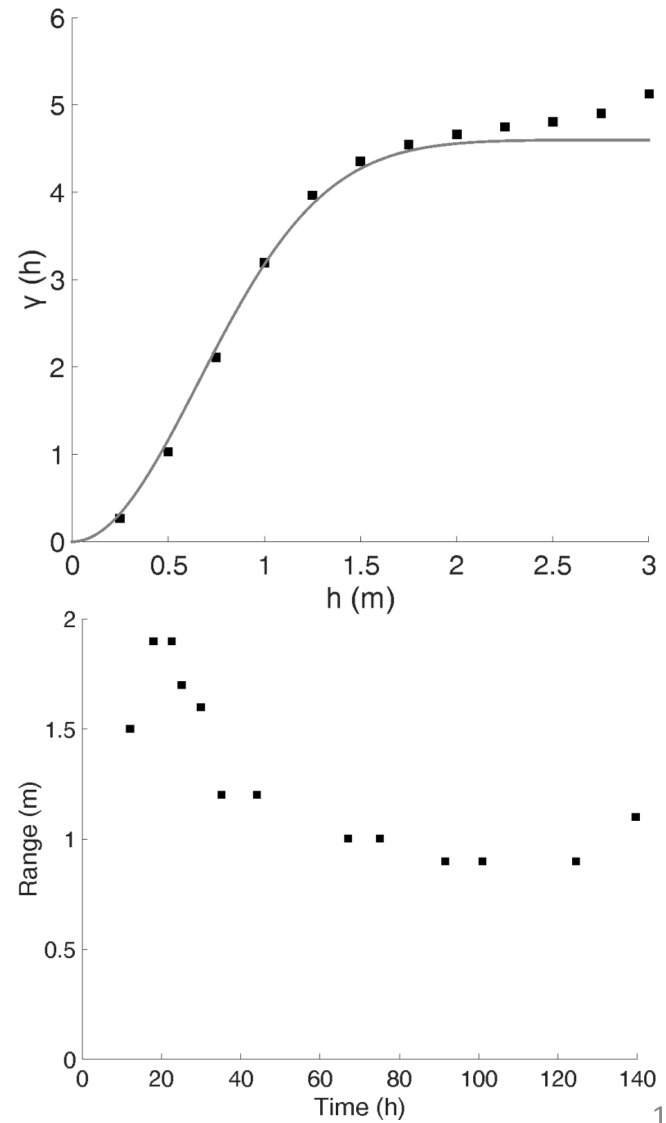


The aspect ratio is equal to 0.75, which is the limit to achieve a reasonable resolution in the middle of the section

