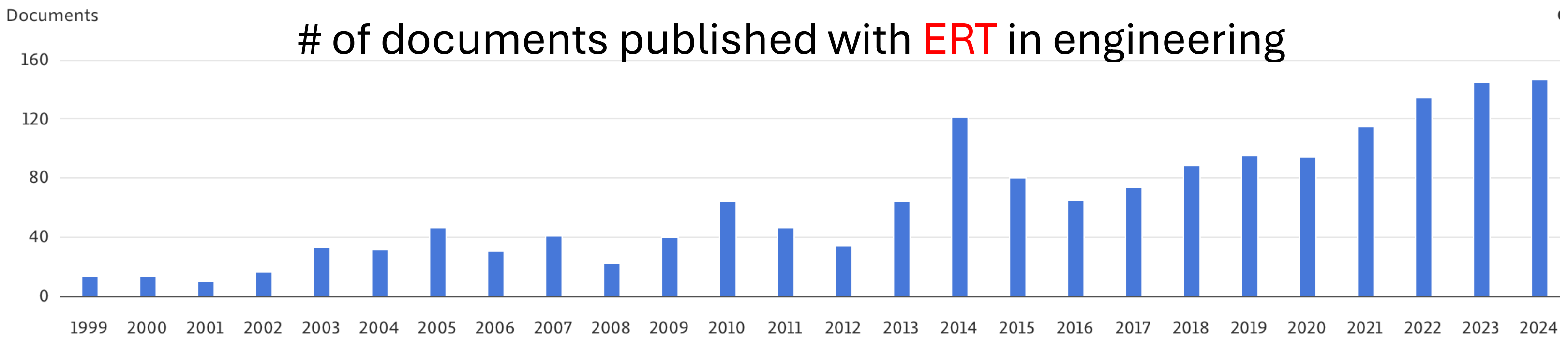
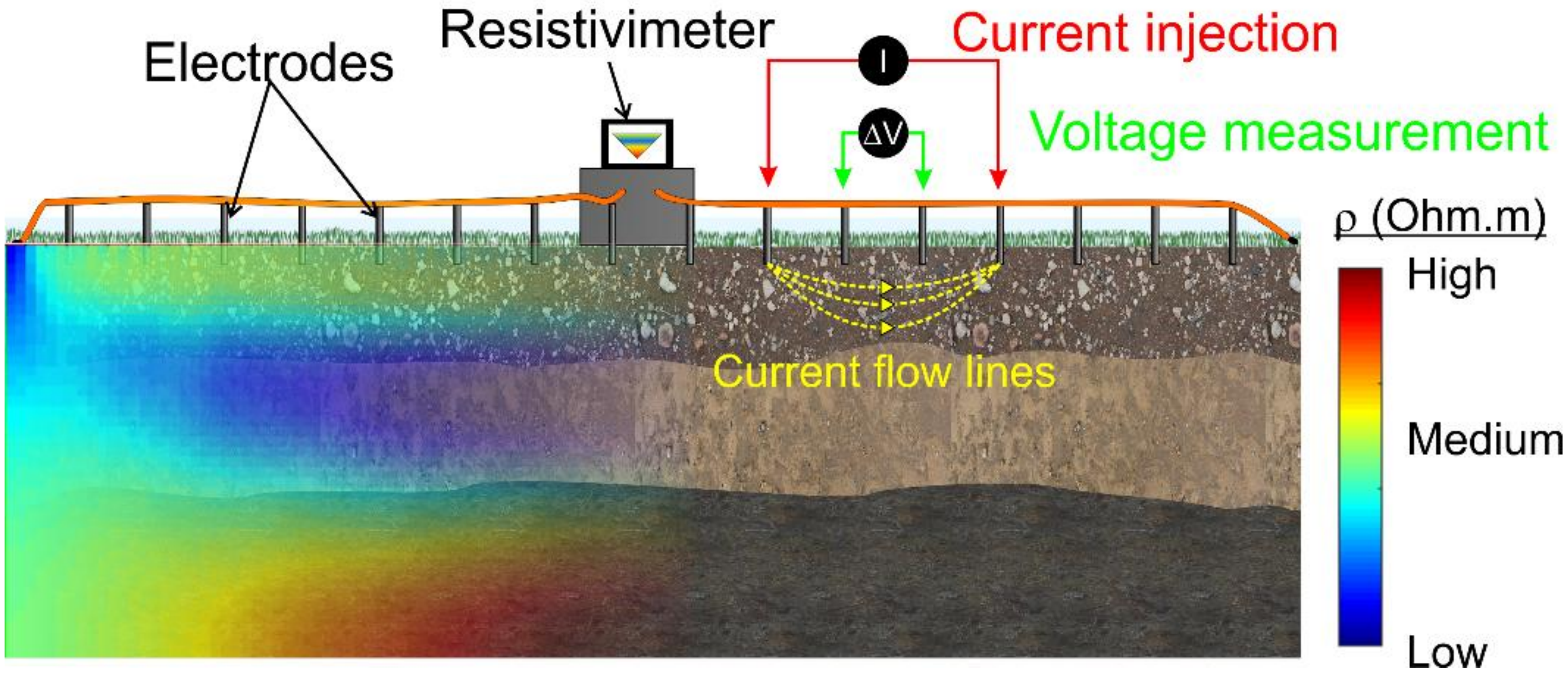
Electrical resistivity tomography (ERT): recent advances and new applications

