EAGE
EUROPEAN ASSOCIATION OF GEOSCIENTISTS & ENGINEERS

CONFERENCE & EXHIBITION

NEAR SURFACE GEOSCIENCE '19

1st Conference on Geophysics for Geothermal-Energy Utilization and Renewable-Energy Storage

THE HAGUE, THE NETHERLANDS

8-12 September 2019

WWW.NSG2019.ORG

#NSG2019

10 years of temperature monitoring experiments using electrical resistivity tomography:

What have we learned?

Thomas Hermans, Frédéric Nguyen, Guillaume De Schepper, Nolwenn Lesparre, &
Tanguy Robert*

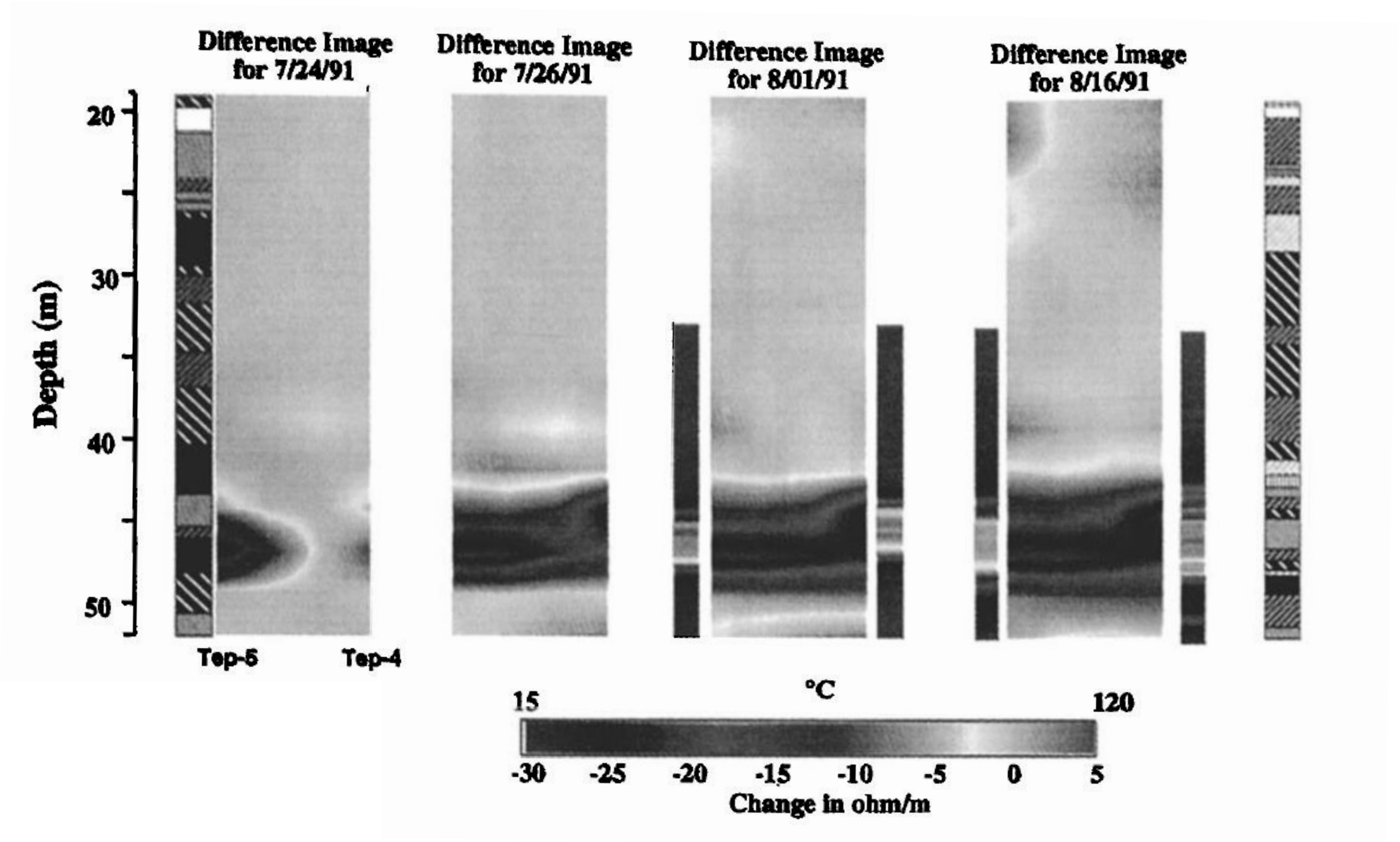
Tanguy.Robert@uliege.be

Paper 25, 11/09/2019

*University of Liège & Fonds National de la Recherche (FNRS), Brussels, Belgium

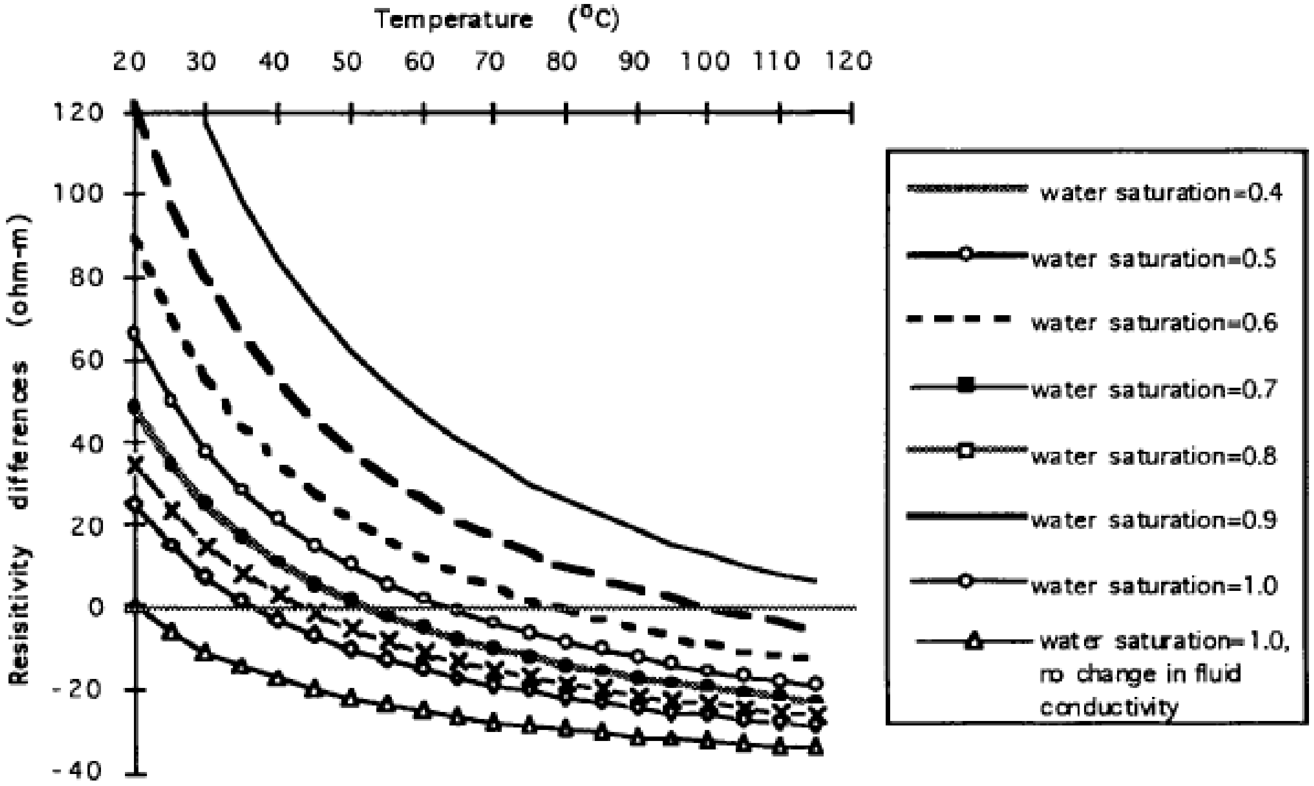
Back to the future

Ramirez et al. 1993, WRR, 29(1), 73-87



Back to the future

Ramirez et al. 1995, JEEG, 0(1), 39-55

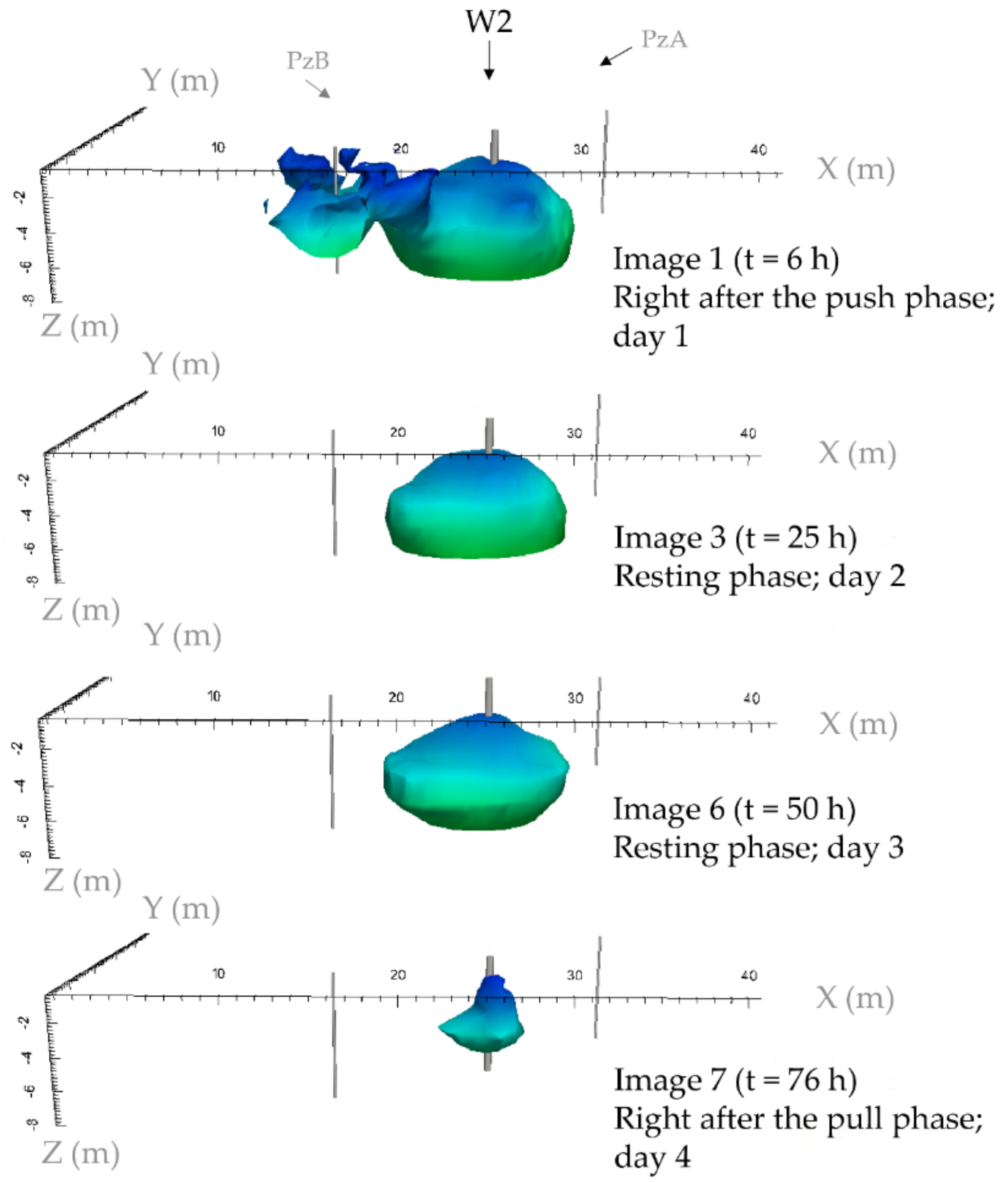


Back to the future

Robert et al. 2019, Geosciences

Special Issue

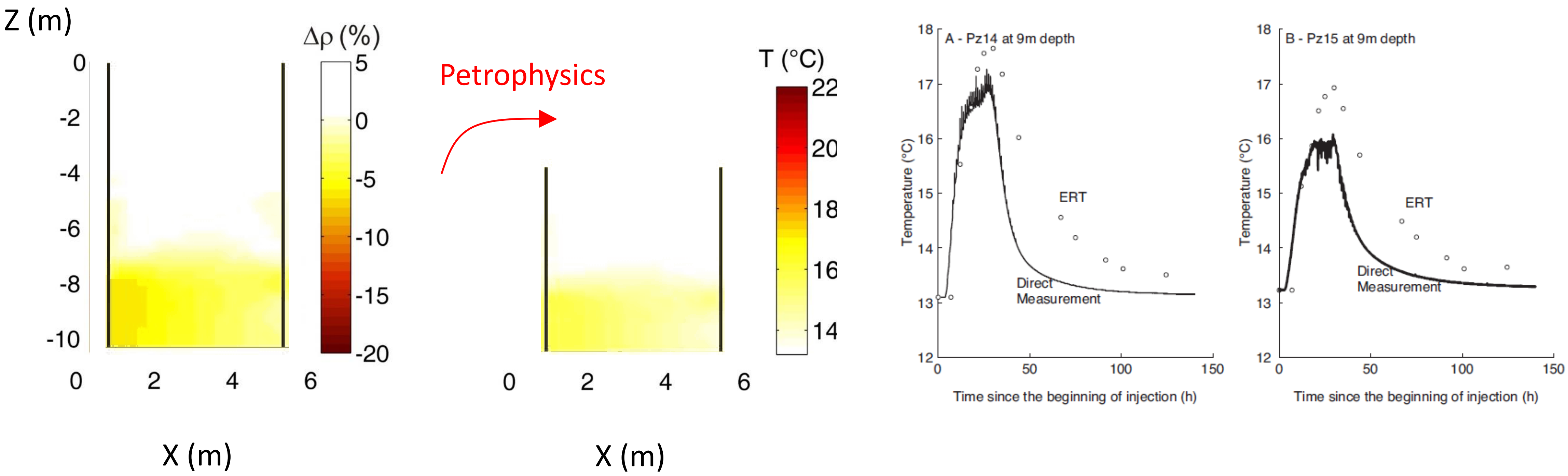
Subsurface thermography …



https://www.mdpi.com/journal/geosciences/special_issues/Subsurface_Thermography

Back to the future

Hermans et al. 2015, Geothermics, 53, 14-26



Petrophysics

Noise in the data

Survey design

Imaging

Petrophysics

