Electrical and ElectroMagnetic methods for the characterization and monitoring of contaminated sites

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Outline

- Electrical methods
  - Induced polarization for the characterization of hydraulic properties
  - Monitoring with modelling of temperature effect
- Electromagnetic methods
  - Unparalleled productivity
  - Airborne EM for mapping at basin scale
  - Ground-EM in continuous acquisition for detailed mapping: tTEM e Loupe systems
- Conclusions

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Induced polarization for the characterization of hydraulic properties

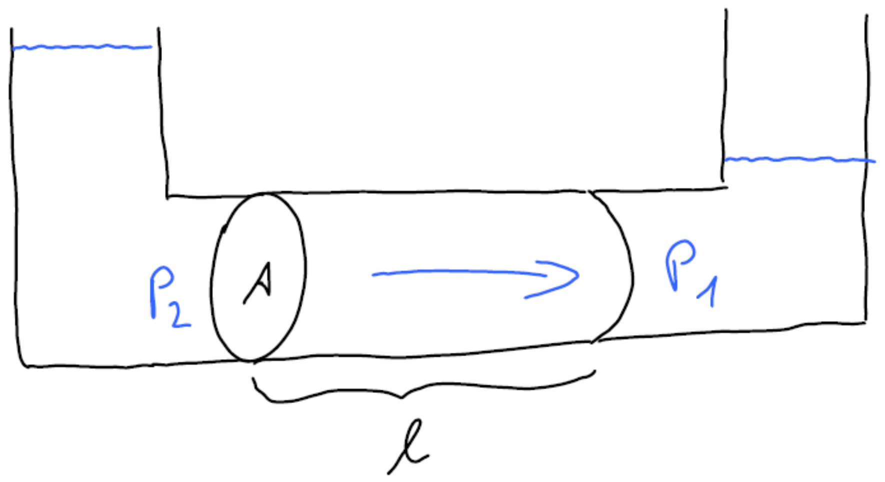
- Characterization of hydrogeological heterogeneity at contaminated sites
- Direct estimation, with petrophysical relations derived in the lab, of hydraulic conductivity in unconsolidated, saturated sediments
- Geophysical models used to inform groundwater and transport modelling

Induced Polarization vs Hydraulic Conductivity K

- Permeability (k)

Darcy's law

$$Q = k \cdot \frac{(p_2 - p_1) \cdot A}{\eta \cdot l}$$



Q=discharge *in* m^3/s
η = viscosity in kg/m·s
k = permeability in m^2

$$1 Darcy = 10^{-12} m^2$$

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Hydraulic conductivity (K) – Permeability (k)

$$K = k \cdot \frac{\rho \cdot g}{\eta}$$

Water: $\rho \approx 1000 \frac{kg}{m^3}$ $\eta \approx 10^{-3}\ Pa \cdot s$ $g \approx 10 \frac{m}{s^2}$

$$K(m/s) = 10^7 k(m^2)$$

IP vs k: petrophysical relations

- Two different approached used in the IP community for estimation of hydraulic conductivity (K)/ permeability (k):
  - k from surface area per unit volume S_{por} (e.g. Weller et al. (2015))

$$k = \frac{a}{F^b \cdot S_{por}{}^c}$$

  - k from the dynamic pore radius Λ (e.g. Revil et al. (2012))

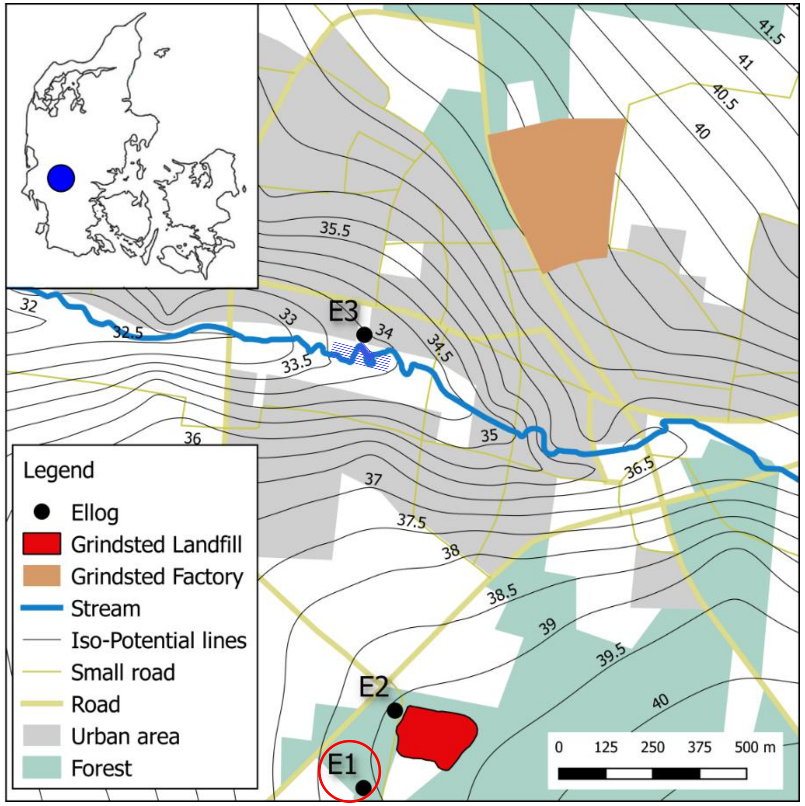
$$k = \frac{\Lambda^2}{8F}$$

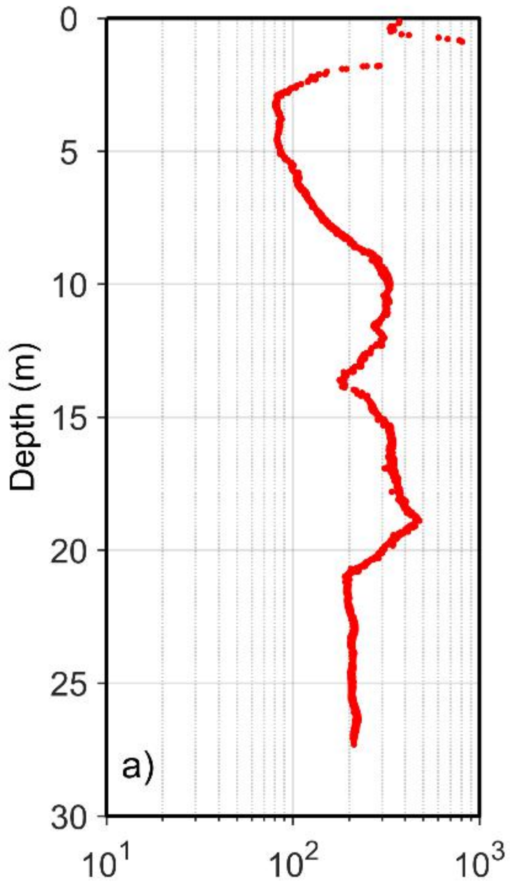
Weller, A., Slater, L., Binley, A., Nordsiek, S., & Xu, S. (2015). Permeability prediction based on induced polarization: Insights from measurements on sandstone and unconsolidated samples spanning a wide permeability range. *Geophysics*, *80*(2), D161-D173

Revil, A., Koch, K., and Holliger, K. (2012), Is it the grain size or the characteristic pore size that controls the induced polarization relaxation time of clean sands and sandstones?*Water Resour. Res.*, 48, W05602

K inversion of field galvanic data

- 3 El-log acquisitions with TDIP data (Fiandaca et al., 2018): 30 m, 27 m and 10 m deep
- Grindsted site, Denmark; 9 slug test and 54 grain size analysis for comparison





Fiandaca, G., Maurya, P. K., Balbarini, N., Hördt, A., Christiansen, A. V., Foged, N., ... & Auken, E. (2018). Permeability estimation directly from logging-while-drilling induced polarization data. *Water Resources Research*, *54*(4), 2851-2870.

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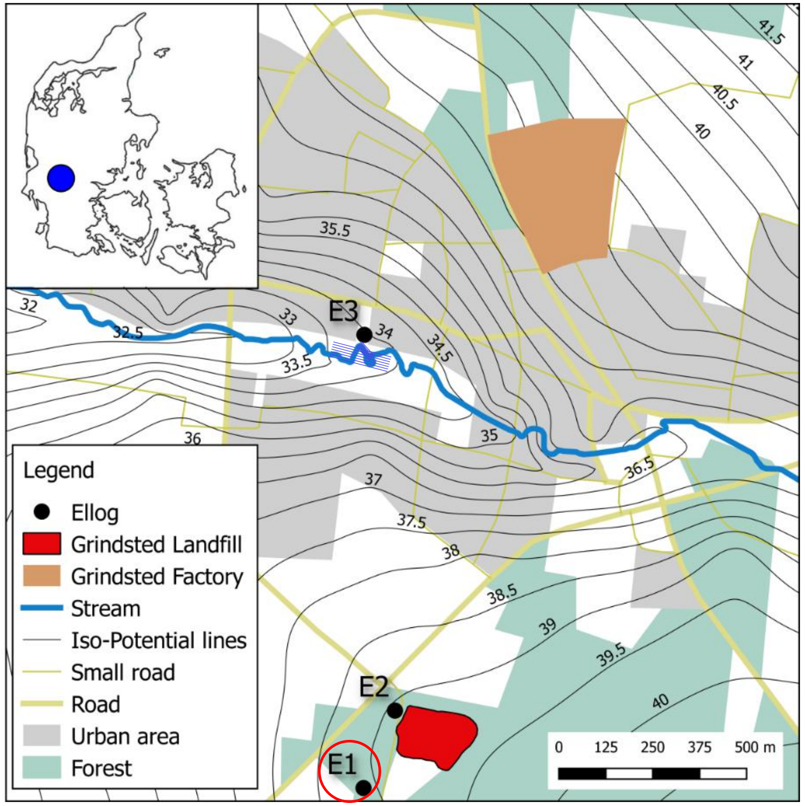

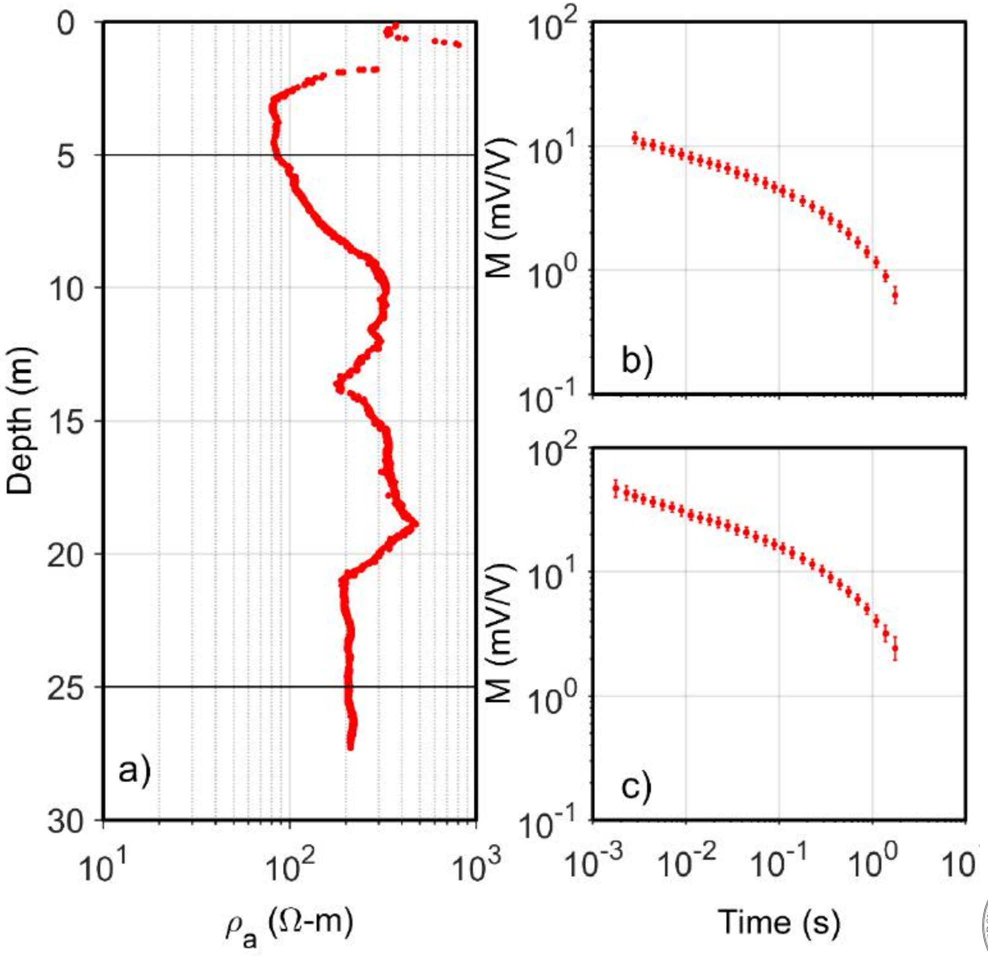

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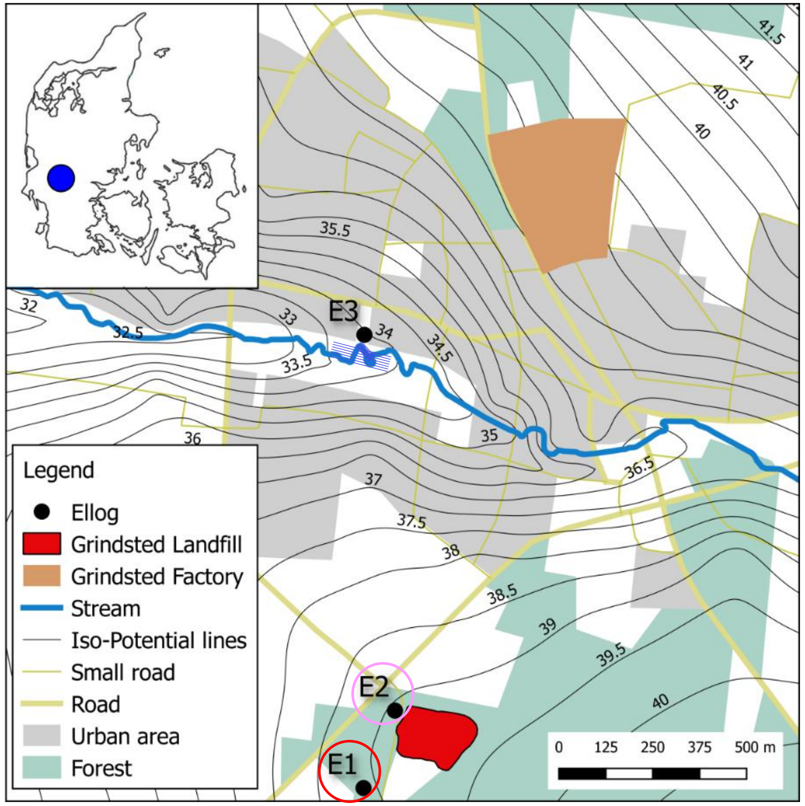

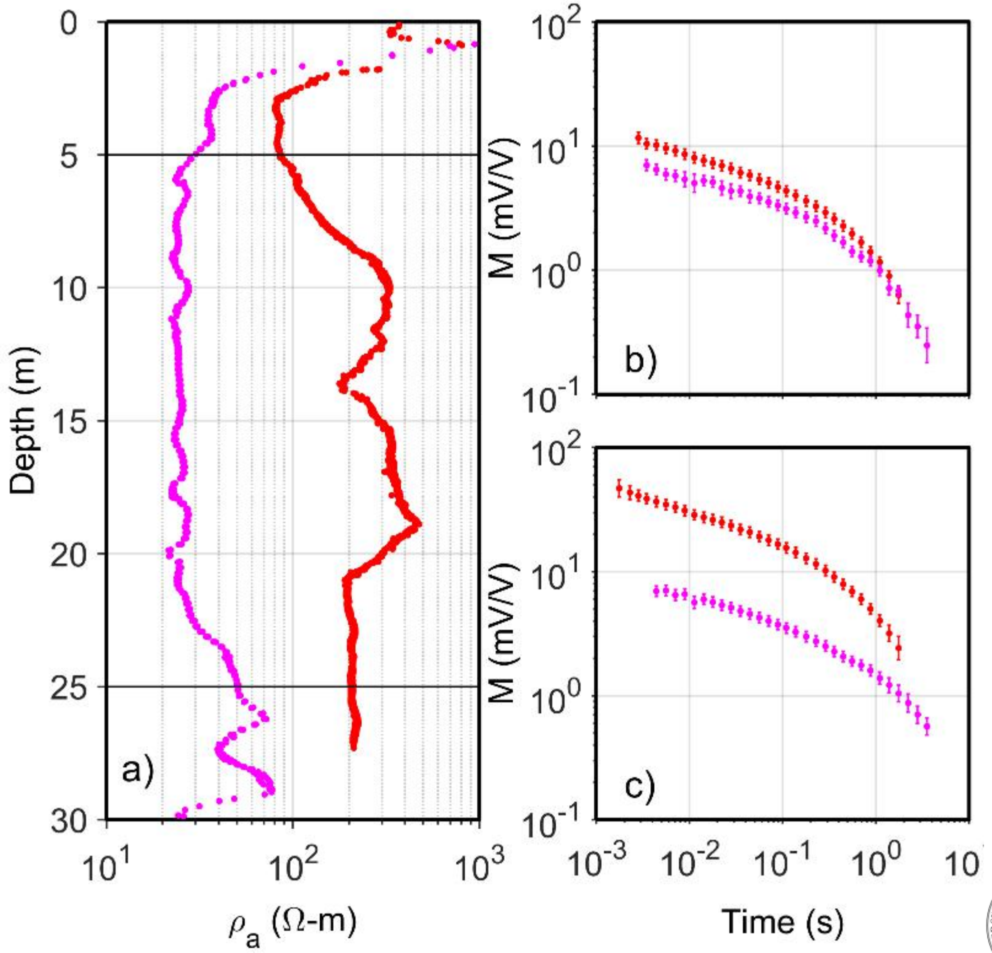

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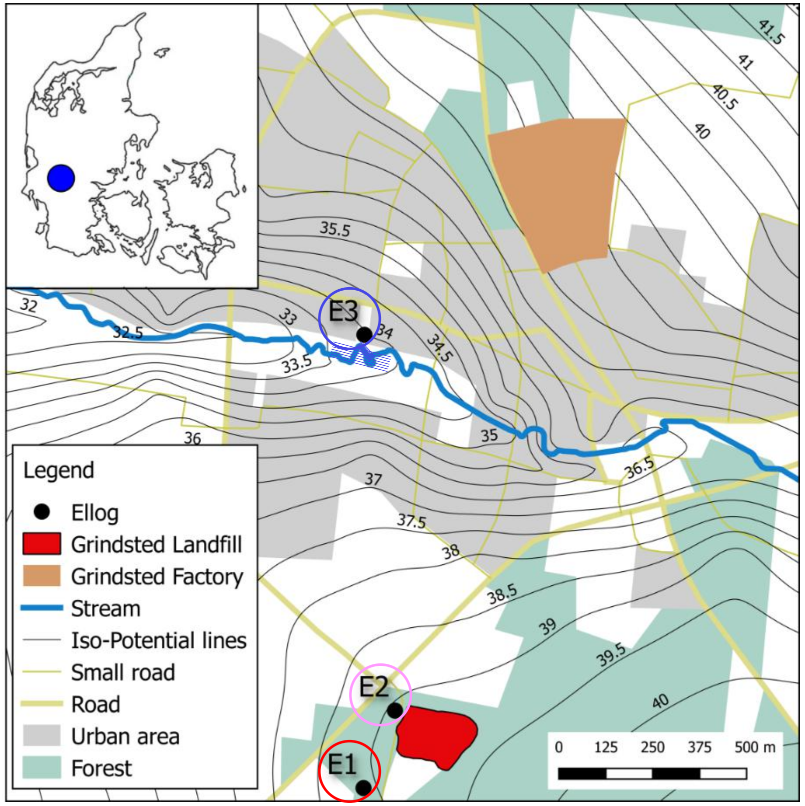

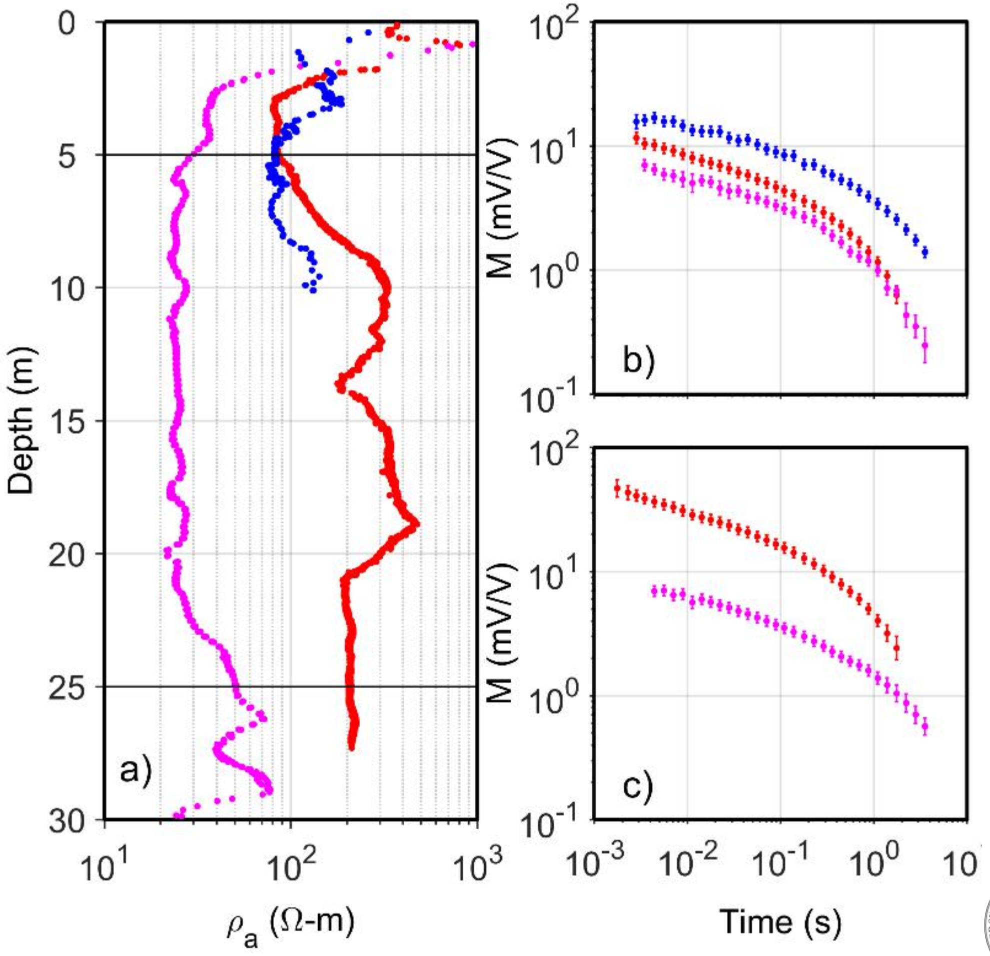

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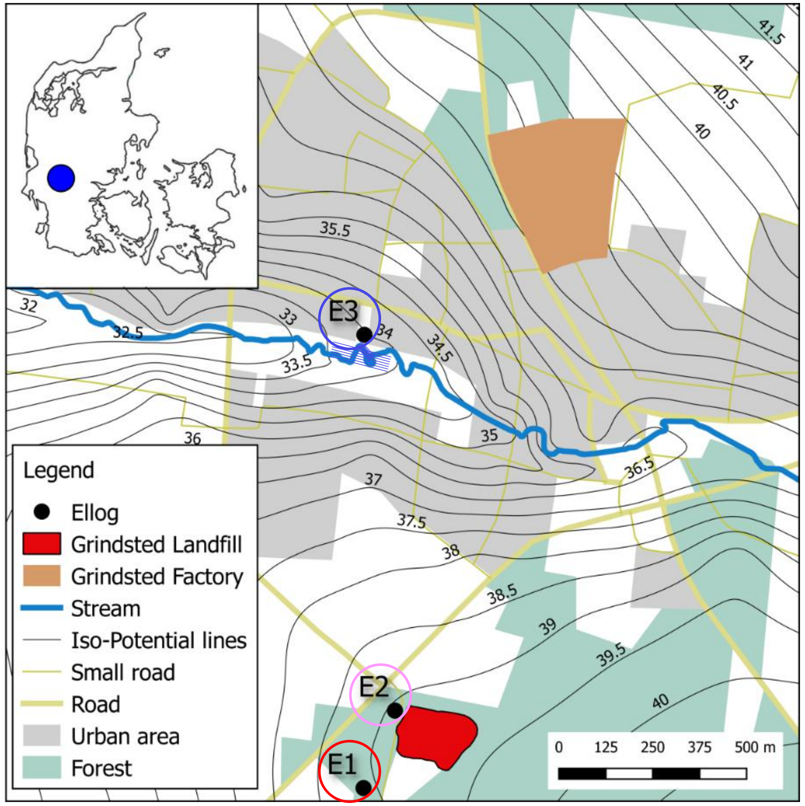

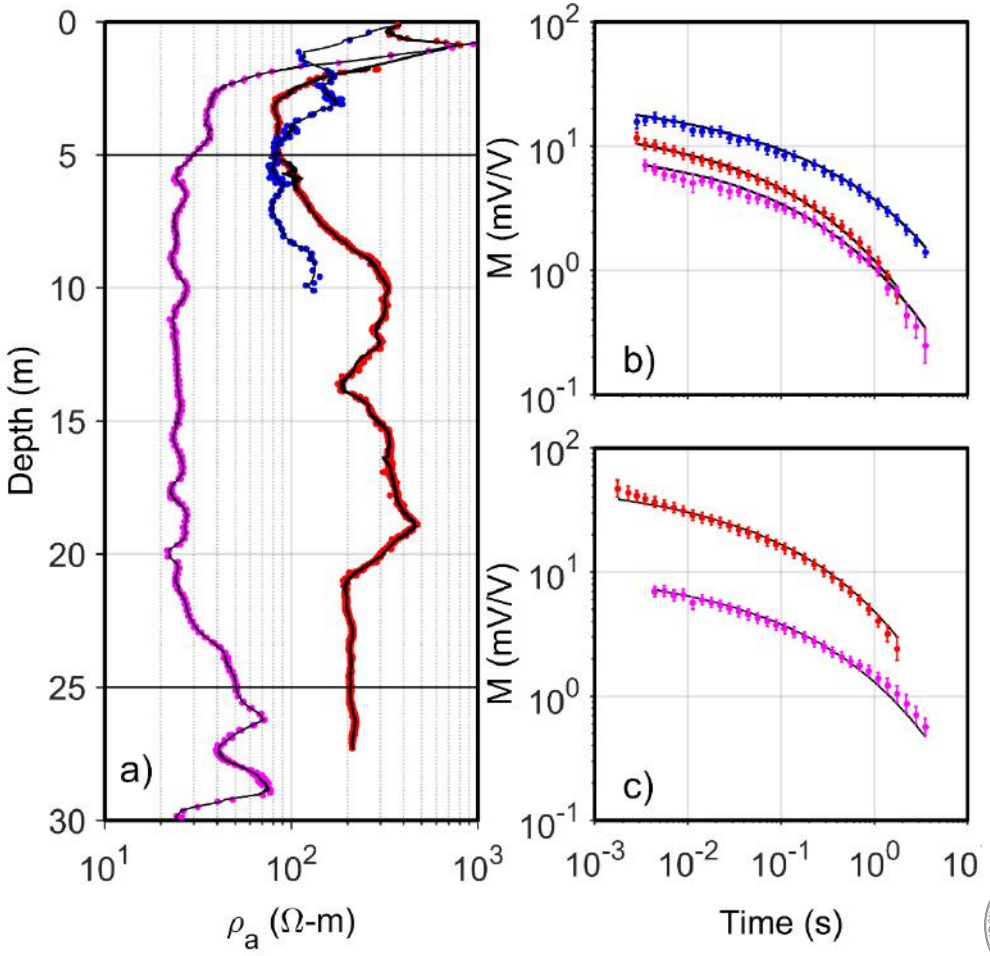

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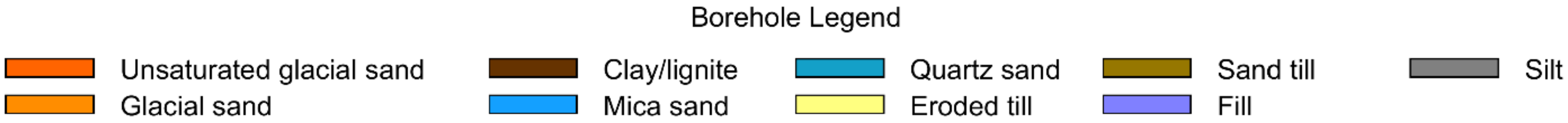
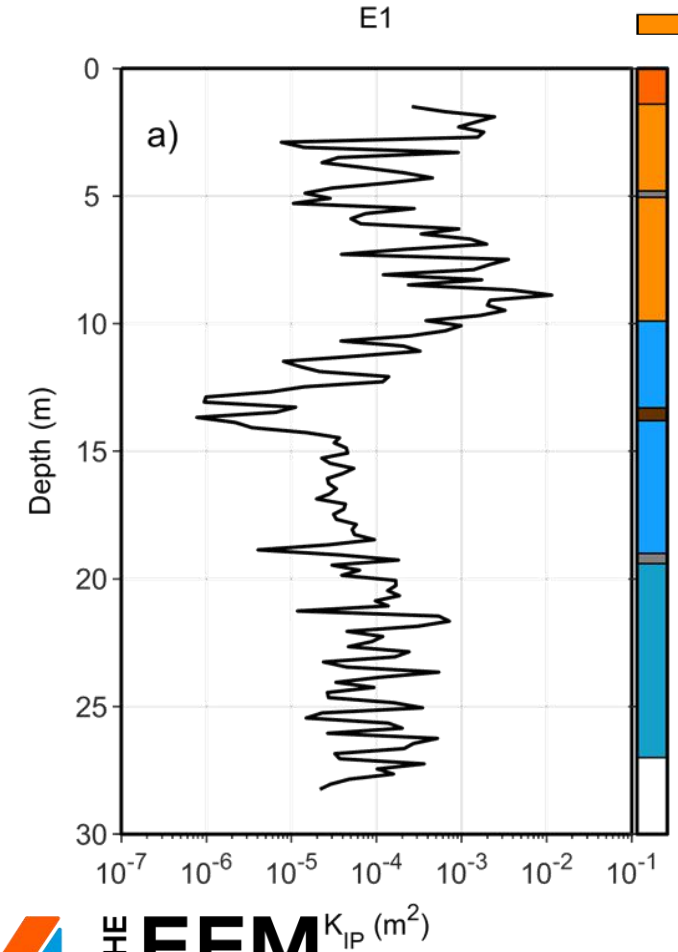
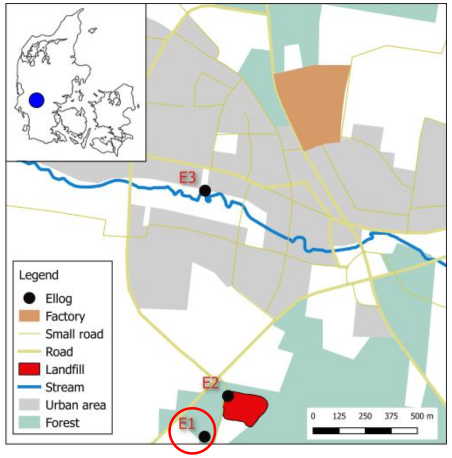
K estimates


