Case study 1: Constraining 3-D surface ERT with GPR reflection data

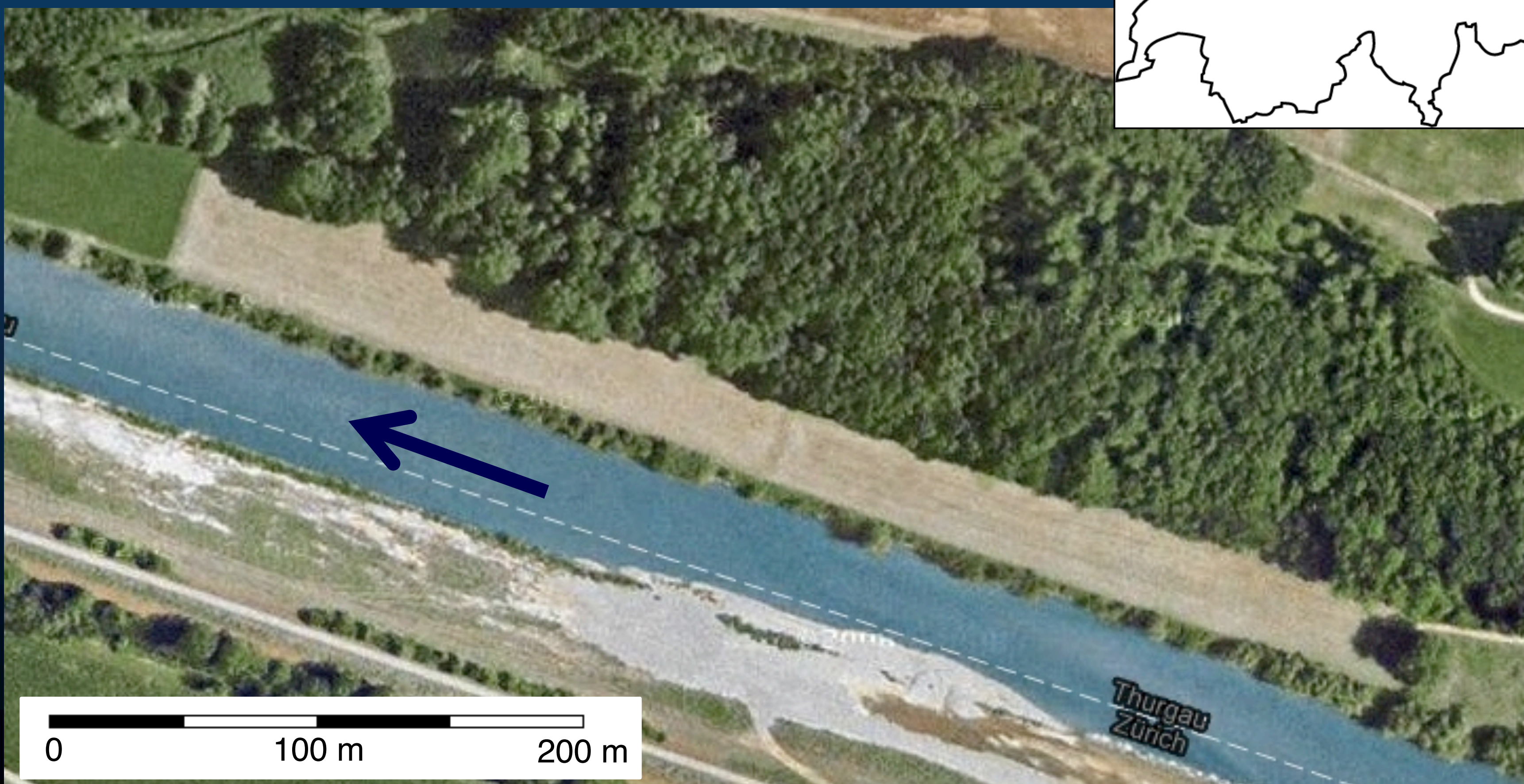
- Aim: hydrogeophysical characterization of gravel bar deposits
- ERT
  - \+ is closely related to relevant properties
  - \- has a low spatial resolution
- GPR
  - \+ can image 3-D geometrical structures at high resolution

⇨ combine strengths of both methods

Doetsch et al. [2012], *J. Appl. Geophys.* **78**, 68–76.

Study area: River Thur

1870 – 1999 (channelized)