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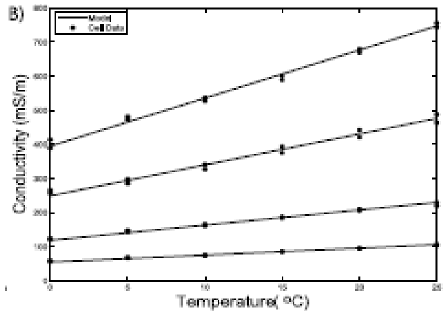
Petrophysical laws exist

Hayley et al. 2007, GRL, 34, L18402



$$\sigma^f = \sigma^{f25}\left[m^f(T-25)+1\right]$$

With $m^f \sim 0.02$ ⟶

$\Delta T = +1$ K equals $\Delta\sigma^f + 2\%$

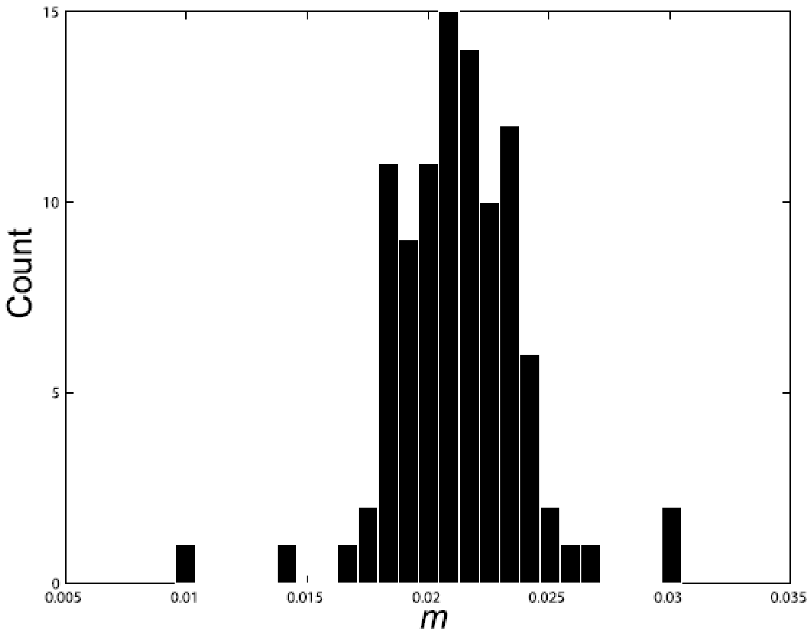


Figure 2. Histogram of extracted slopes from the analysis of the *Scott and Kay* [1988] study. This distribution has a mean of 0.021 and a standard deviation of 0.03.

They are applied to retrieve T

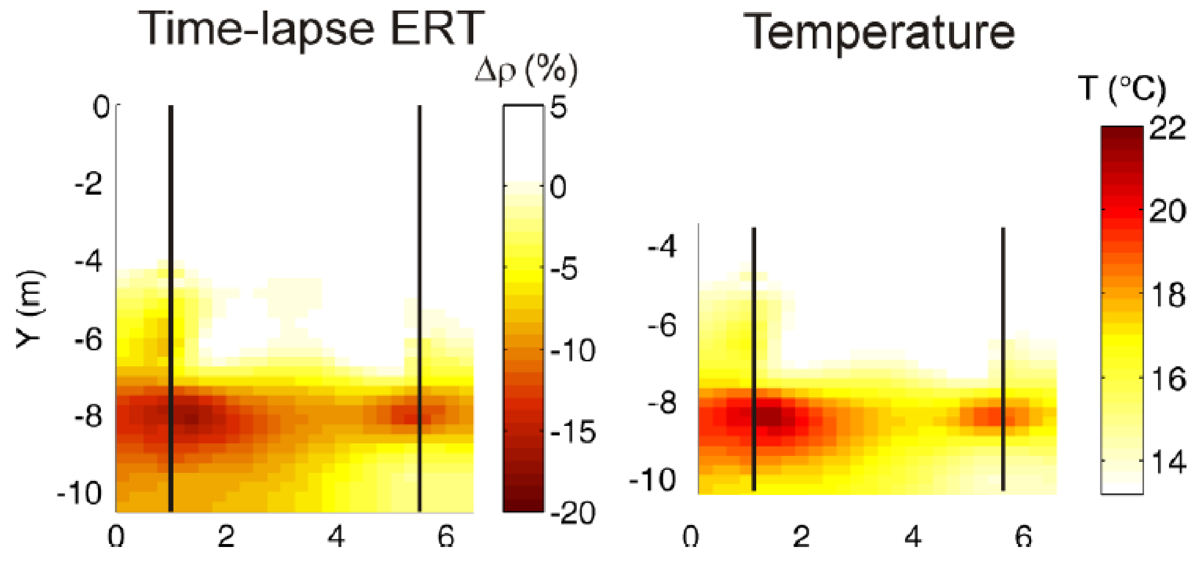
Hermans et al. 2014, Energies, 7(8), 5083-5118

$$T_i = 25° + \frac{1}{m_f}\left[\frac{\sigma_{b;ti}}{\sigma_{b;t_0}}\,\frac{\sigma_{f;t_0}}{\sigma_{f;25°}} - 1\right]$$

laboratory experiment

ERT

laboratory measurement



But strong assumptions remain

Robert et al. 2013, NSG2013, Tu S2a 10, Bochum, Germany

e.g. Hayley et al. 2007

$$\frac{\sigma_{fluid}^{T}}{\sigma_{fluid}^{T_{ref}}} = m_f\,(T - Tref) + 1$$

1° absence of chemical reactions

Archie's law

$$\sigma_{bulk} = \frac{\sigma_{fluid}}{F}$$

2° $\sigma_{surface}$ neglected

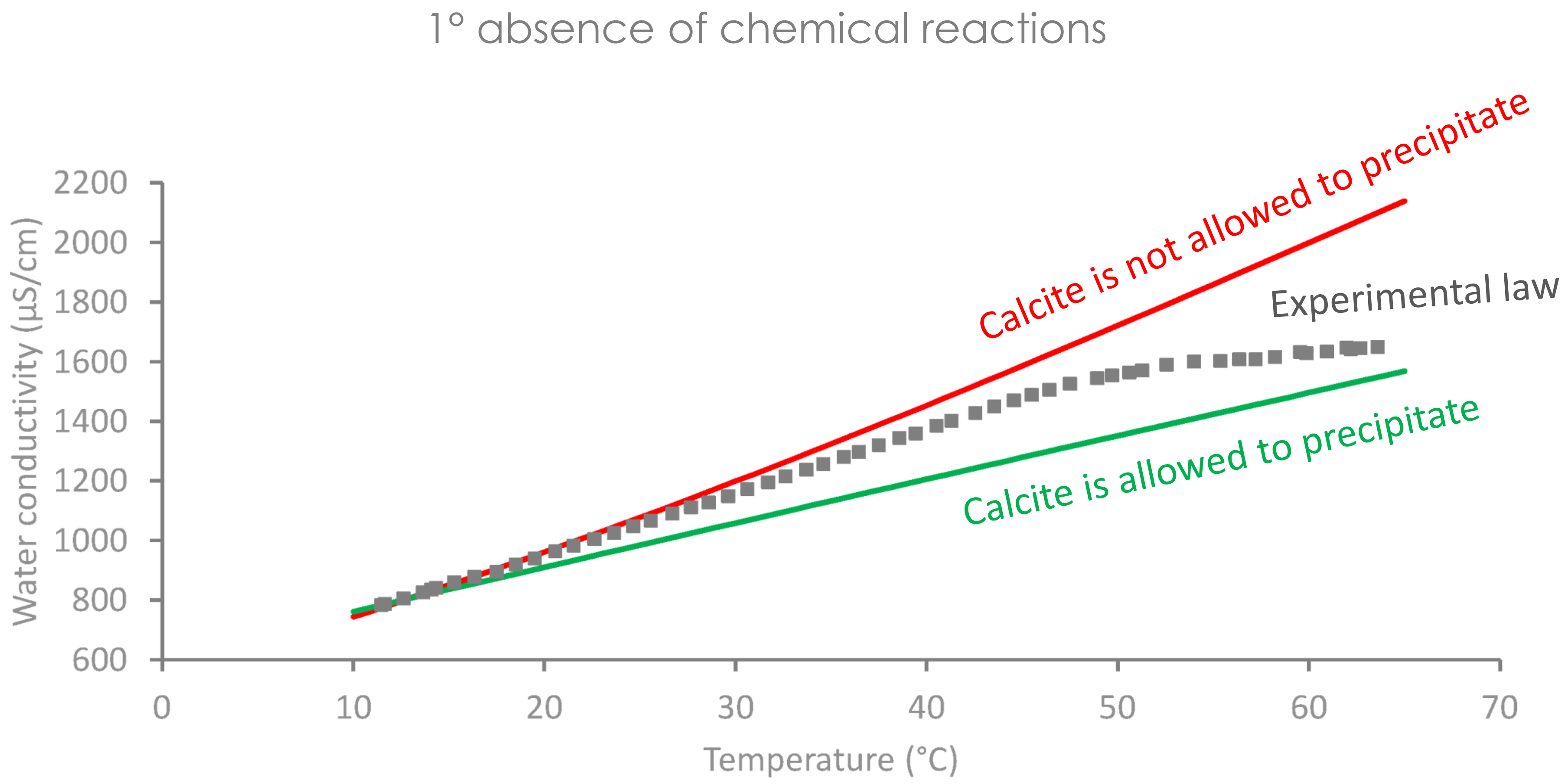
Ratio of Archie's law

$$\frac{\sigma_{bulk;ti}}{\sigma_{bulk;t_0}} = F = \frac{\sigma_{fluid;t_0}}{\sigma_{fluid;ti}}$$