Borehole Legend
Unsaturated glacial sand
Glacial sand
Clay/lignite
Mica sand
Quartz sand
Eroded till
Sand till
Fill
Silt


E1
a)
Depth (m)
0
5
10
15
20
25
30
10^{-7} 10^{-6} 10^{-5} 10^{-4} 10^{-3} 10^{-2} 10^{-1}
K_{IP} (m^2)


E3
E2
E1
Legend
Ellog
Factory
Small road
Road
Landfill
Stream
Urban area
Forest
0 125 250 375 500 m

K estimates

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Unsaturated glacial sand
Glacial sand
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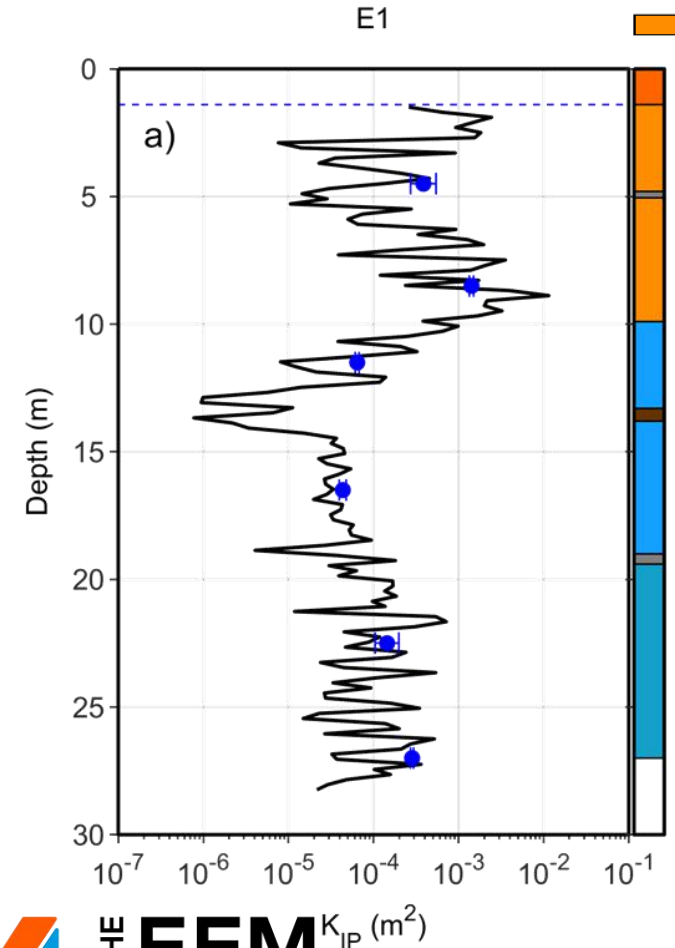

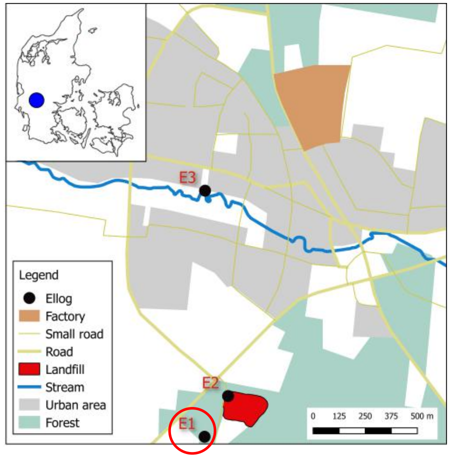

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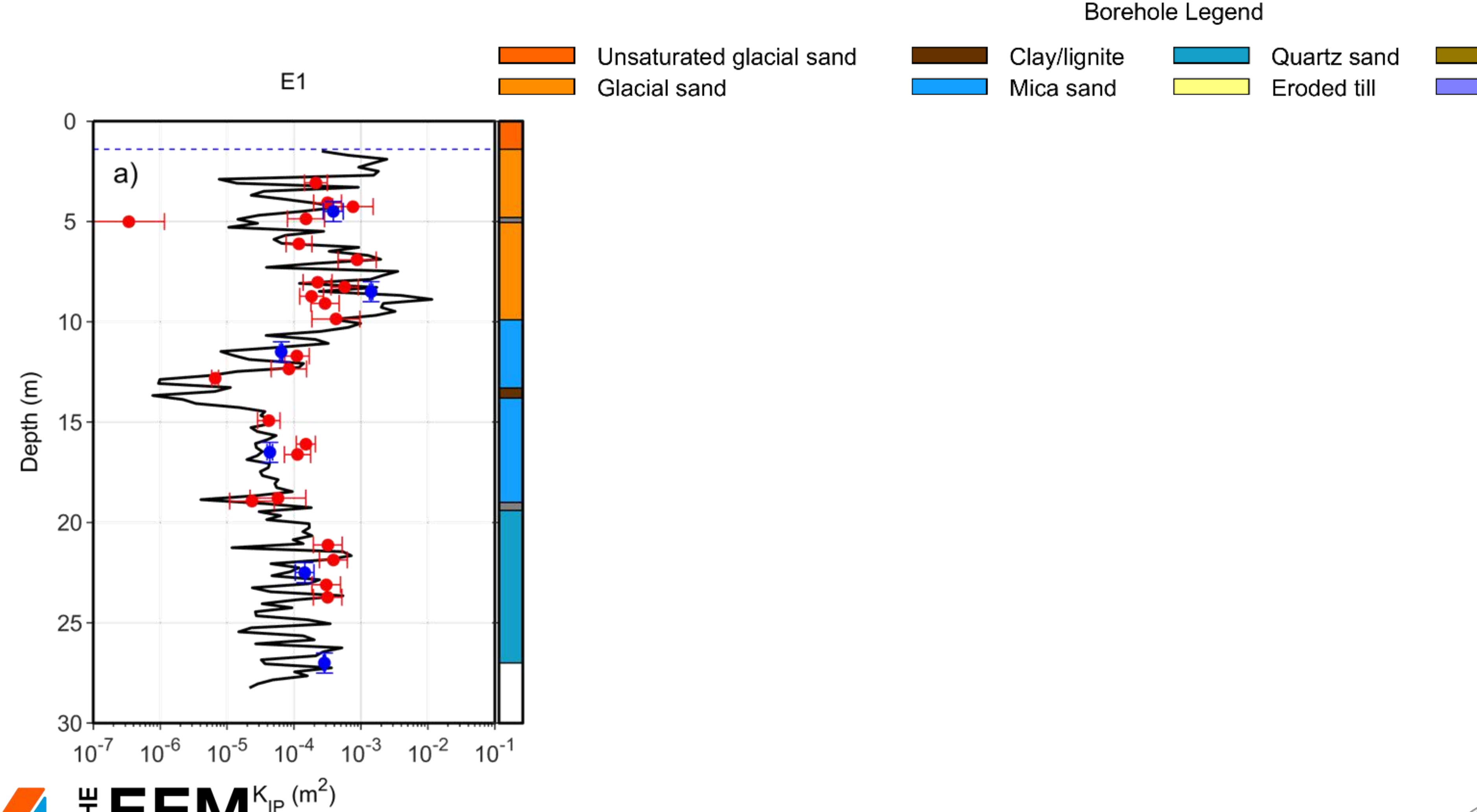

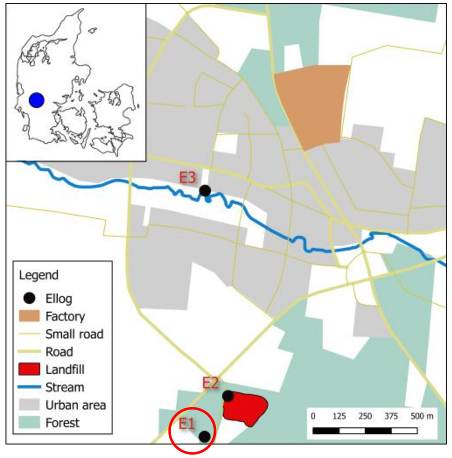

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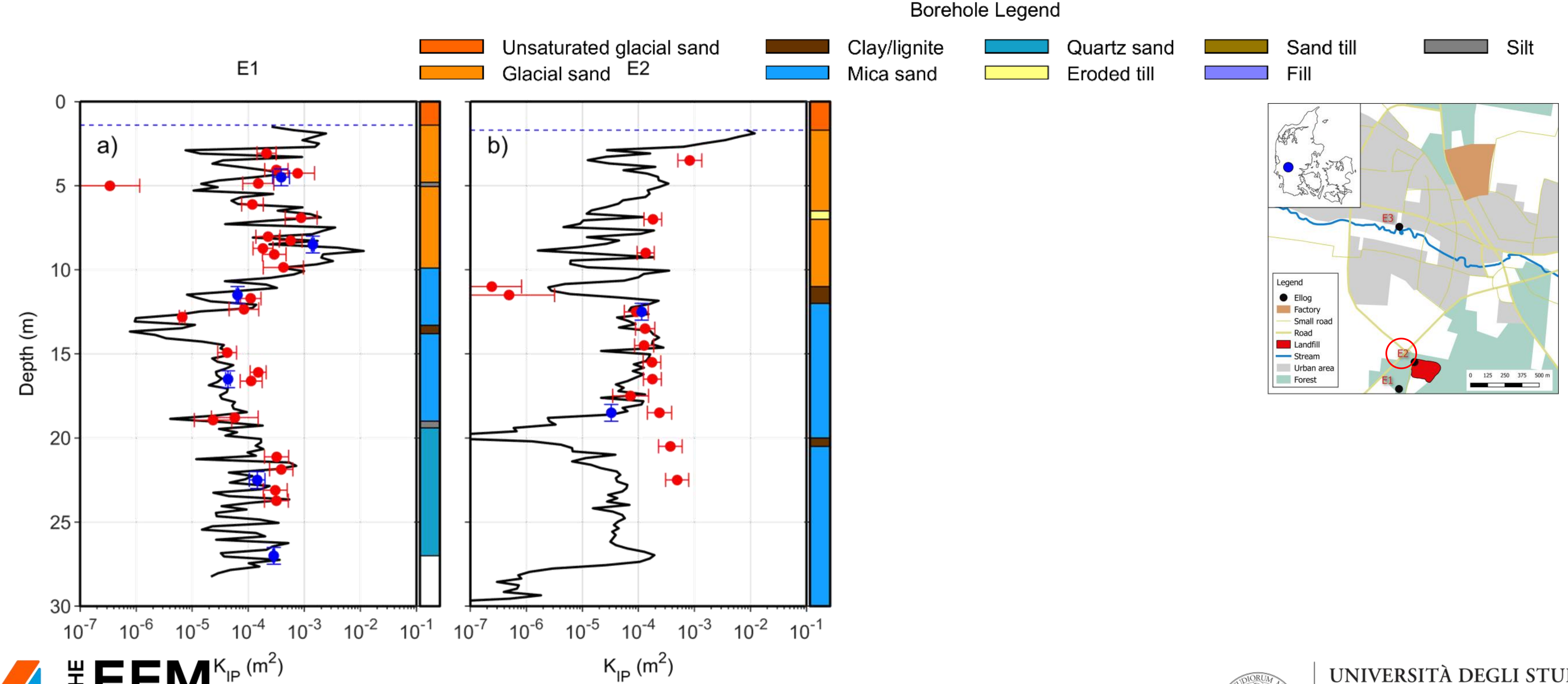

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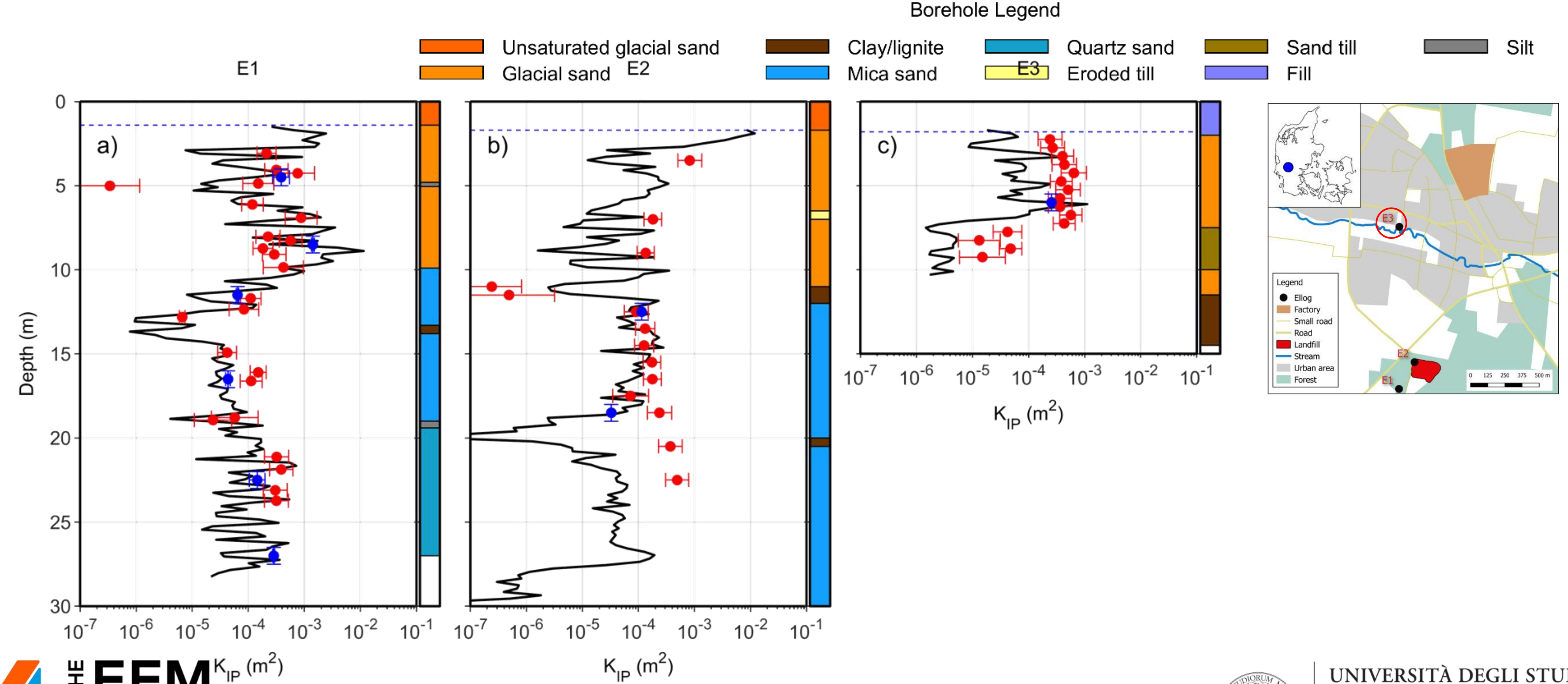

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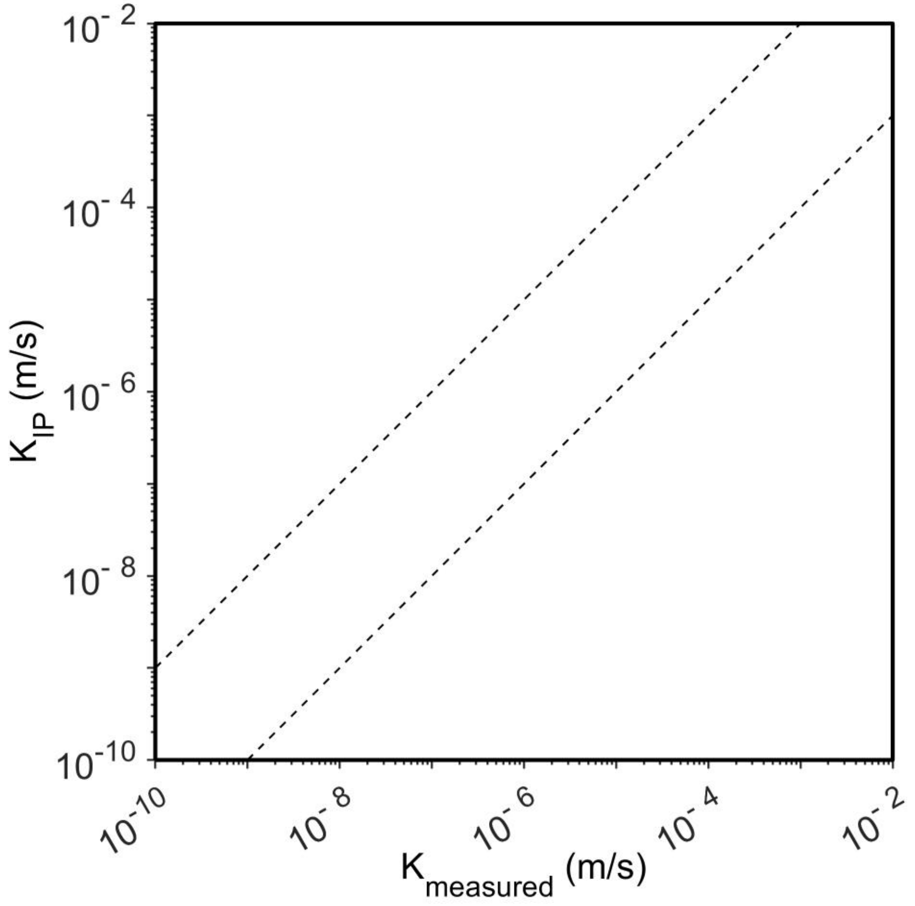

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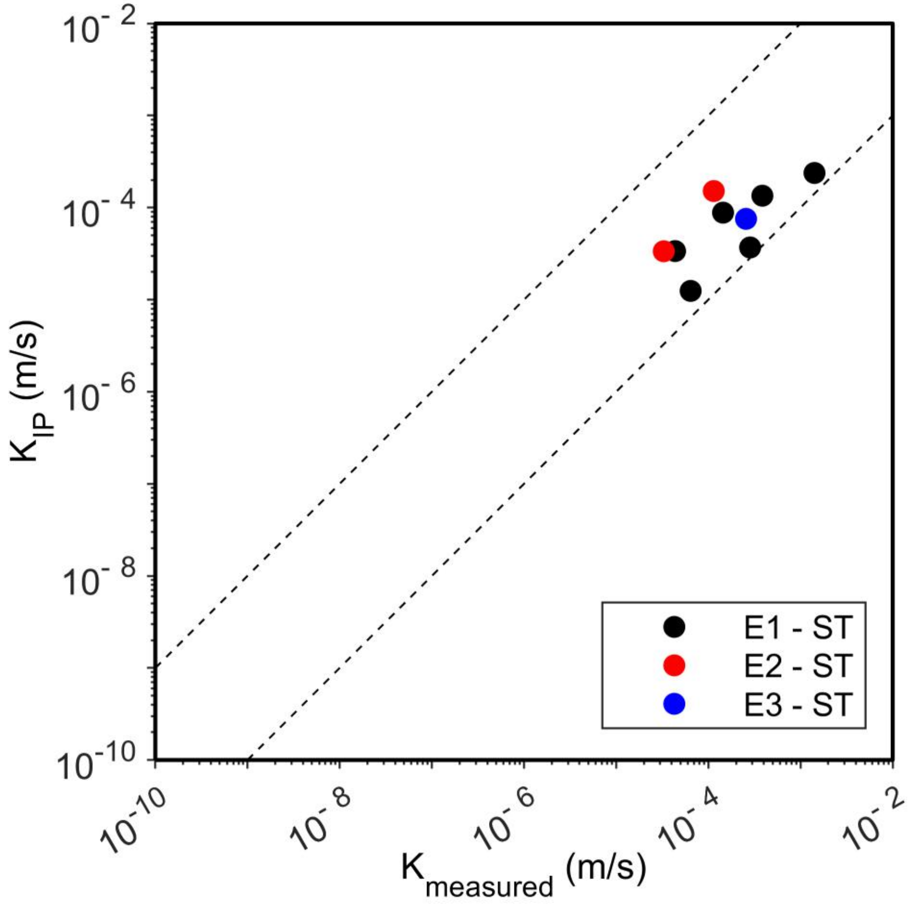

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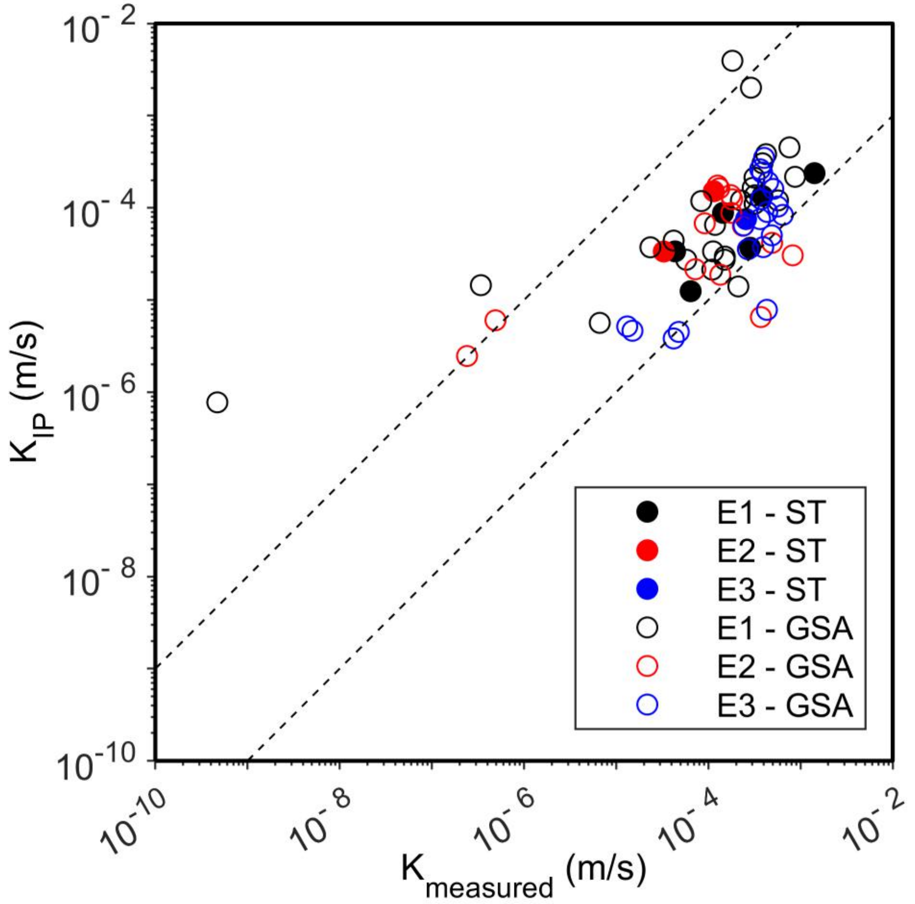

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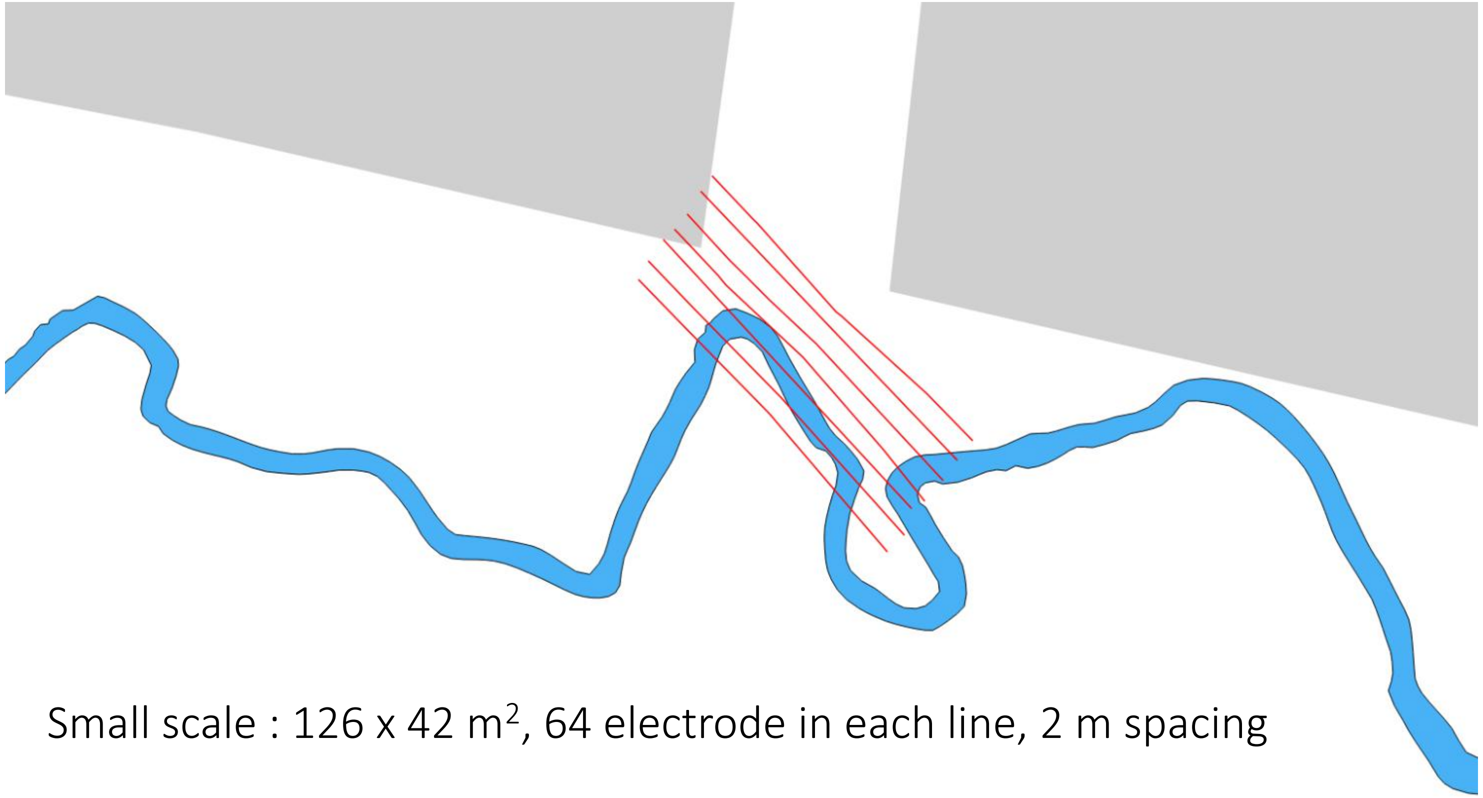
Surface profiles