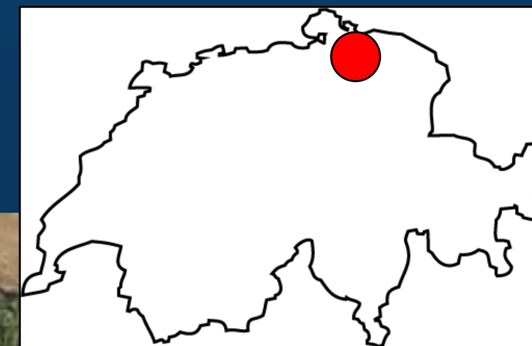


image taken 1997, source: maps.google.com

River Thur: A very dynamic river

River restoration ~2000

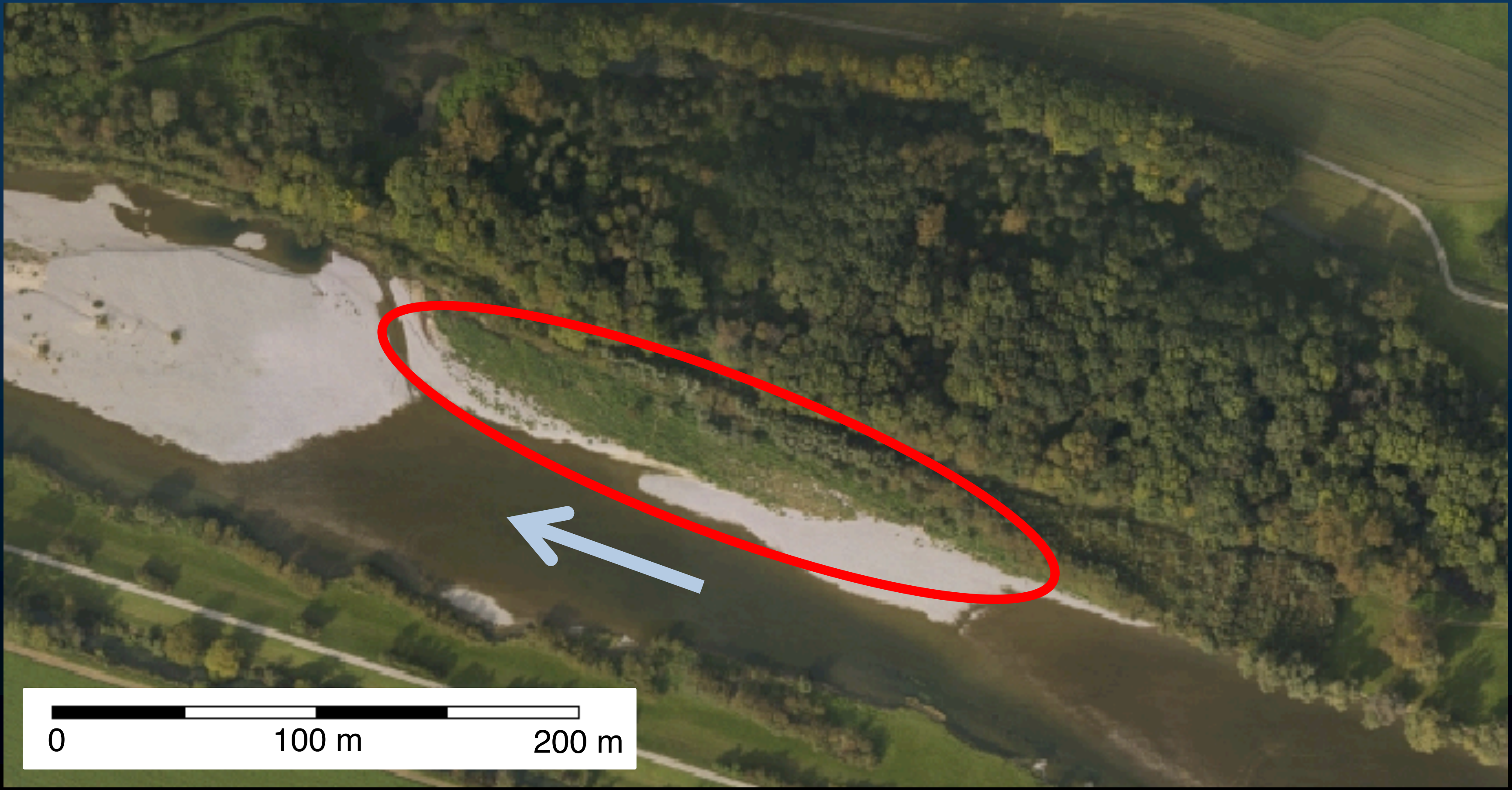


image taken 2008, source: Kanton Thurgau and Zürich

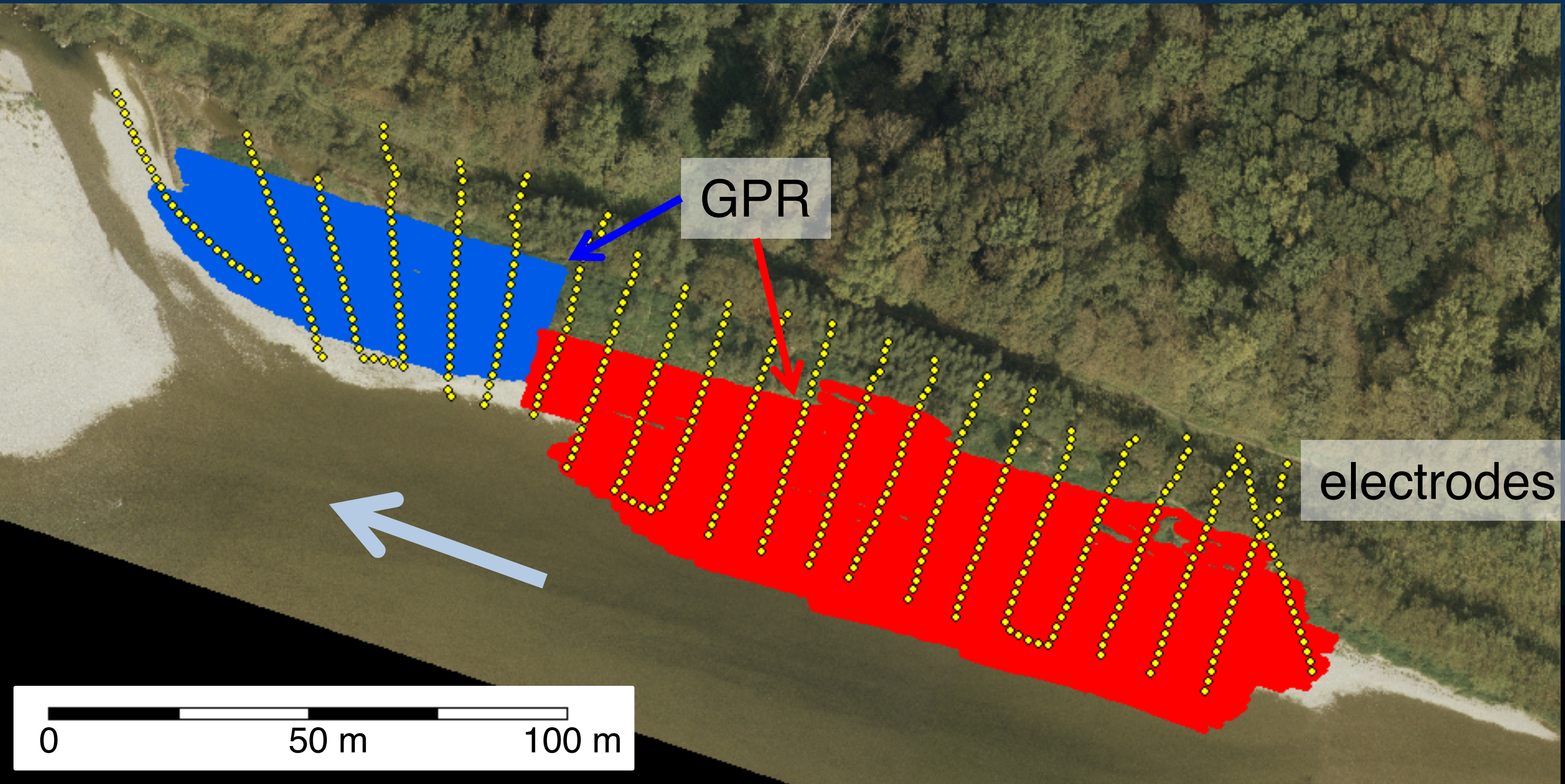
Static GPR and ERT data

GPR

- 100 MHz PulsEkko Pro system
- differential GPS tracking

ERT

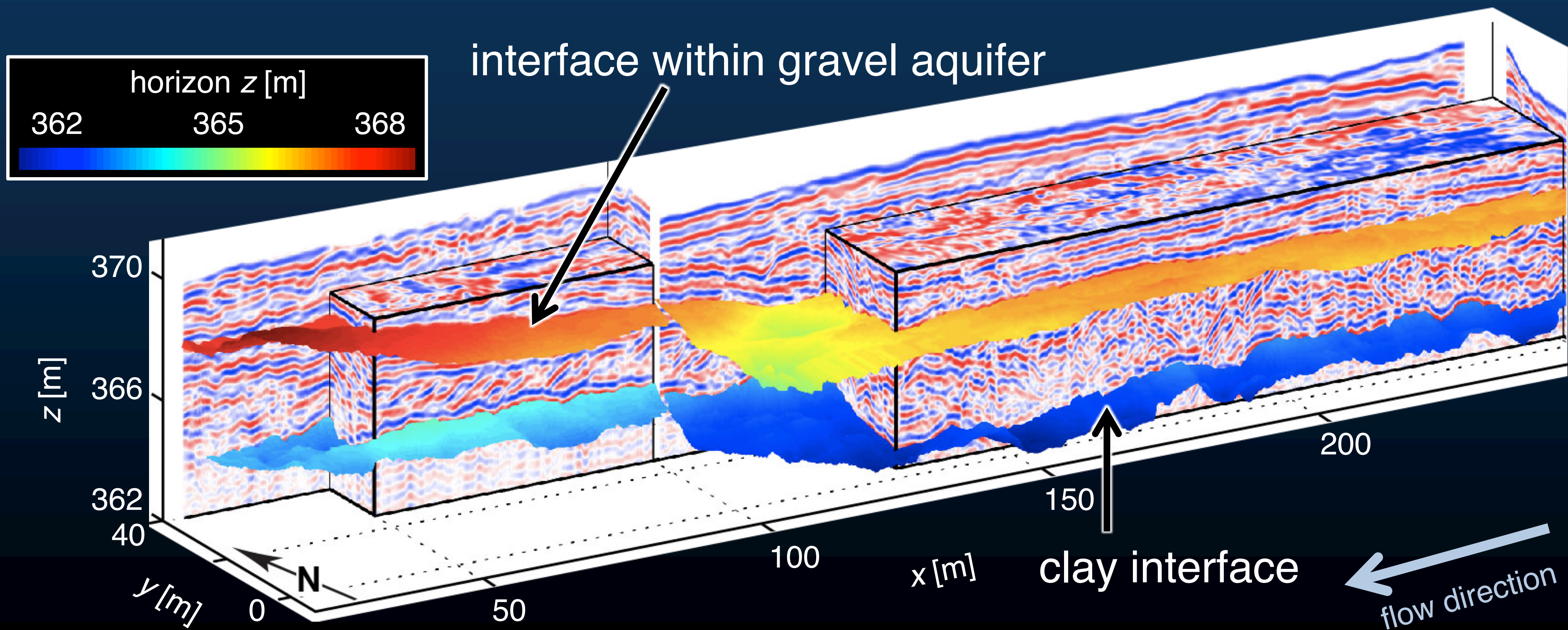
- 522 electrodes in 22 lines,
  3-D meas. across 6 lines
- Syscal Pro unit with 144 channels



GPR interpretation

2 continuous horizons were traced through data volume

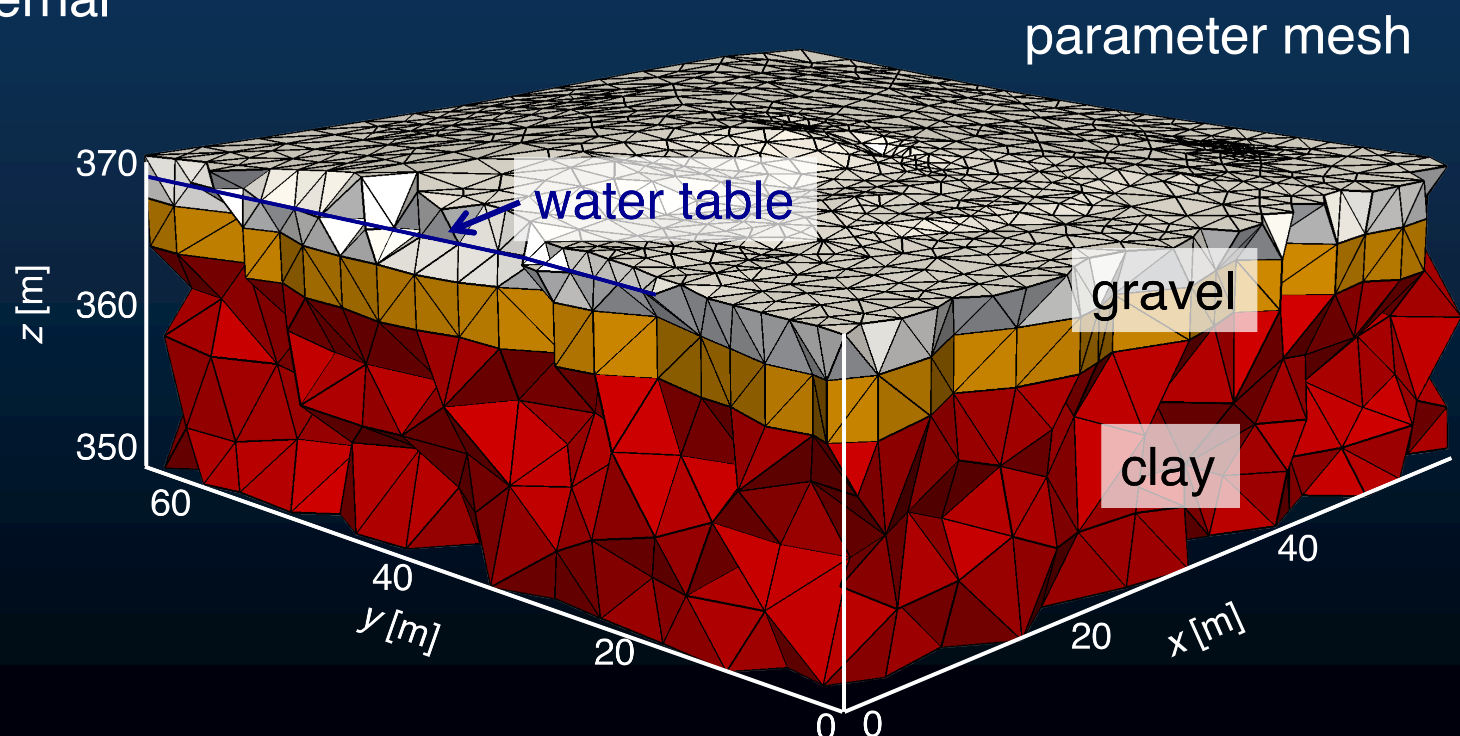
- interface gravel (aquifer) – clay (aquitard)
- horizon within gravel



vertical exaggeration 5:1

ERT mesh generation

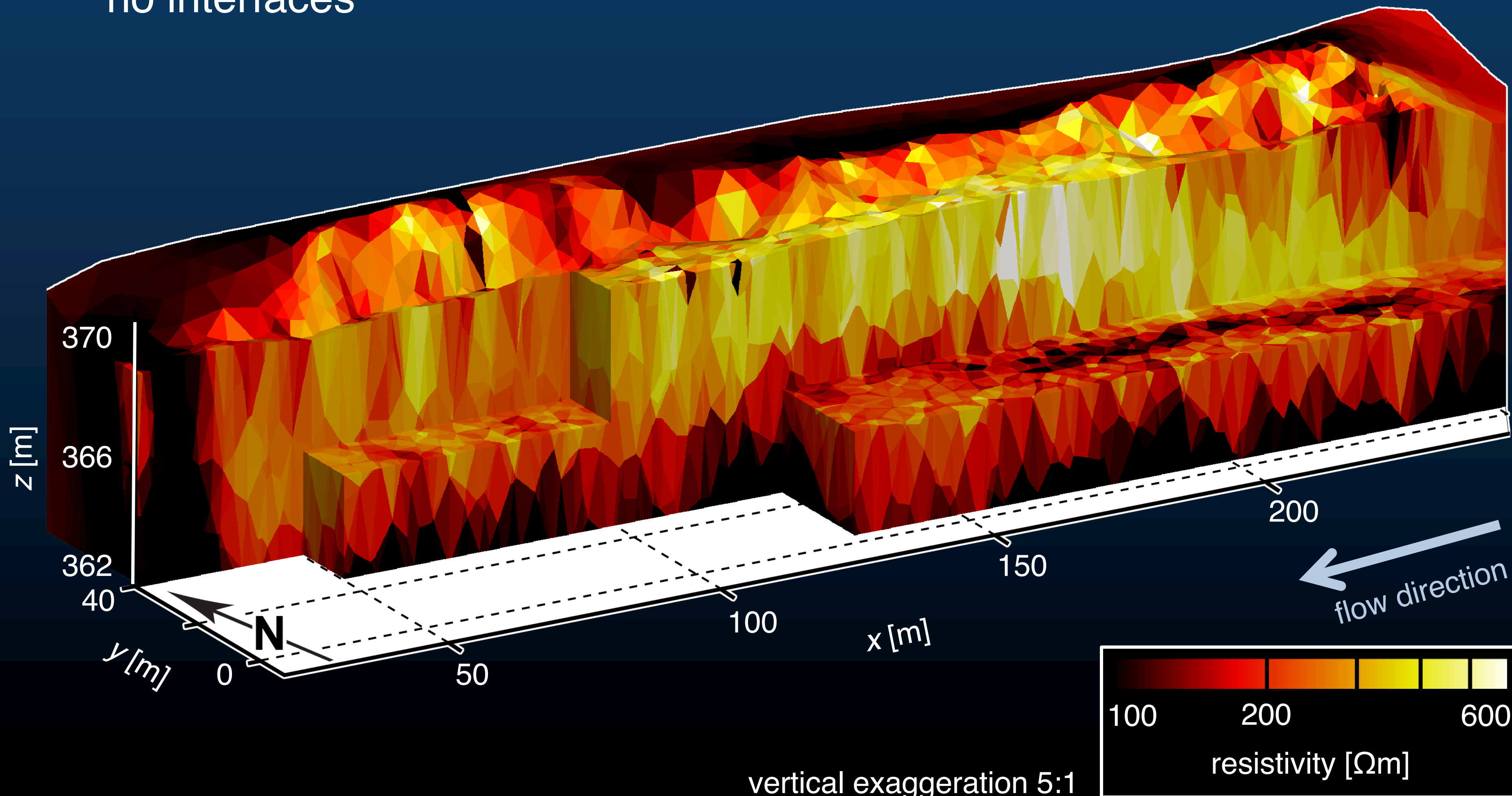
- 3-D tetrahedral (unstructured) mesh
- including surface topography
- 1 or 2 internal horizons