3° F remains constant

But strong assumptions remain

Robert et al. 2013, NSG2013, Tu S2a 10, Bochum, Germany



Petrophysics

Noise in the data

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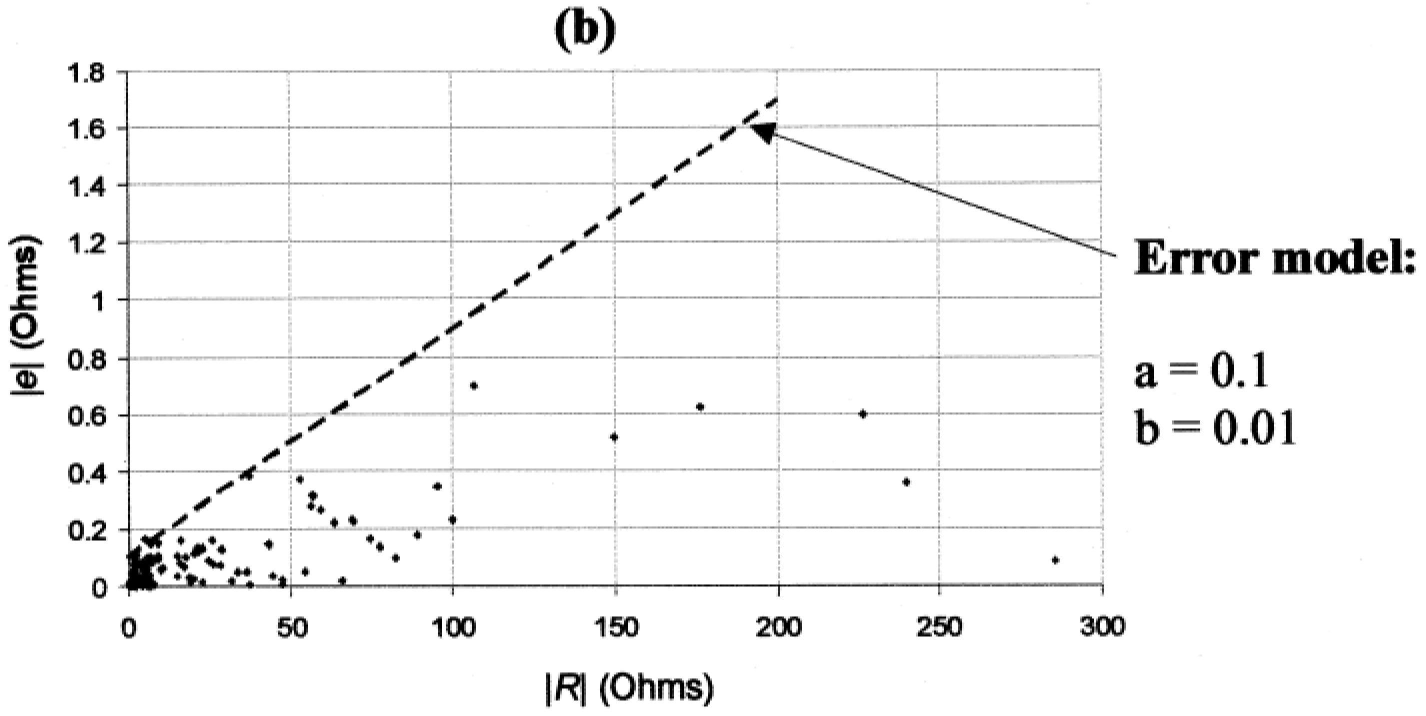
Imaging

Authors use reciprocals to estimate noise

Slater et al. 2000, JAG, 44(2), 85-102

Static error model

$$|e| = a + b|R|$$

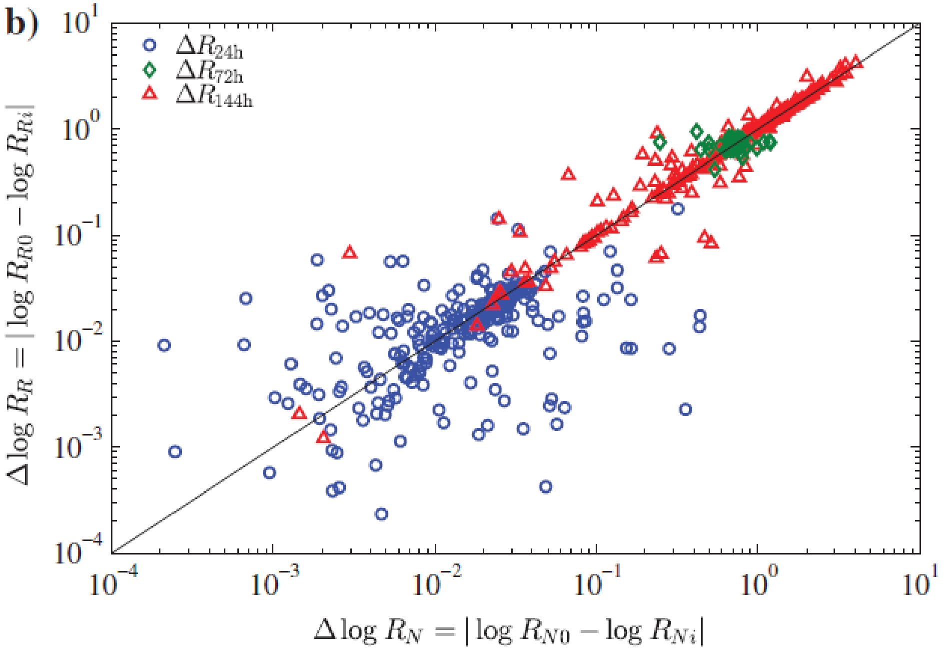


Authors use reciprocals to estimate noise

Lesparre et al. 2017, Geophysics, 82(6), E325-E333

Time-lapse error model

$$|\Delta \log R_N - \Delta \log R_R| = \frac{a}{R} + b$$

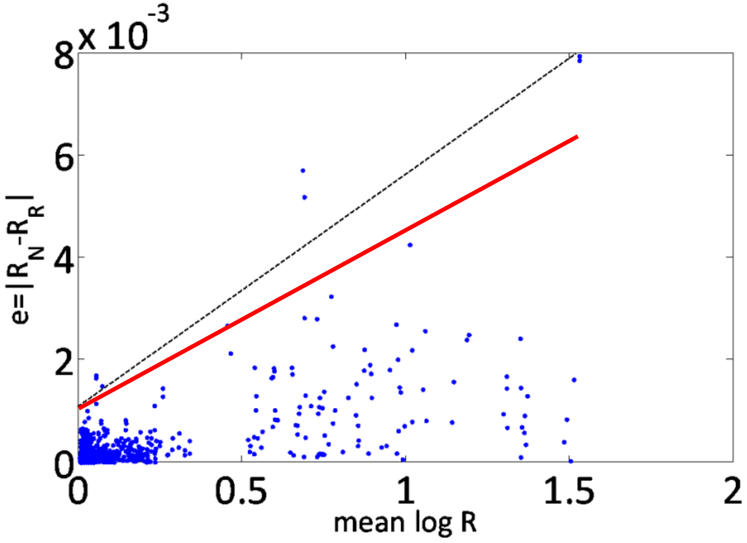


Noise estimation is crucial

Robert 2012 (unpublished PhD thesis, Liège, Belgium)

$e = a + bR$

with
a = 1 mΩ and b = 2%



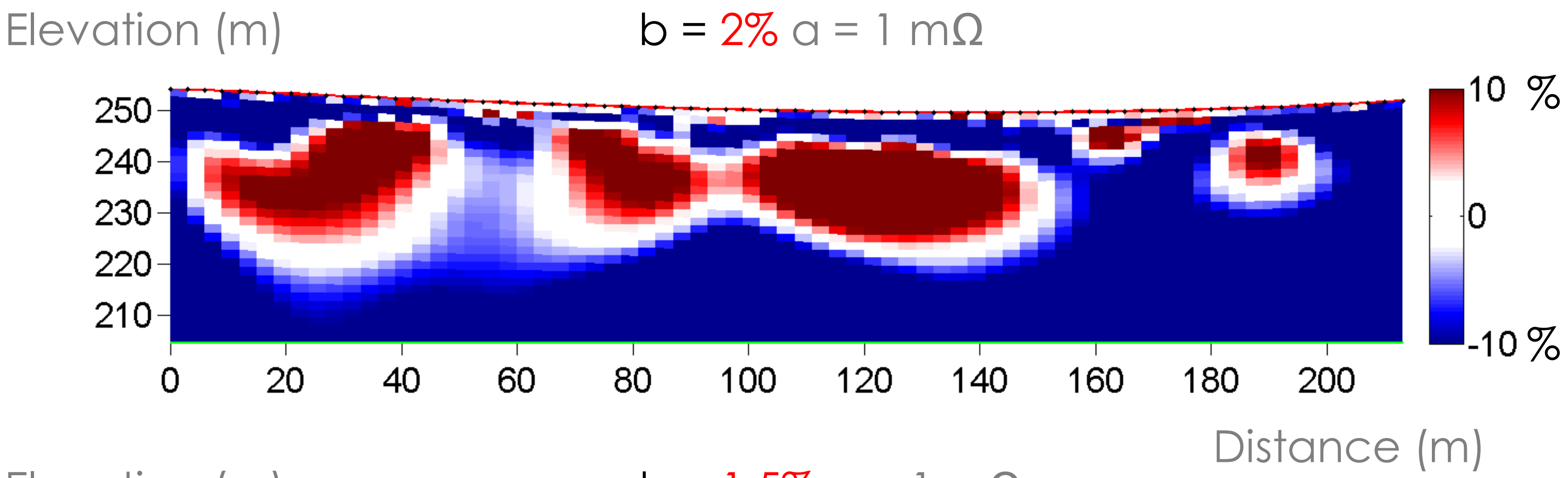
what if
a = 1 mΩ and b = 1.5%

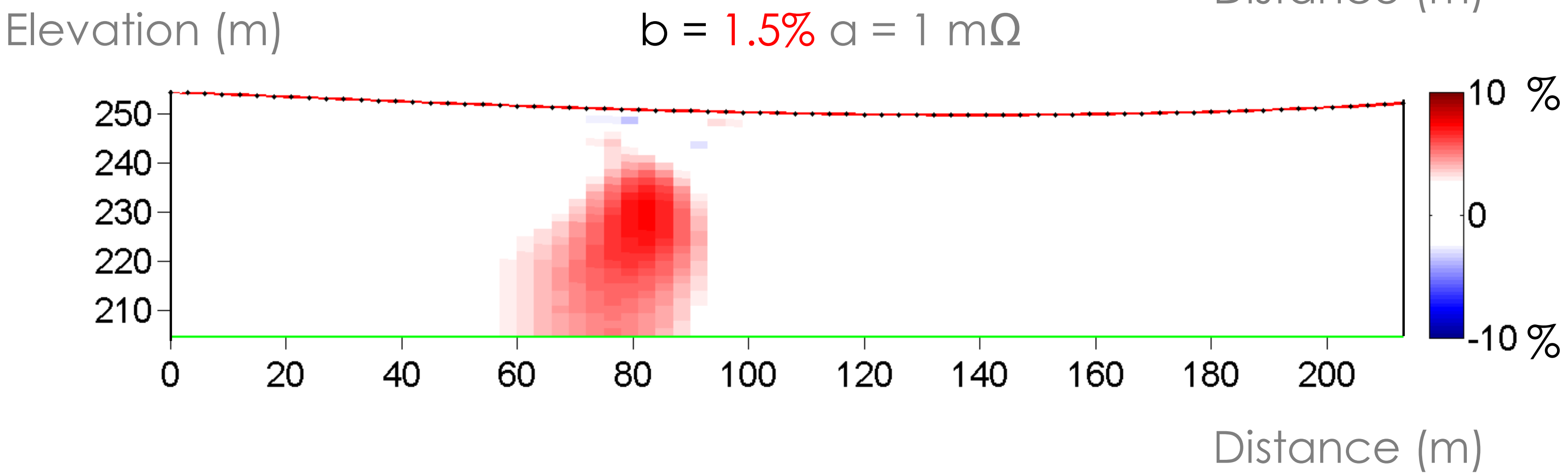
?

Let the data speak...