Small scale : 126 x 42 m^2, 64 electrode in each line, 2 m spacing

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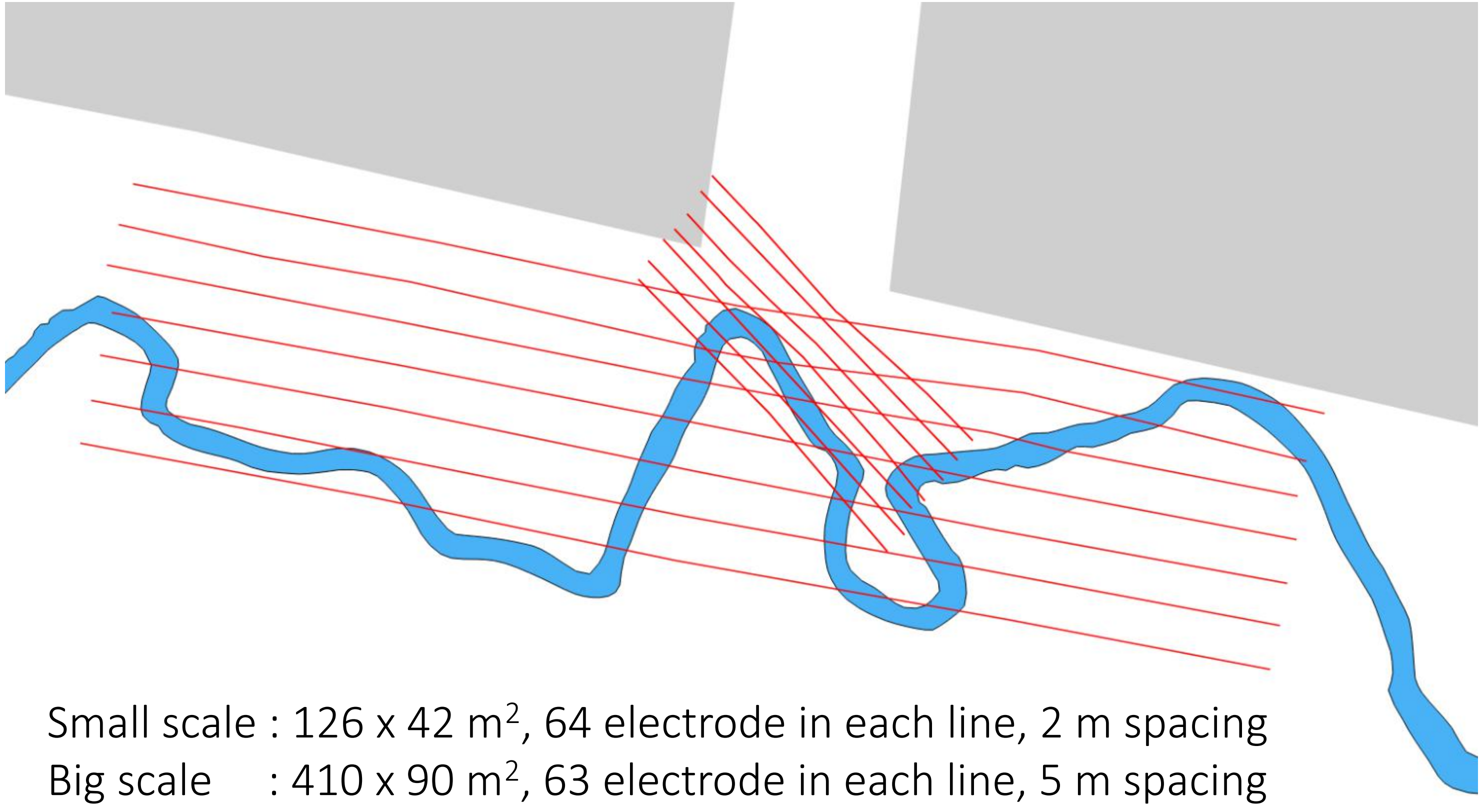
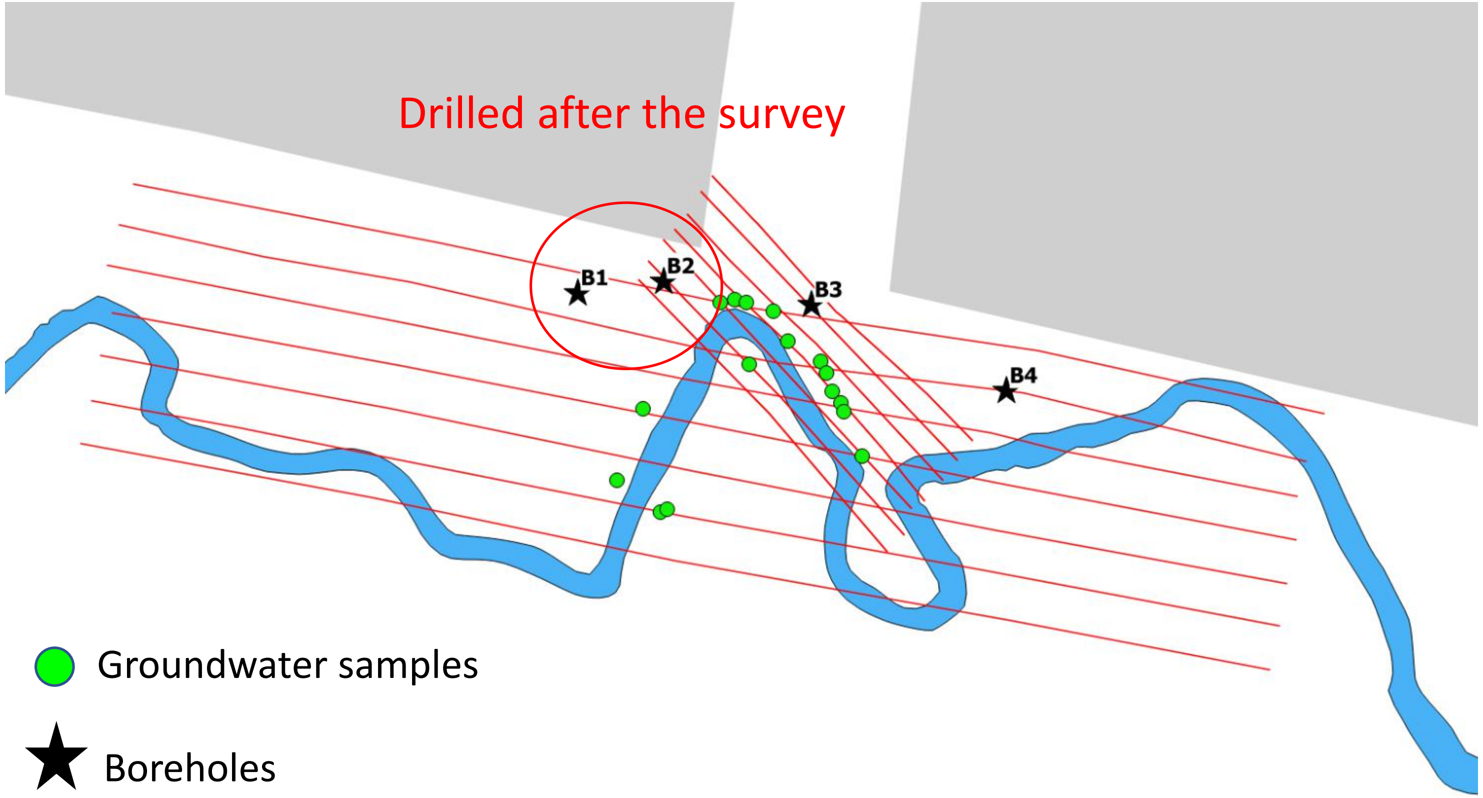


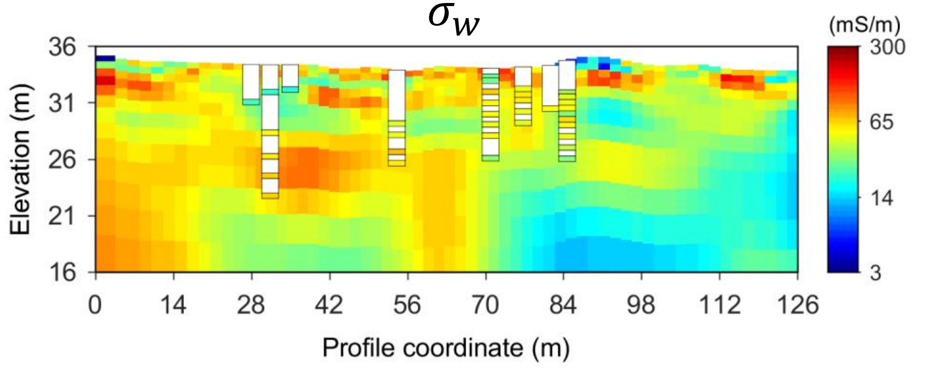
Small scale : 126 x 42 m^2, 64 electrode in each line, 2 m spacing
Big scale : 410 x 90 m^2, 63 electrode in each line, 5 m spacing

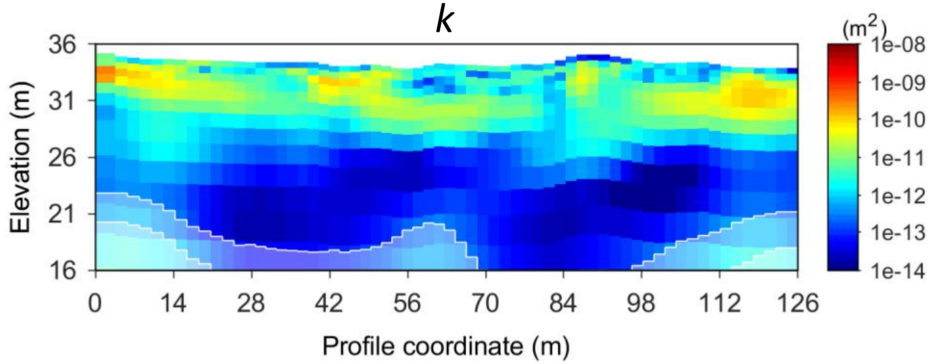
Surface profiles

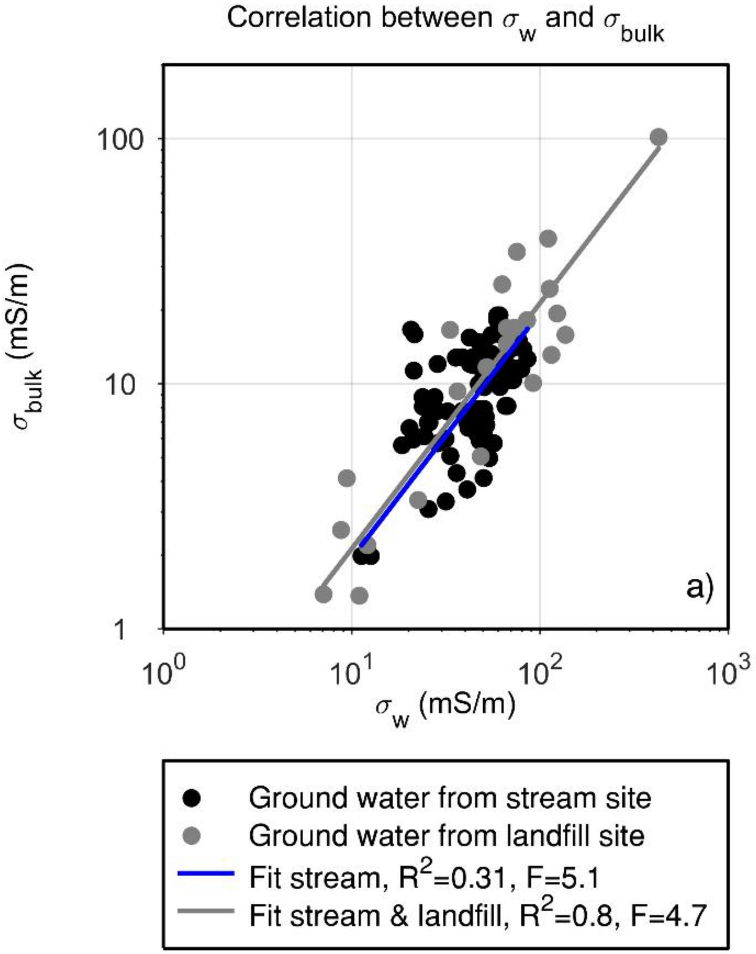


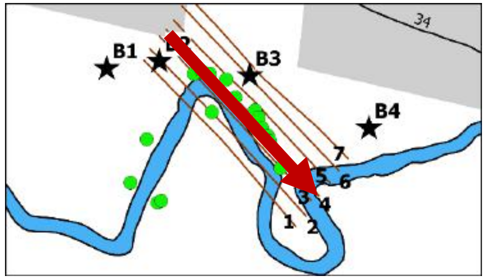
Results

- Mapping σ_w and permeability, unconfined (shallow) aquifer









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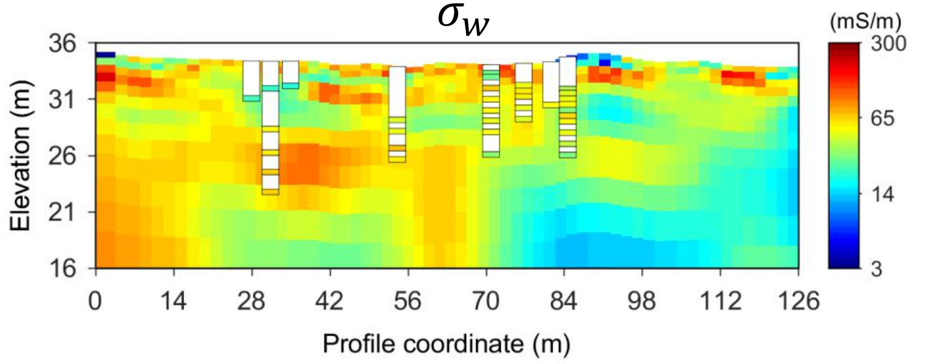

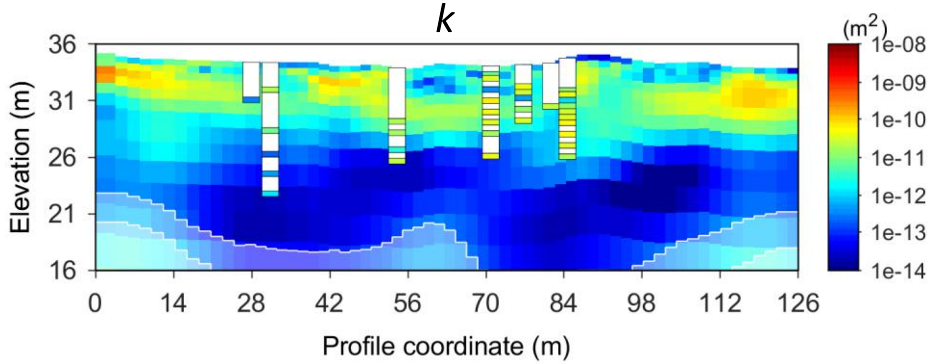

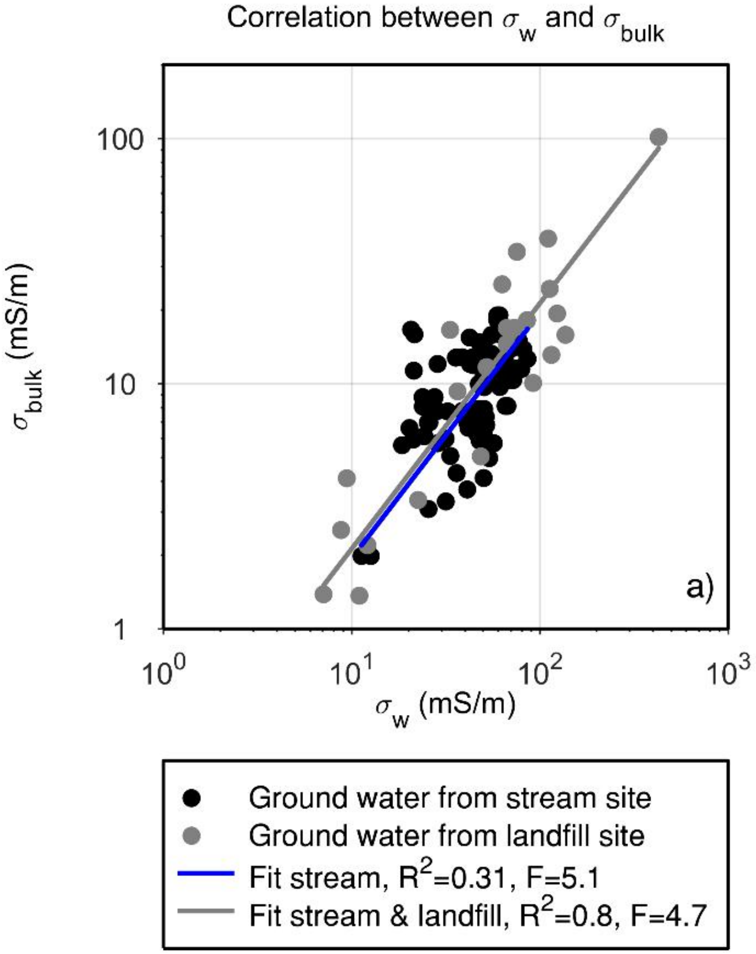

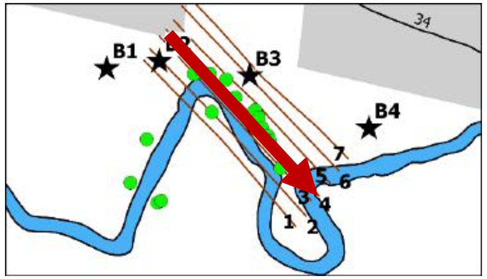

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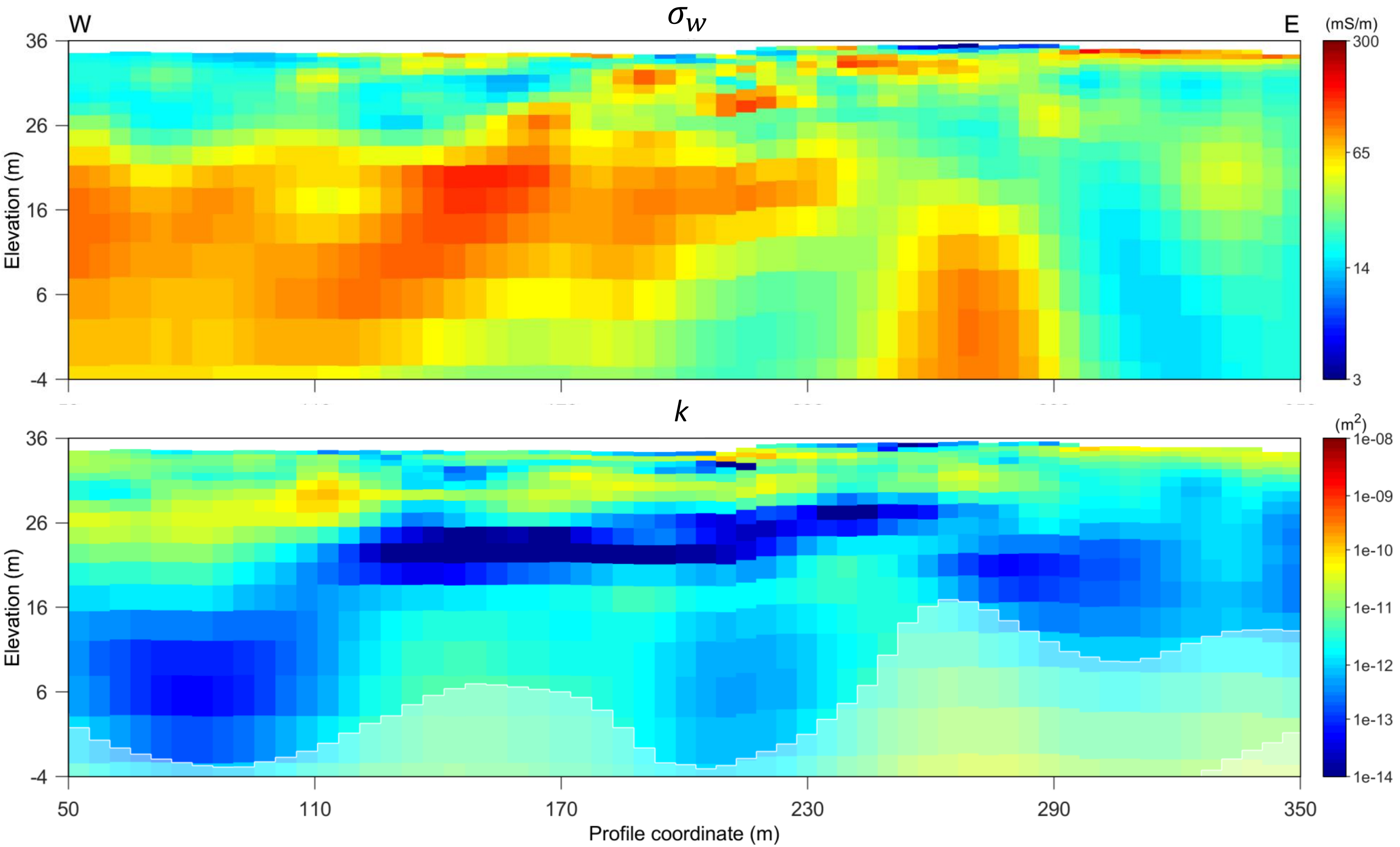

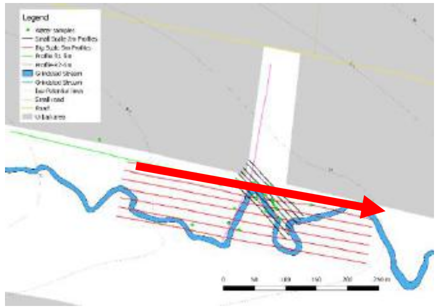

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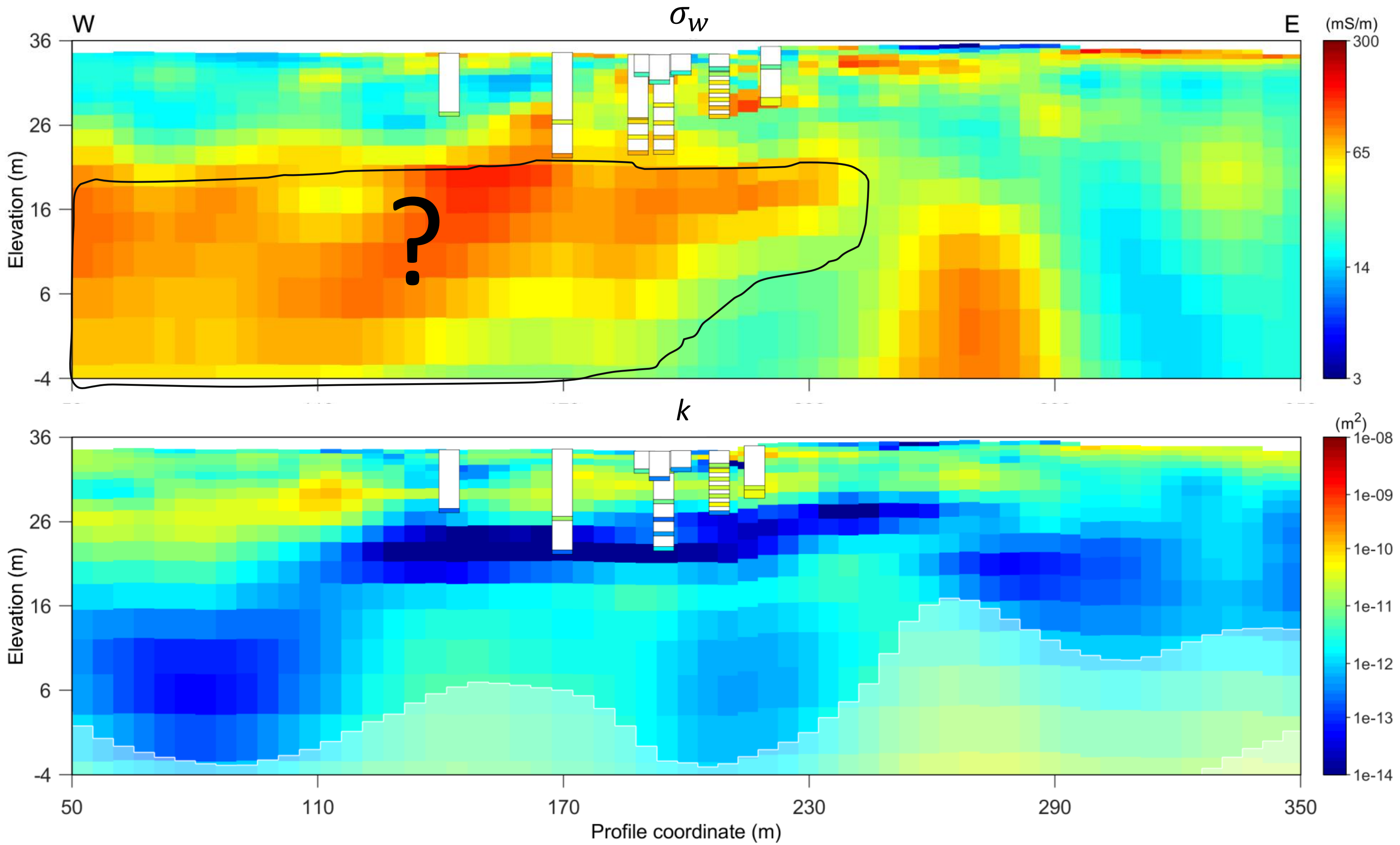

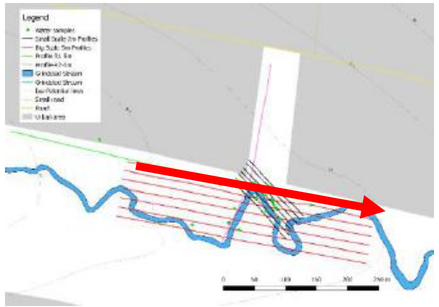

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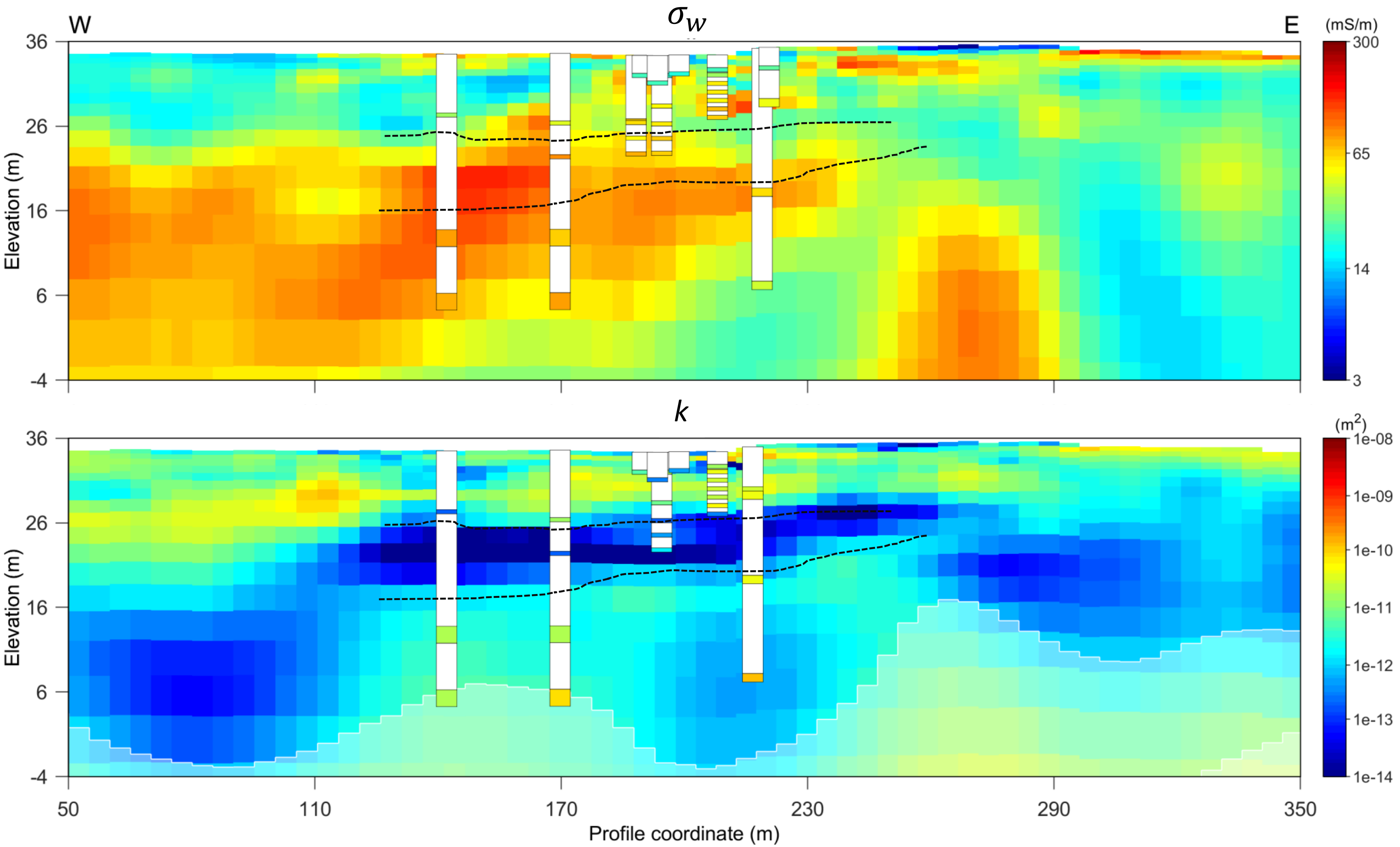