ERT inversion

Case A:

no interfaces

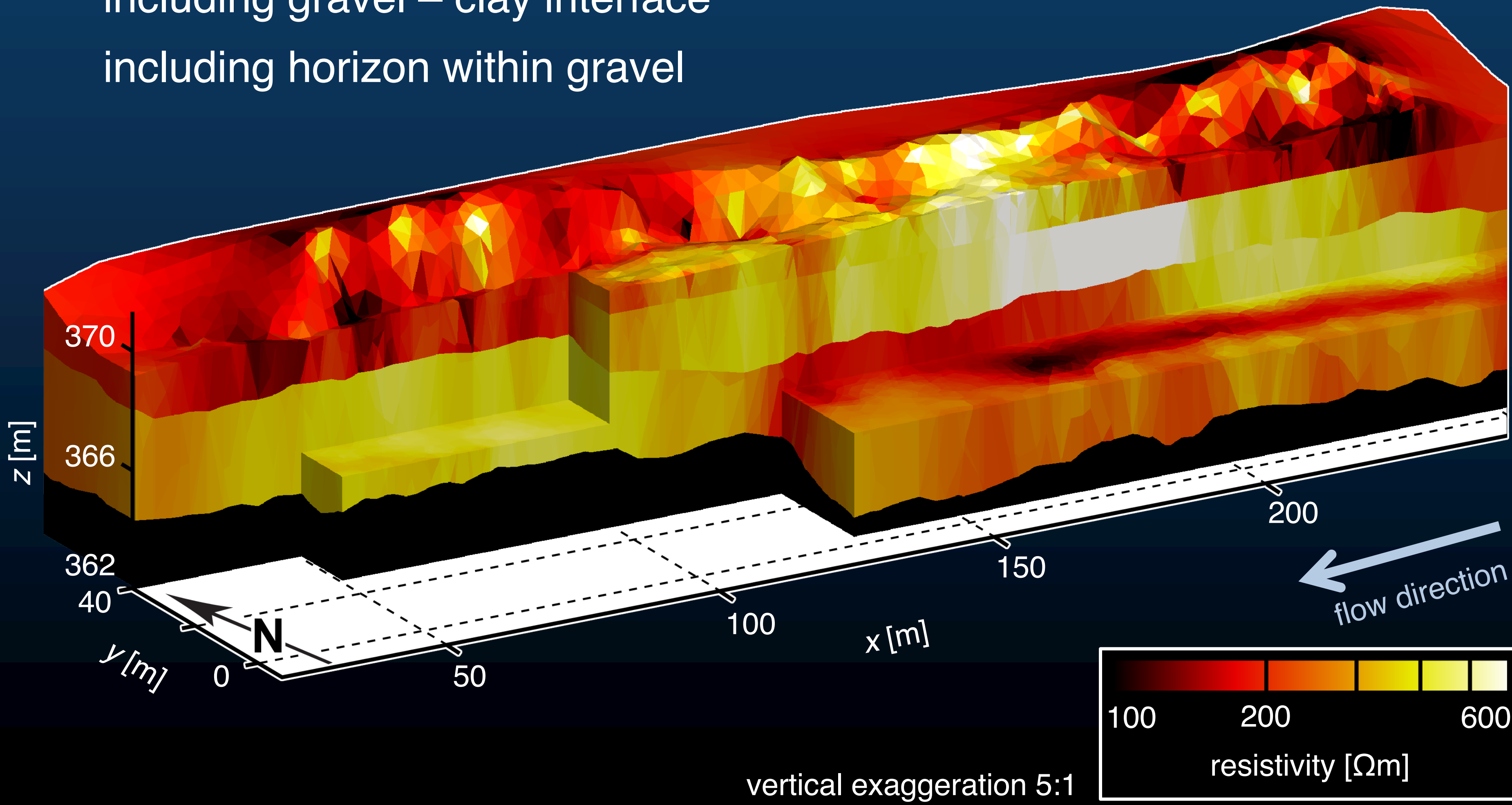


ERT inversion

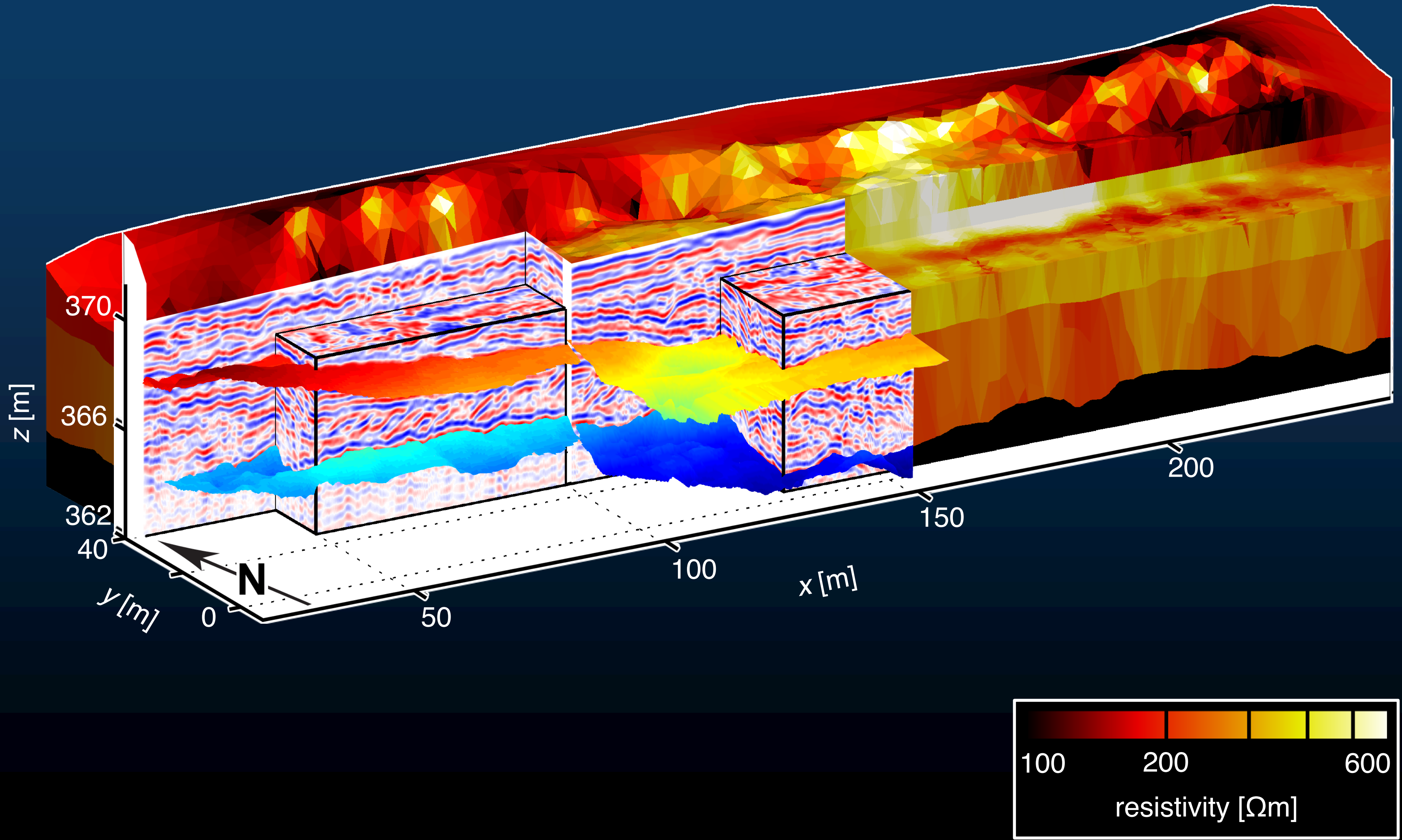
Case B:

including gravel – clay interface

including horizon within gravel



Discussion



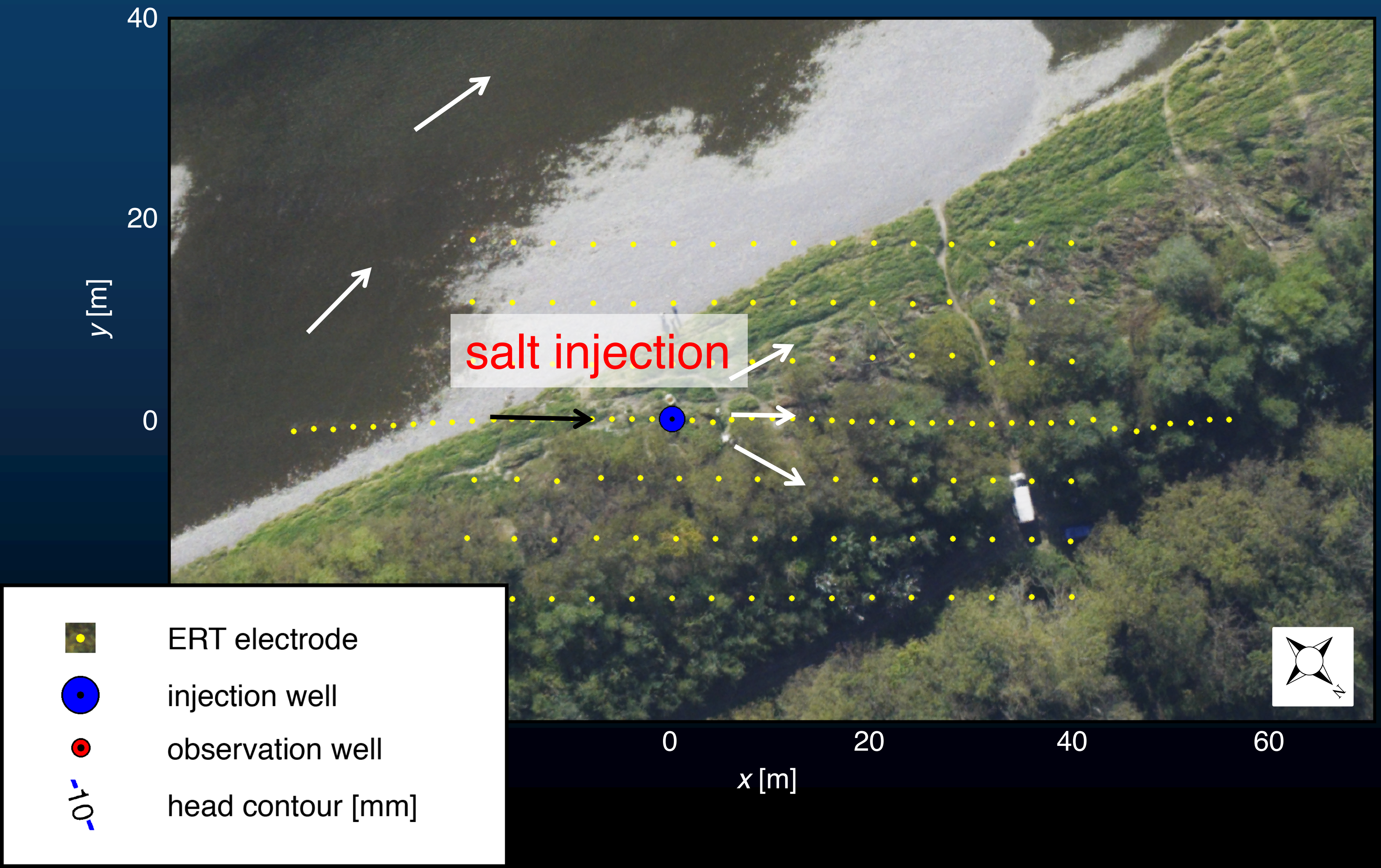
370
366
362
z [m]
40
0
y [m]
N
50
100
150
200
x [m]
100
200
600
resistivity [Ωm]