Robert 2012 (unpublished PhD thesis, Liège, Belgium)

standalone
inversions



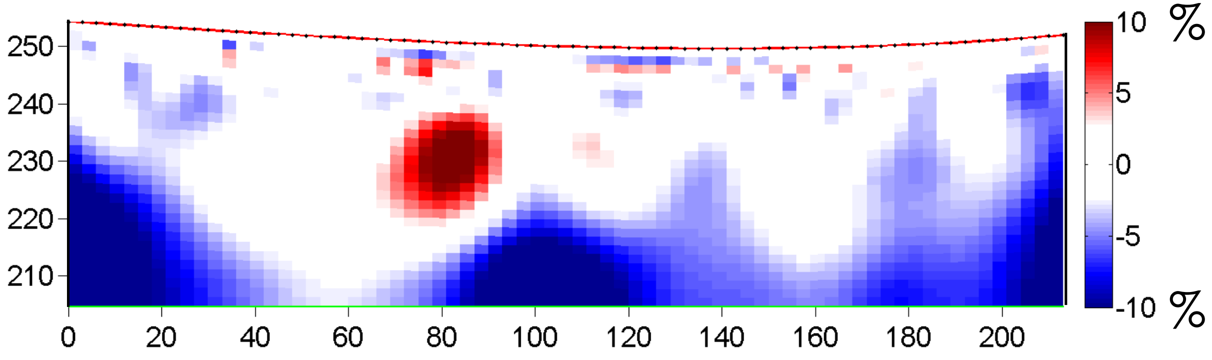


... but pay attention not to model noise

Robert 2012 (unpublished PhD thesis, Liège, Belgium)

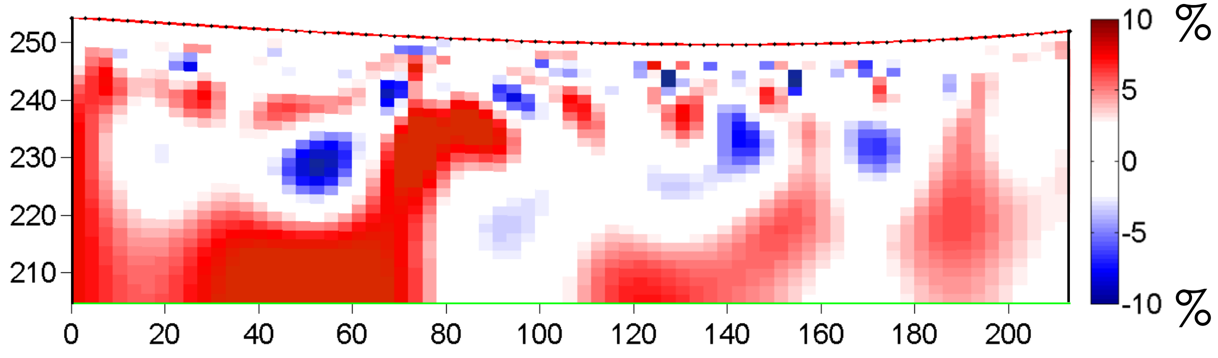
data difference inversions

Elevation (m) higher noise assumption



Distance (m)

Elevation (m) lower noise assumption



Distance (m)

Petrophysics

Noise in the data

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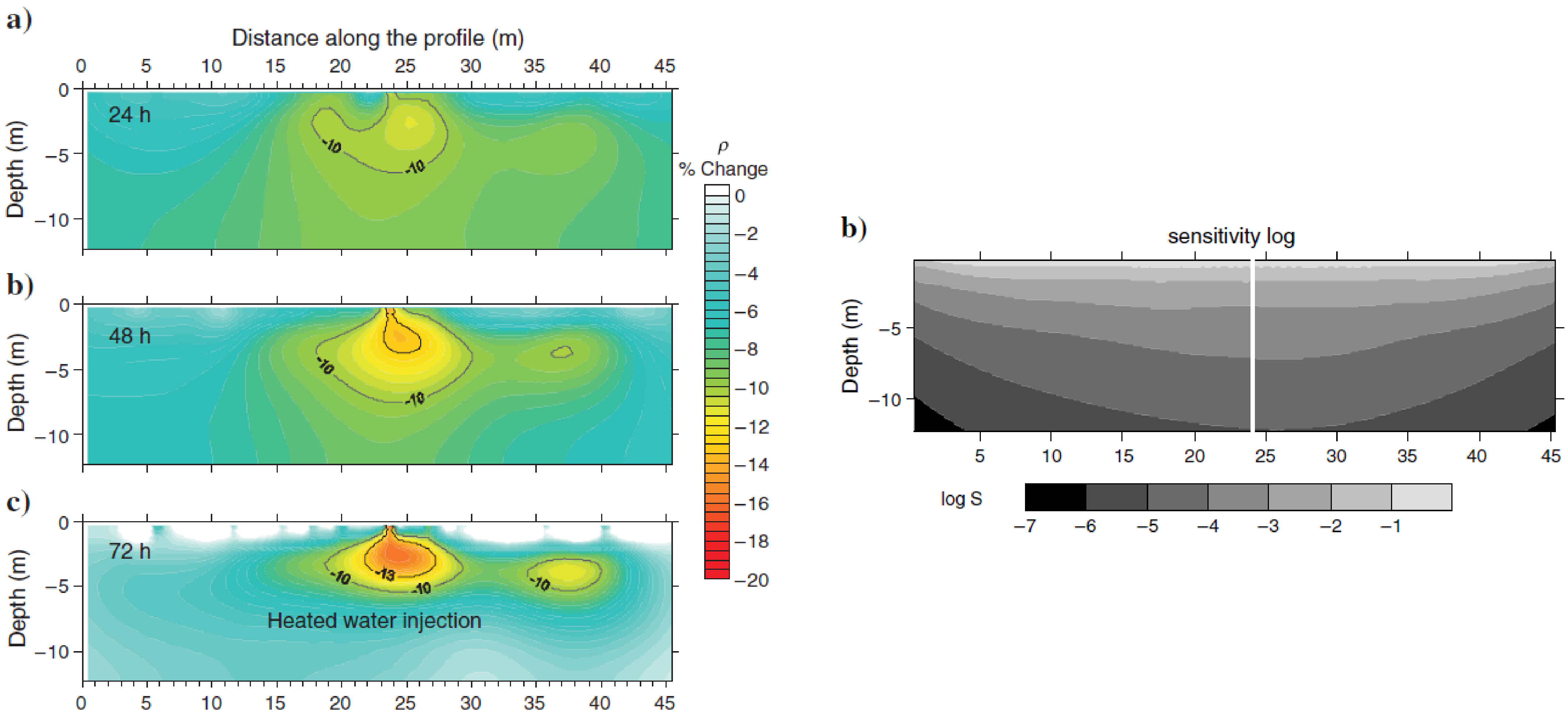
Imaging

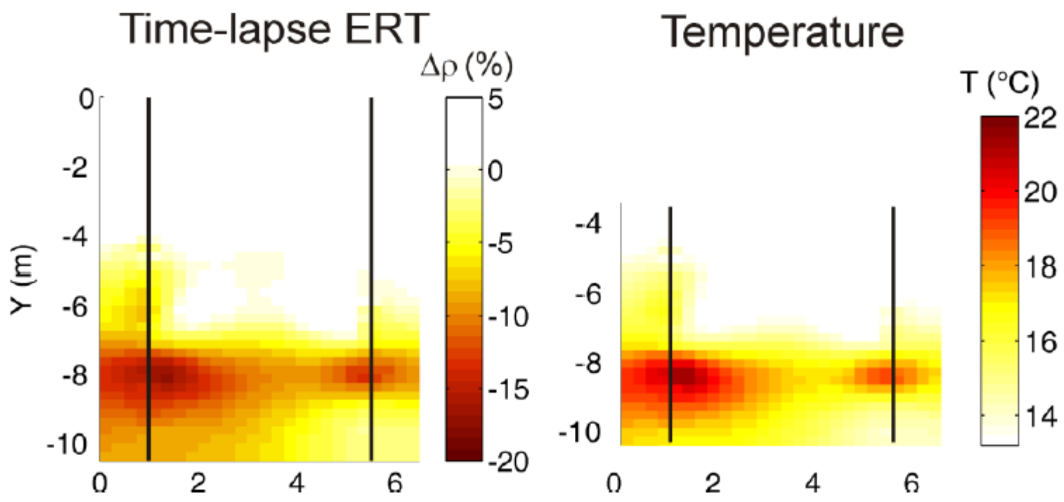
Surface vs. cross-hole

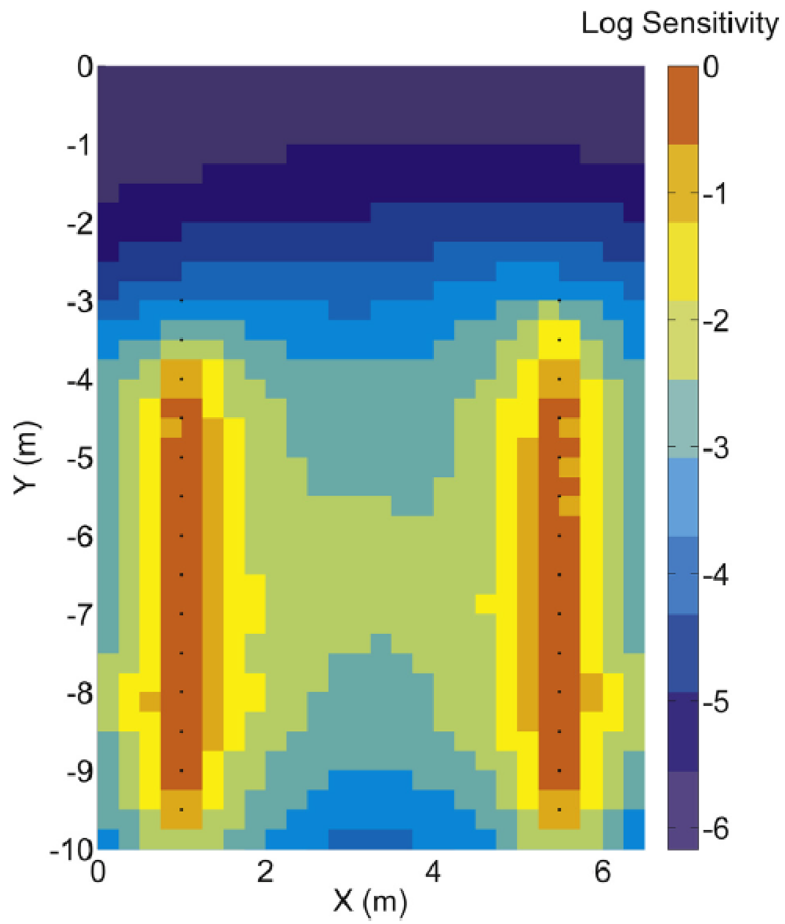
Hermans et al. 2012, Geophysics, 77(1), B11-B21



Surface vs. cross-hole

Hermans et al. 2015, Geothermics, 53, 14-26

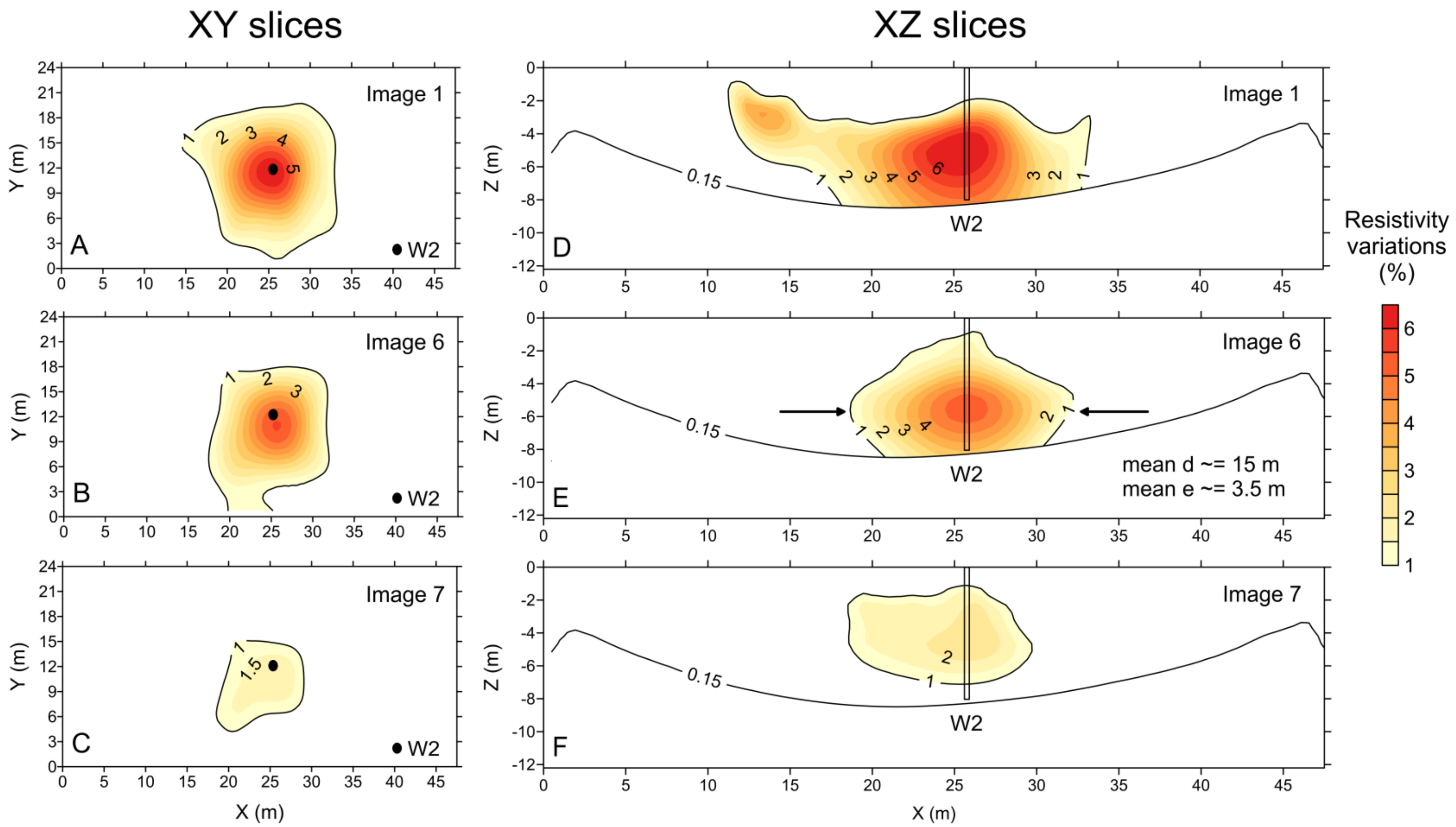




Obviously, better sensitivity (resolution) with cross-hole ERT
But (at least) 2 boreholes are needed
DOI depends on the depth of boreholes