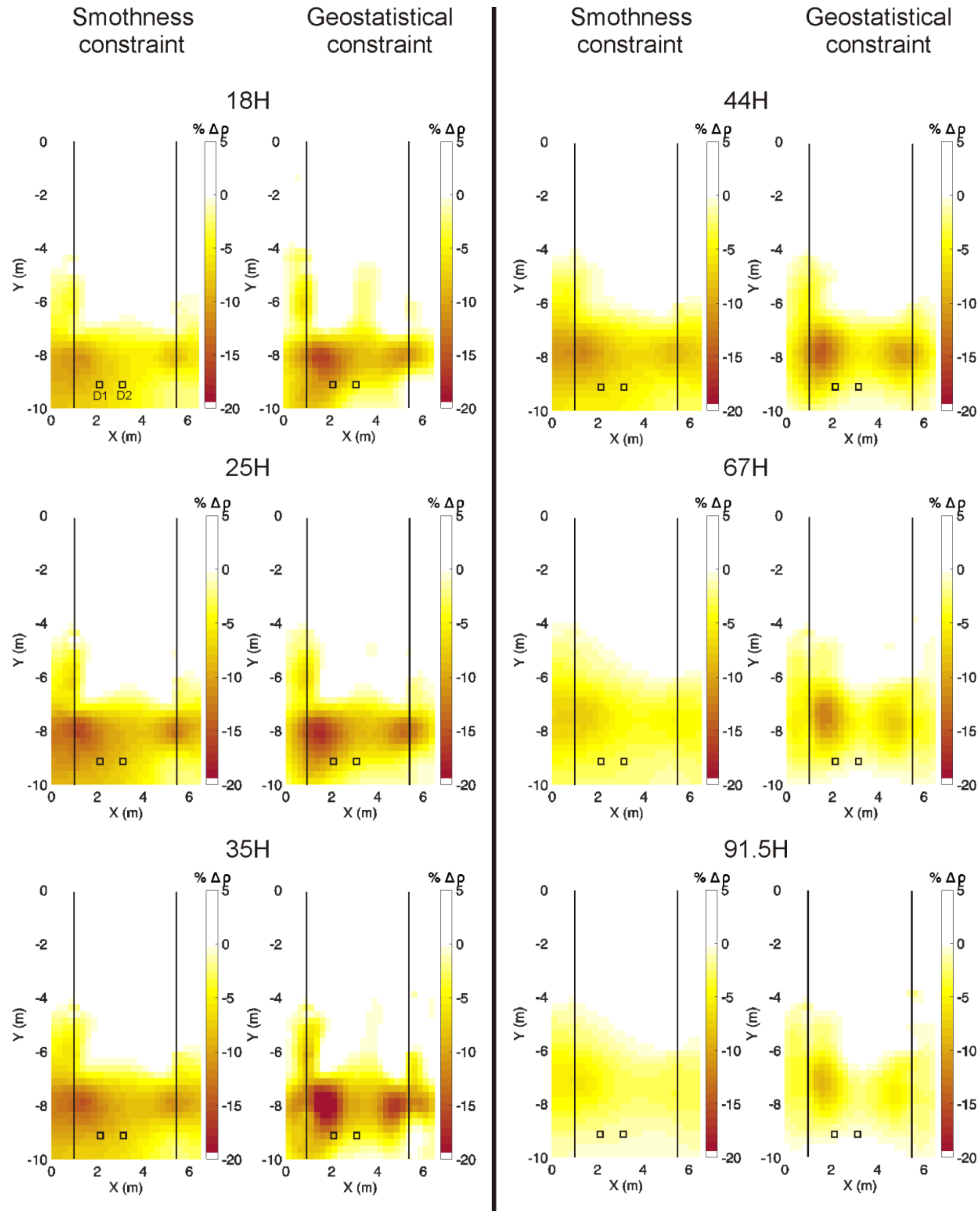
Reciprocal were used to assess the error level of each data set during the study

The ranges are computed using DTS vertical temperature profile, isotropy is assumed