Case study 2: Salt tracer monitoring with 3-D surface ERT

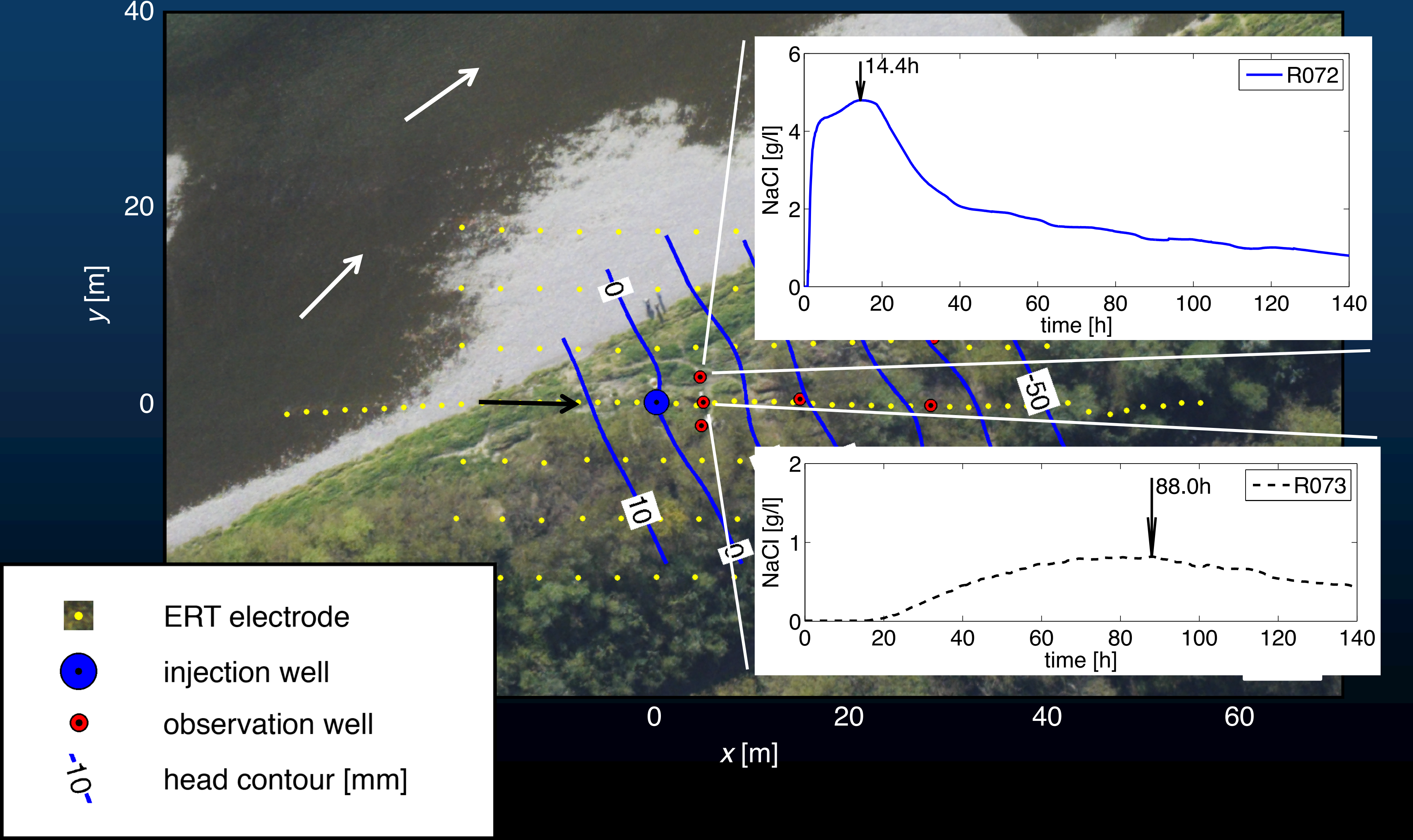
- Study groundwater movement
- Injection of 18 kg salt in 500 l of water
- Monitoring with surface ERT and loggers (conductivity, head and temperature) in boreholes

Doetsch et al. [2012], *Geophysics.* **77**, B207-B218.