2D vs. 3D

Robert et al. 2019, Geosciences

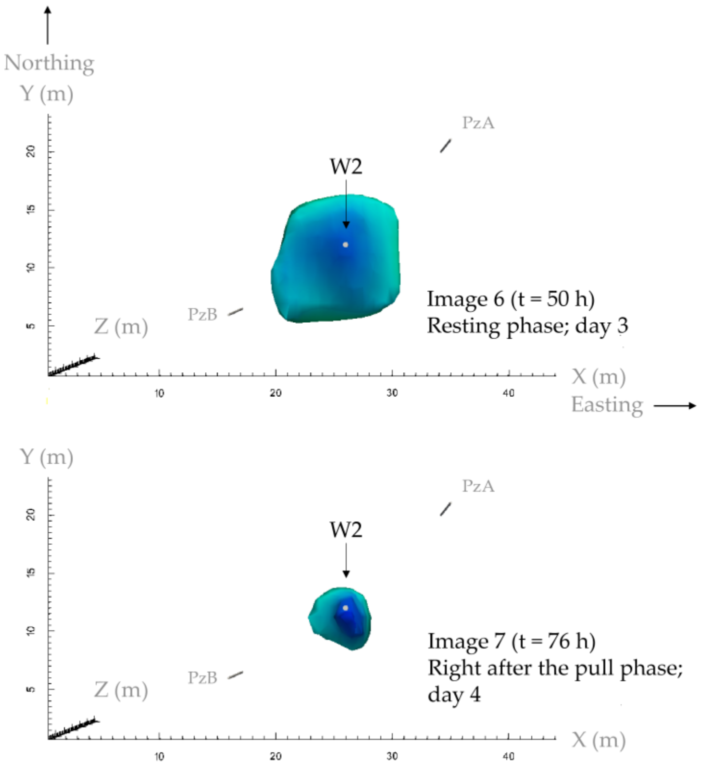


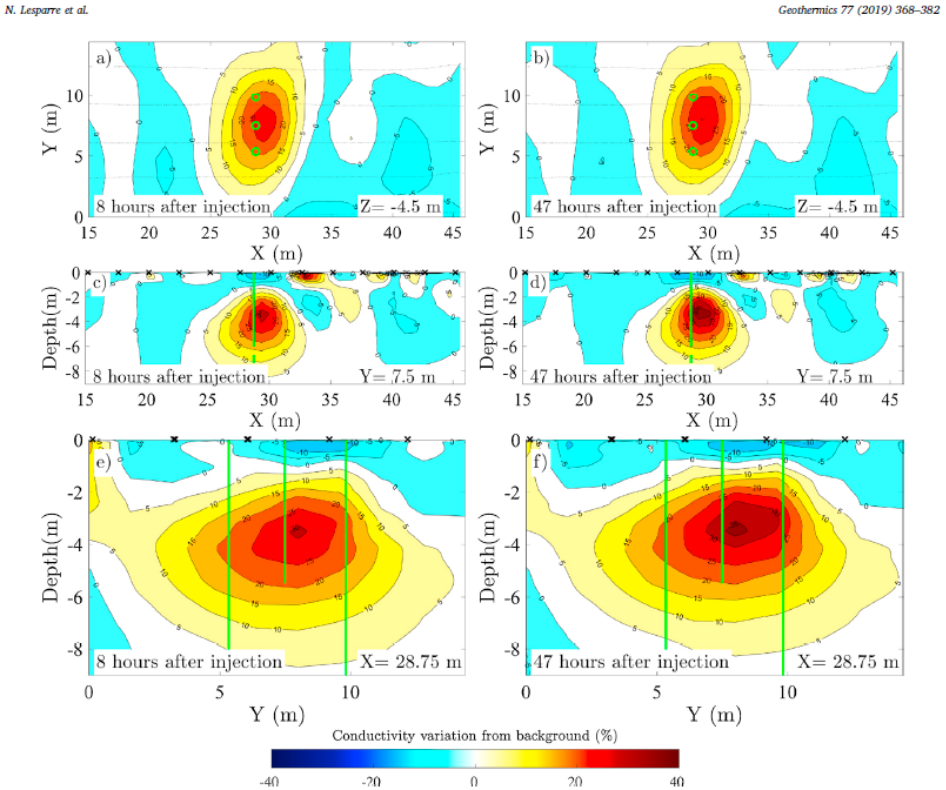
3D is a powerful visual tool

e.g. to estimate the thermal affected zone (TAZ)

Robert et al. 2019, Geosciences

Lesparre et al. 2019, Geothermics, 77, 368-382





Petrophysics

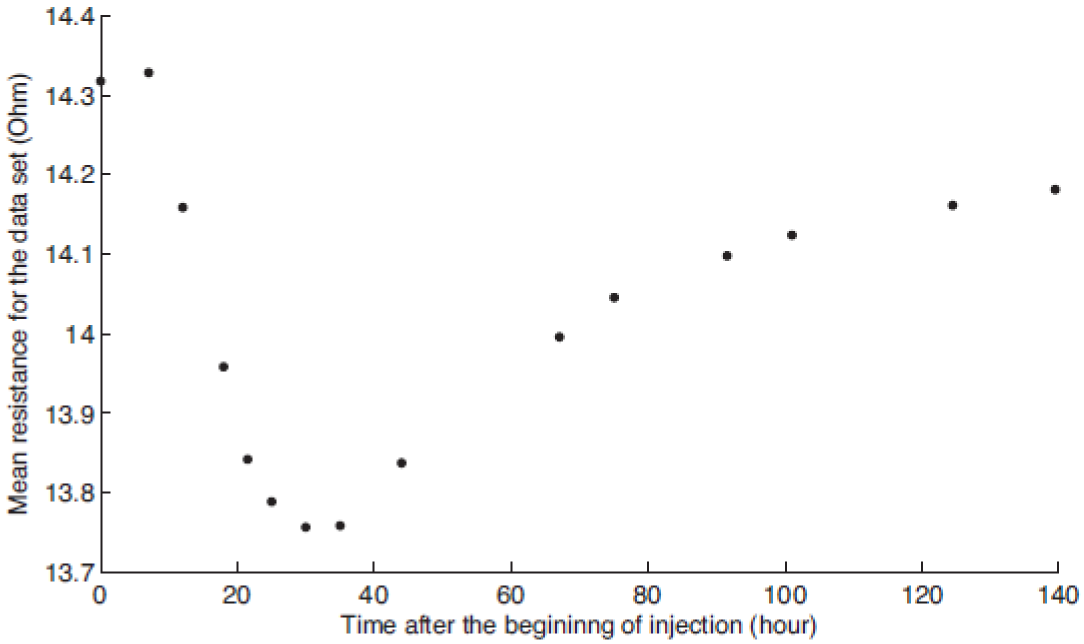
Noise in the data

Survey design

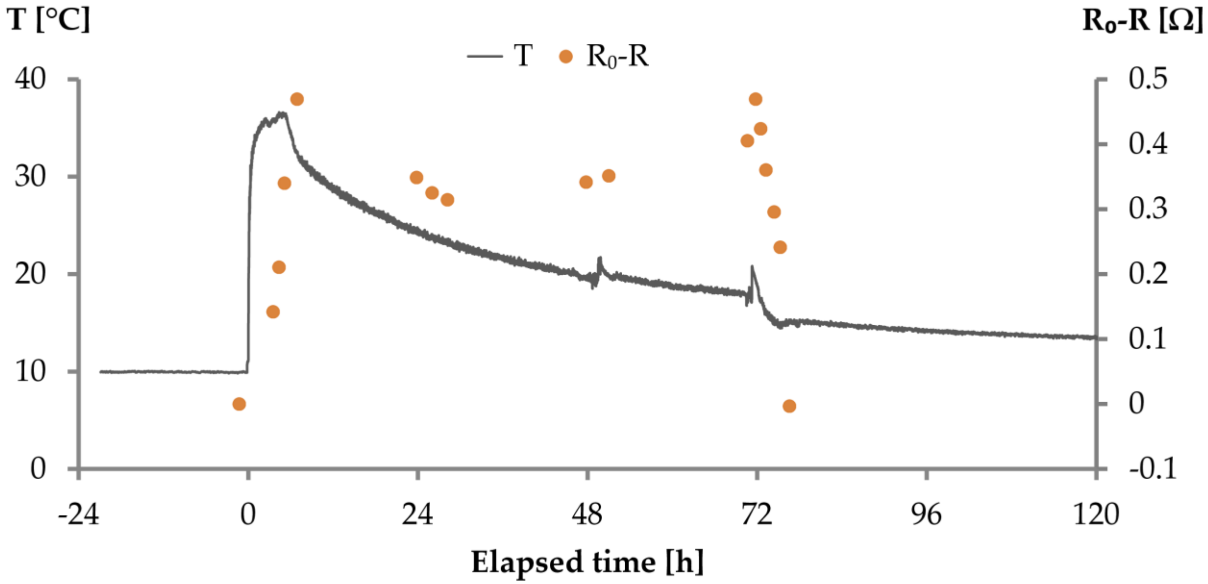
Imaging

First, check if your data contains information about temperature variations

Hermans et al. 2012, Geophysics, 77(1), B11-B21



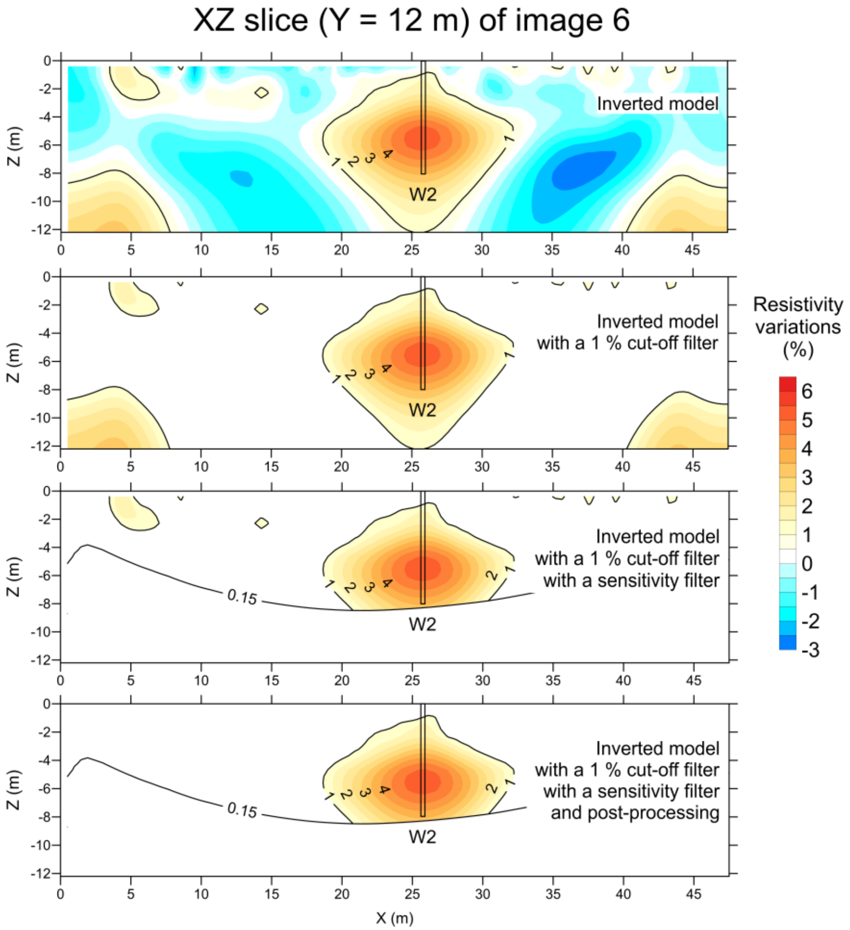
Robert et al. 2019, Geosciences



Choose an appropriate technique

Standalone inversion, data-difference inversion, active time-constrained inversion (Karaoulis et al. 2011, JAG, 73, 25-34), BEL, and many more...