Frédéric Nguyen, Guillaume Blanchy, David Caterina, Tom Debouny, Hadrien Michel, and Yannick Forth

+ published work from Itzel Isunza Manrique and Gaël Dumont, (former PhD ULiège)

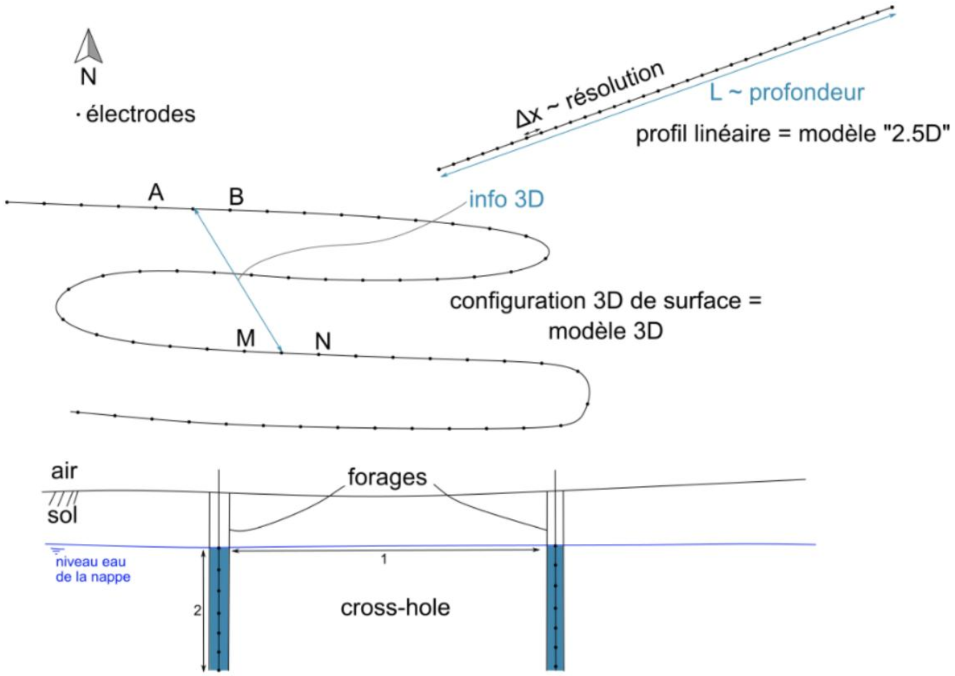


What is electrical resistivity tomography ?