Salt tracer test: field layout

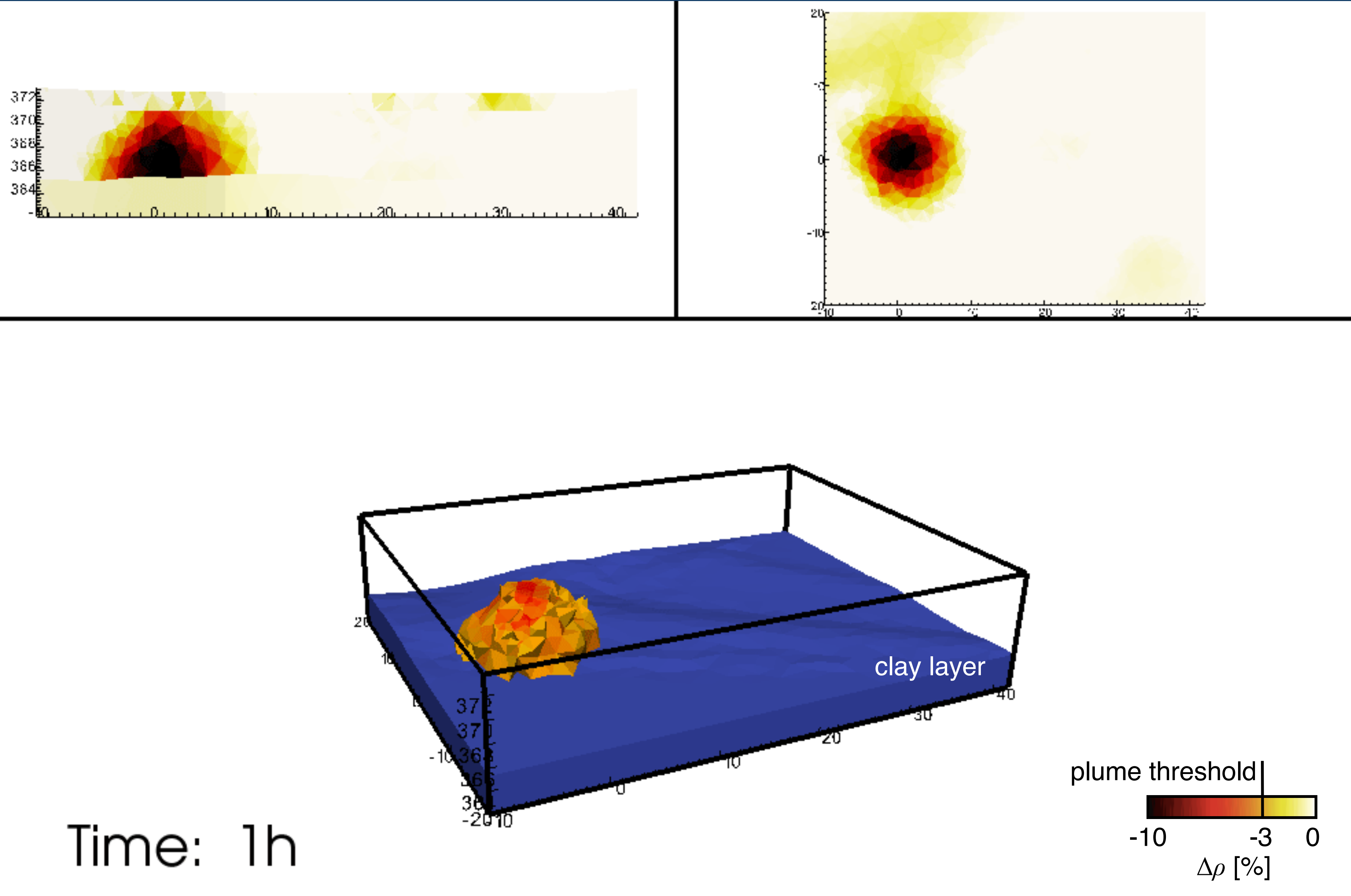


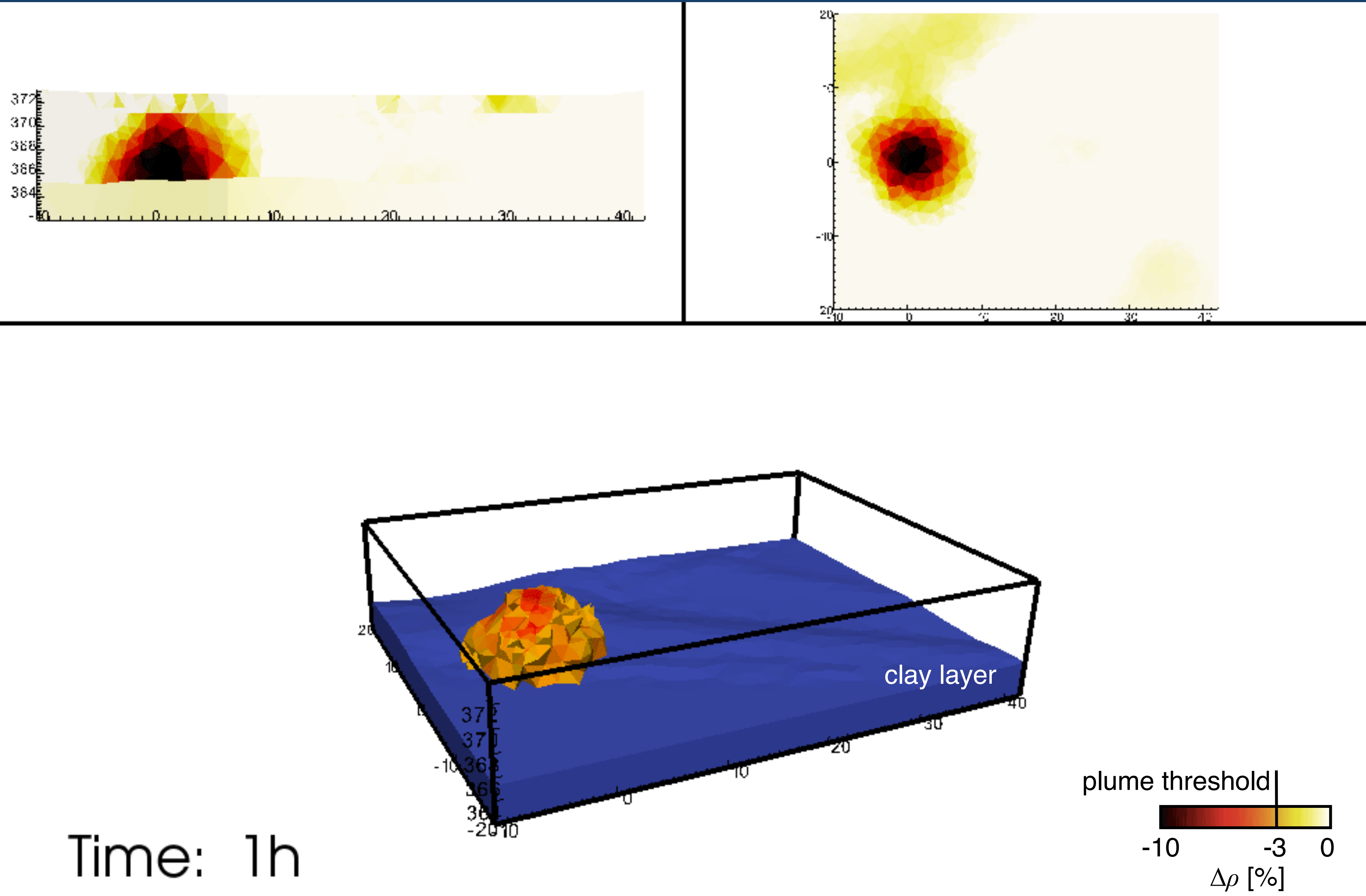
Salt tracer test: hydraulic head



ERT time-lapse inversion

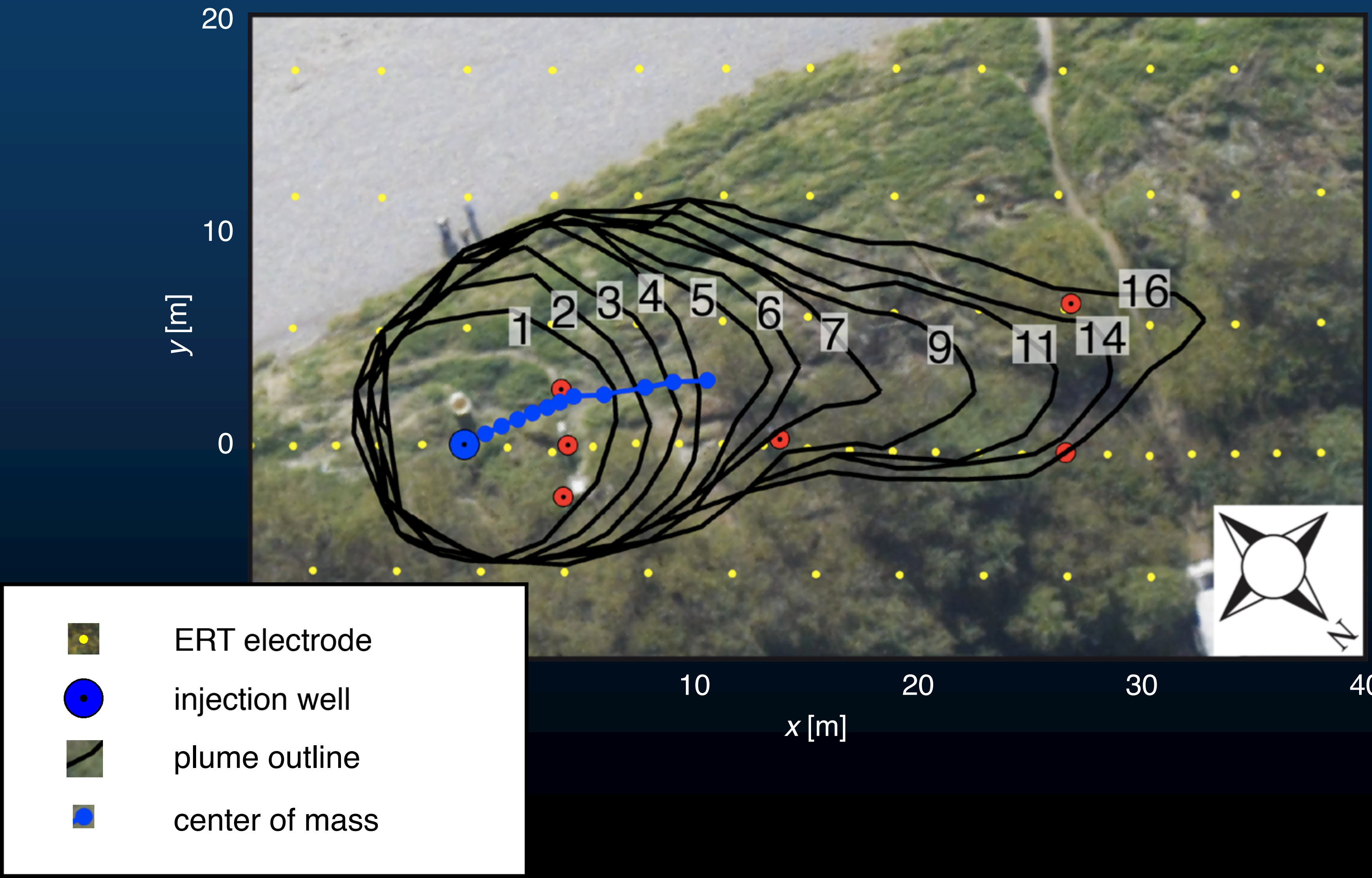
- Invert for the difference to a baseline model for each time-lapse data set using differences in the data
- Fast moving tracer: measure continuously and interpolate measurement values to specific inversion times
- Time-lapse error 14 times smaller than baseline error


clay layer
plume threshold
-10
-3
0
Δρ [%]
Time: 1h



clay layer
plume threshold
-10
-3
0
Δρ [%]
Time: 1h

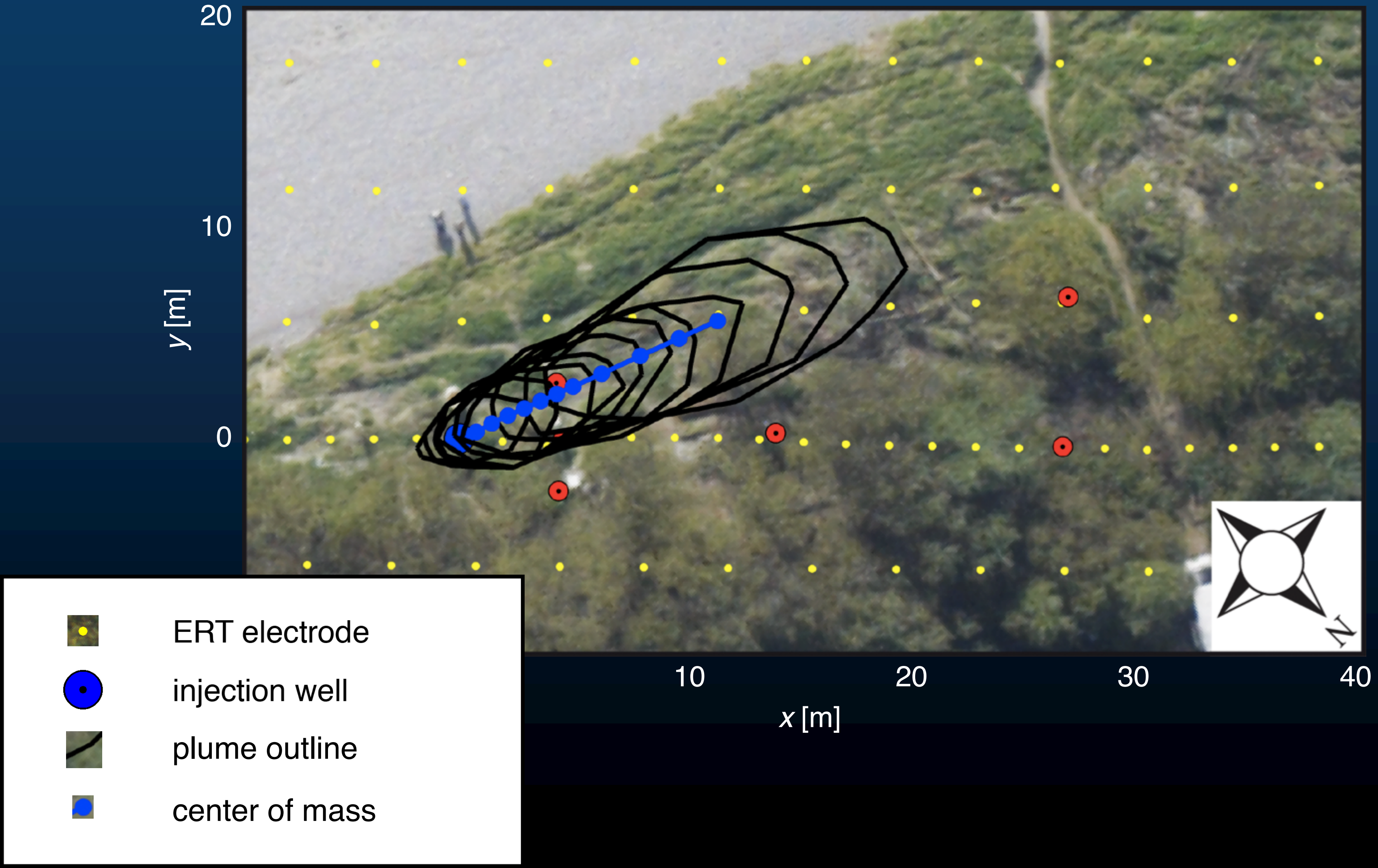
ERT time-lapse inversion: plume outline



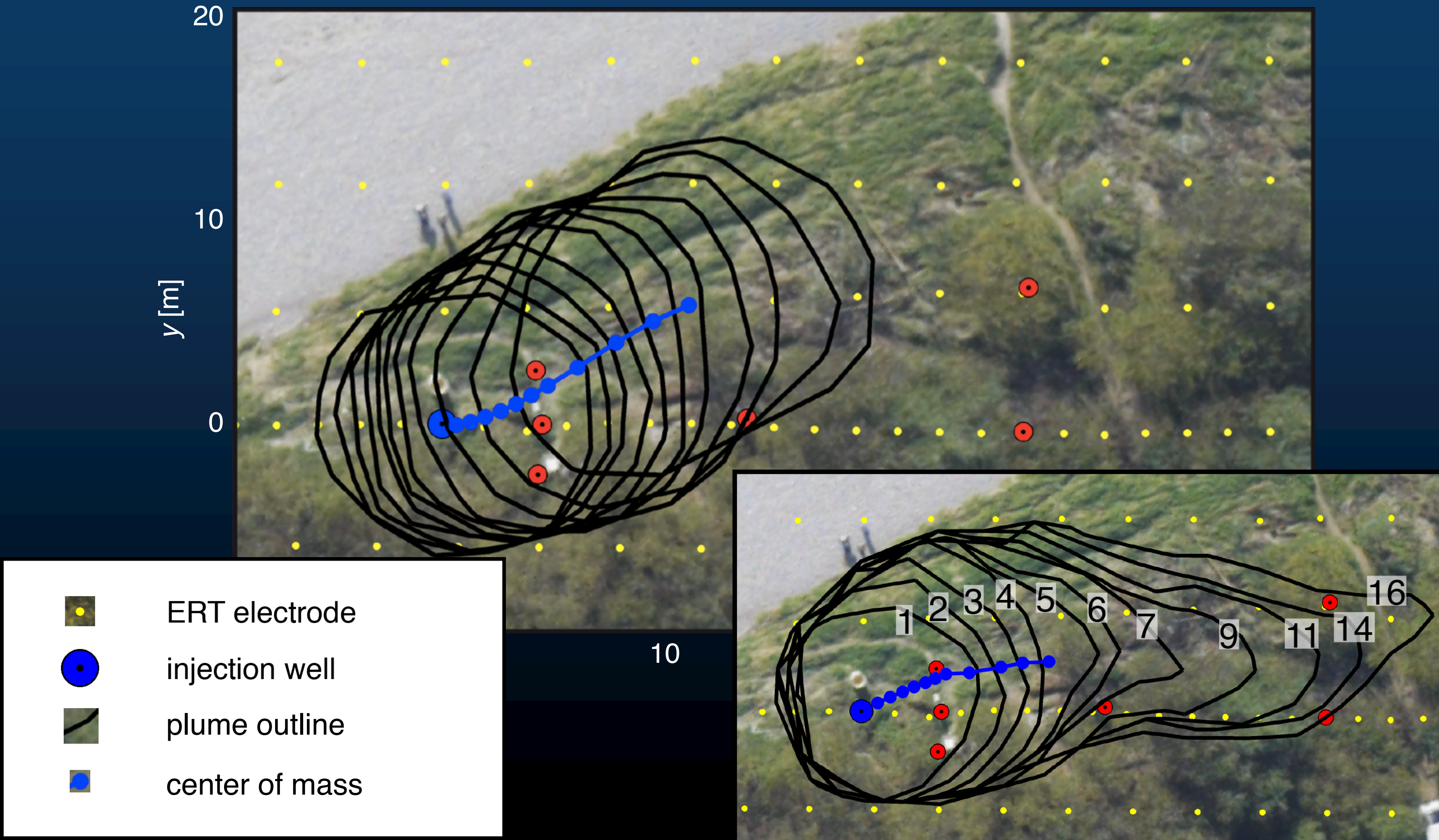
Groundwater simulation

- Using MODFLOW and SEAWAT 4.0 (including density effects of the salt)
- Homogeneous 3-D box model, hydraulic gradient from measurements
- Calibrate homogeneous hydraulic conductivity to fit movement of the center of mass