and eventually use filters



Petrophysics

Noise in the data

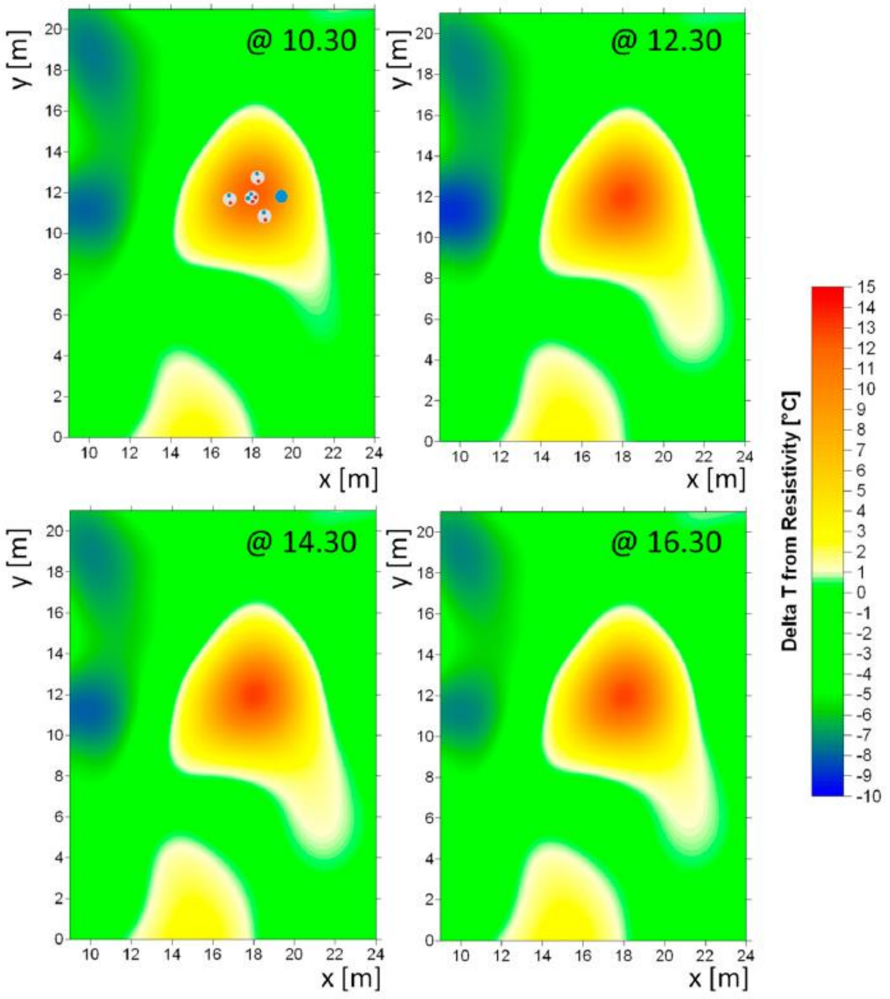
Survey design

Imaging

Applications in real-world studies

Borehole thermal energy storage BTES

Comina et al. 2019, Geosciences



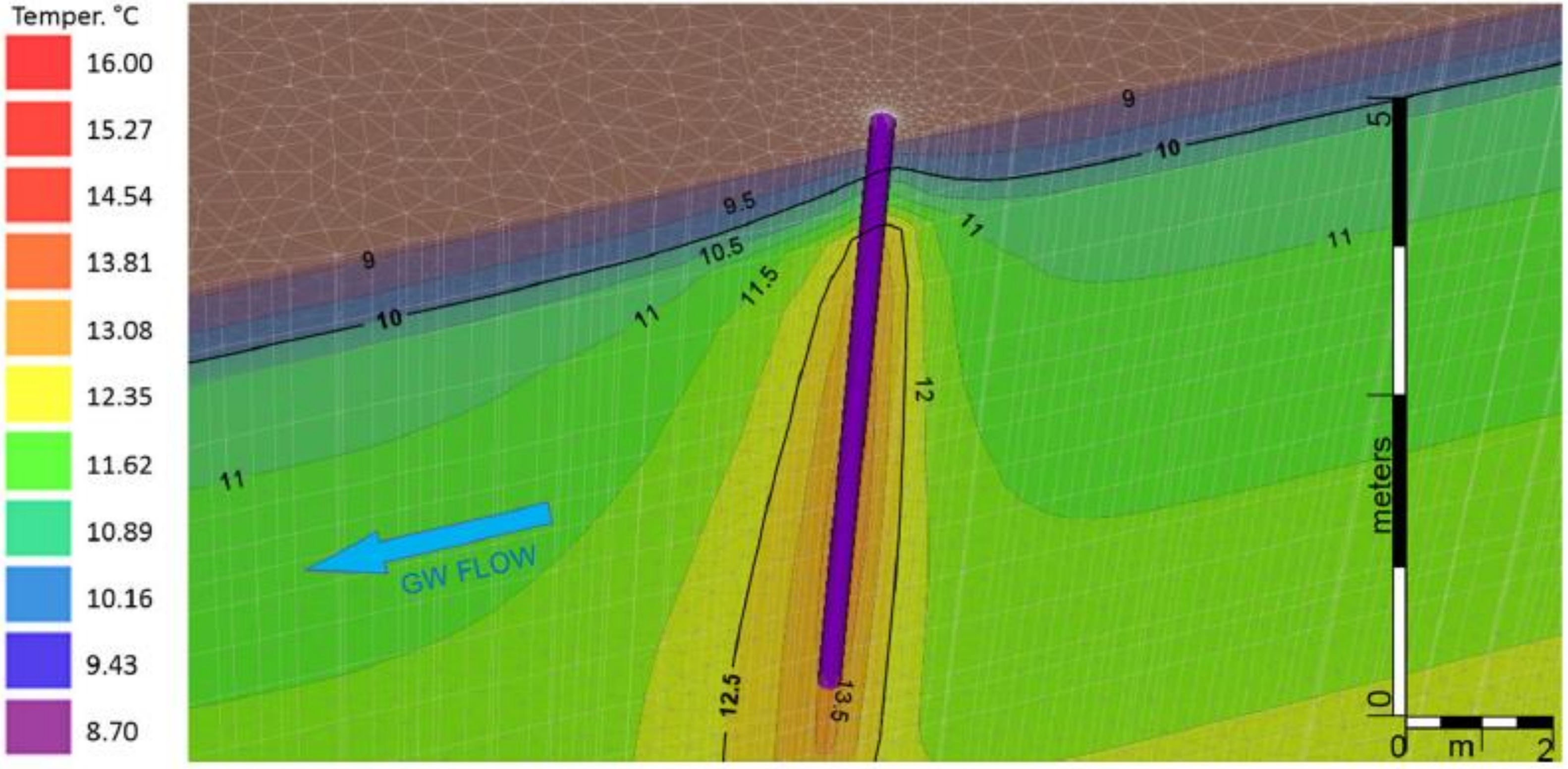
Monitoring TAZ

Borehole thermal energy storage BTES

Cultrera et al. 2018, HJ, 26(3), 837-851

Hydrogeol J (2018) 26:837–851 847

Fig. 11 Heat transfer due to the groundwater flow advection and the conduction processes after 5 days of heat power running



Aquifer thermal energy storage ATES

De Schepper et al. 2019, Applied Energy, 242, 534-546

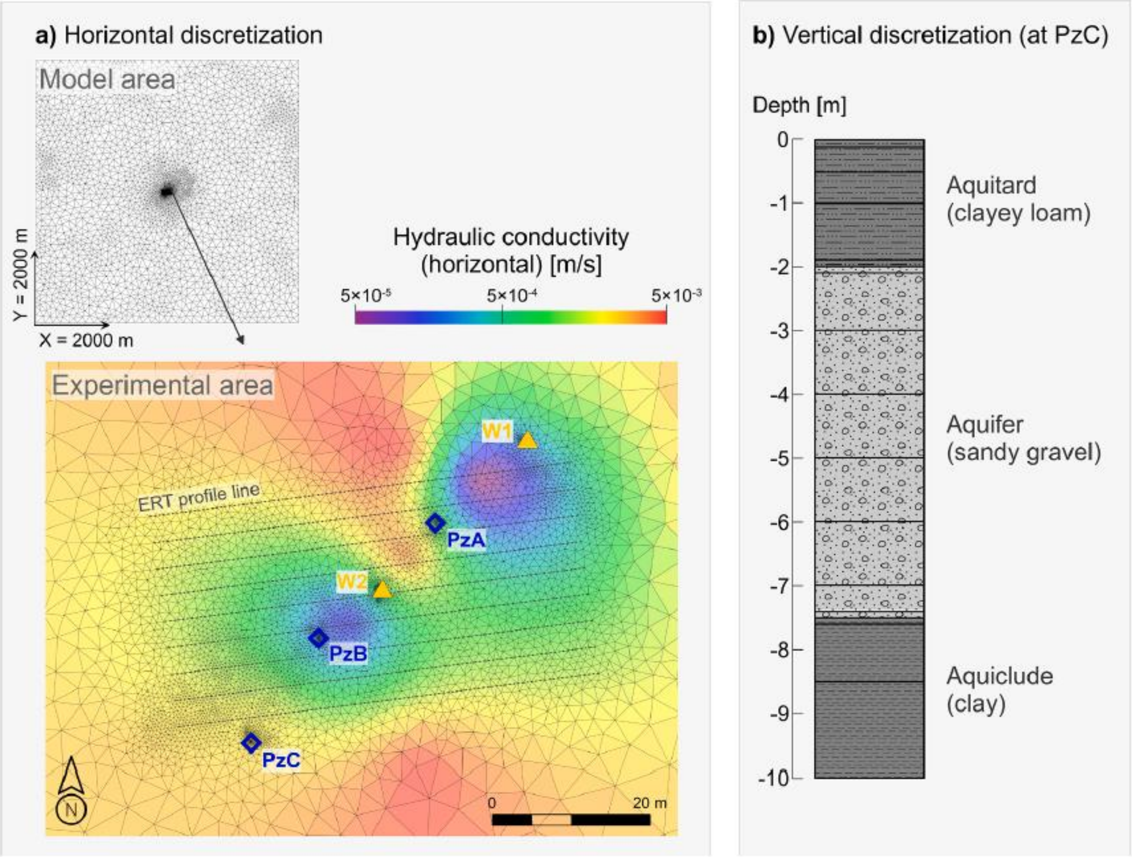


Table 4
Energy recovery rate values (η, in %) for the 77 DSM simulated scenarios (7 storage periods Δt, 11 temperature differences induced ΔT).

η [%]		ΔT [K]										
		−4	3	6	11	35	40	45	50	55	60	65
Δt [h]	0.25	87	87	87	87	71	71	70	68	67	66	65
	1	87	87	87	87	71	71	69	68	67	66	65
	6	87	87	87	87	71	71	70	68	67	66	65
	12	86	87	87	87	71	70	69	68	66	65	64
	24	84	84	84	83	67	67	65	64	63	61	61
	48	84	83	83	84	67	66	65	63	62	60	59
	72	78	78	78	78	62	60	58	57	55	54	53