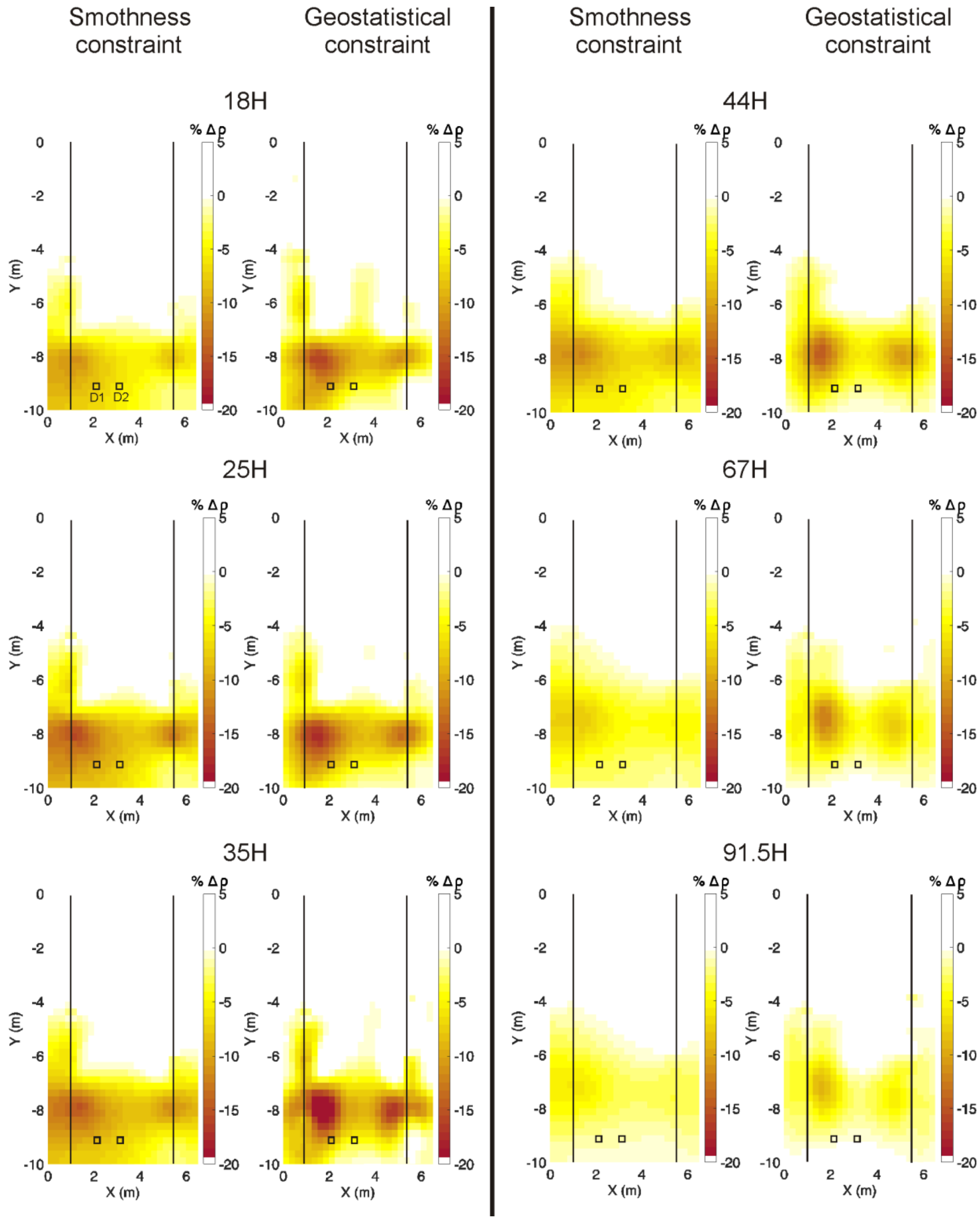
Crosshole ERT enables to image spatially and temporally variation of resistivity related to the tracer arrival across the panel



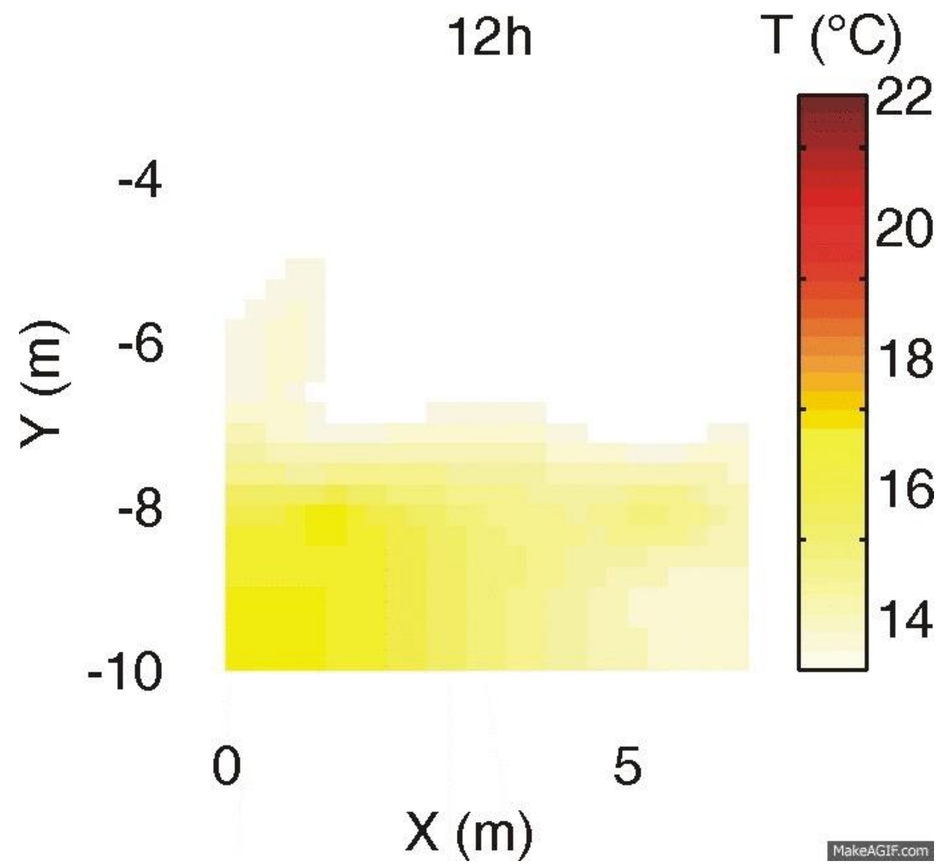
Less smoothing is obtained using the geostatistical constraint