Groundwater simulation

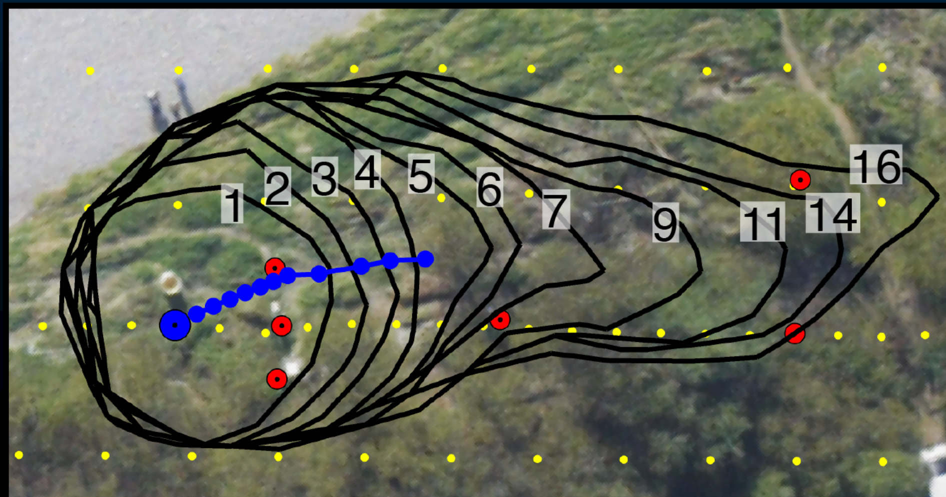


ERT inversion of simulated data (based on groundwater simulation)



Discussion

- We can follow the tracer until it leaves our electrode array
- The groundwater model predicts the tracer movement for the first 5h
- After 5h, a preferential flow path controls the tracer movement



Case study 3: Non-intrusive monitoring of CO_2-induced geochemical changes using geoelectrical monitoring

Auken, E., Doetsch, J., Fiandaca, G., Christiansen, A.V., Gazoty, A., Cahill, A.G., Jakobsen, R., 2014. Imaging subsurface migration of dissolved CO2 in a shallow aquifer using 3-D time-lapse electrical resistivity tomography. *Journal of Applied Geophysics* **101**, 31–41. doi:10.1016/j.jappgeo.2013.11.011
Doetsch, J., Fiandaca, G., Auken, E., Christiansen, A.V., Cahill, A.G., Jakobsen, R., 2015. Field scale time-domain spectral induced polarization monitoring of geochemical changes induced by injected CO2 in a shallow aquifer. *Geophysics* **80**, WA113-126.

AARHUS UNIVERSITY

CO_2-GS

HydroGeophysics Group AARHUS UNIVERSITY

Electrical resistivity monitoring of CO_2

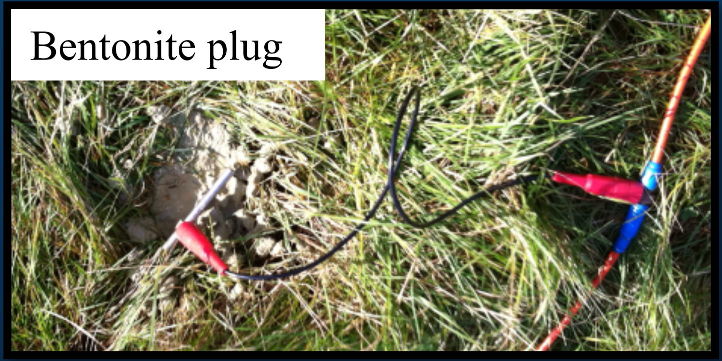
1. Crosswell monitoring of supercritical CO_2 in deep reservoirs
   - Strong signal due to non-conducting supercritical CO_2
   - Instrumentation challenges for deep reservoirs
   - Successful examples include Ketzin, Germany and Cranfield, USA
2. Monitoring of dissolved CO_2 in shallow aquifers
   - No direct CO_2 signal, only geochemical changes induced by the CO_2 can be observed
   - Decreasing resistivity due to higher ion concentration, but effect highly site dependent (e.g., Dafflon et al., 2013, ES&T)
   - Induced Polarization (IP) monitoring of geochemical changes?

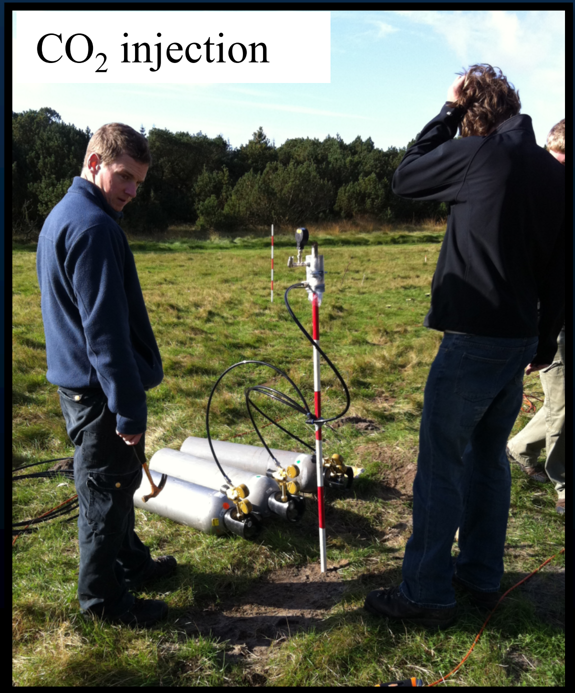
CO_2 injection experiment

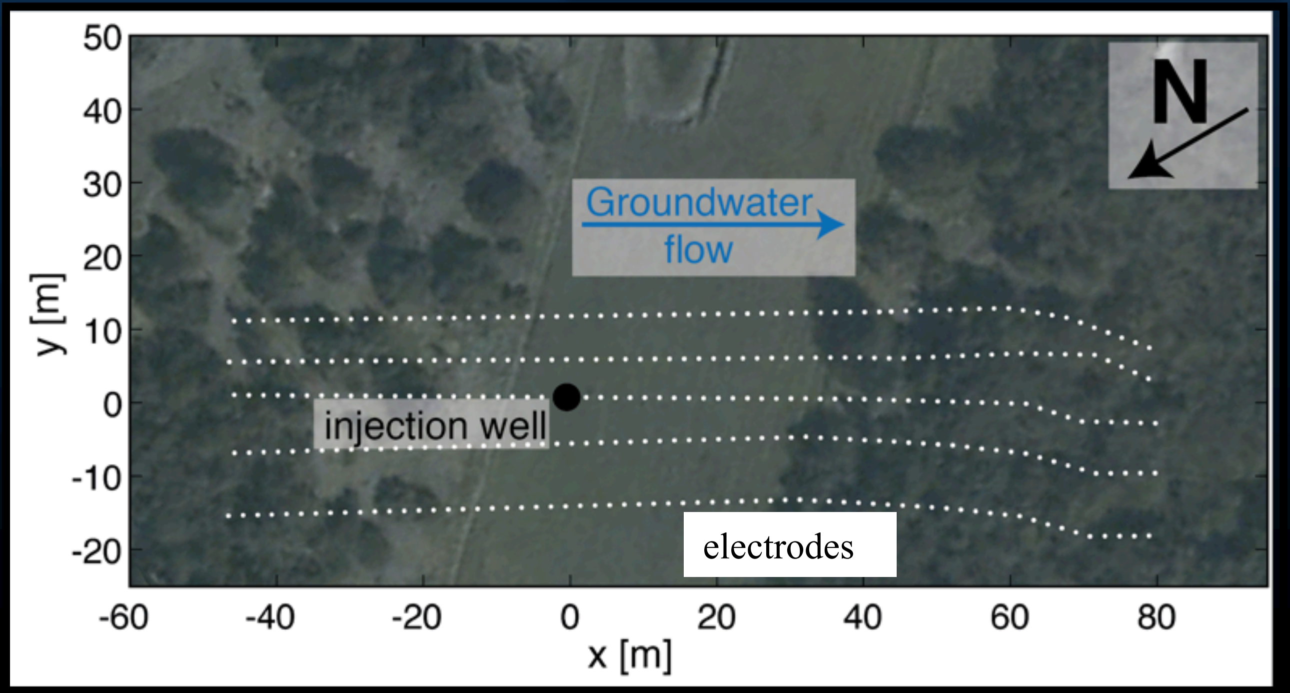
- Field site in western Denmark
- Geology consisting of
  - Aeolian sand (0-5 m depth)
  - Glacial sands (5-10 m depth)
  - Marine sands (below 10 m depth)
- Groundwater table at 2 m depth
- CO_2 injection
  - 4 injection points at 5 and 10 m depth
  - Injection started on May 14^{th} 2012, 12 L/min
  - reduced to 6 L/min after 14 days
  - Total of 1600 kg CO_2 injected in 72 days
- Pilot study showed consistent decrease of resistivity with increasing CO_2 concentrations

ERT monitoring setup 1/2

- 320 electrodes at 2 m spacing in 5 lines (5-8 m line spacing)
- Electrodes installed in bentonite plugs