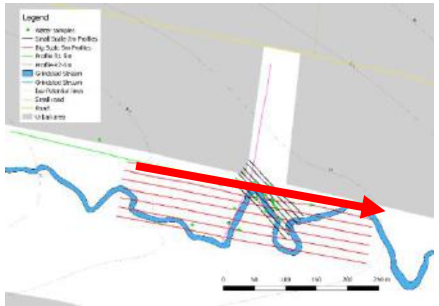

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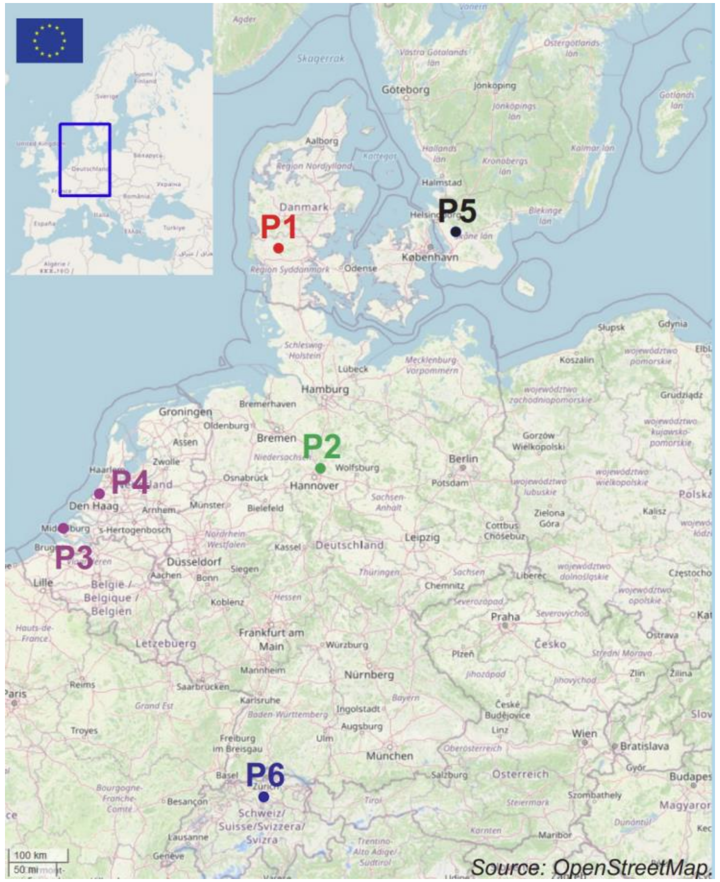
2D IP profiles from 5 different European countries

- 2D profiles from 5 countries:
  - Denmark
  - Sweden
  - Germany
  - The Netherlands
  - Switzerland
- Tens of grain size analyses and slug tests for comparison



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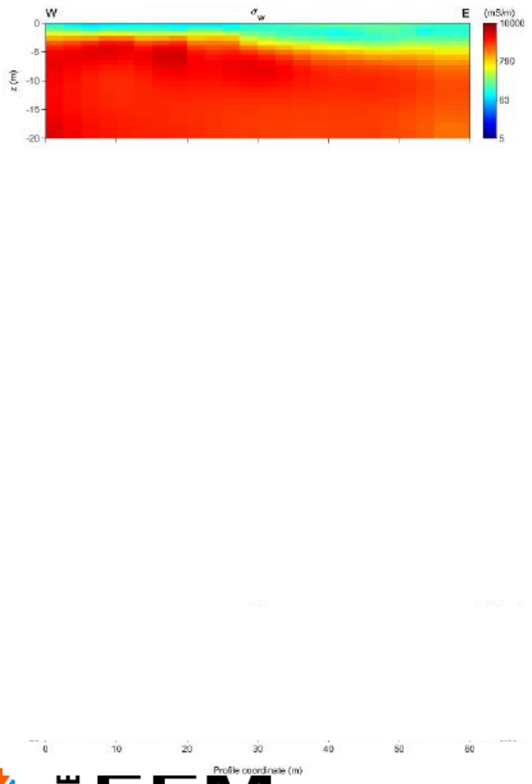
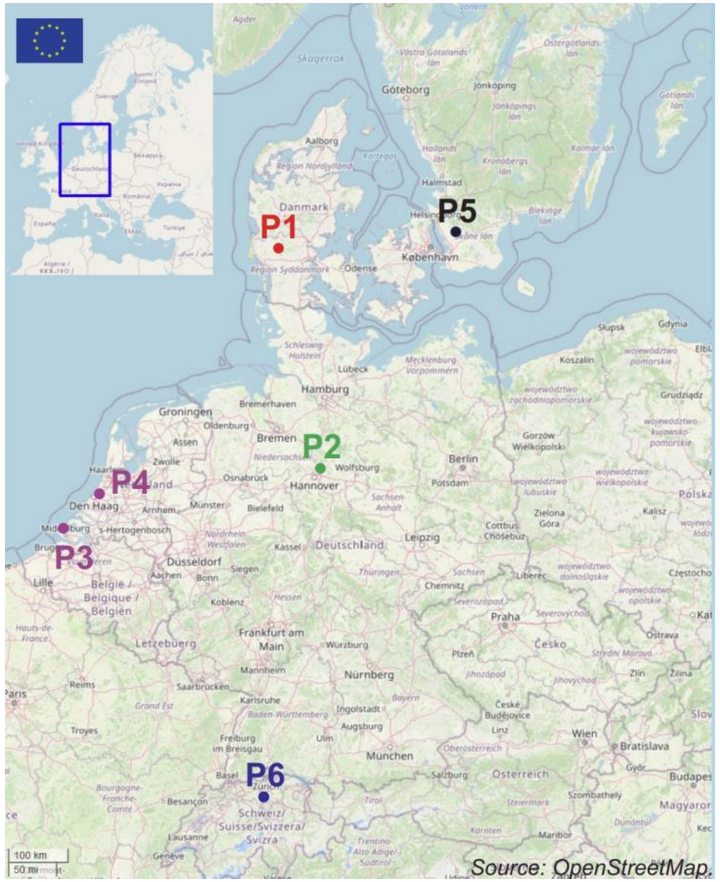
2D IP profiles from 5 different European countries

- The Netherlands





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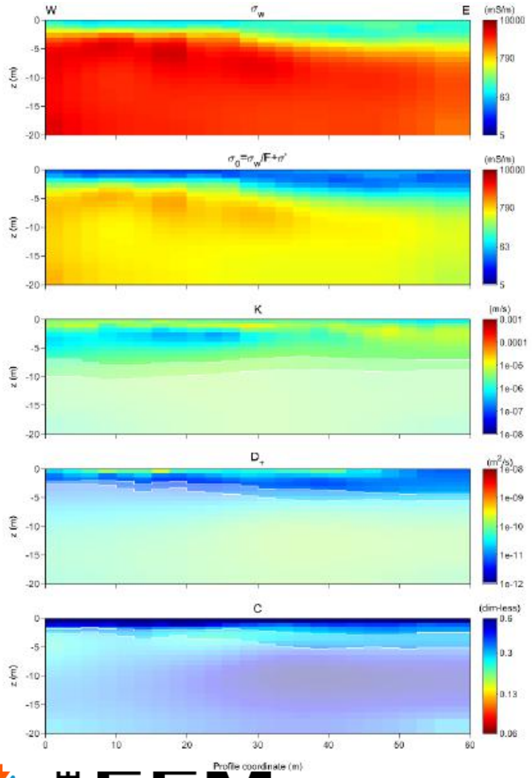
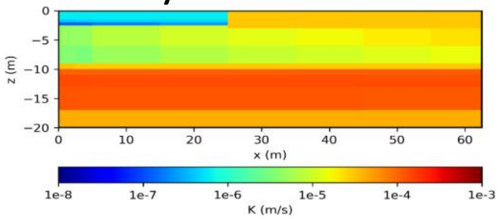
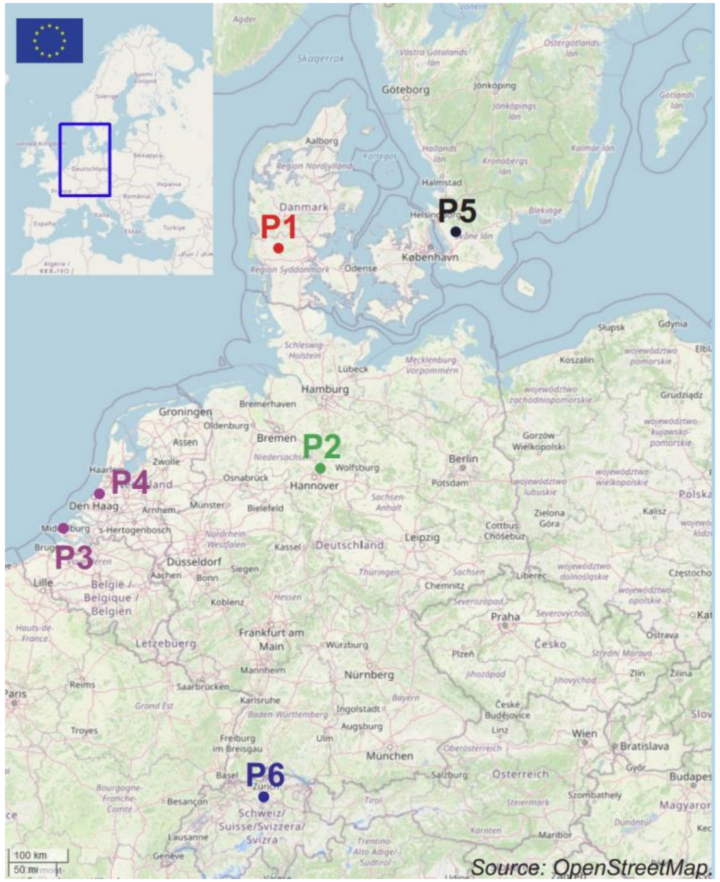
2D IP profiles from 5 different European countries

- The Netherlands



Model from geological survey database





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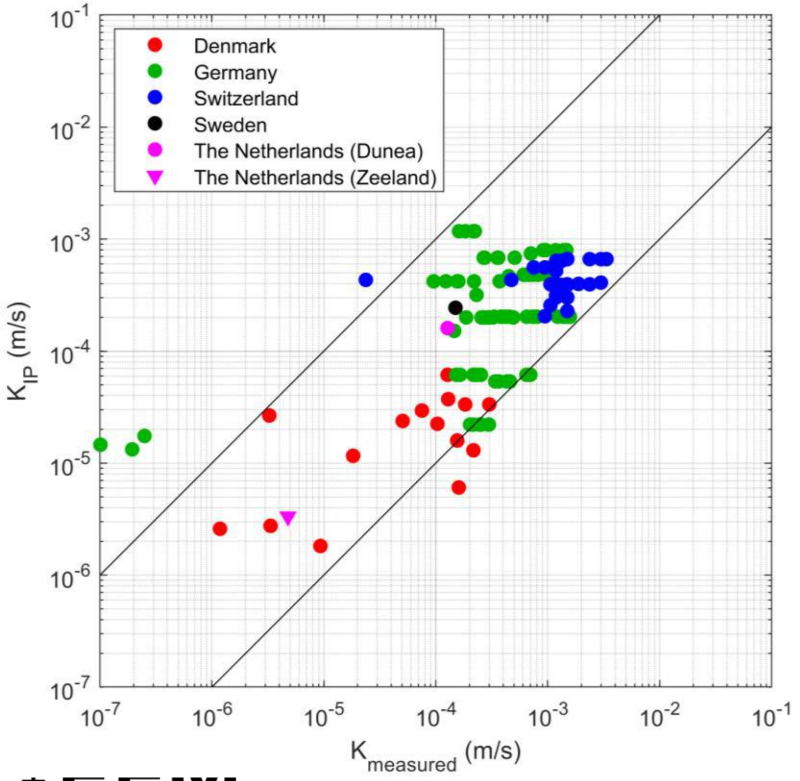
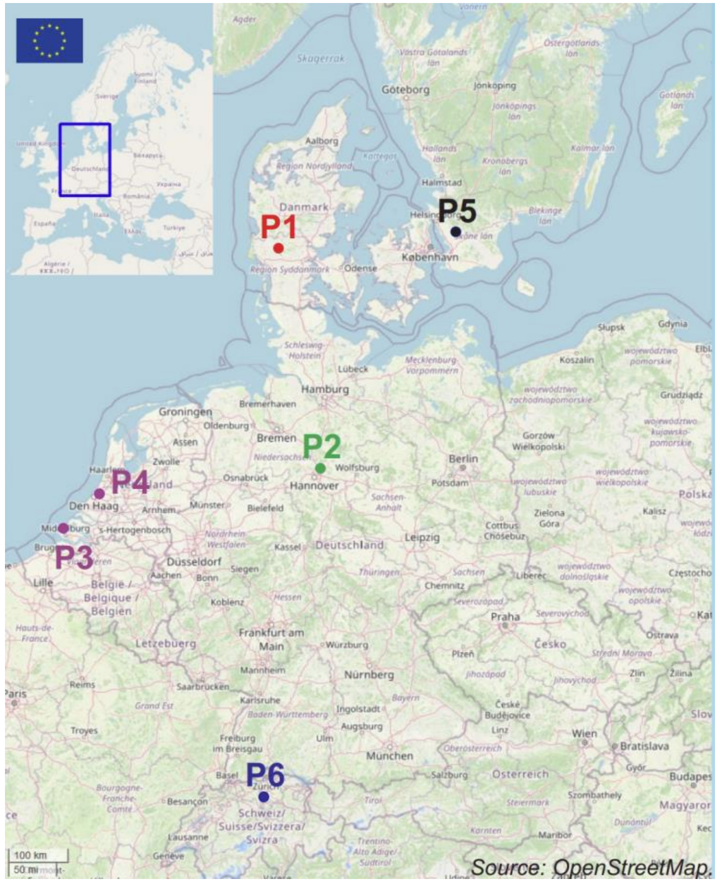
2D IP profiles from 5 different European countries

- All other countries:





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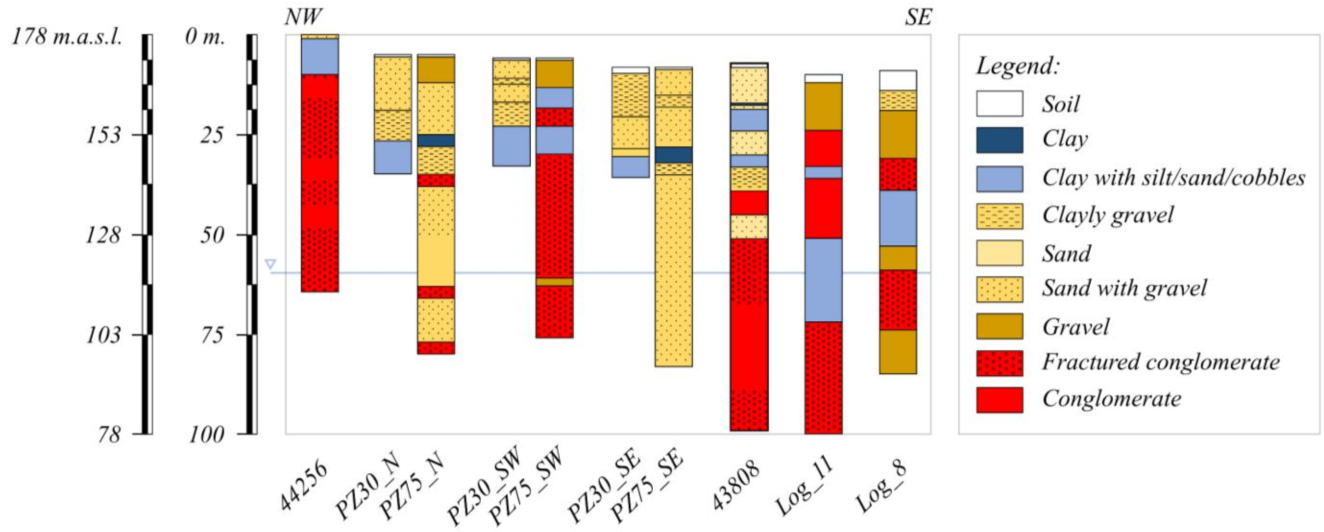
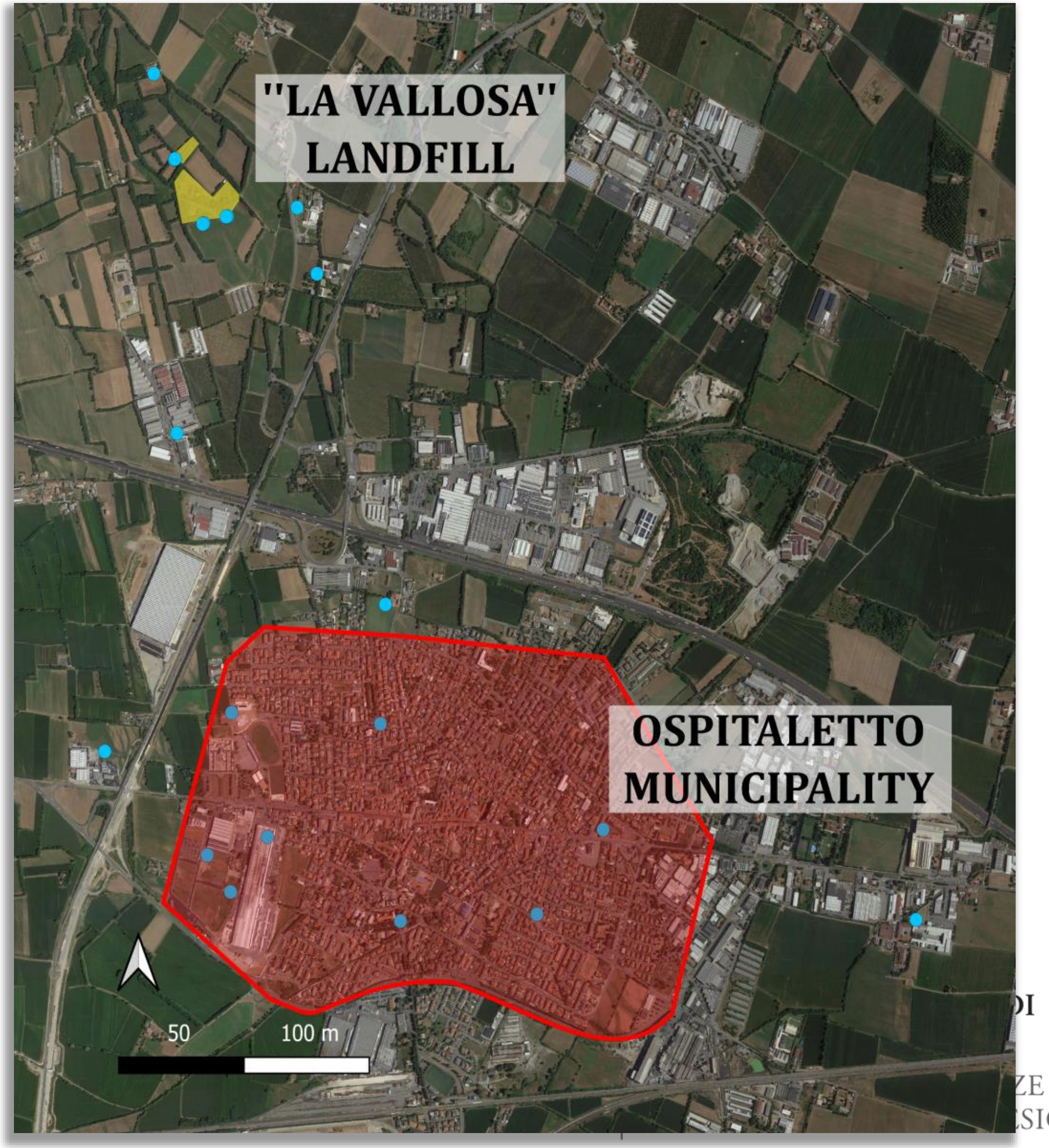
Former Gravel Pit “Vallosa”, Brescia, SIN Caffaro

- Mostly unconsolidated formations in the first 60 meters
- Main aquifer in conglomerate formations, below 60 meters





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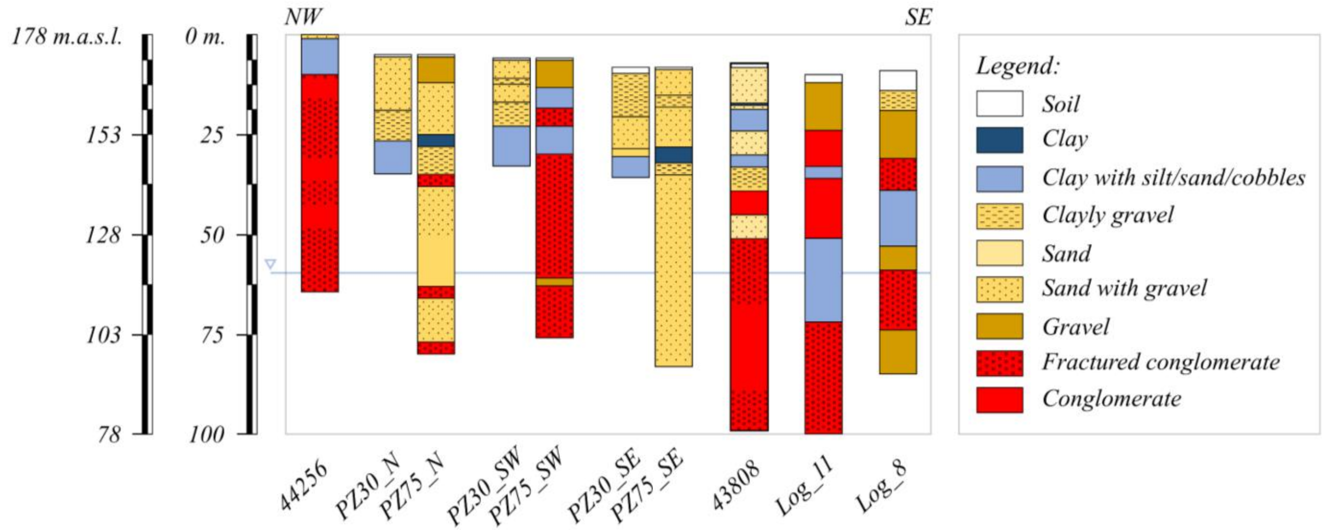
a2a LIFE COMPANY | Ciclo Idrico

Former Gravel Pit "Vallosa", Brescia, SIN Caffaro

Contamination

- PCBs (Polychlorinated Byphenyls)
- TPH (Total Hydrocarbons)
- Iron and Nickel

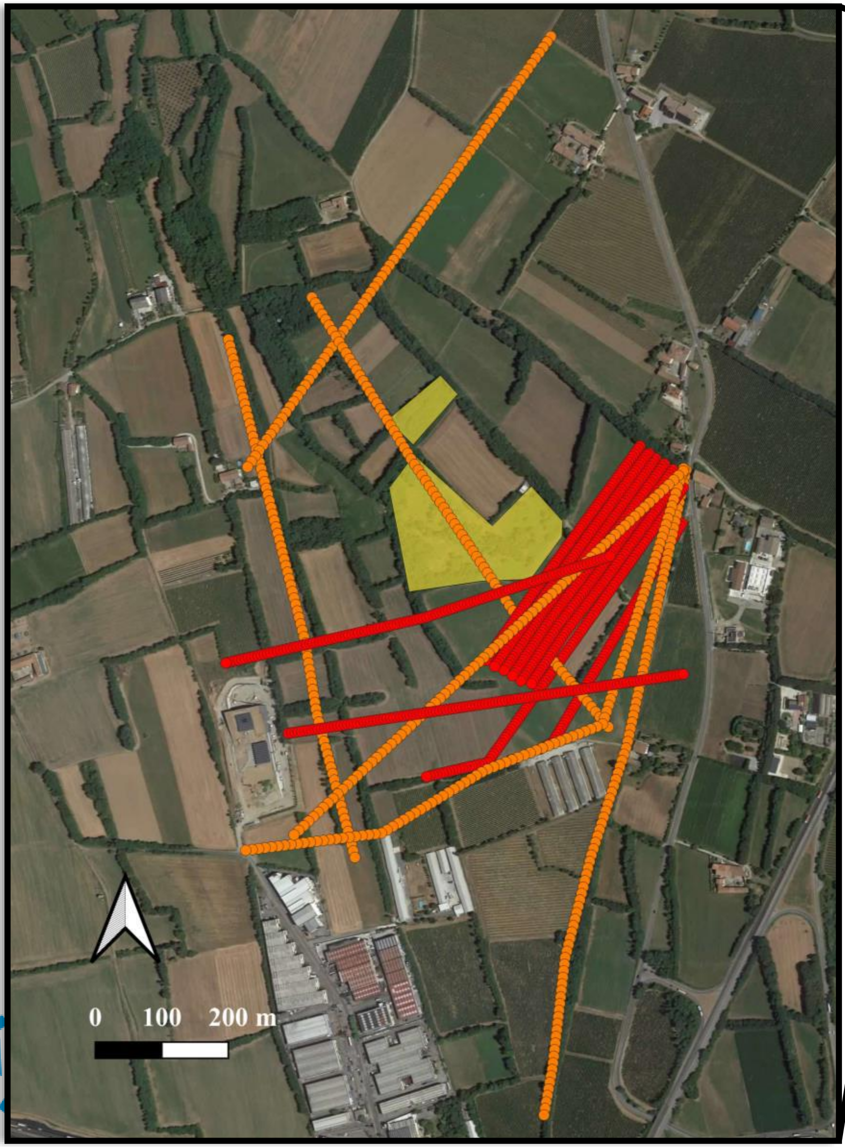


Former Gravel Pit "Vallosa", Brescia, SIN Caffaro

Orange
- 5 profiles
- 10 m spacing
- 800 – 1000 m

Red
- 10 profiles
- 5 m spacing
- 400 – 600 m

9.8 km of lines



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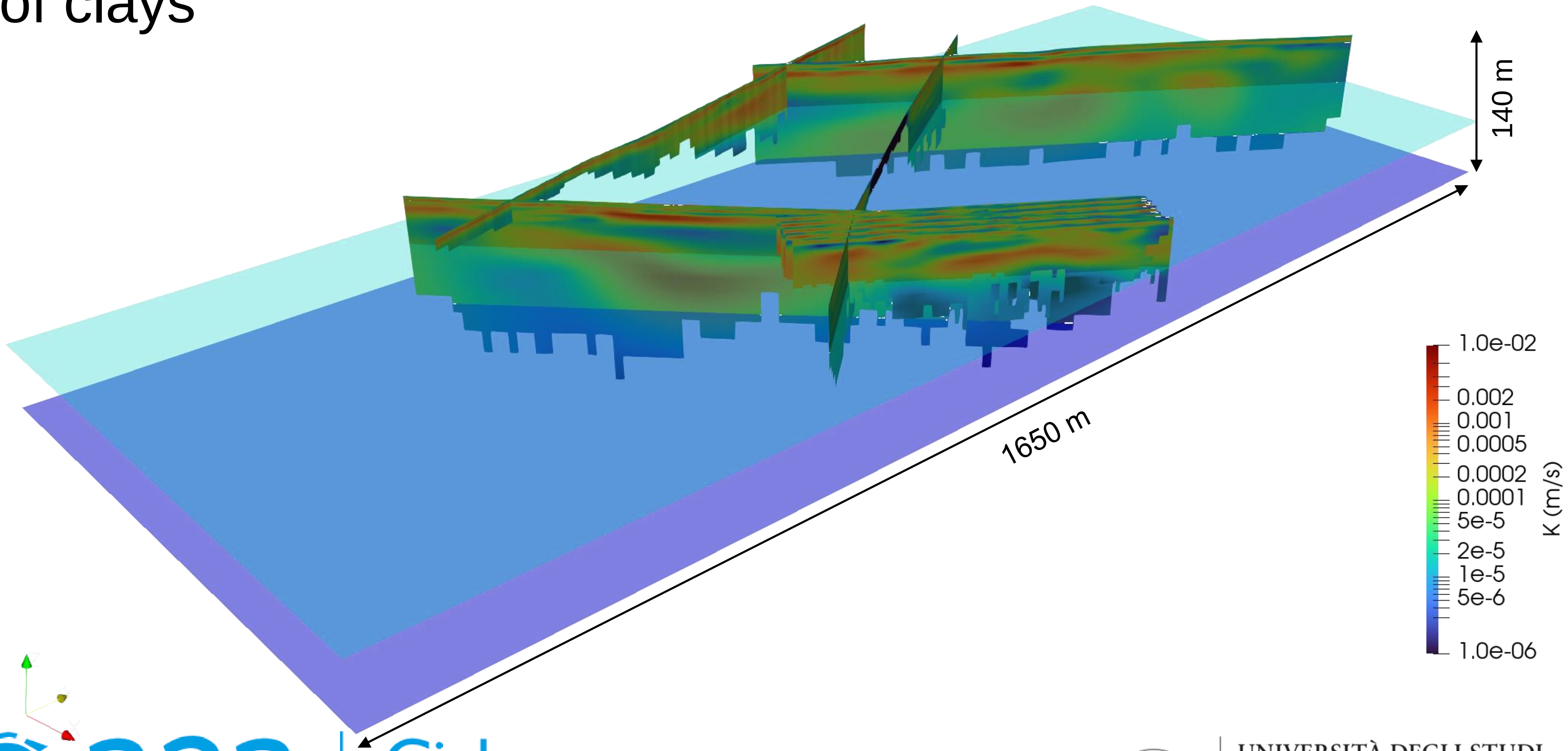
Former Gravel Pit “Vallosa”, Brescia, SIN Caffaro