Aquifer thermal energy storage ATES

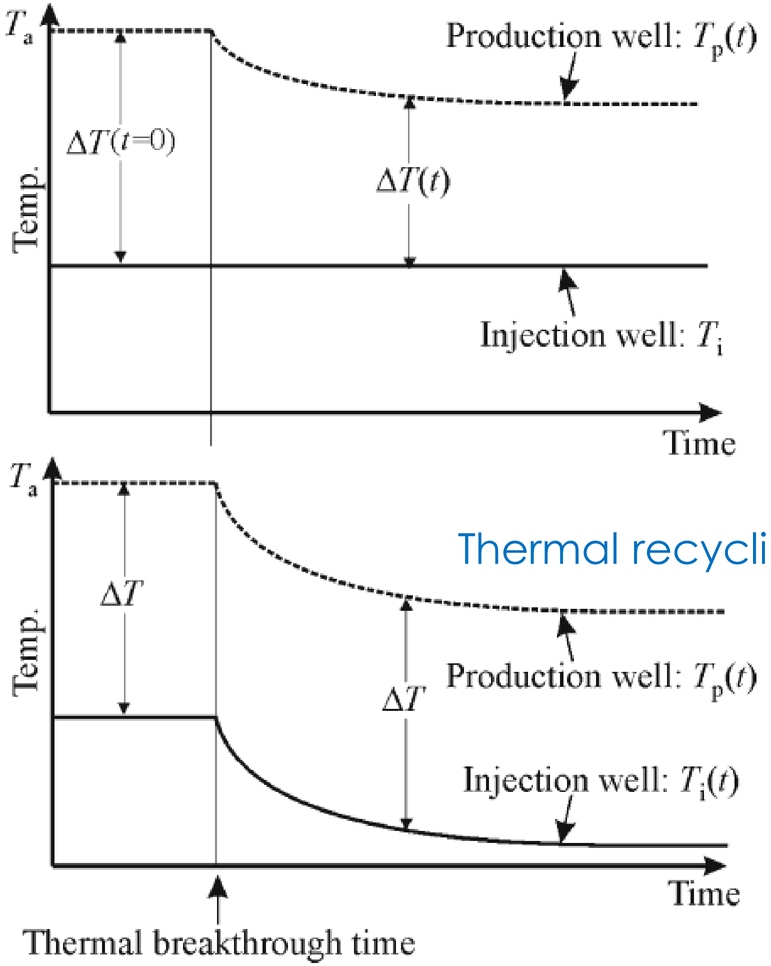
Robert et al. In preparation

Idea:
Repeat ATES
& recovery cycles

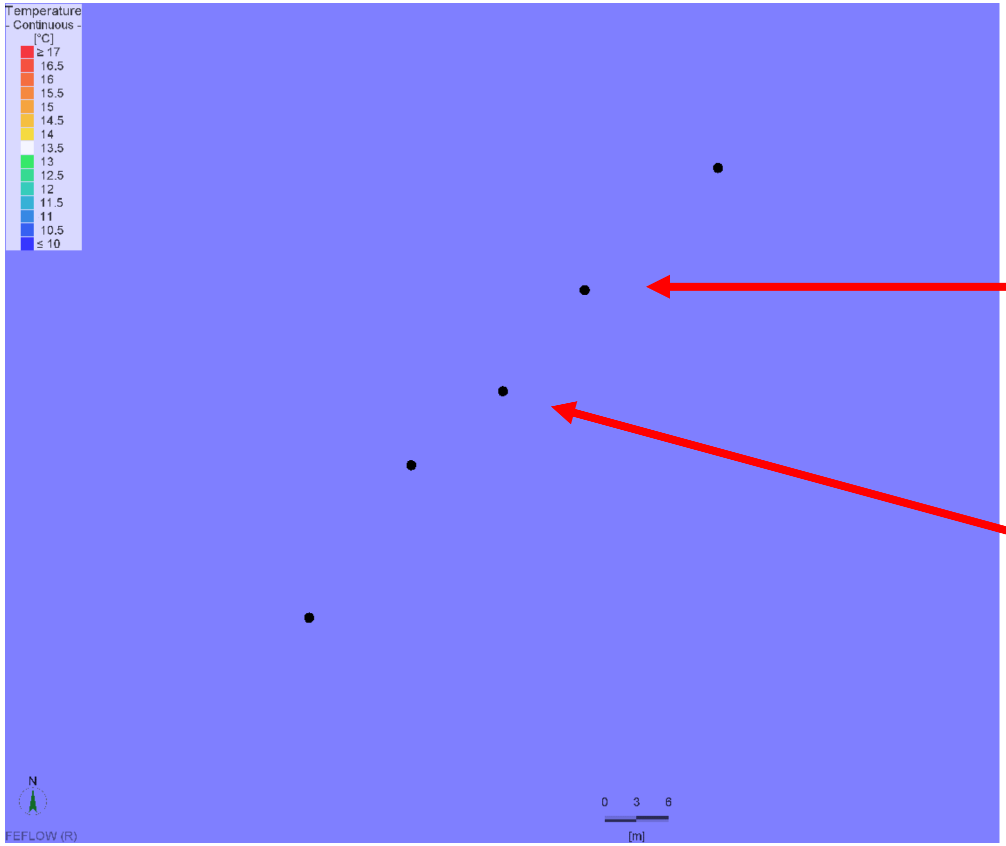
This time,
with thermal recycling

Milnes & Perrochet (2013)