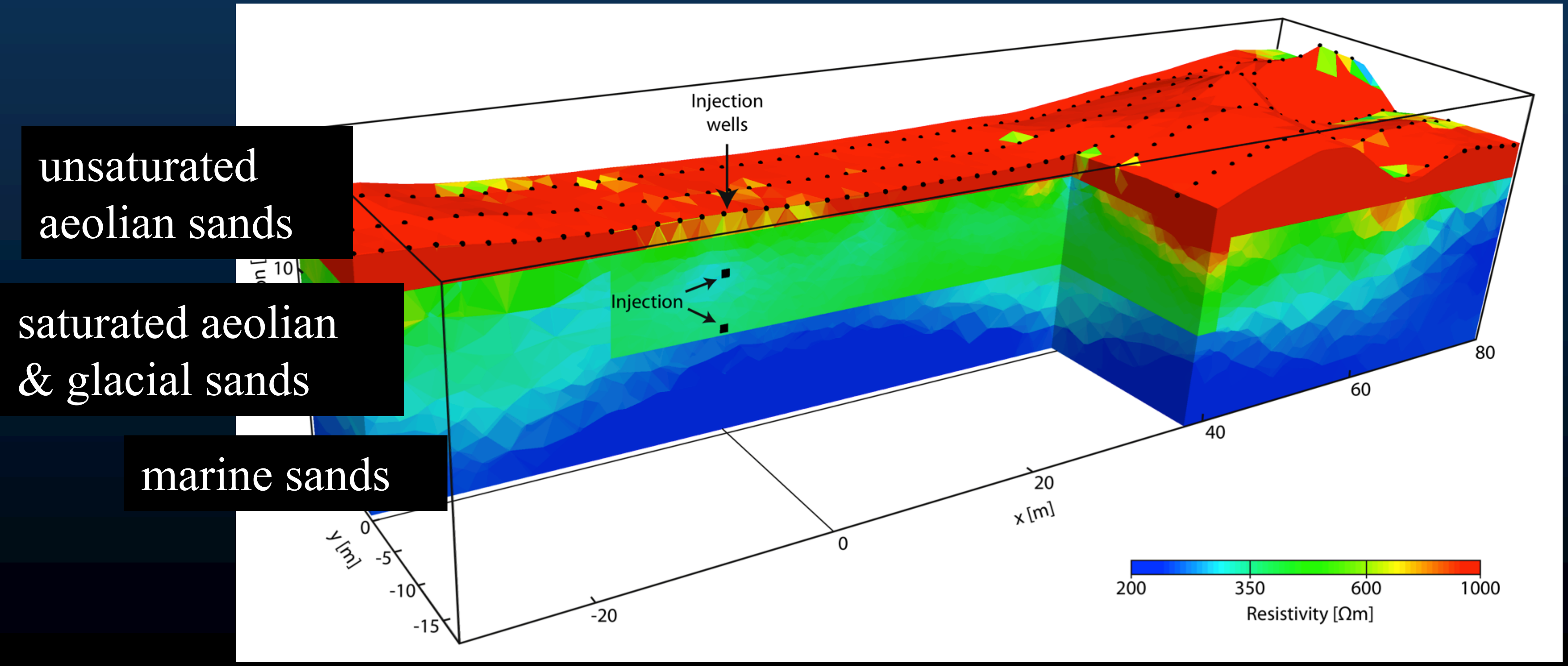






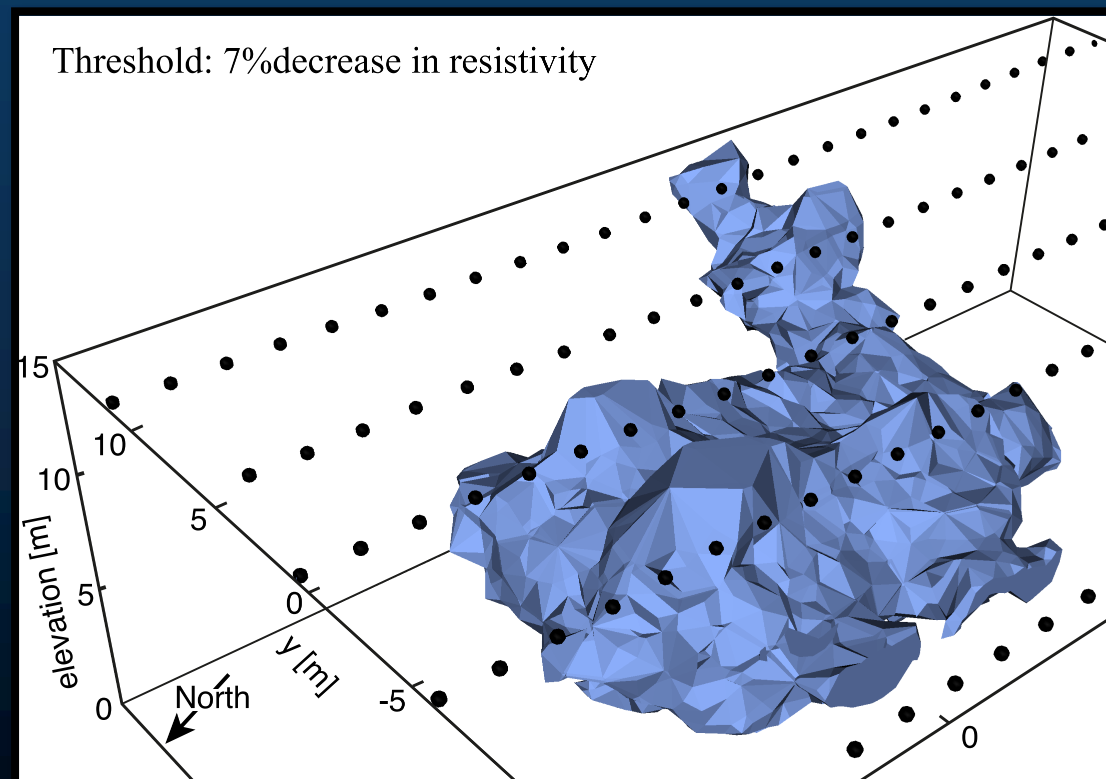
Baseline ERT inversion

- Undisturbed pre-injection resistivity distribution
- Unstructured finite-element mesh allows to include arbitrary geometry
- Inversion using BERT (Günther et al., 2006, GJI)



3-D time-lapse ERT inversion

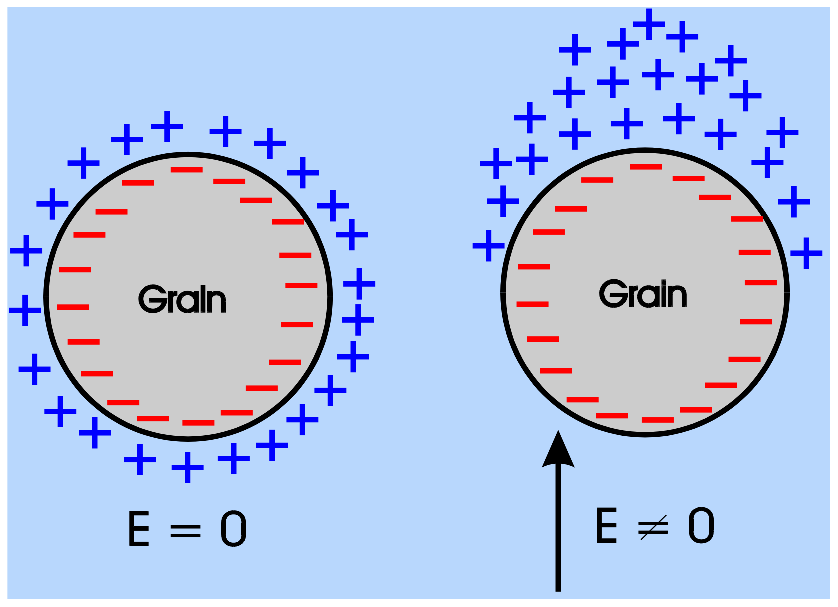
- CO_2 plume imaged as decrease in electrical resistivity
- Imaging of CO_2 migration in 3-D for 120 days
- Good agreement with water electrical conductivity measurements at 79 sampling locations



Auken et al., 2014, J. Applied Geophysics 101, 31

Induced Polarization: Introduction

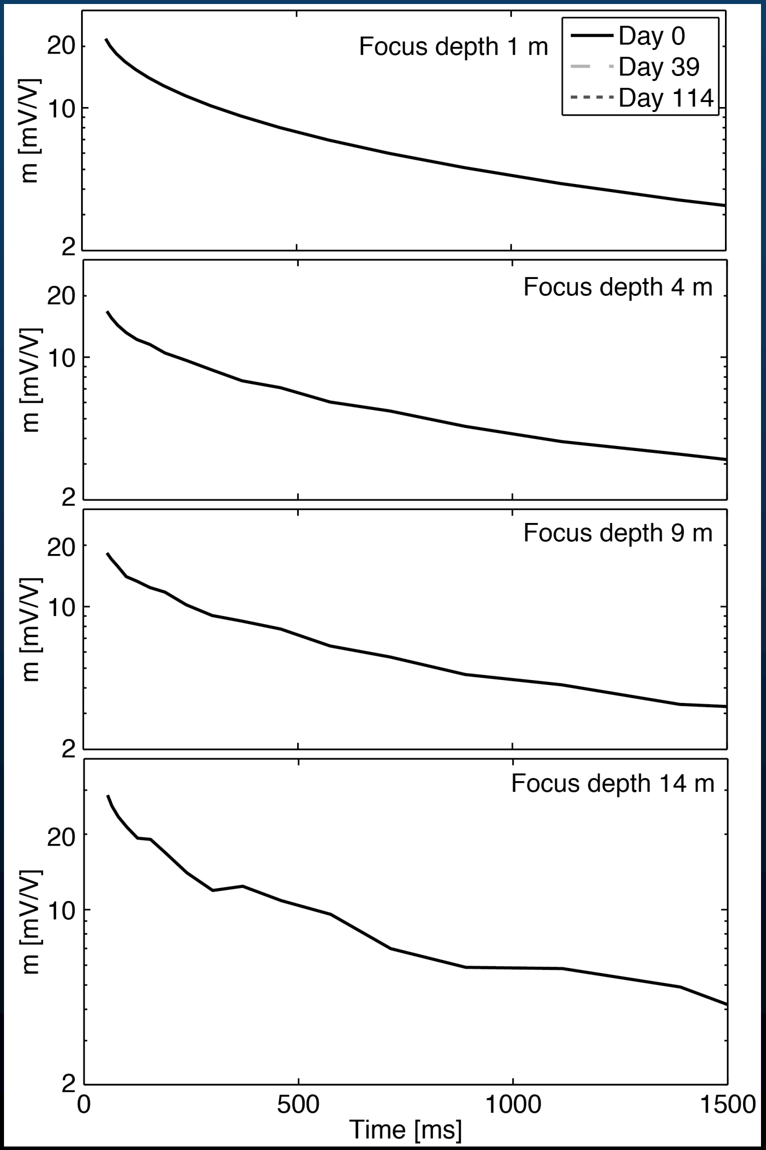
- Induced Polarization measures sub-surface chargeability.
- Chargeability describes the soil capacity to charge up and store electrical charges in presence of time-varying electric fields.



Schematic for polarization of electrical double layer of interconnected pore surface around a single mineral grain

Induced polarization (IP) processing

- Full IP decay (20 gates) recorded for each DC measurement
- 2 s on/off time, 4 stacks
- Clear and consistent change of IP decays during injection
- Error estimation based on measured voltage (0.2 mV) + 4% relative error (median of 5% for first gate, 20% for last gate)

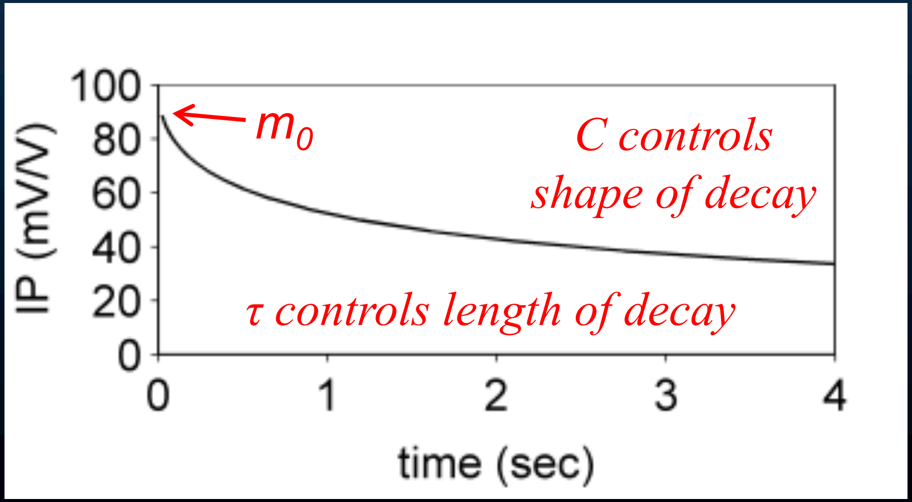


IP parameterization: Cole-Cole Model

- Invert for four model parameters, using full decay curve
- Complex resistivity

$$\zeta(\omega) = \rho\left[1 - m_0\left(1 - \frac{1}{1+(i\omega\tau)^C}\right)\right]$$

- Cole-Cole model parameters
  - Resistivity ρ [Ωm]
  - Chargeability m_0 [mV/V]
  - Mean relaxation time τ [s]
  - Frequency exponent C [dimension-less]