- Identification of clays



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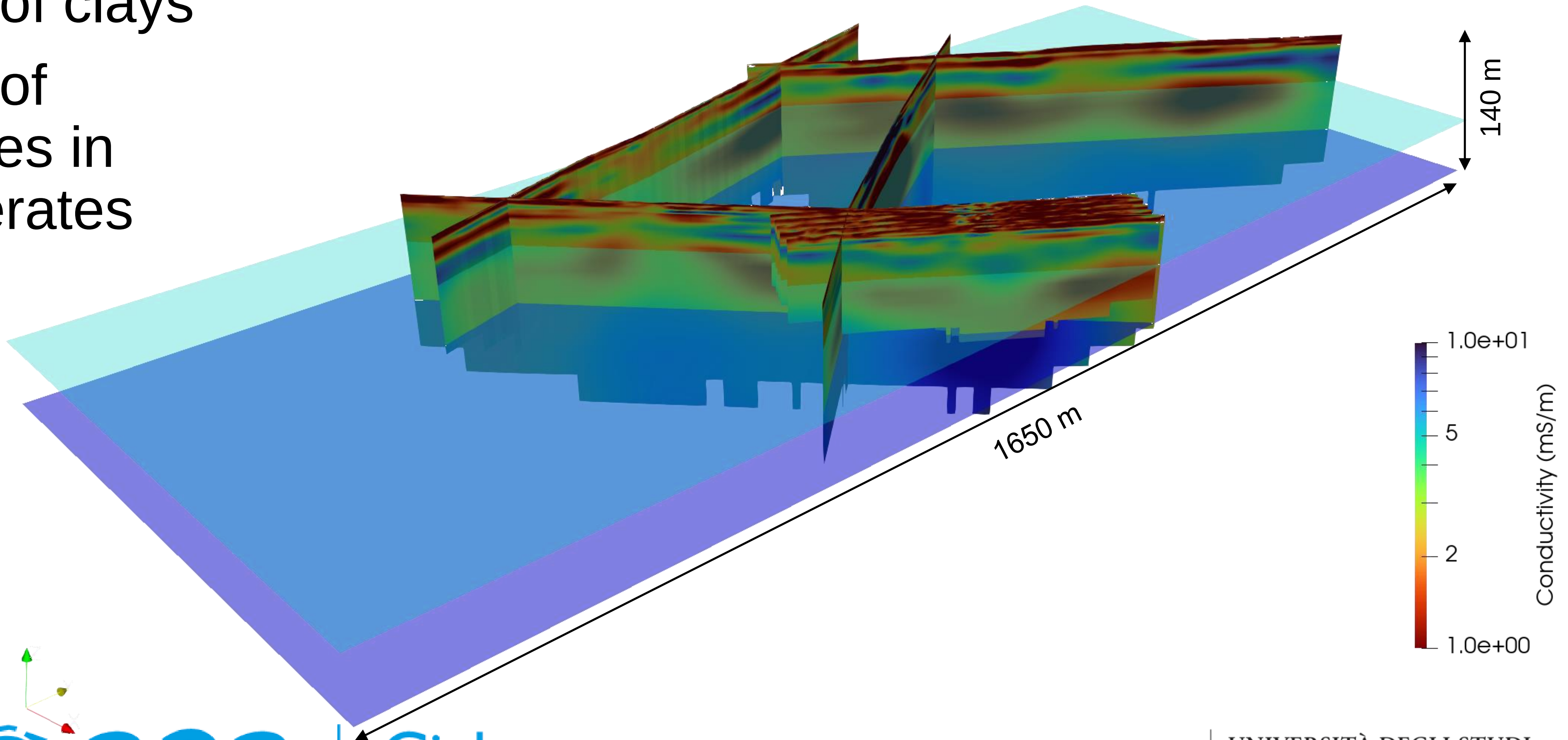
Former Gravel Pit “Vallosa”, Brescia, SIN Caffaro

- Identification of clays
- Identification of heterogeneities in the conglomerates



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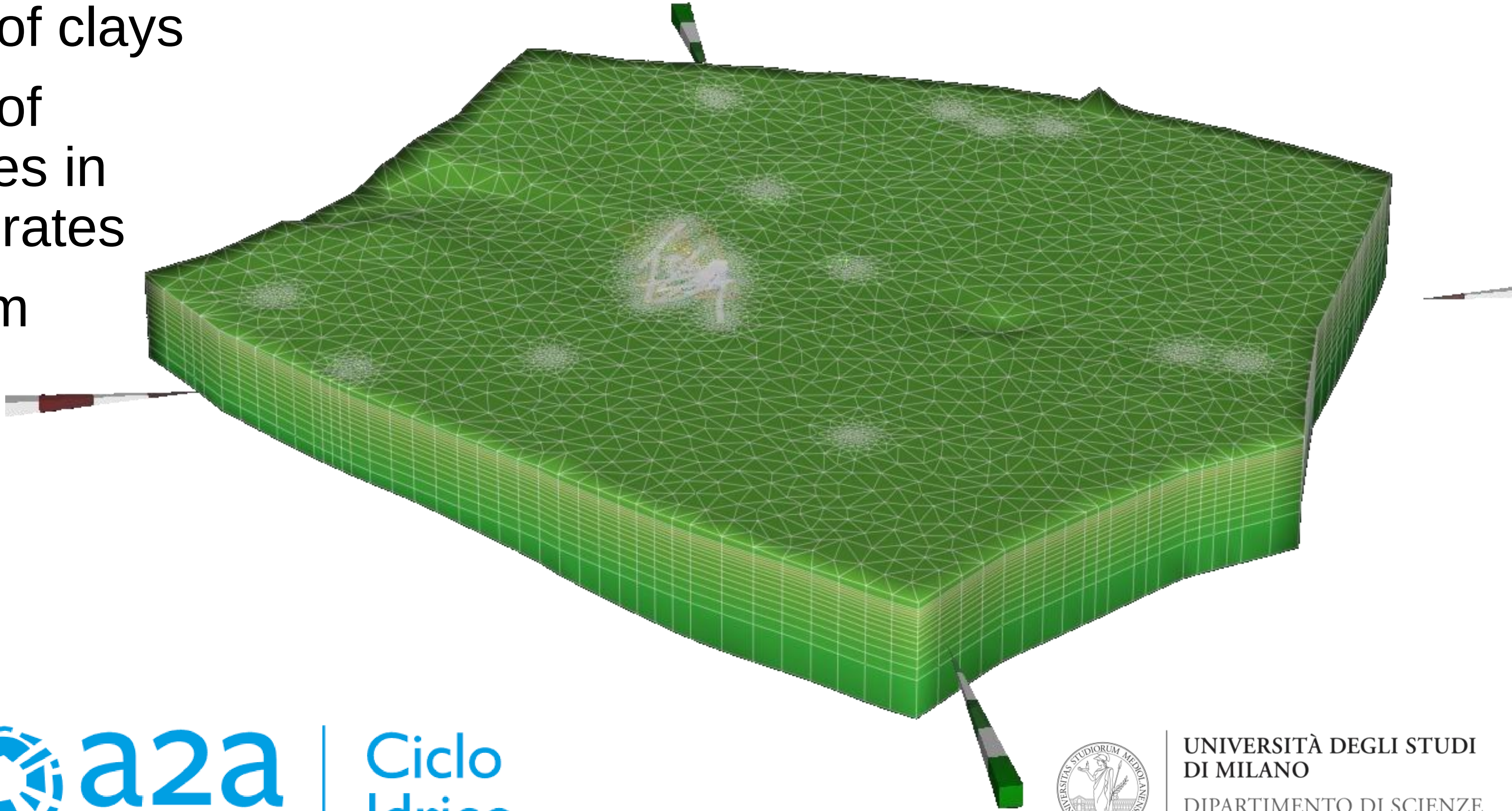
Former Gravel Pit "Vallosa", Brescia, SIN Caffaro

- Identification of clays
- Identification of heterogeneities in the conglomerates
- Used to inform groundwater modelling



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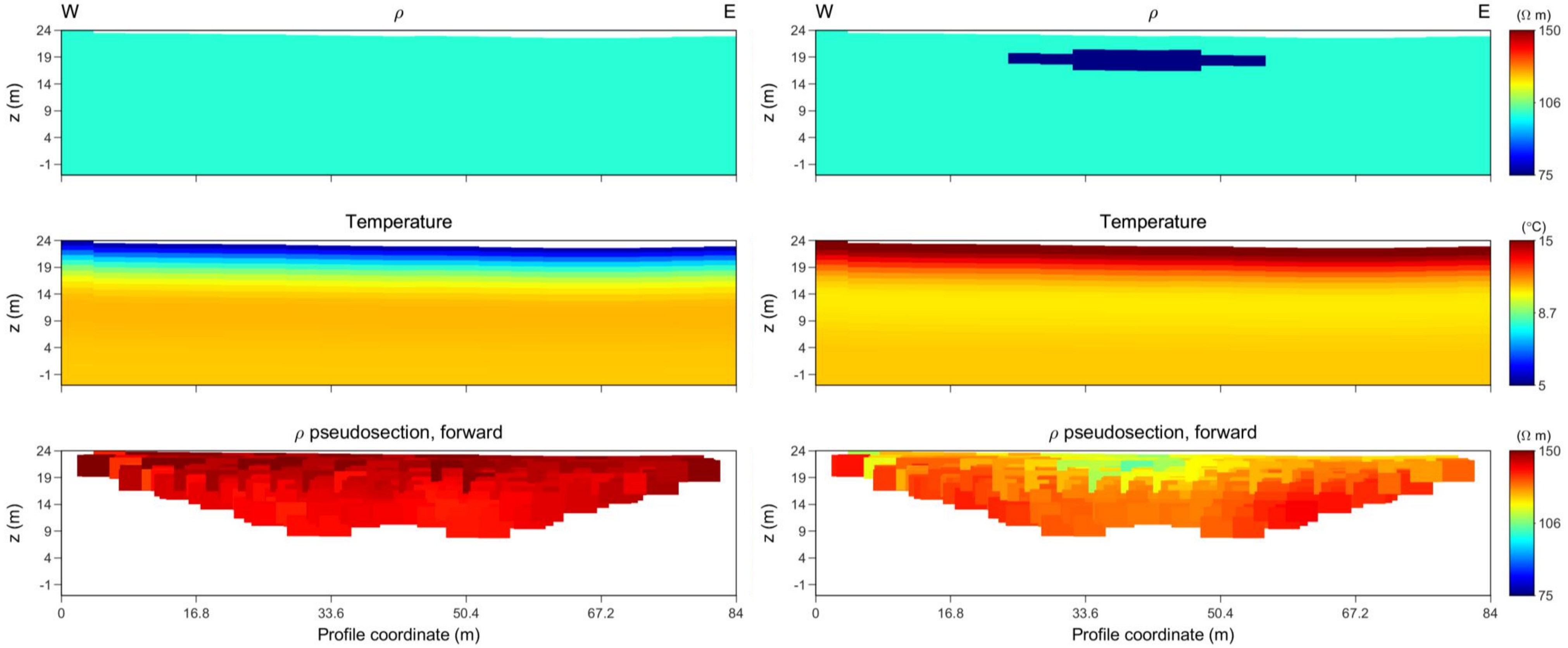
Outline

- Electrical methods
  - Induced polarization for the characterization of hydraulic properties
  - Monitoring with modelling of temperature effect
- Electromagnetic methods
  - Unparalleled productivity
  - Airborne EM for mapping at basin scale
  - Ground-EM in continuous acquisition for detailed mapping: tTEM e Loupe systems
- Conclusions

Monitoring with modelling of temperature effect

- Electrical resistivity/conductivity depends on temperature:
- $\sigma_{Ref} = \left(1 + m(T - T_{Ref})\right)\sigma_T$



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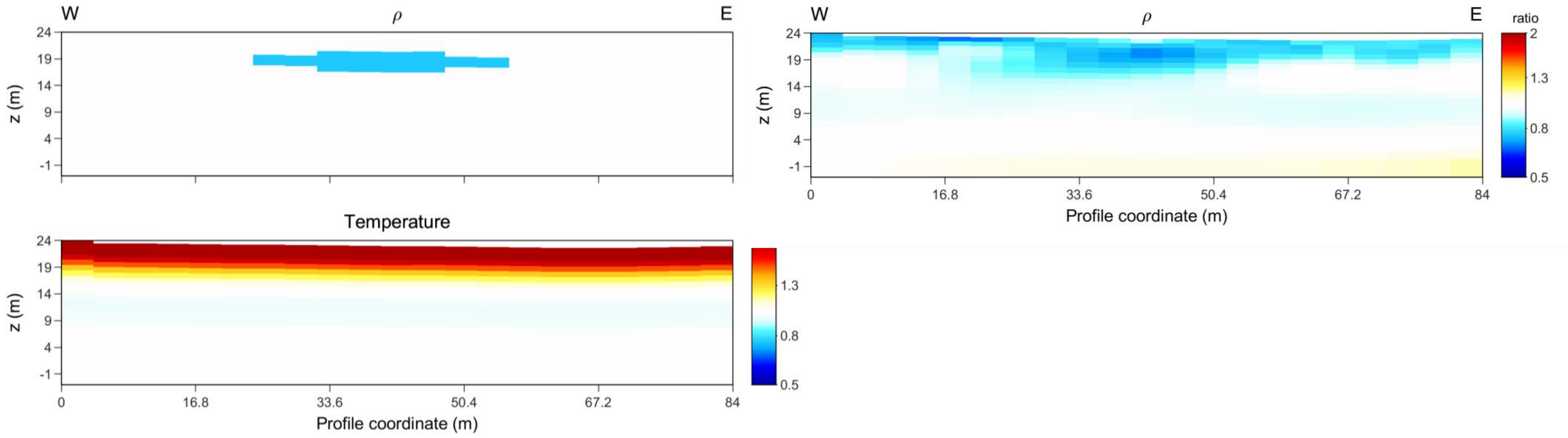
Monitoring with modelling of temperature effect

- Ratio between synthetic models
- Time-lapse inversion neglecting temperature



Monitoring with modelling of temperature effect

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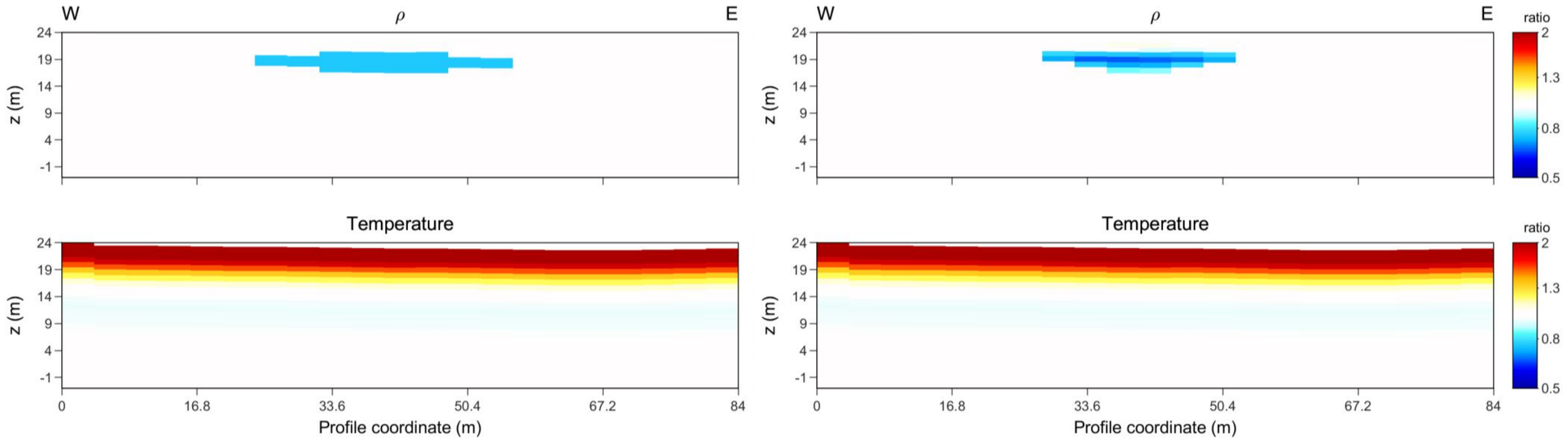

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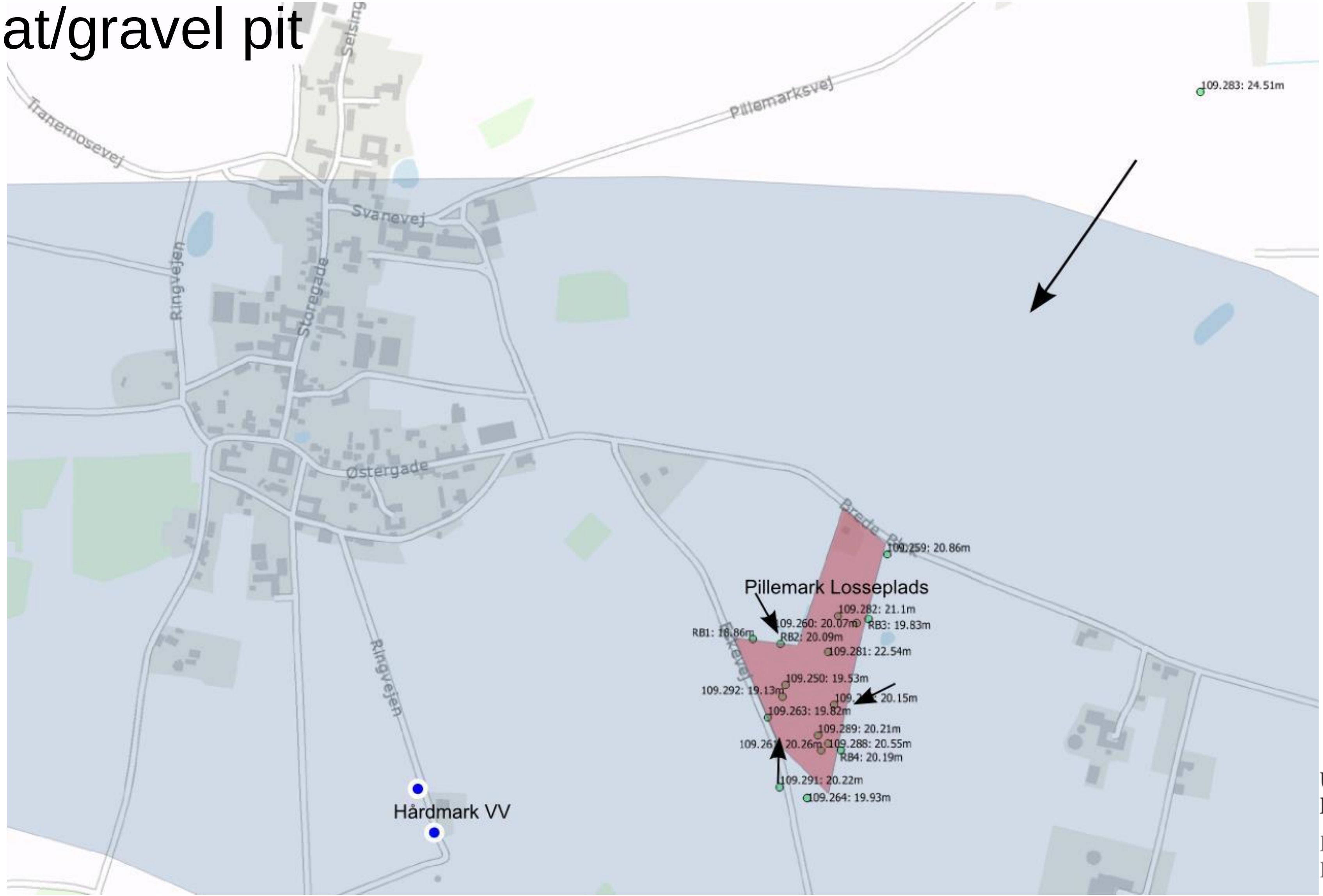
Pillemark landfill, Denmark

- Former peat/gravel pit



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Pillemark landfill, Denmark

- Former peat/gravel pit
- Used as a landfill
  1950 – 1988
- Salts, ammonia, pesticides

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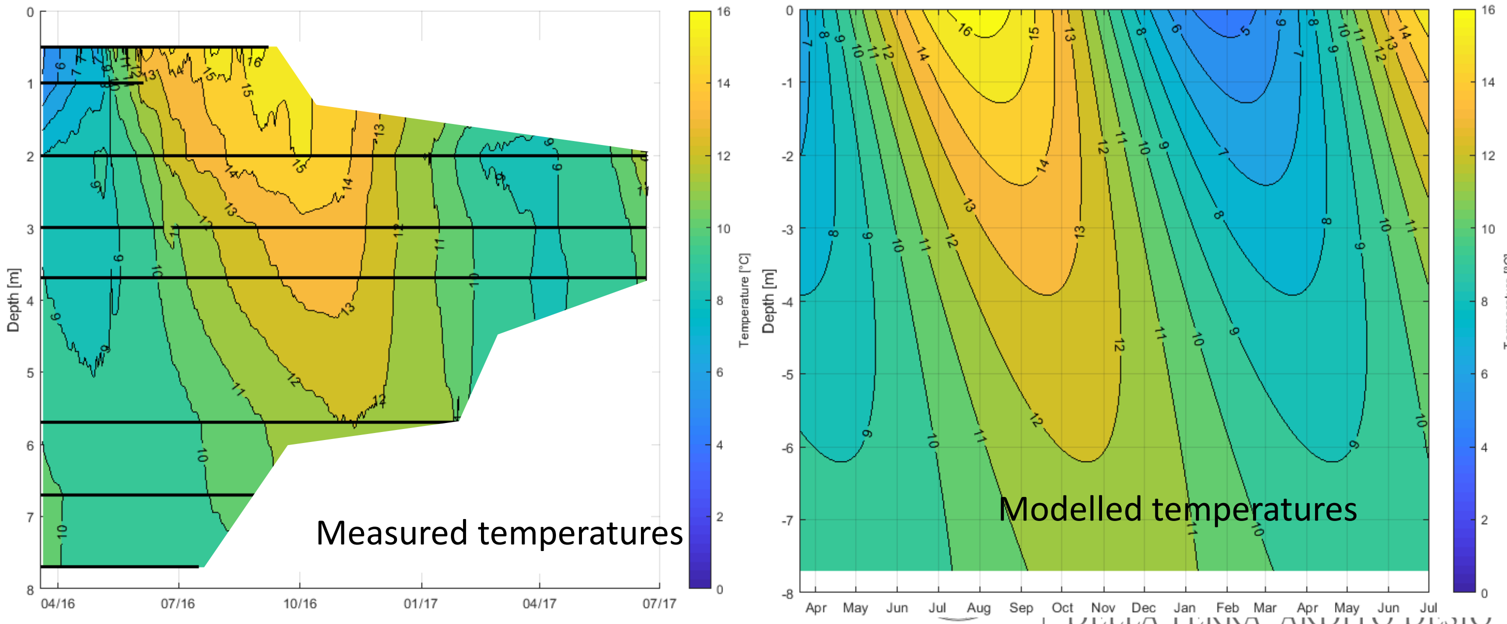
Pillemark landfill, Denmark

- Installation of monitoring system
- Two DCIP profiles, March 2016
  - 504 m, 64 electrodes, 8 m spacing
  - 124 m, 32 electrodes, 4 m spacing
- 20 x 20 cm electrodes, buried in a 30 cm trench

Temperature measured/modelled

- Temperature sensors (0.5-7.7 m)
  - Poor quality
  - Only three survived project period
- Temperature modelling
  - $T(z,t) = T_0 + \Delta T e^{-z\sqrt{\frac{\omega}{2\kappa}}} \cos\left(\omega t - z\sqrt{\frac{\omega}{2\kappa}}\right)$
  - T_0= 6 °C, ΔT = 6 °C, κ =2.0 x 10^{-6} m^2/s



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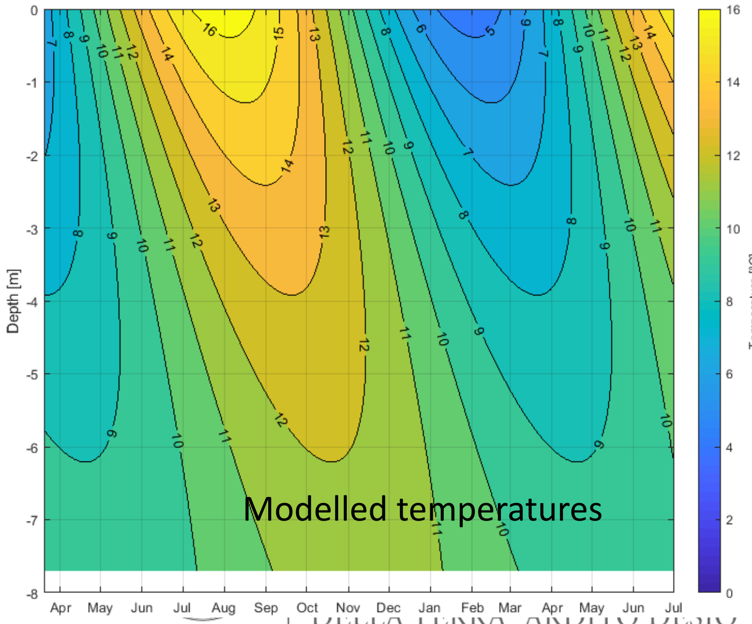
Inversion in EEMverter

- Temperature effect
  - **No data correction, but temperature modelling!**
  - Temperature correction by Haley et al. 2007:

$$\sigma_{Ref} = \left(1 + m\left(T - T_{Ref}\right)\right)\sigma_T$$

  - The temperature, T is incorporated in the model space, cell by cell, based on modelled temperatures
  - We invert for σ_{Ref}
  - We compute σ_T based on T and σ_{Ref}
  - Forward responses calculated using σ_T