There are lateral variations related to heterogeneity in the deposits

Spatially, temperatures increase only in the bottom part of the aquifer (clean gravel)

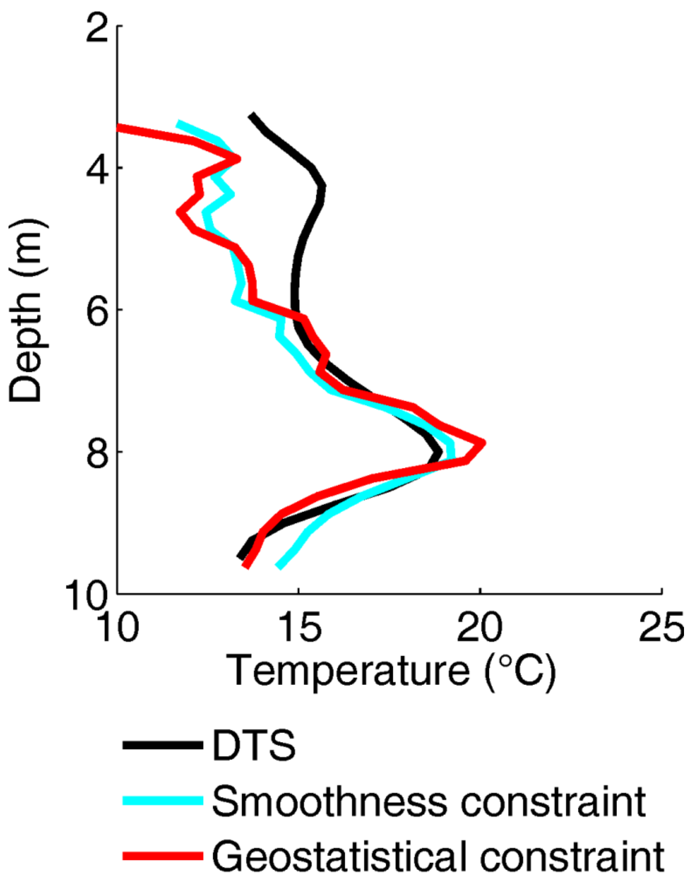


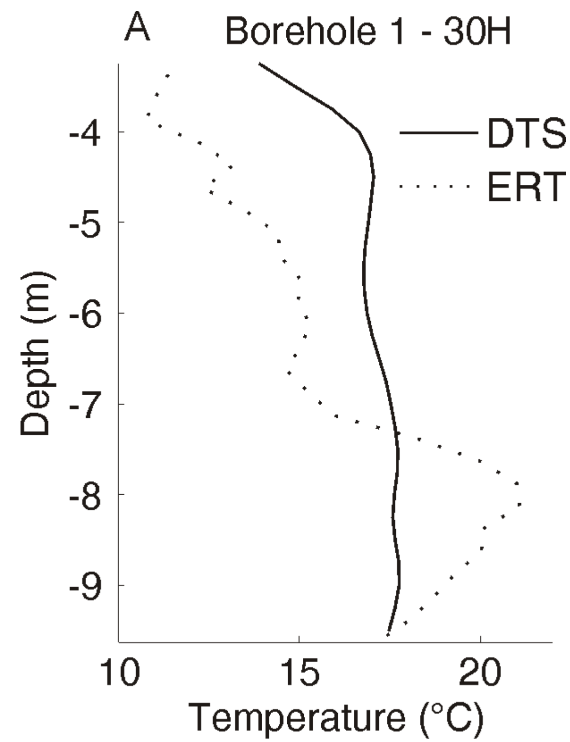
Interpretation in terms of temperature is valid only in the saturated zone with a maximum temperature of 21°C (ΔT = +8 °C)