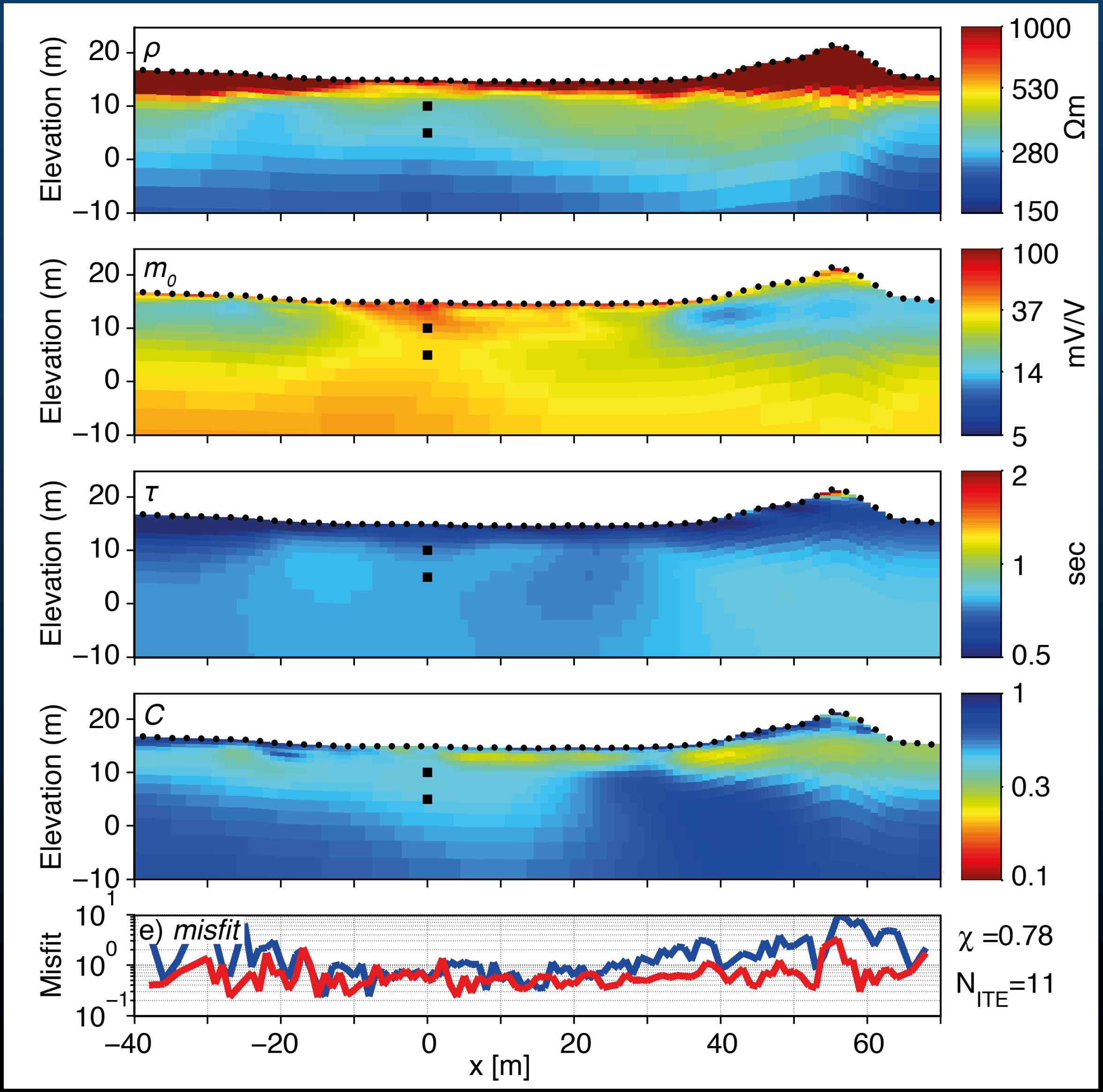
2D baseline inversion

Resistivity ρ

Chargeability m_0

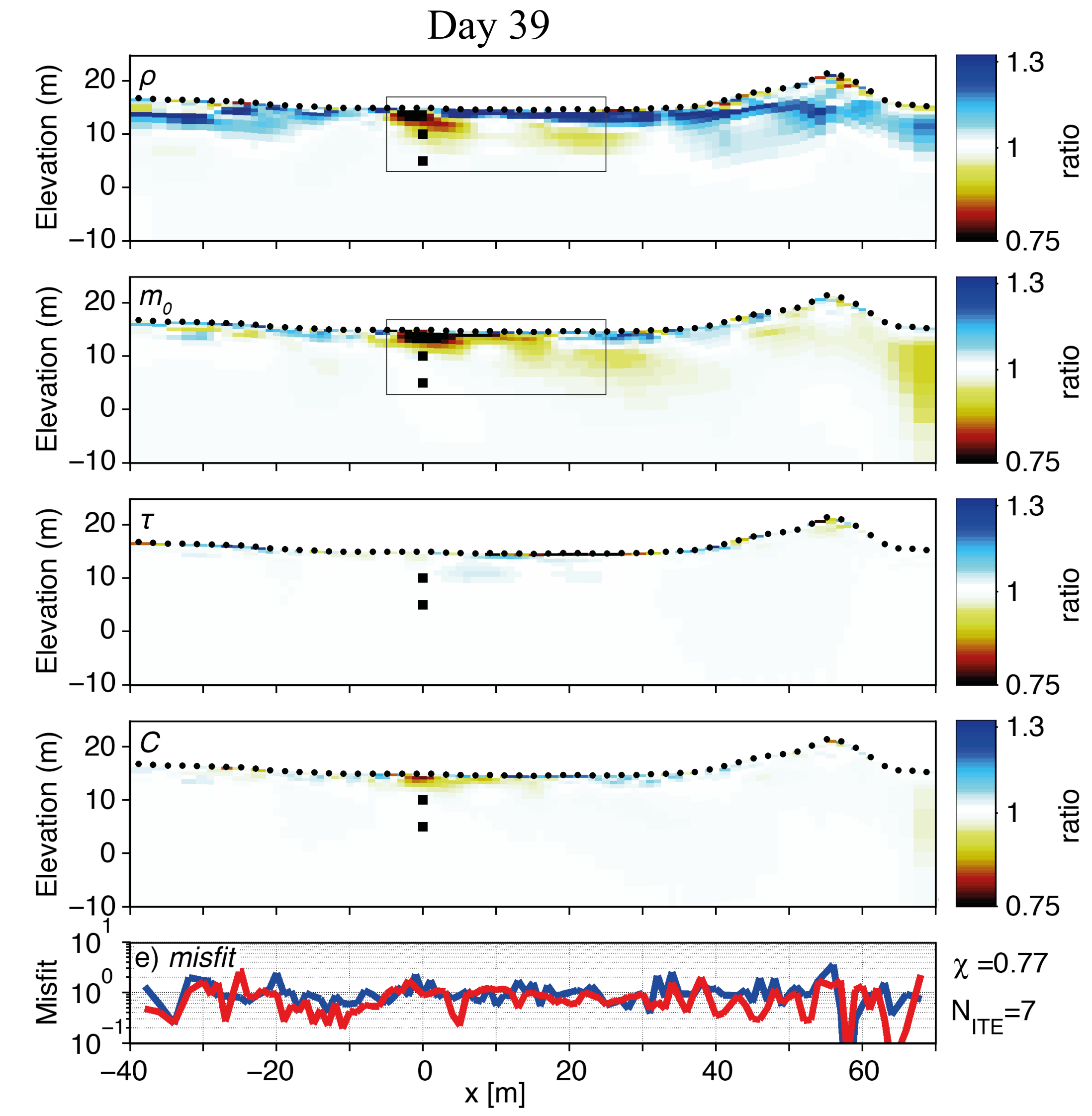
Mean relaxation time τ

Width of the frequency distribution C



Time-lapse inversion

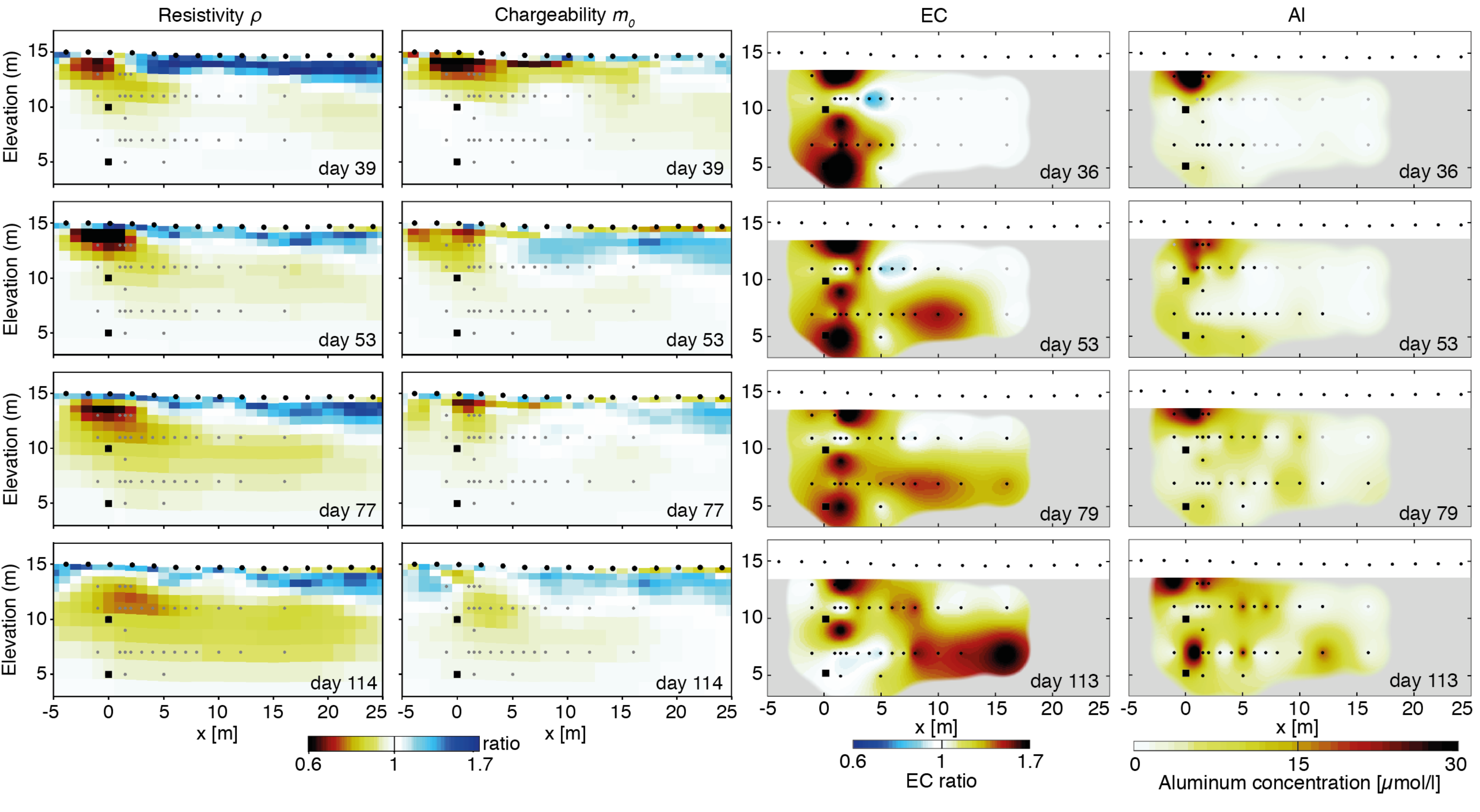
- Difference inversion for all parameters
- Changes in ρ and m_0 necessary to fit data
- Changes in τ and C not resolved
- Decrease in ρ and m_0 close to injection well
- Near-surface anomalies due to groundwater table variation



Chemical data: EC and Al

- Water samples from 33 locations on main transect
- Analyzed for Electrical conductivity (EC) – comparison with bulk resistivity
- Analyzed for Aluminum (Al) and other dissolved element concentrations. Al is the only compound that exceeded drinking water limits

DC/IP inversion results – chemical data



Discussion

2 chemical mechanisms imaged:

1. **Advective pulse** from carbonic acid reacting with Al-hydroxide minerals forming bicarbonate and Al ions releasing other cations by surface processes (primarily ion exchange) imaged by lower **DC-resistivity**
2. **pH is lowered** by the carbonic acid, changing surfaces directly (by dissolution) and indirectly by altering the surface charge, the combined effect being picked up in the **IP signal**

Conclusions

- Changes in groundwater chemistry (caused by dissolved CO_2) give a clear resistivity and chargeability signal
- Resistivity changes can be imaged in 3-D for extended periods (>100 days) using surface electrodes (electrodes below water table preferred)
- Induced polarization monitoring data can be (reliably) acquired and the full decays inverted using state of the art algorithms
- DC resistivity monitoring is ready for large scale implementation (e.g., CO_2 sequestration, sea-water intrusion, permafrost, fracking)
- IP monitoring can be reliably implemented, further research needed to understand IP mechanisms in detail
- 3-D inversion of full IP decay curve available soon