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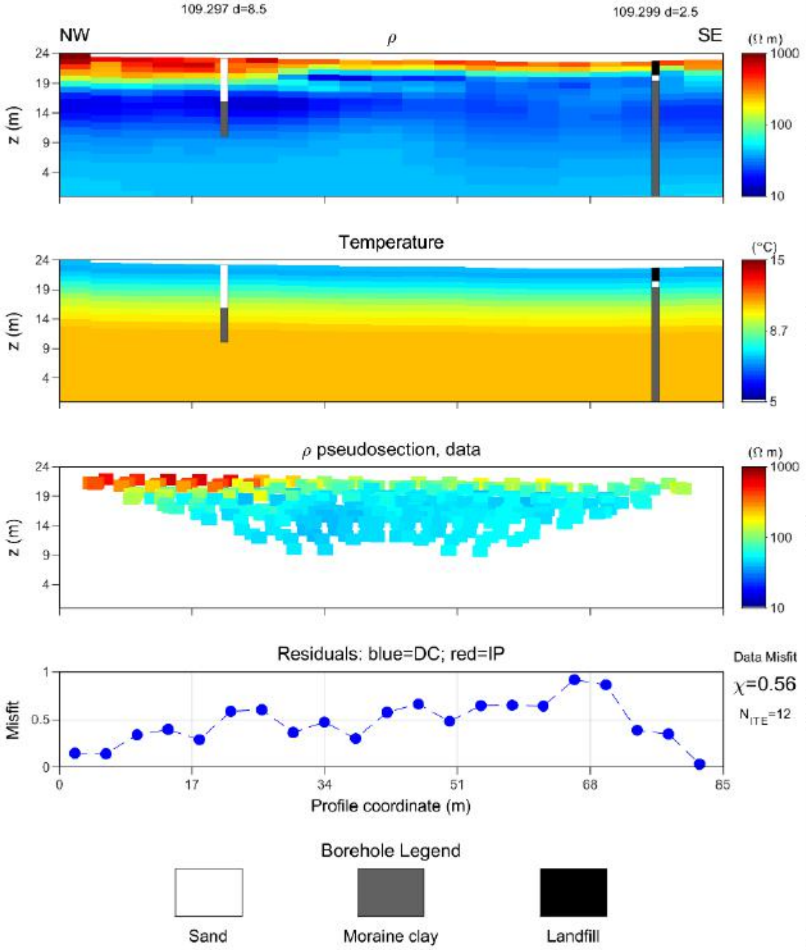
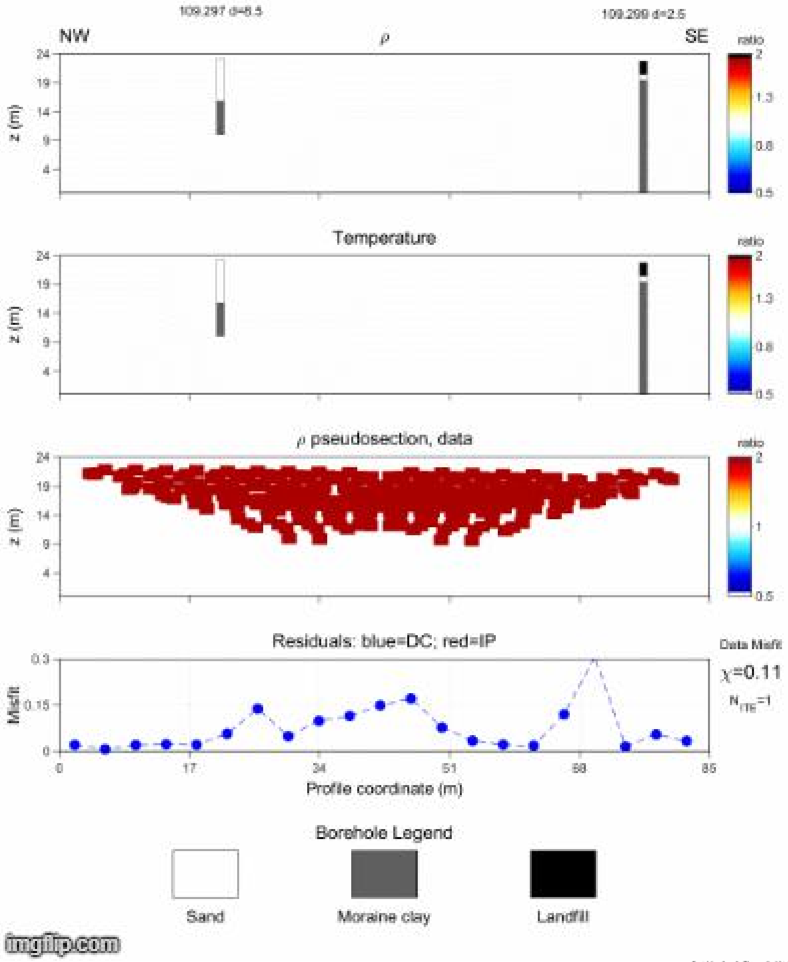
Results

Reference



Time-lapse inversion



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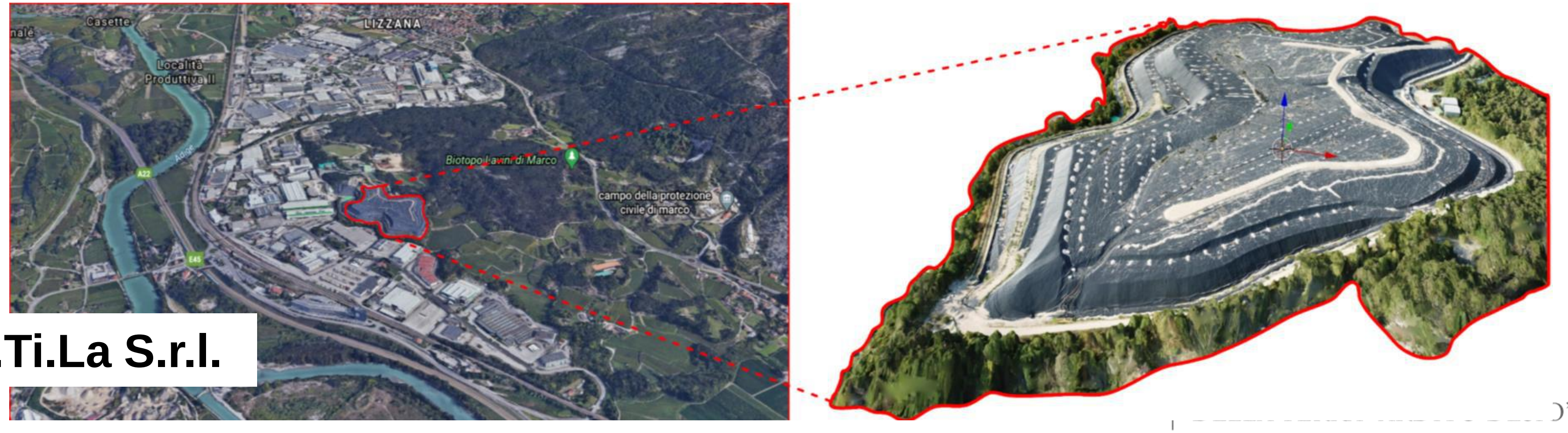
MSW Landfill, Lavini di Marco, Rovereto (TN)

2 year long DC monitoring on an Italian Municipal Solid Waste **MSW landfill**

- Master project of Alessandro Signora, in collaboration with Geo.Ti.La S.r.l.
- HDPE cover for avoiding rain water infiltration & improving biogas capture
- 4 lines with 18 electrodes, 5 m spacing
- 2 measurements per day (every 12 hours)



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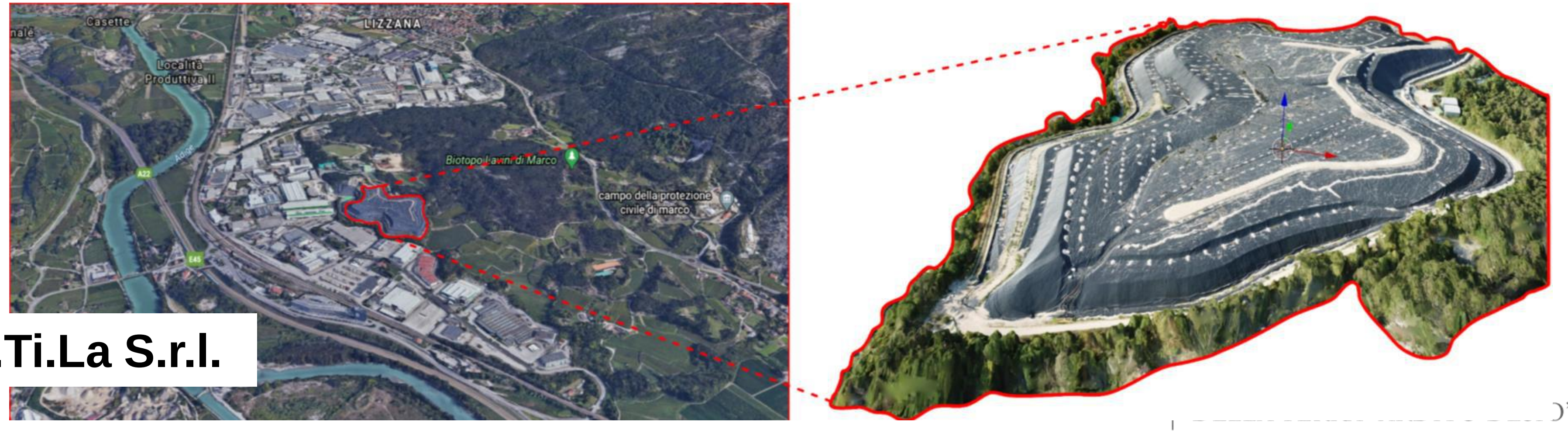

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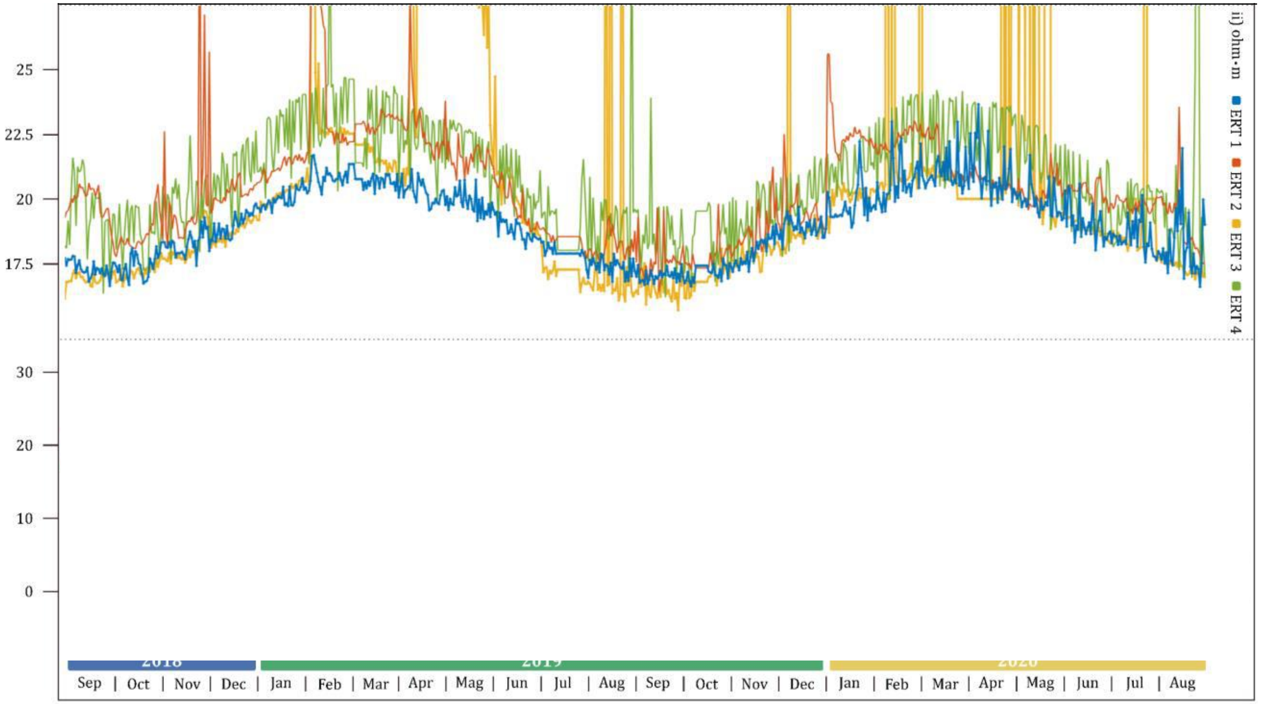

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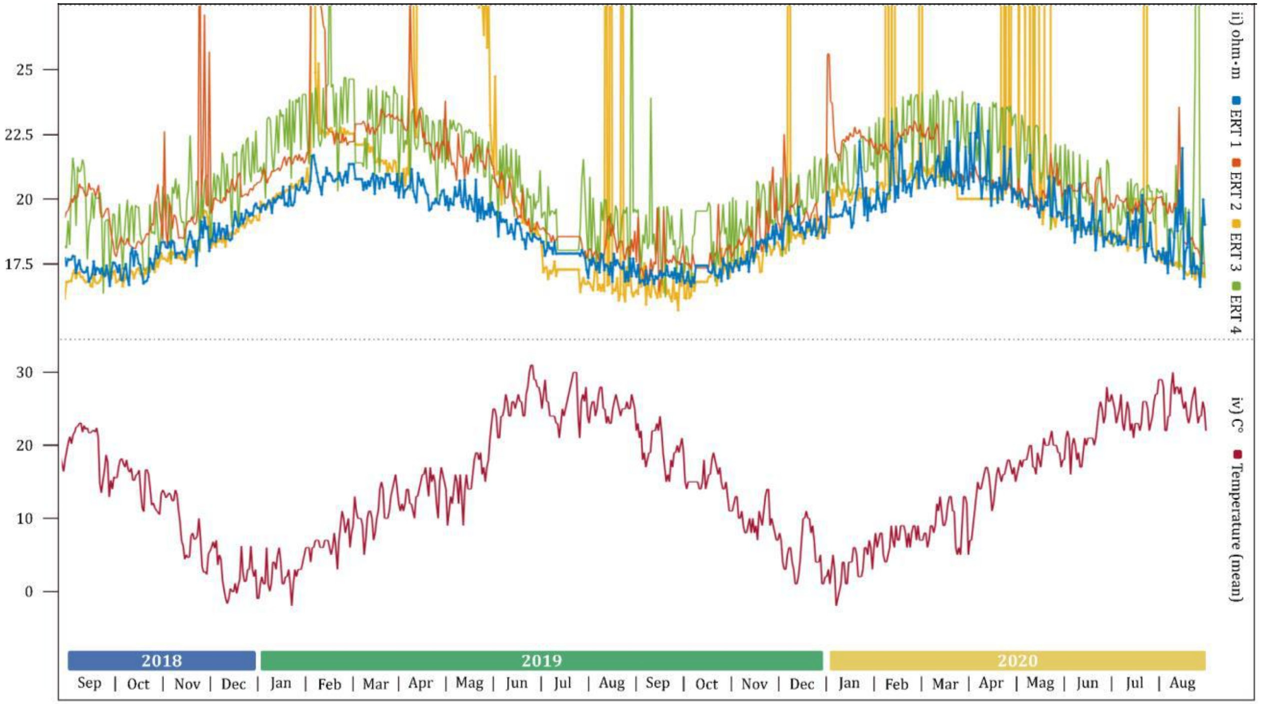

Temperature measured at the closest weather station

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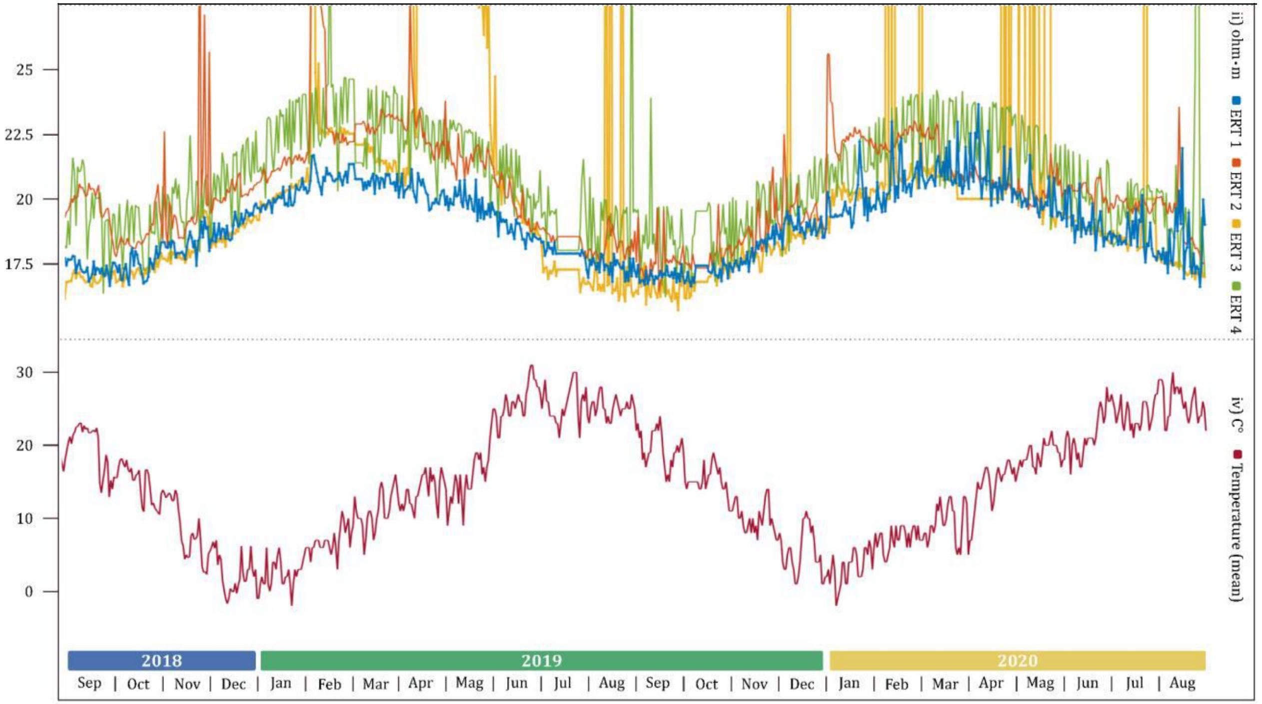
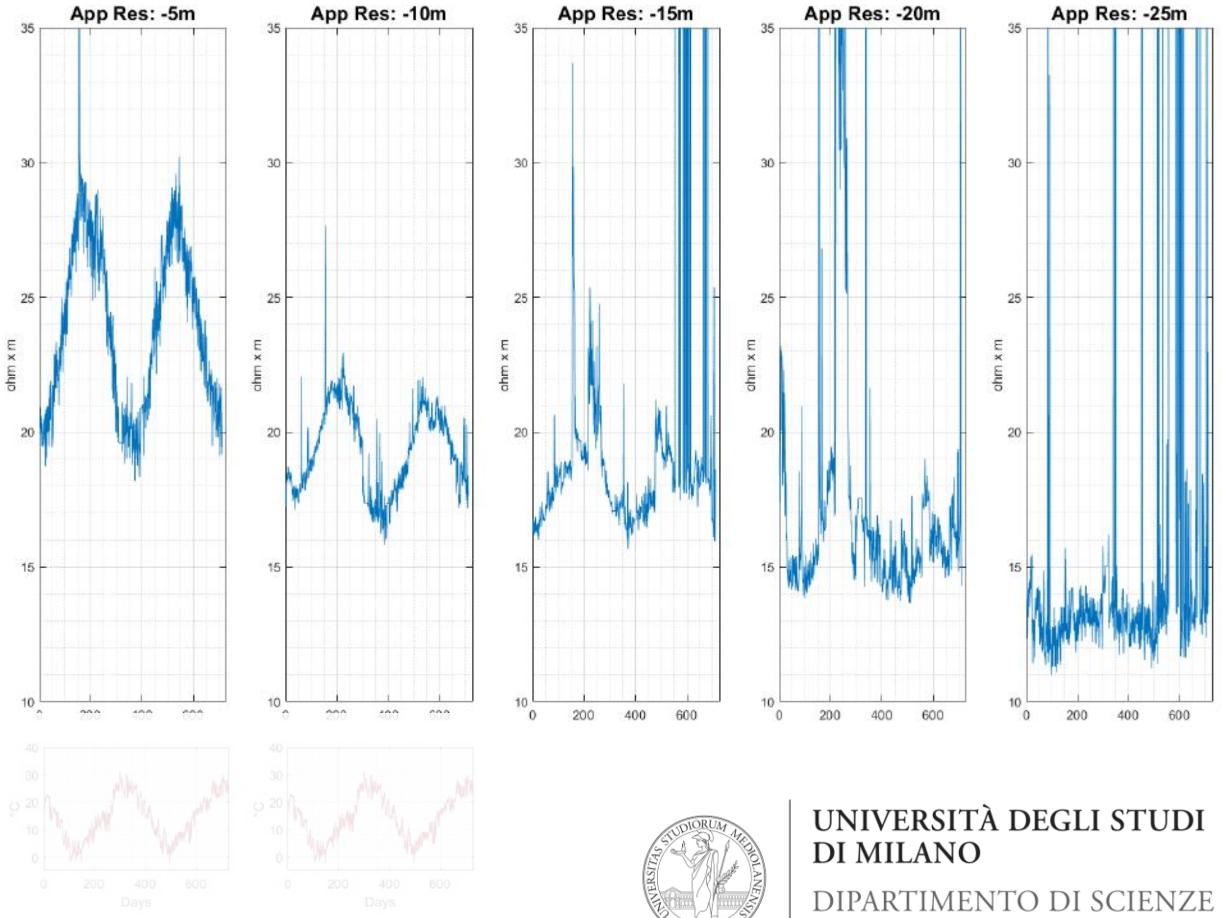


Apparent resistivity grouped for pseudo-depth



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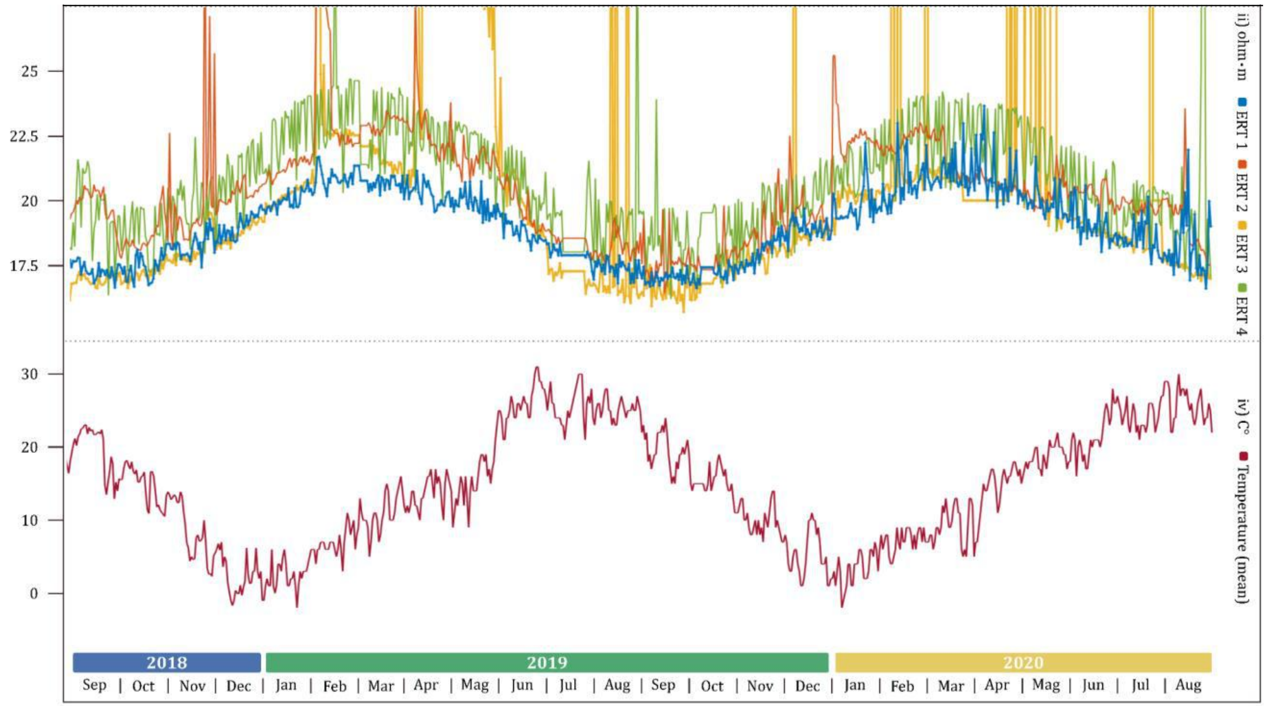

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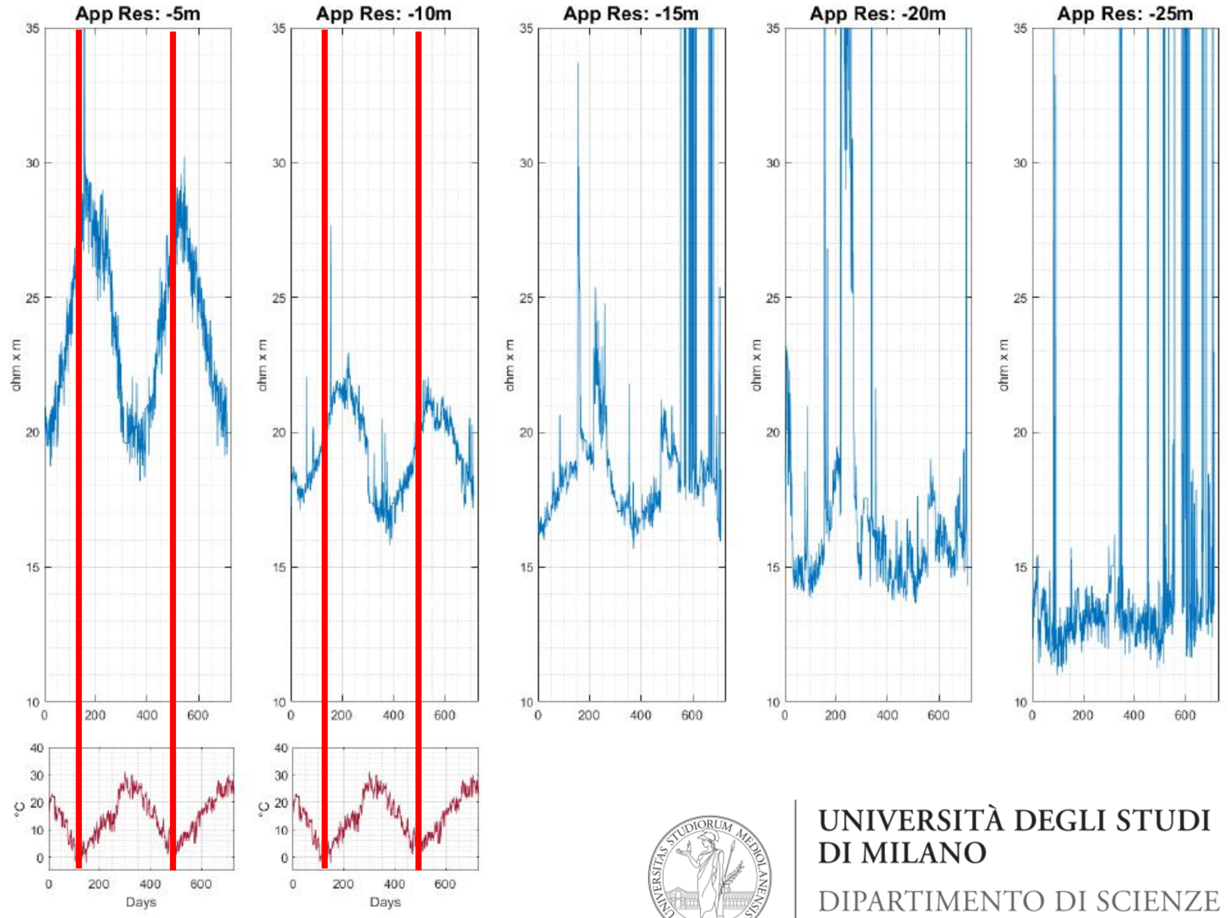