We used a mean temperature of 13.2°C to transform globally ERT into temperature (based on temperature measurements in the ERT borholes)

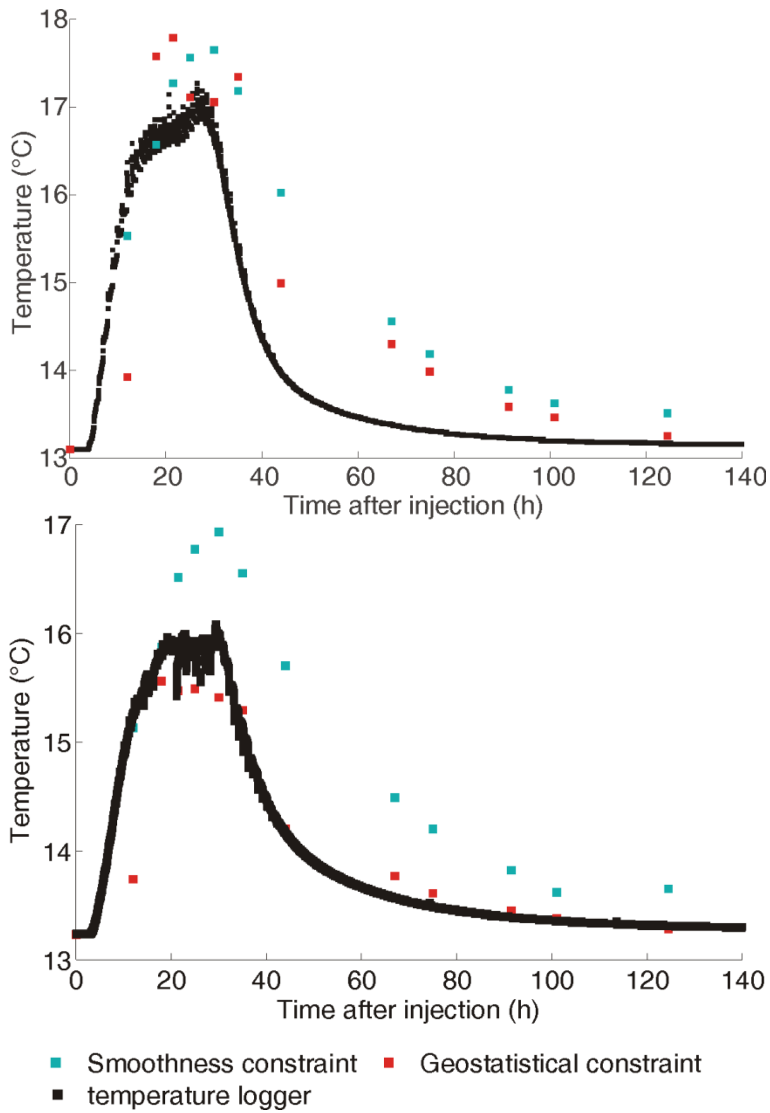
Near boreholes, the sensitivity is high so that both solutions are similar and relatively close to direct measurements (except in first ERT borehole)





Due to mixing?

In the central part of the sections, regularization becomes stronger and the geostatistical constraint is more appropriate than the smoothness constraint.