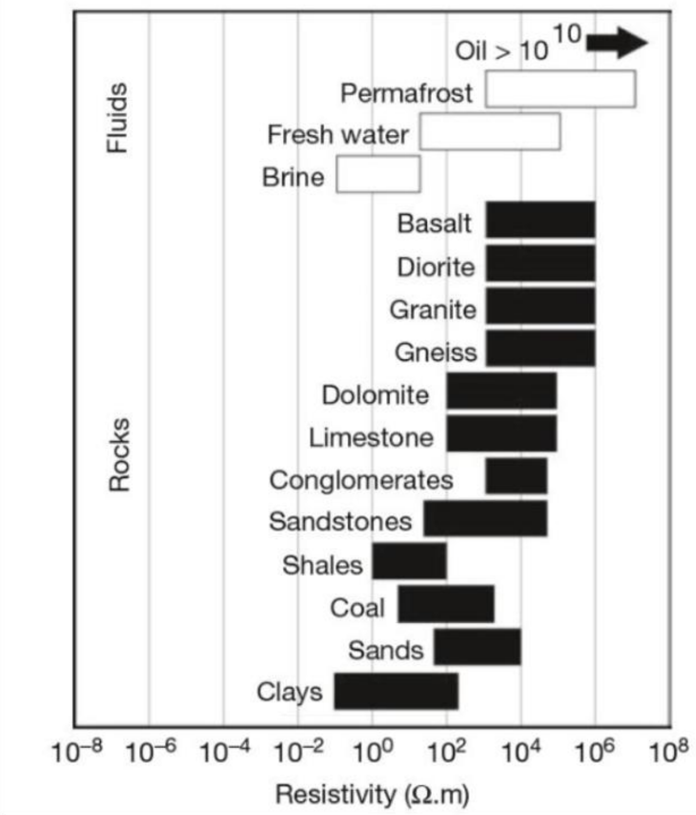


Why a Focus on electrical resistivity ?

« Flexible » set-up

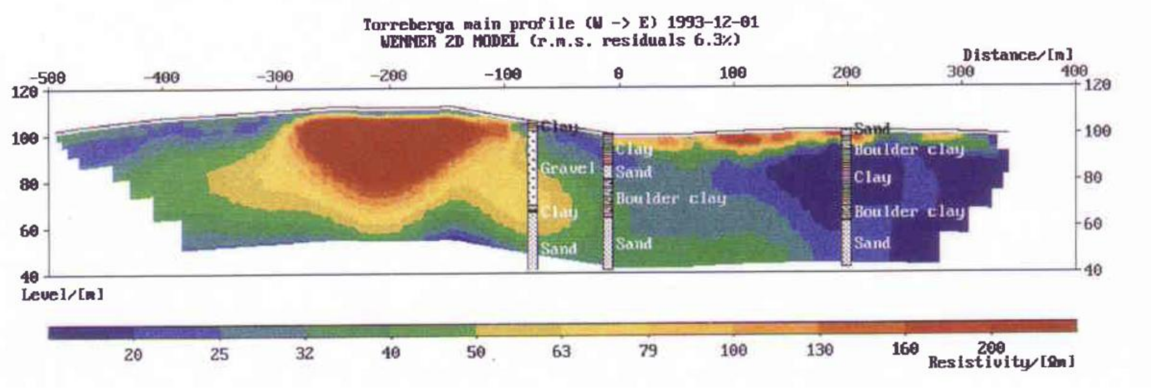


Large range of contrast

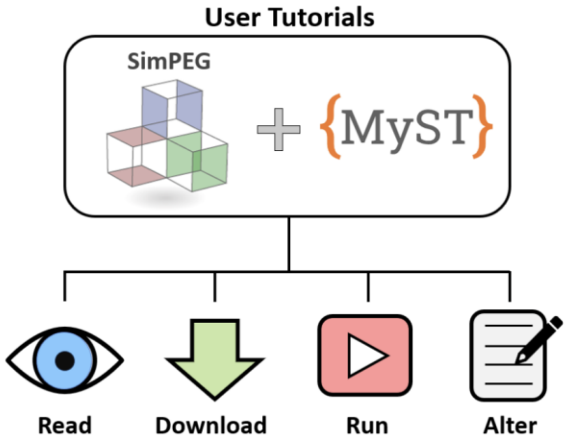


A brief and non-exhaustive ERT history

- 1990s : Automatic centralized resistivity meters
- 2000s: Increased number of channels
- ➢ 2000s: Electrode design
- 2010s: Integration with studied processes
- 2010s Data processing : from commercial to open-source suites
- ➢ 2010s: Remote operation
- ➢ 2010s : Decentralization through autonomous GPS-PPS synchronized electrical field recorders
- ➢ 2020s: Machine learning and open hardware