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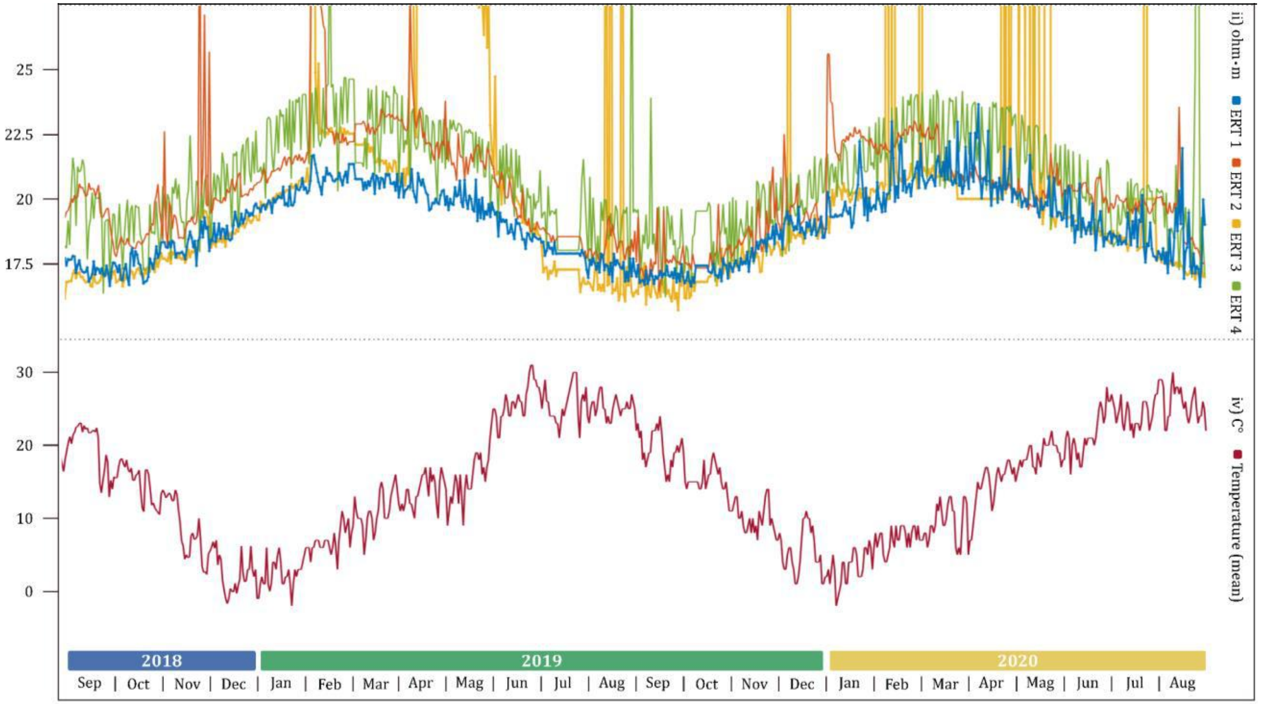

Unfortunately, no monitoring of temperature has been installed in the waste body

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Temperature effect & heat equation

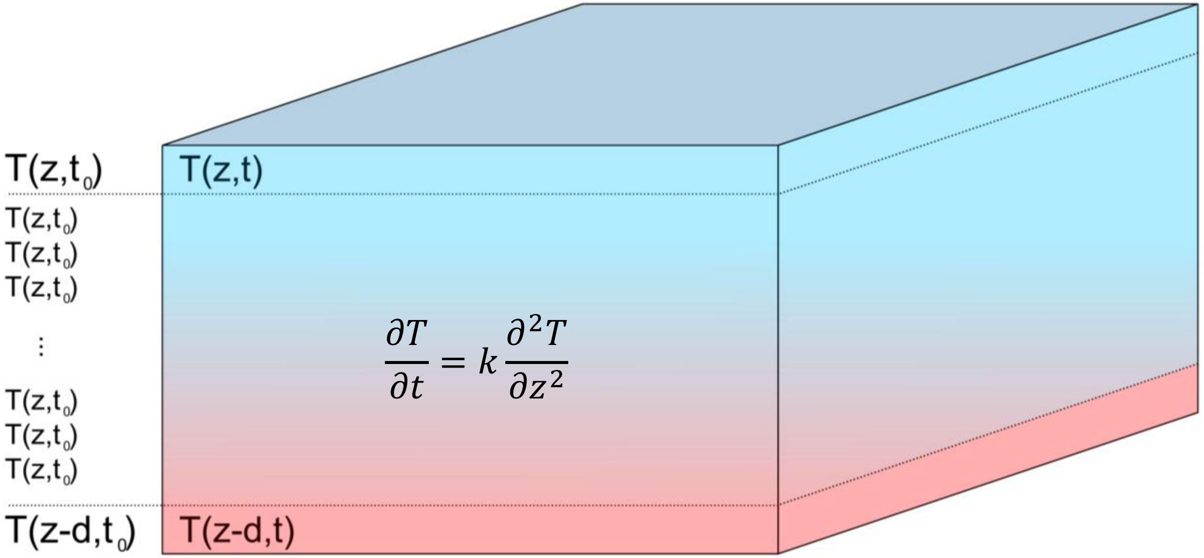
Let's consider a simple thermal modelling of a 1D slab with homogeneous thermal diffusivity k:

$$\frac{\partial T}{\partial t} = k\frac{\partial^2 T}{\partial z^2}$$

The temperature as a function of depth can be modelled giving the boundary conditions, such as:

- Temperature at z=0 and z=-d for any time t
- Temperature at any z for t=0

Can we solve the heat equation without temperature measurements in the ground as a function of depth?



Inversion strategy

Invert all time steps at once in a unique inversion process

Set up time-lapse constraints among models at different time steps

Use the **temperature measured at the surface as boundary condition** for retrieving thermal diffusivity and temperature at the bottom of the model directly from the inversion

Use the resistivity at 25 °C as other inversion parameter : imposing minimum variations among models **gives information on the heat diffusion parameters**

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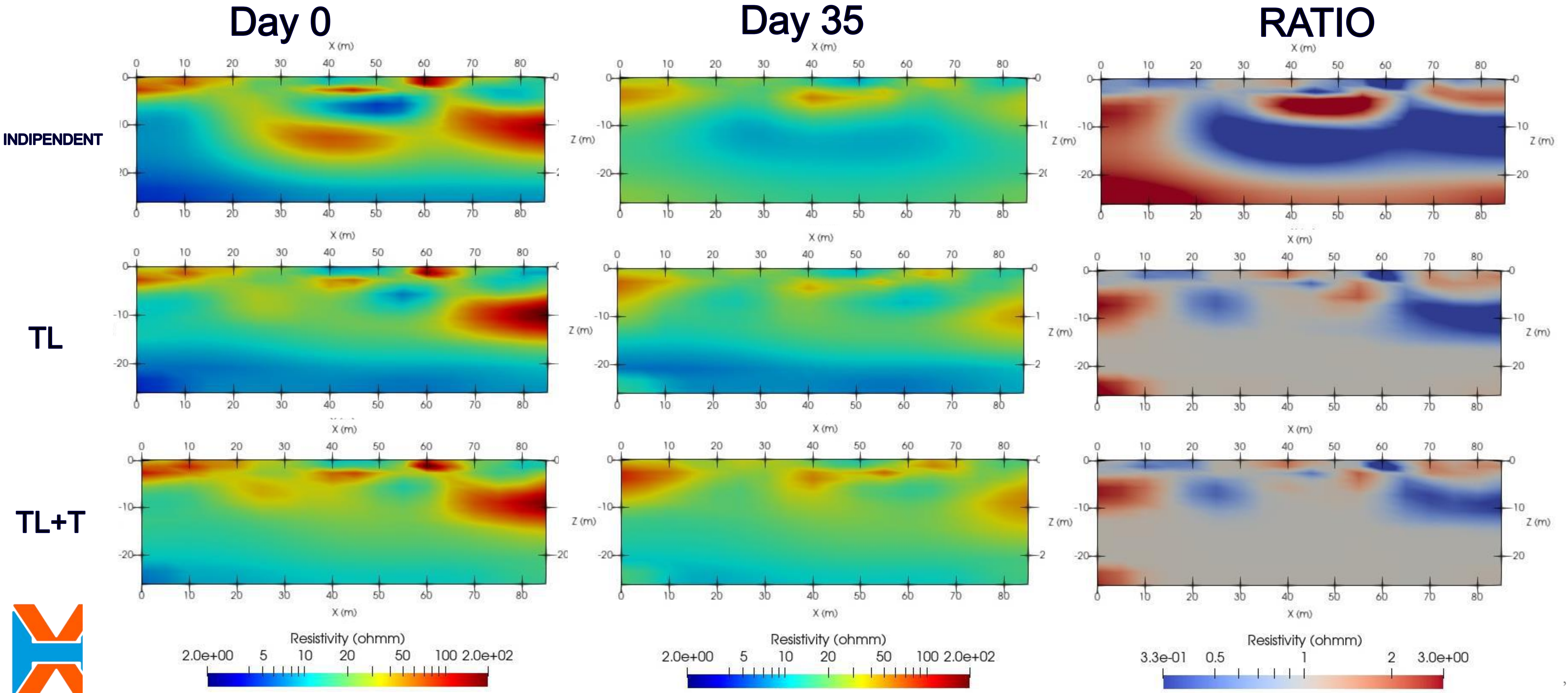
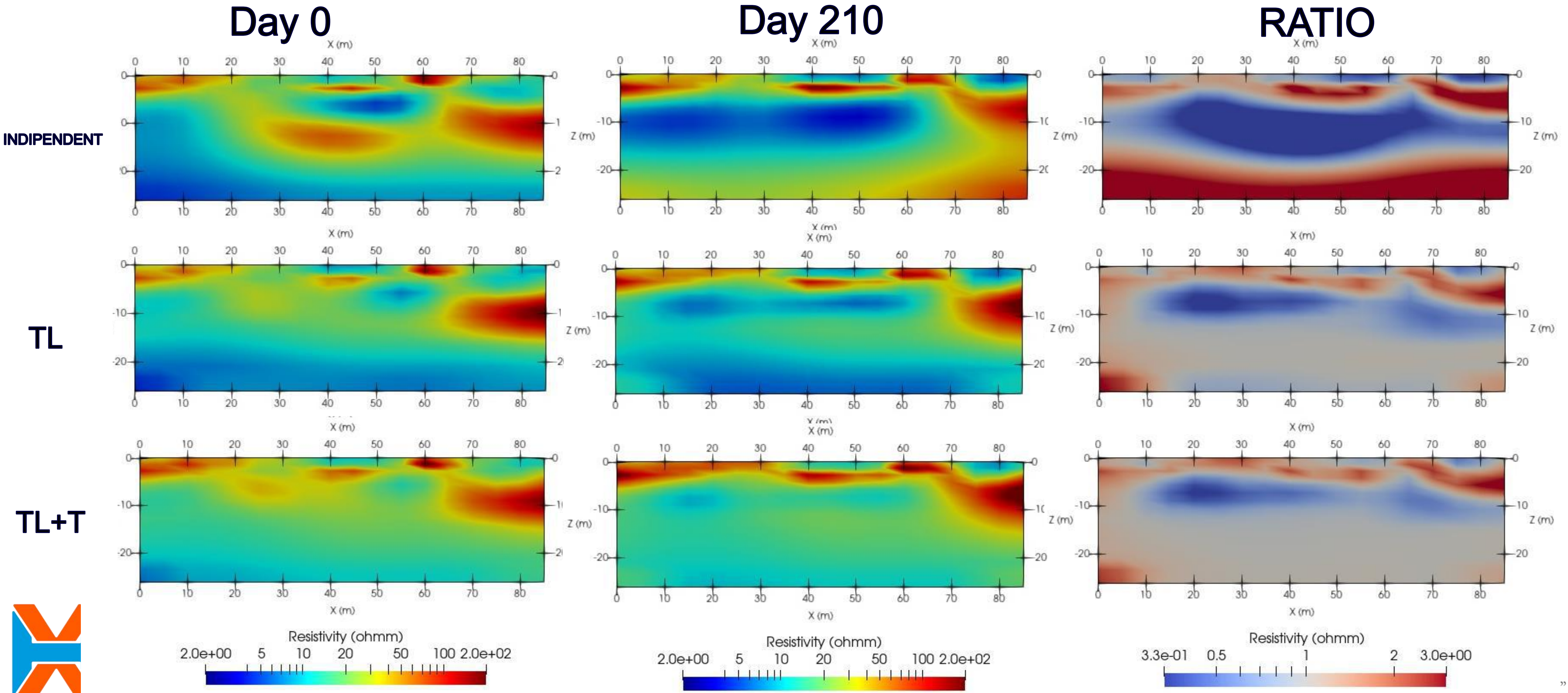
Day 35


Day 0
Day 35
RATIO
INDIPENDENT
TL
TL+T
X (m)
Z (m)
Resistivity (ohmm)
2.0e+00 5 10 20 50 100 2.0e+02
3.3e-01 0.5 1 2 3.0e+00

Day 210

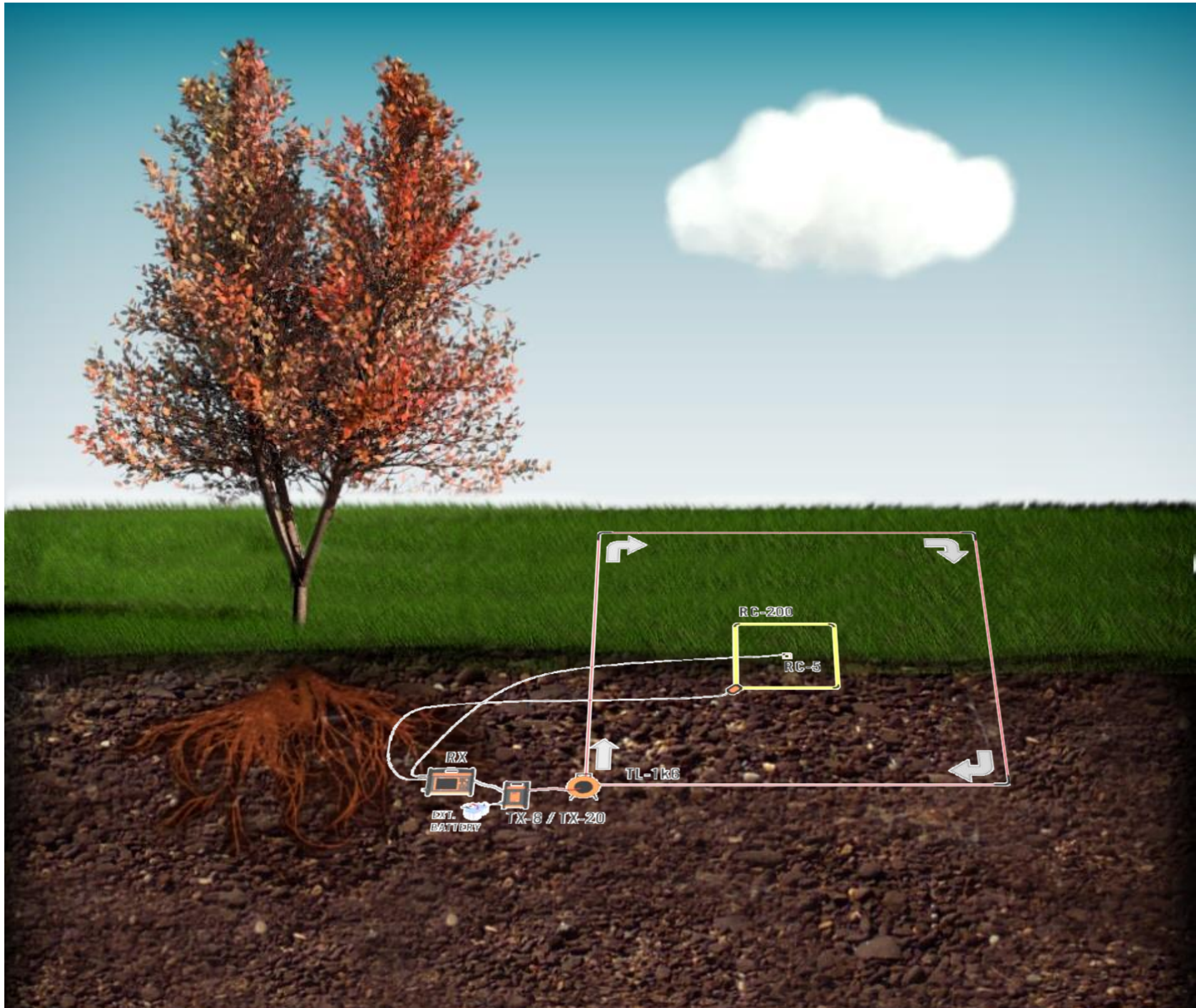

Day 0
Day 210
RATIO
INDIPENDENT
TL
TL+T
X (m)
Z (m)
Resistivity (ohmm)
2.0e+00 5 10 20 50 100 2.0e+02
Resistivity (ohmm)
2.0e+00 5 10 20 50 100 2.0e+02
Resistivity (ohmm)
3.3e-01 0.5 1 2 3.0e+00

Outline

- Electrical methods
  - Induced polarization for the characterization of hydraulic properties
  - Monitoring with modelling of temperature effect
- Electromagnetic methods
  - Unparalleled productivity
  - Airborne EM for mapping at basin scale
  - Ground-EM in continuous acquisition for detailed mapping: tTEM e Loupe systems
- Conclusions

Electromagnetic methods – unparalleled productivity

- Let's put a transmitter on the ground (red square)
- When we turn off the power on the transmitter
  - Eddy currents are induced in the ground, opposing the variation of the B flux (Lenz's law)
  - The eddy currents generate e secondary magnetic field, measurable through a receiver-loop
  - The time-variation of the Eddy currents depends on the resistivity distribution in the ground



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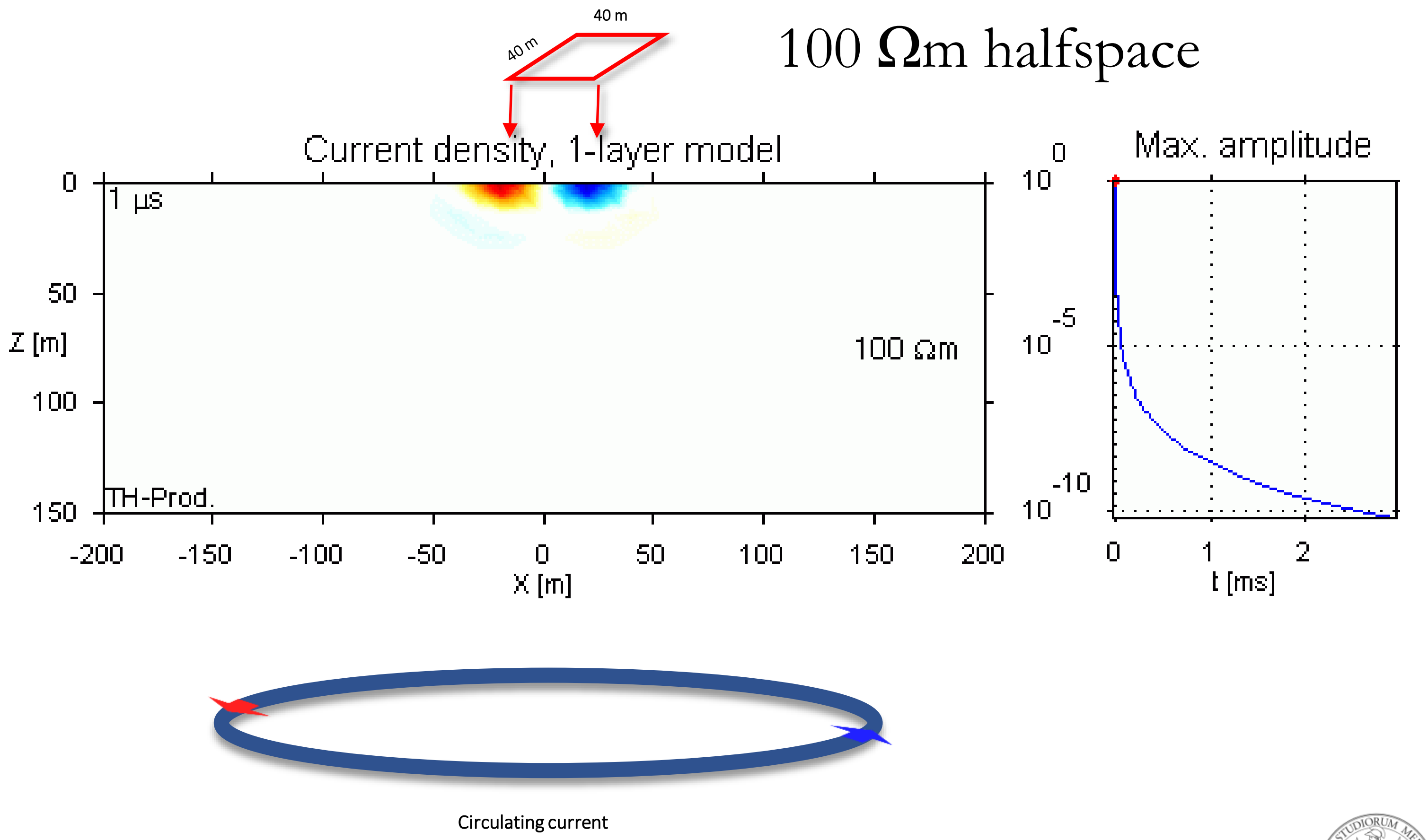
Electromagnetic methods – unparalleled productivity

- Current distribution in the ground



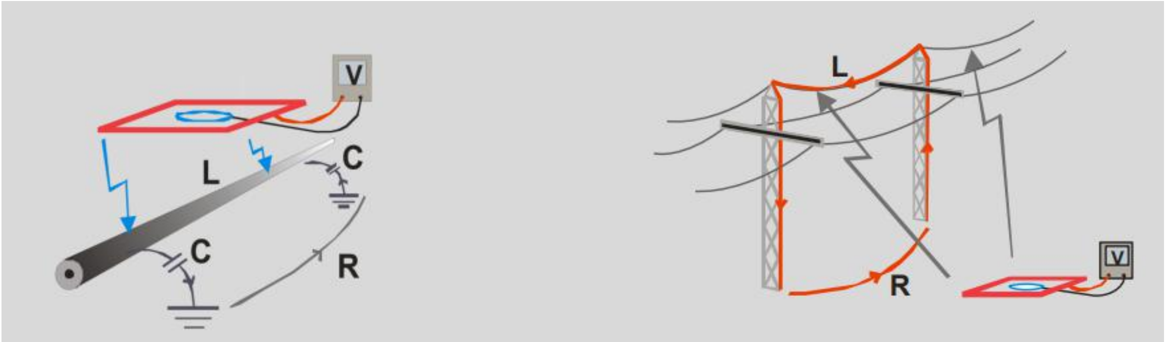
Electromagnetic methods – unparalleled productivity

No need of direct contact with ground for carrying measurements out:

- You tow your instrument on the ground
- On water
- You can fly!

Not all roses and flowers

- Coupling with metal elements
  - powerline, railway lines, gas pipelines
- No urban areas
- Careful planning and processing

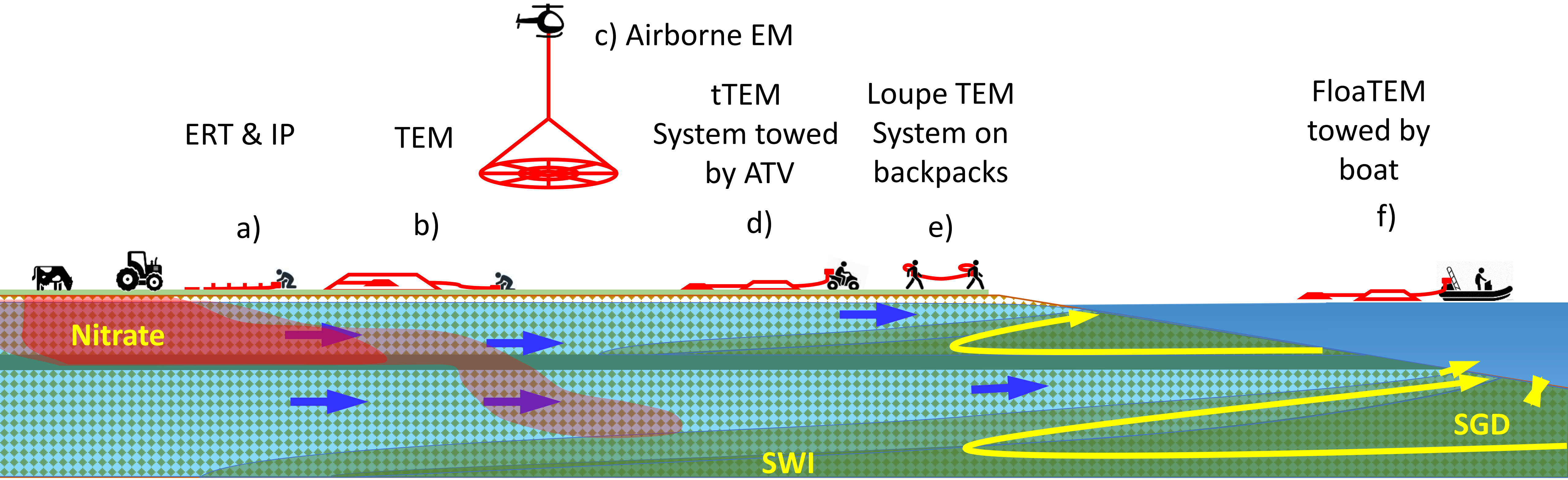


Capacitive coupling

Galvanic coupling

Electromagnetic methods – unparalleled productivity

Method	a)	b)	c)	d)	e)	f)
Depth of Investigation (m)	50-250	~250	~300	~120	~50	30-100



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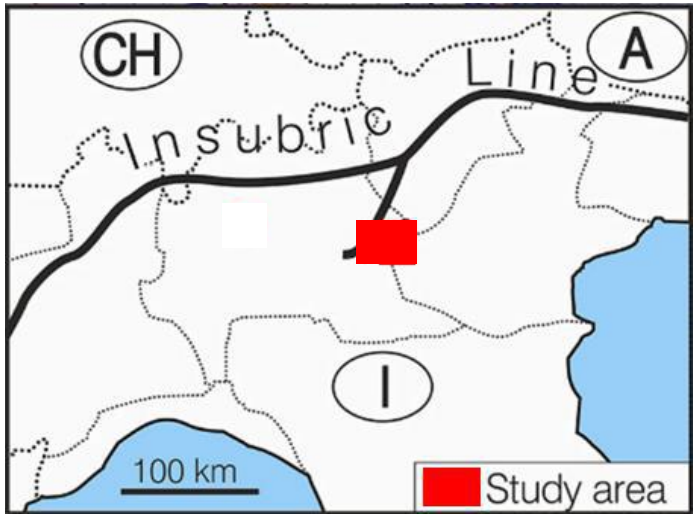
Airborne EM for mapping at basin scale

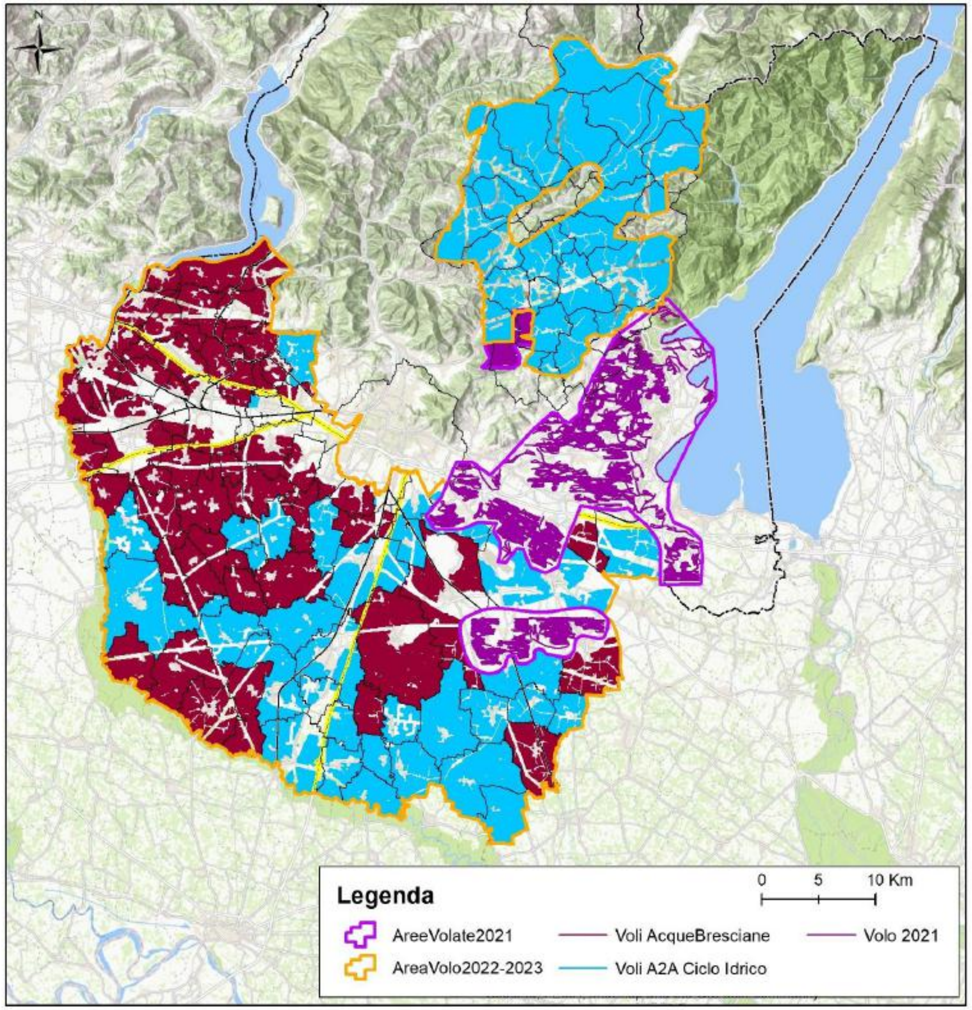
- The largest Aiborne EM (AEM) campaign in Italy undergoing in Brescia province for aquifer characterization