Thermal feedback



Thermal recycling helps containing the heat plume in the area of interest

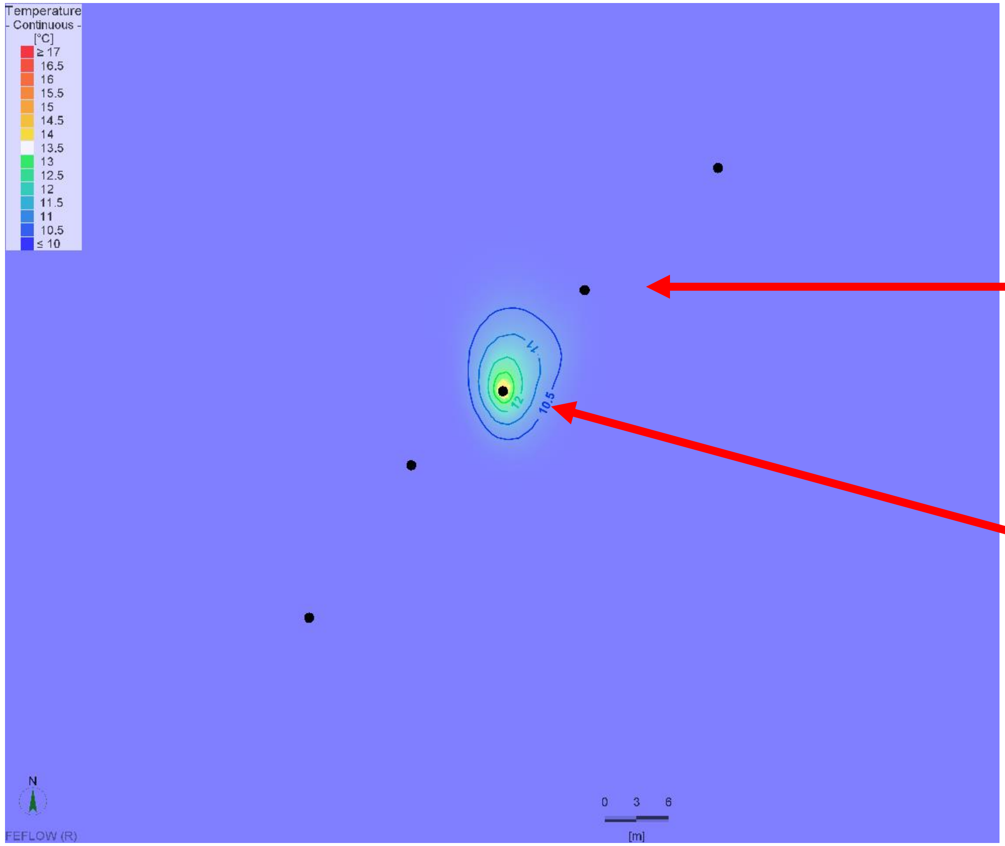


Productio
n well

Injection
&
recovery
well

Example of LT-ATES (ΔT = 6K) – Day 0

Thermal recycling helps containing the heat plume in the area of interest

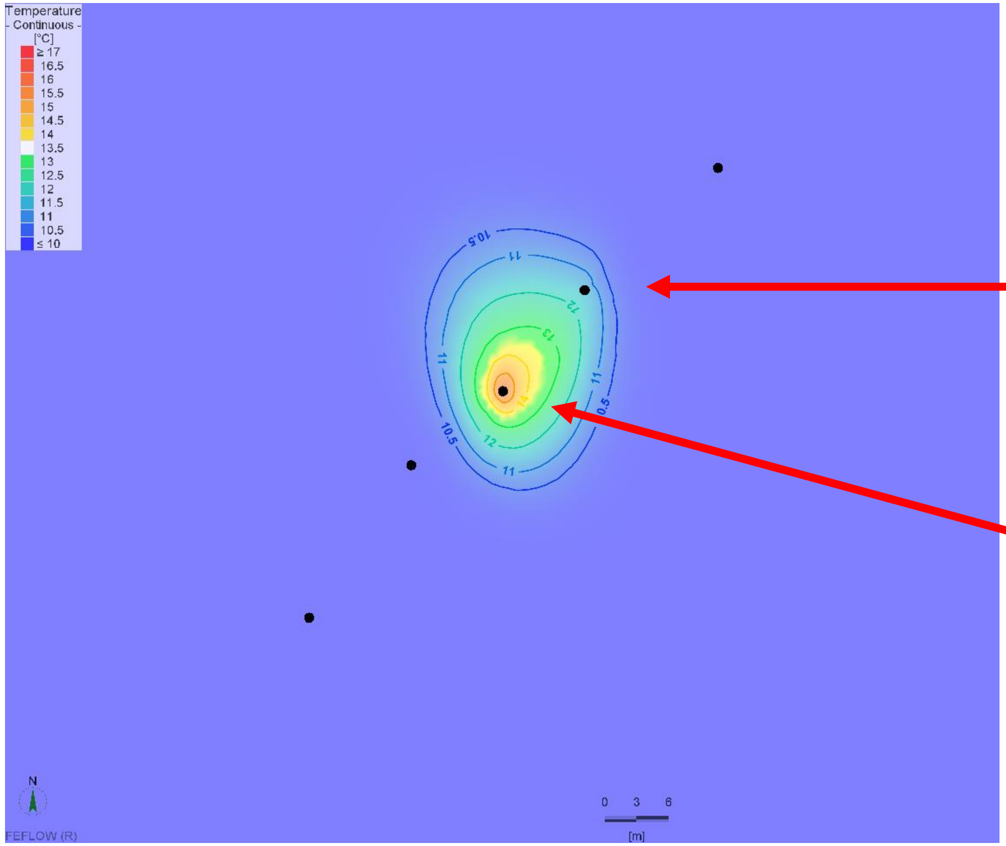


Productio
n well

Injection
&
recovery
well

Example of LT-ATES (ΔT = 6K) – Day 1

Thermal recycling helps containing the heat plume in the area of interest

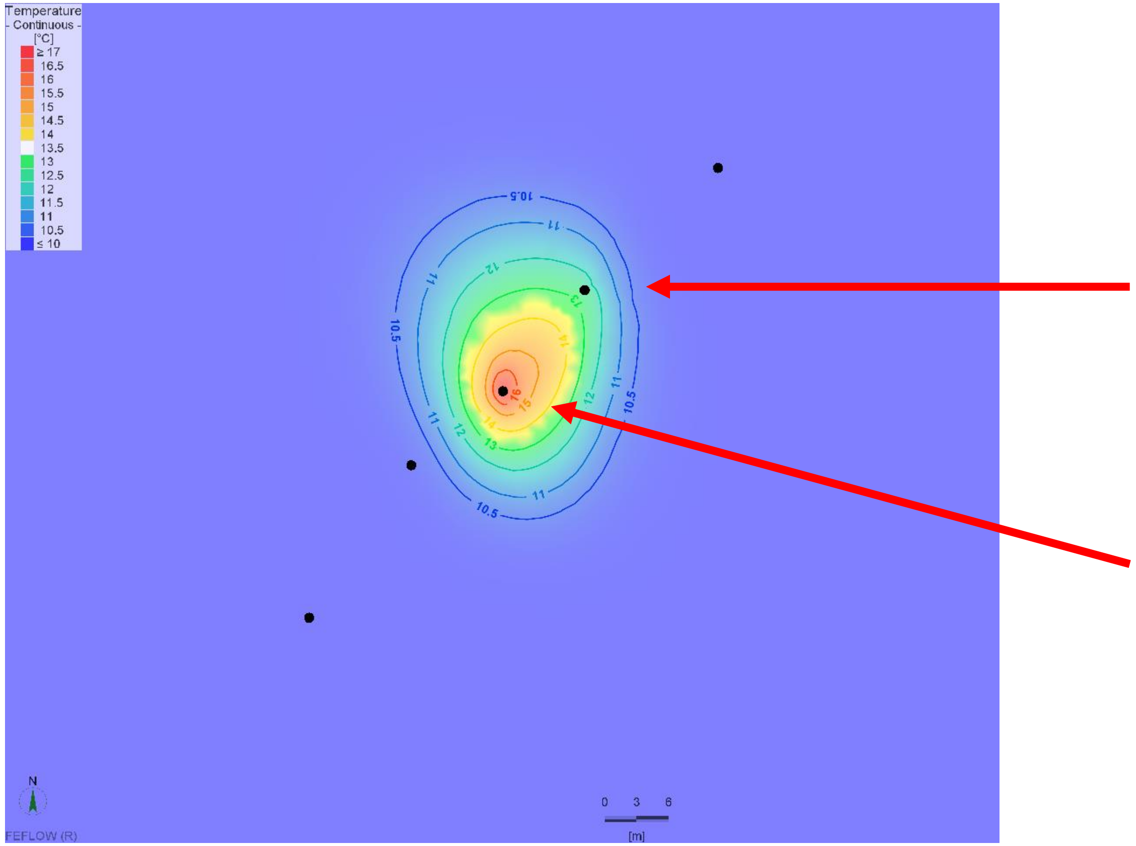


Productio
n well

Injection
&
recovery
well

Example of LT-ATES (ΔT = 6K) – Day 7

Thermal recycling helps containing the heat plume in the area of interest

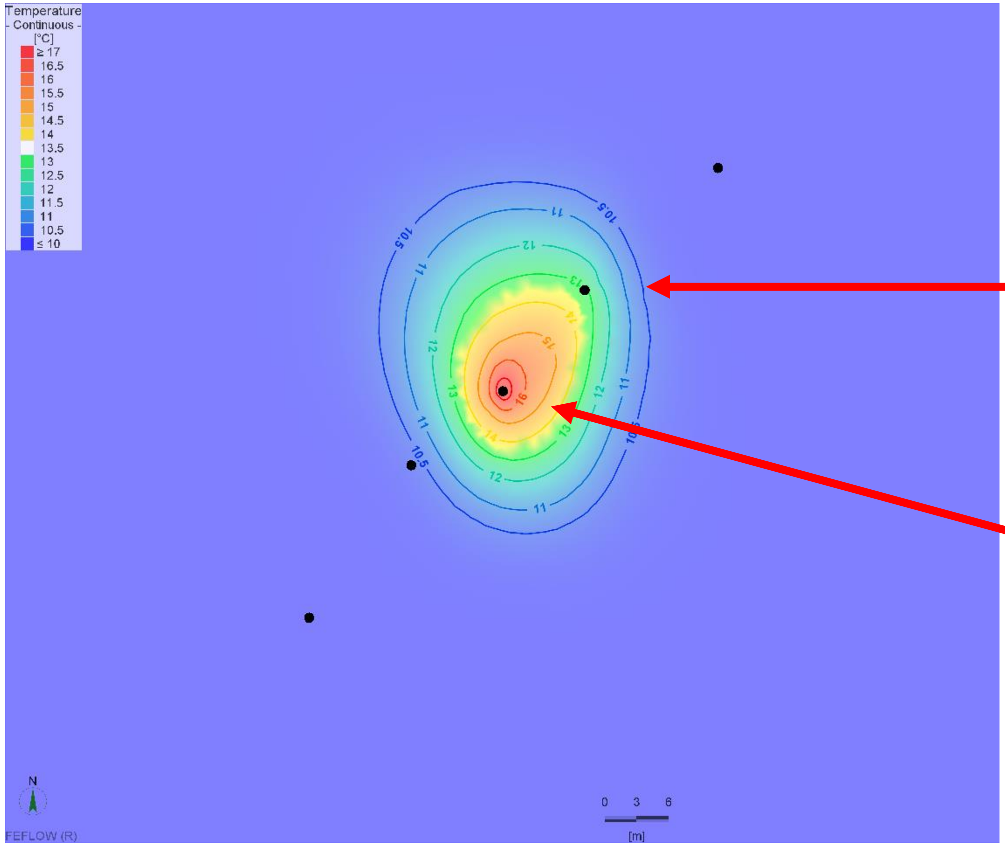


Production well

Injection & recovery well

Example of LT-ATES (ΔT = 6K) – Day 14

Thermal recycling helps containing the heat plume in the area of interest

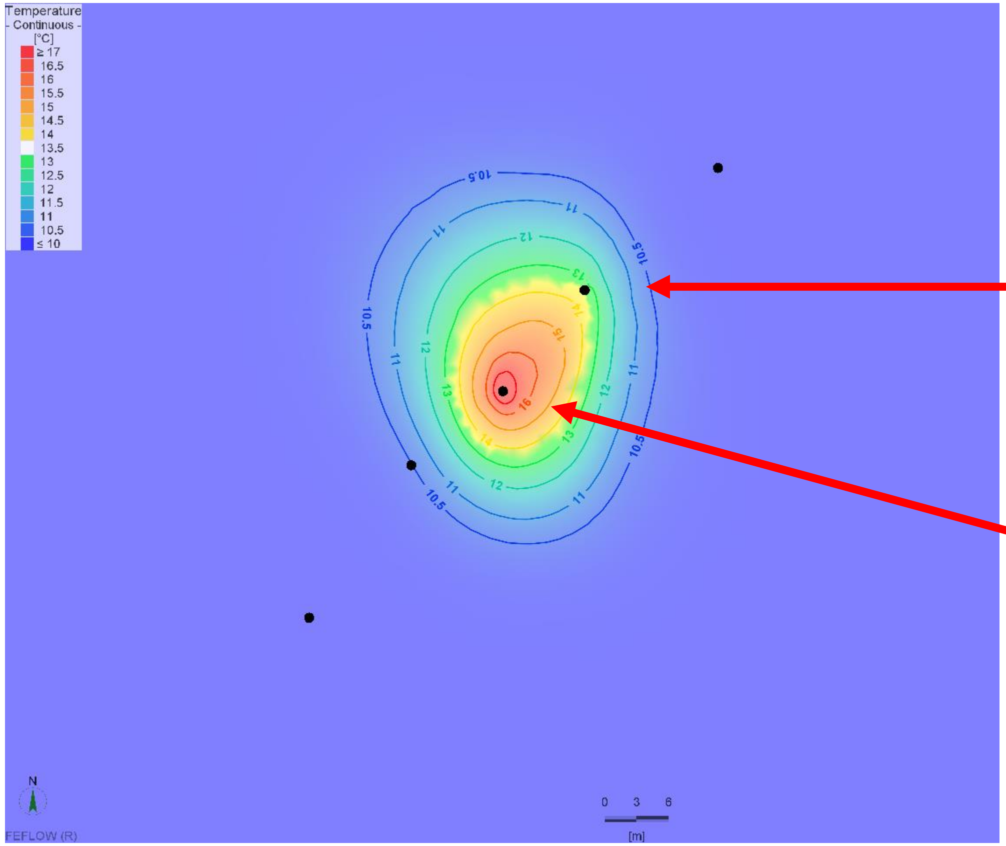


Productio
n well

Injection
&
recovery
well

Example of LT-ATES (ΔT = 6K) – Day 21

Thermal recycling helps containing the heat plume in the area of interest



Productio
n well

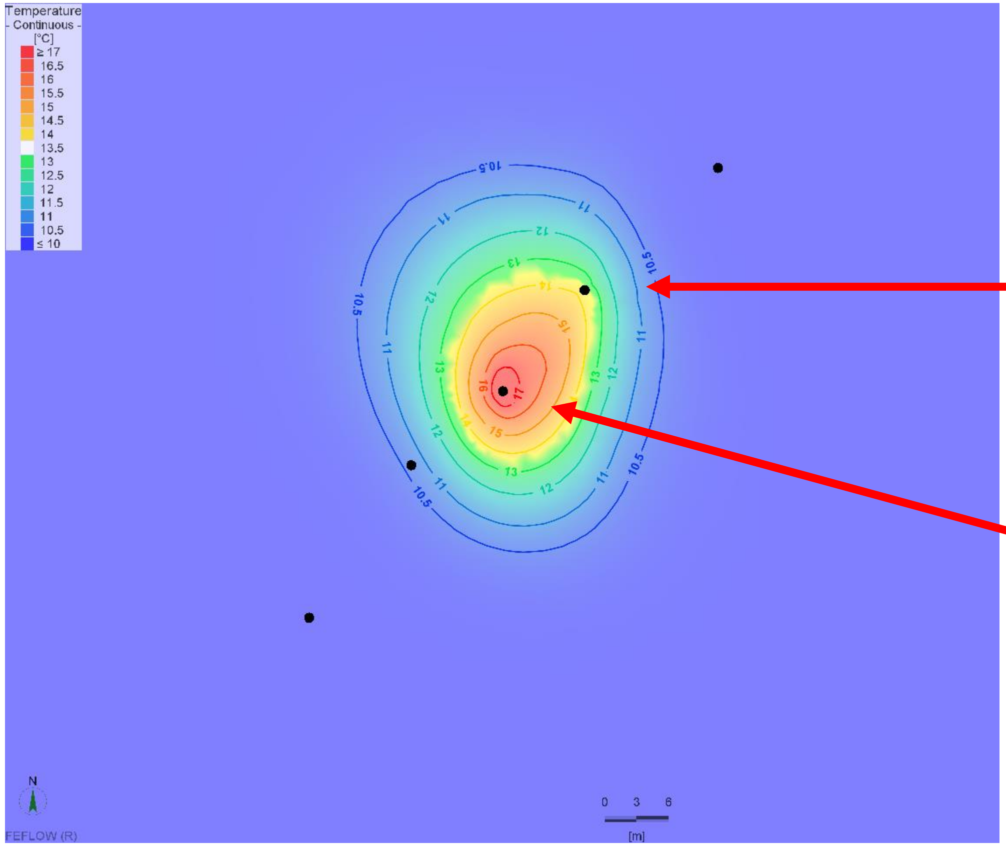
Injection
&
recovery
well

Example of LT-ATES ($\Delta T = 6K$) – Day 28

Thermal recycling helps containing the heat plume in the area of interest

gw flow direction

~10 m/y

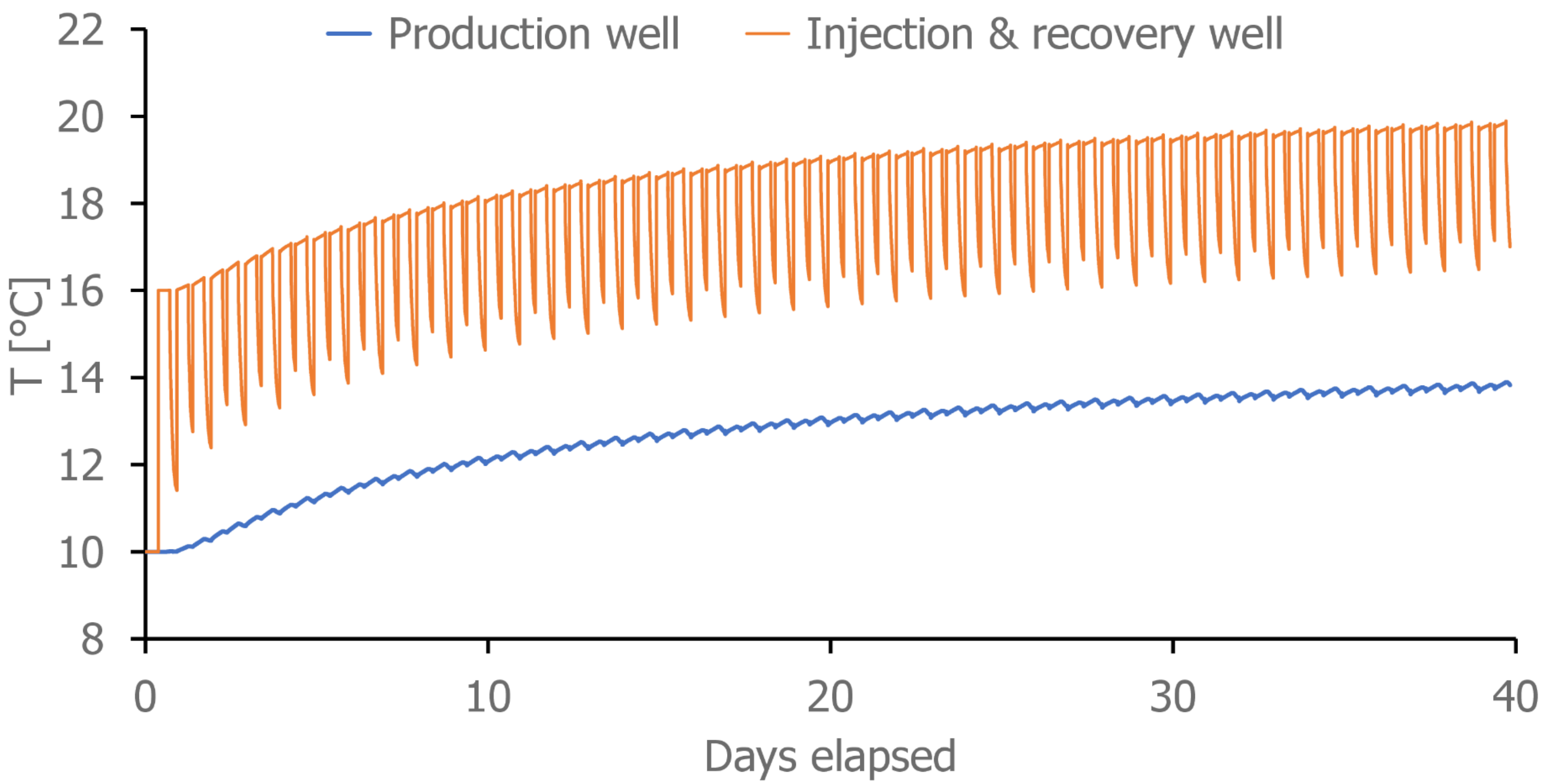


Production well

Injection & recovery well

Example of LT-ATES (ΔT = 6K) – Day 35

For LT-ATES ($\Delta T = 6K$), this strategy works



Heat is stored during off-peak periods and recovered during peak periods (of heat demand)

Heat is then either stored or recovered for heating applications

The key message
is to focus on the survey design
and the collection of a good data set

From then, anything is possible