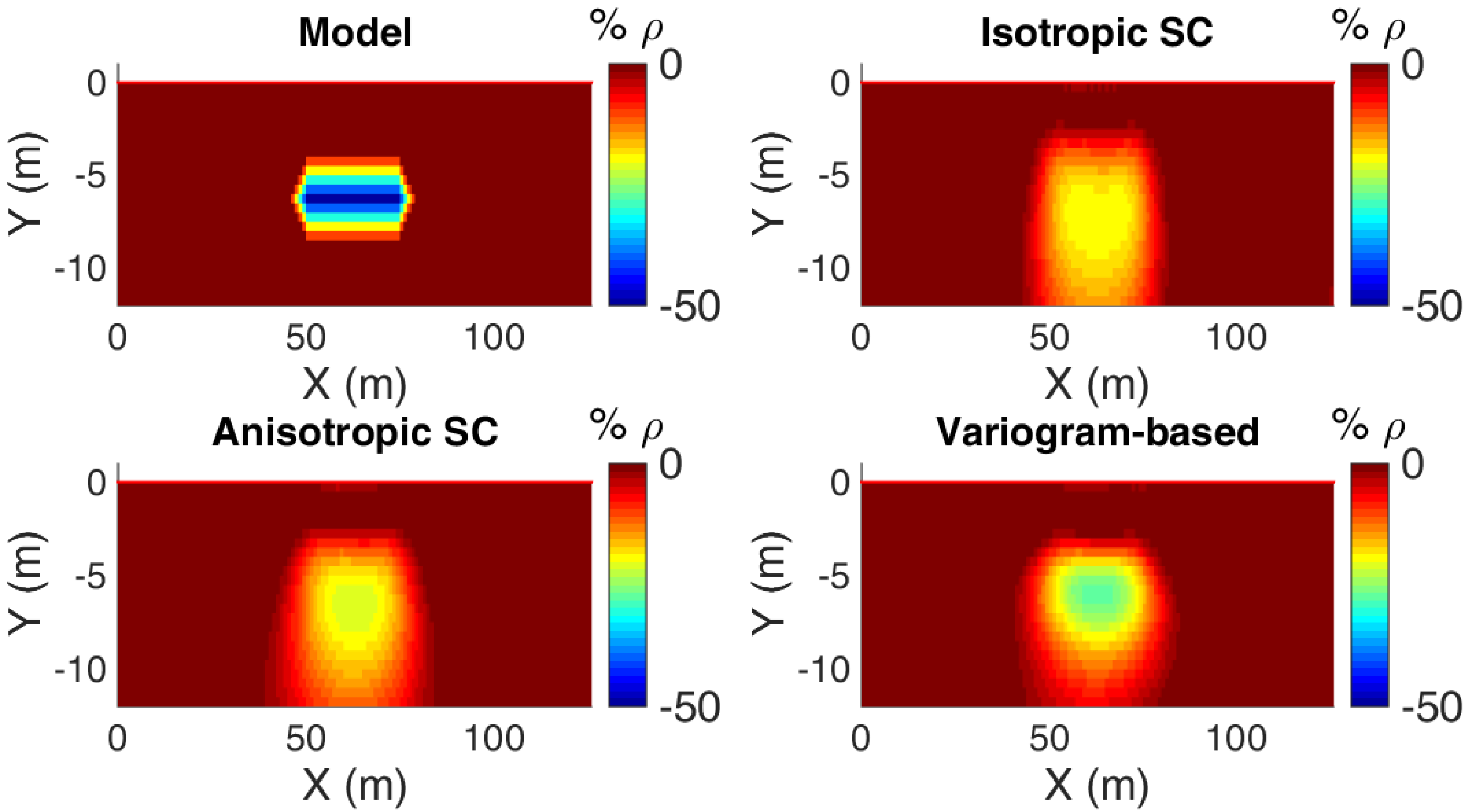


Field case : Conclusion

- Similar results qualitatively
- Smoothing less pronounced
- Improvement in the zone of lowest sensitivity: breakthrough curves without overestimation of temperature
- Quantitatively, ERT temperatures are very closed to direct measurements

ADDITIONAL SLIDES

Fair comparison: smoothness constraint with same anisotropy ratio (10/1)