Airborne EM for mapping at basin scale

- The largest Aiborne EM (AEM) campaign in Italy undergoing in Brescia province for aquifer characterization

- 18000 line km of data acquired within spring 2023



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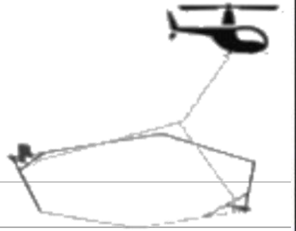
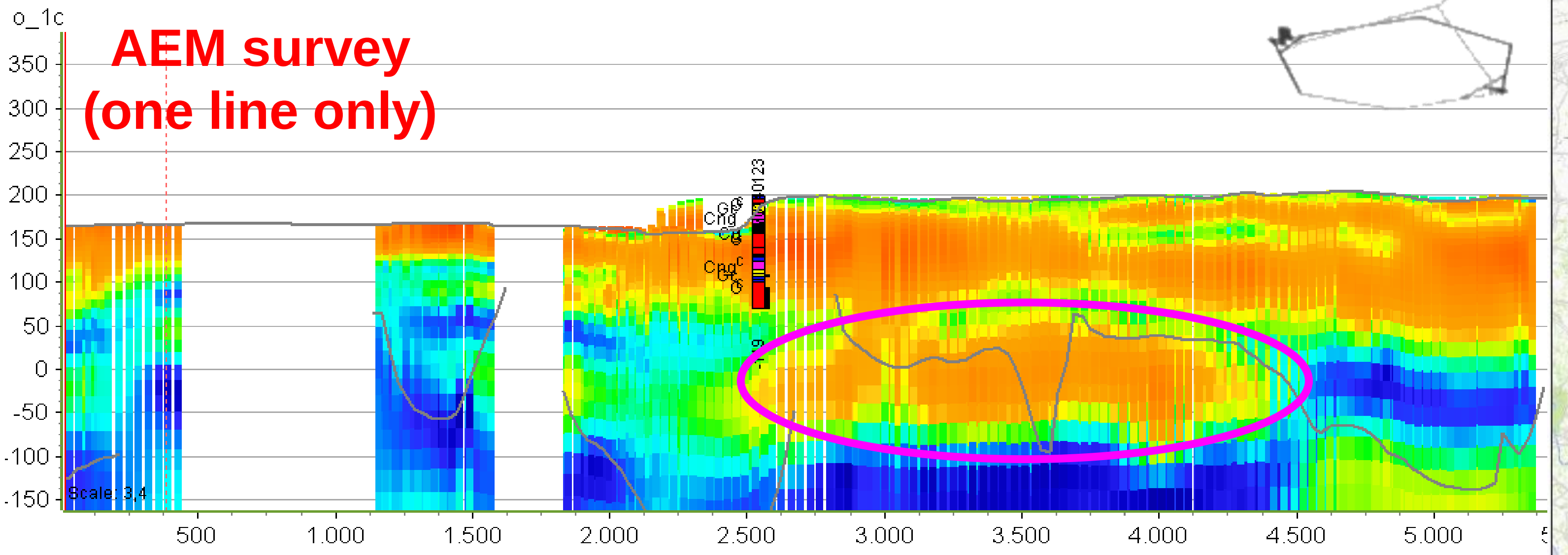
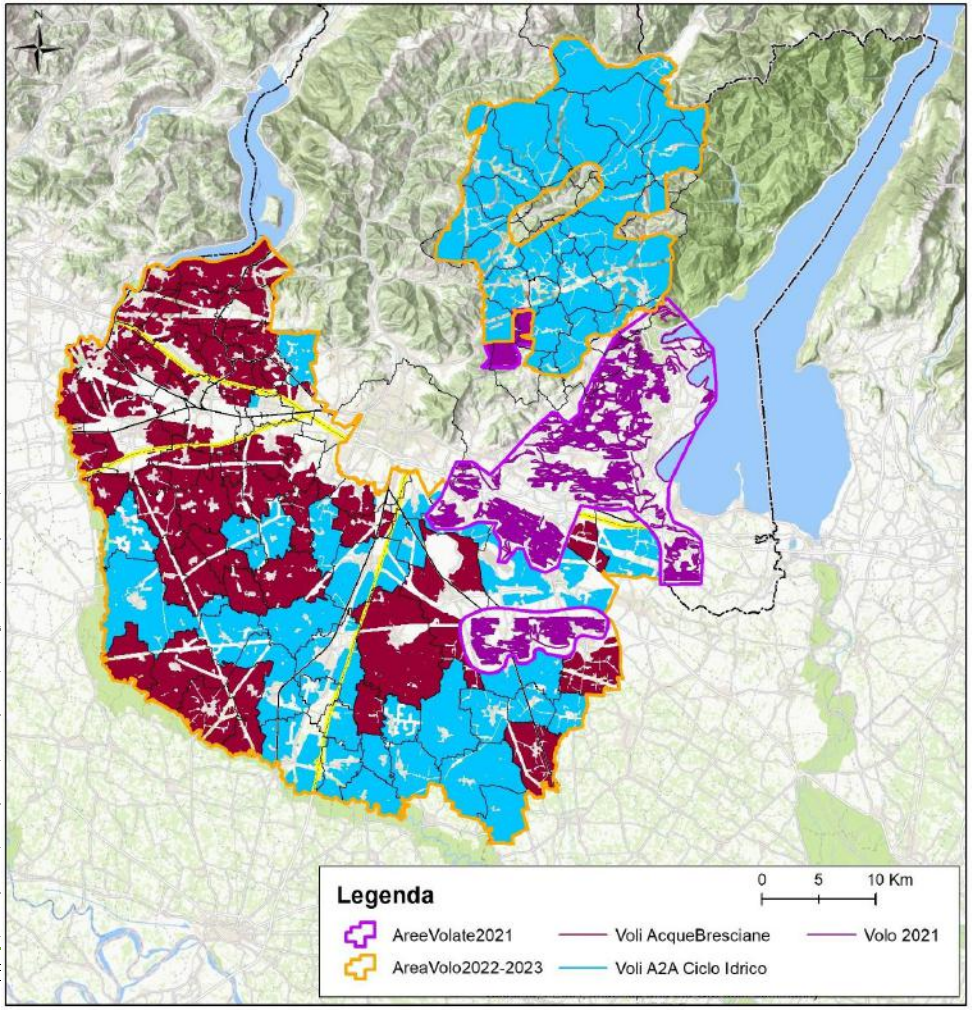
Airborne EM for mapping at basin scale

- Acquisition speed up to 80 km/h
- 30-40 m of ground clearance
- We see down to 300-400 m
- 50 km^2/day







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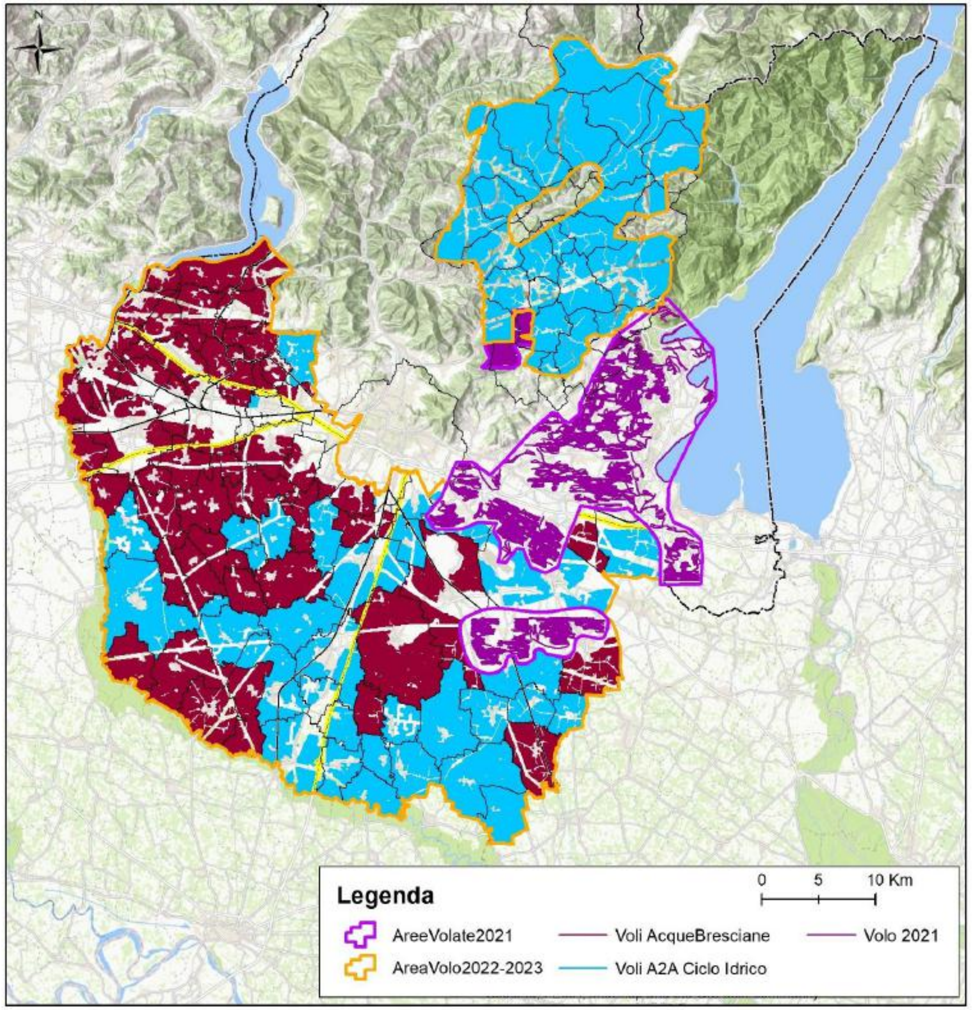
Airborne EM for mapping at basin scale

- Example of use for studying contamination
- Well in Lonato (Brescia)
  - Local protection from 10 m of clay
  - Nitrates Contamination of deep aquifer observed since last five years



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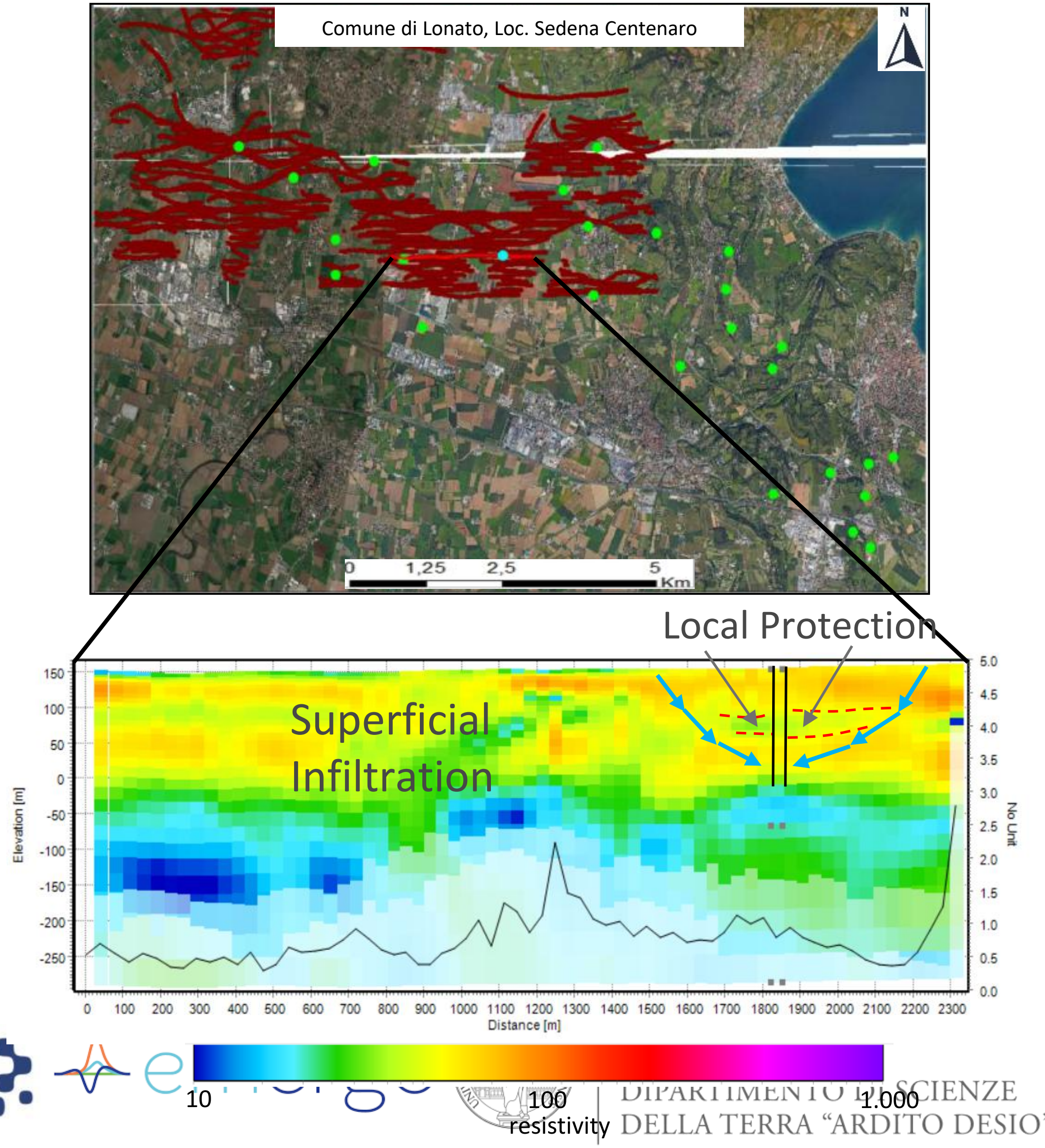
Airborne EM for mapping at basin scale

- Example of use for studying contamination
- Well in Lonato (Brescia)
  - Local protection from 10 m of clay
  - Nitrates Contamination of deep aquifer observed since last five years
- AEM findings
  - Hydraulic communication of deep and shallow aquifers
  - Lack of superficial waterproof screen, protecting the deep aquifer



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Ground-EM in continuous acquisition for detailed mapping: tTEM e Loupe systems

- Not only Airborne!
- Two new instruments for the first time in Italy for continuous acquisition

- **tTEM** (towed Transient EM)
  - Imaging down to 100-120 m
  - Acquisition speed up to 15-20 km/h

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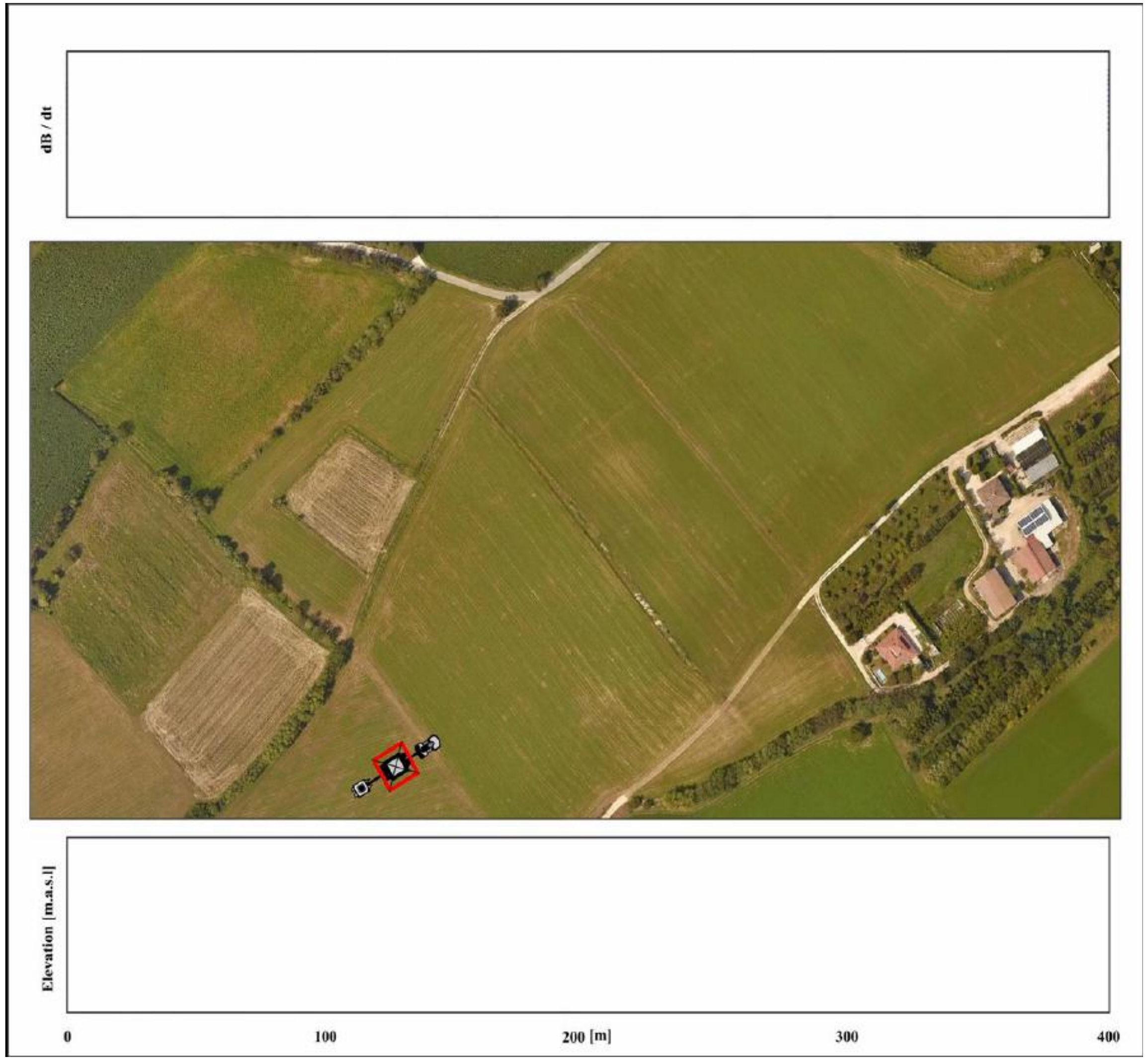

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Ground-EM in continuous acquisition for detailed mapping: tTEM e Loupe systems

- Not only Airborne!
- Two new instruments for the first time in Italy for continuous acquisition

- **Loupe** system
  - Imaging down to 30-40 m
  - Up to 10-15 km/day

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The HydroGeoSITe – reference & calibration site for E&EM and hydrogeophysics

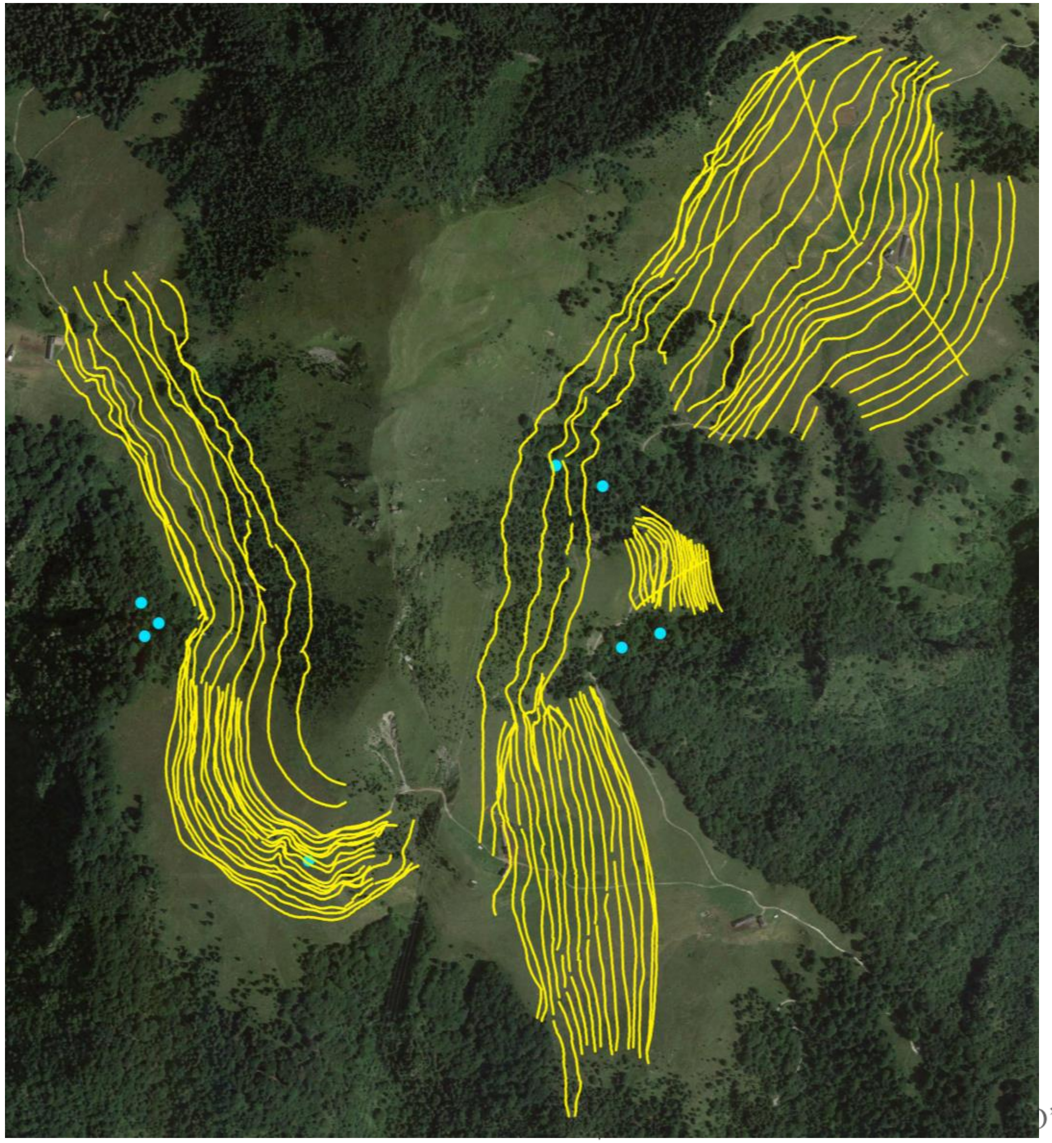
HydroGeoSITe so far

- Around 23 km of Loupe data acquired
- Several tTem and electrical surveys carried out

Aquifer characterization

Val Sabbia:

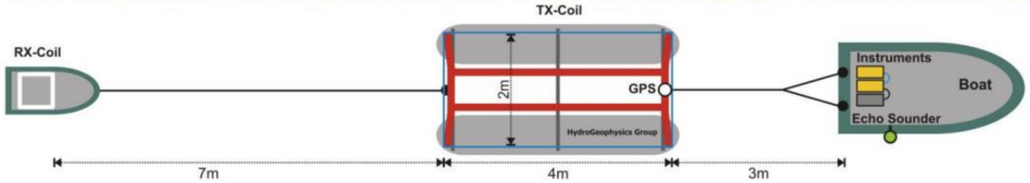
- More than 43 km of Loupe data acquired
- Around 5 km of electrical lines acquired
- Future target of AEM survey

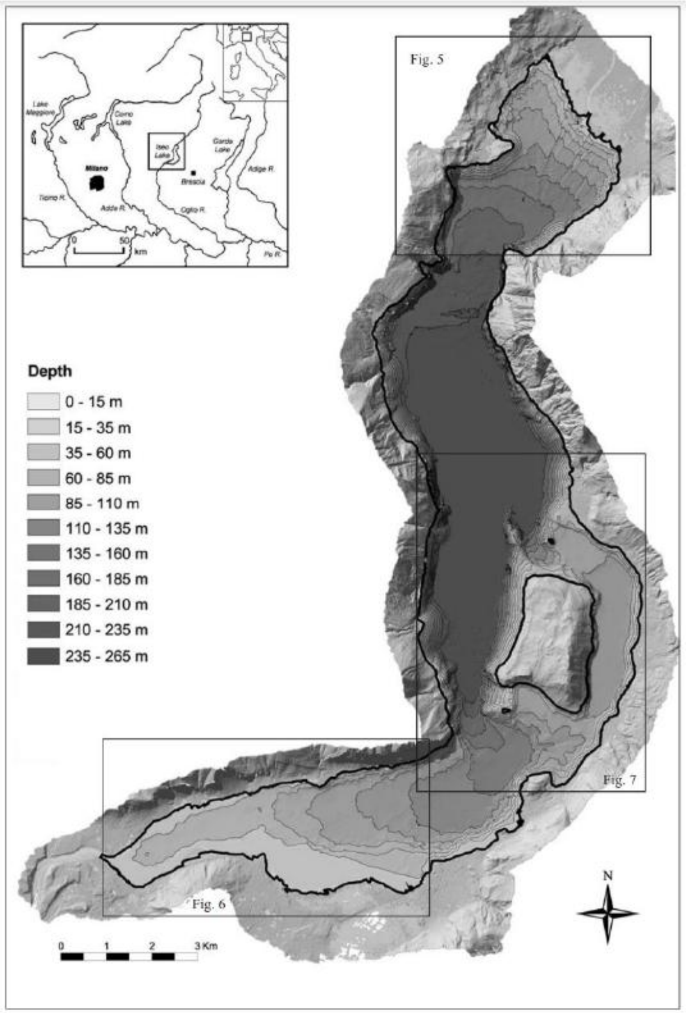


Surface/groundwater interaction

Iseo lake:

- FloaTEM acquisition
- Mapping surface water/groundwater interaction
- 160 km of acquisition lines in spring 2023





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Acque Bresciane Servizio Idrico Integrato

UNIVERSITÀ DEGLI STUDI DI MILANO
DIPARTIMENTO DI SCIENZE DELLA TERRA "ARDITO DESIO"

Outline

- Electrical methods
  - Induced polarization for the characterization of hydraulic properties
  - Monitoring with modelling of temperature effect
- Electromagnetic methods
  - Unparalleled productivity
  - Airborne EM for mapping at basin scale
  - Ground-EM in continuous acquisition for detailed mapping: tTEM e Loupe systems
- Conclusions

Conclusions

- Electrical and Electromagnetic methods very effective in characterizing and monitoring contaminated sites
- Electrical methods:
  - Access to hydraulic properties
  - Monitoring, but careful treatment of temperature is needed!
- Electromagnetic methods
  - Unparalleled productivity
  - Airborne: 50 km^2/day
  - tTEM: 50 hectares/day
  - Loupe: 10 hectares/day
  - But careful planning and processing due to coupling issues

Acknowledgements

- The students
  - PhDs: Alessandro Signora, Alice Lucchelli, Francesco Dauti, Stefano Galli
  - PostDocs: Nicole Sullivan, Arcangela Bollino, Jian Chen
  - Bachelor/Master graduates & trainees: Silvia Spagna, Mattia Lonardi, Barkha Burkhey, Giulia Tezzon, Giulia Airoldi, Alessia Barbagallo, Valeria Fedeli, Federico Fasolato etc.

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  - PON 1061, 2021-2024, MUR/A2A ciclo idrico/Emergo
    - HydroGeosITe – Italian Hydrogeophysical site
    - IPRaMa – Induced Polarization for Raw Materials
    - MountainHydro – Hydrology in Mountains
  - HydroEEMaging – Electric and Electromagnetic imaging of Hydro resources, 2022-2025, A2A ciclo idrico
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