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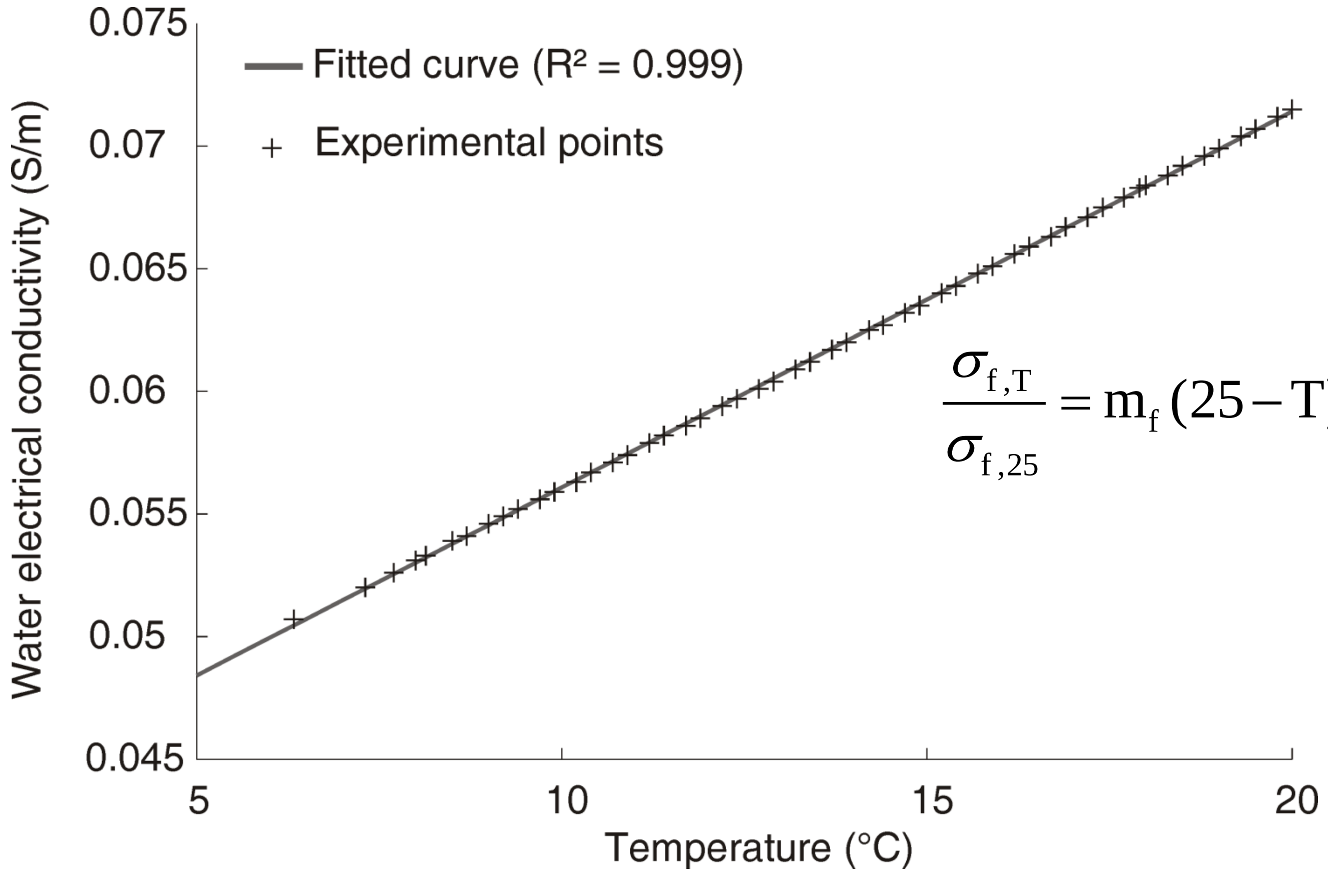
There is a linear relationship between temperature and water electrical conductivity with about 2% change per °C



$$\frac{\sigma_{f,T}}{\sigma_{f,25}} = m_f(25 - T) + 1$$

In this specific case, we found in the lab m_f = 0.0194 °C^{-1} on the temperature range observed during the test

To transform ERT results into temperature, we consider Archie's law between the background and the time-lapse series

$$\sigma_b = \frac{\sigma_f}{F}$$

Surface conductivity is neglected since we are working in clean gravel

Ratio between Time 1 and Time 2

$$\frac{\sigma_{b2}}{\sigma_{b1}} = \frac{\sigma_{f2}}{\sigma_{f1}} \quad \Rightarrow \quad \sigma_{f2} = \frac{\sigma_{b2}}{\sigma_{b1}} \sigma_{f1}$$

Replacing the expression of σ_{f2} by its expression in terms of temperature

$$\frac{\sigma_{f,T}}{\sigma_{f,25}} = m_f (25 - T) + 1$$

we have

$$T = \frac{1}{m_f} \left[\frac{\sigma_{b2,T}}{\sigma_{b1}} \frac{\sigma_{f1}}{\sigma_{f,25}} - 1 \right] + 25$$

where everything is measured during the experiment