Dalhin, 1996



https://simpeg.xyz/

IRIS ® fullwaver

Engineering geology : investigating deep structures for the Einstein Telescope

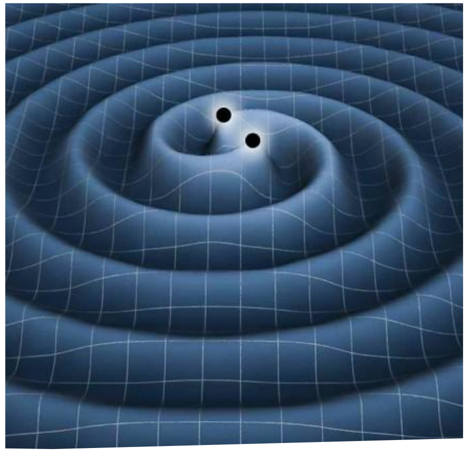
How decentralized acquisition systems allows to image geology at great depth (500m)

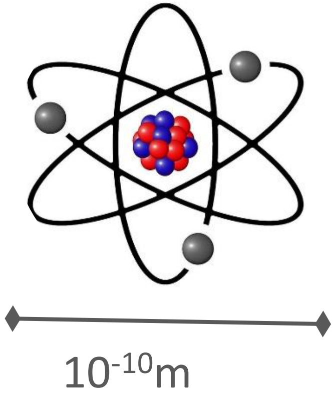
ETGEO team @ULiège

Pourquoi s’intéresser au sous-sol alors que l’on cherche à comprendre l’univers lointain ?

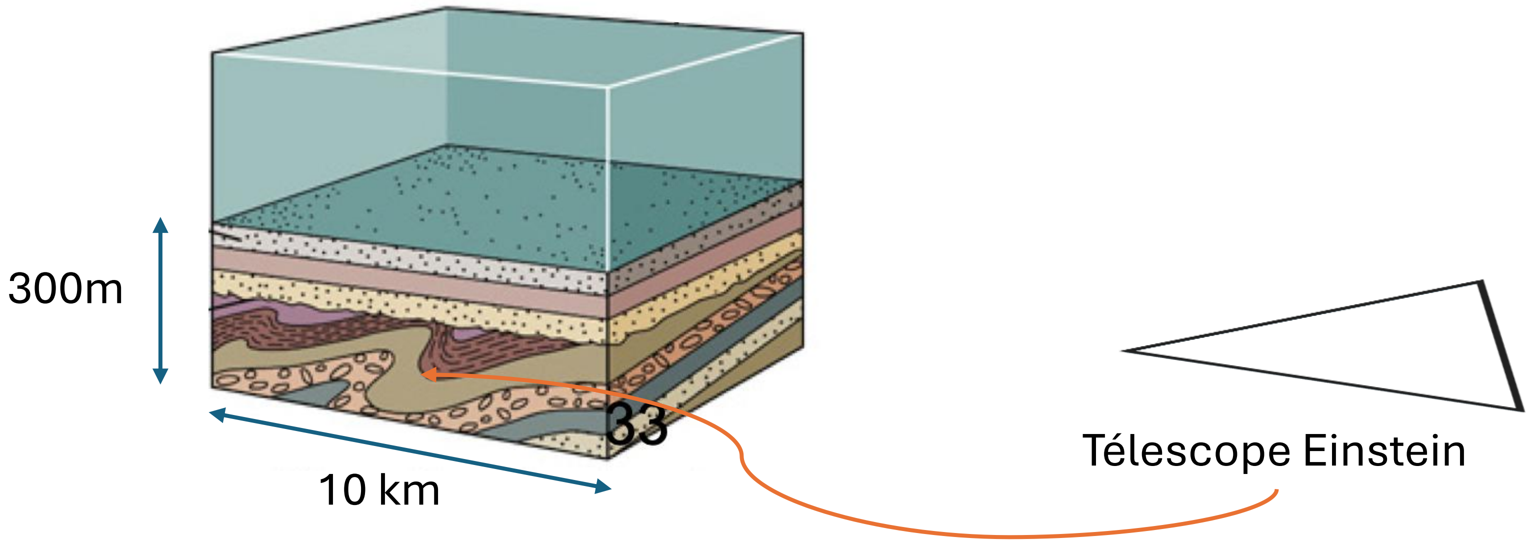
La fusion d’objets massifs (trous noirs) génère des déformations de l’espace créant des déplacements de **10^{-18} m** entre des objets situés à 1 km de distance alors que le sol vibre naturellement à 10^{-6}m

S’enterrer permet de **s’affranchir (en partie) des vibrations** anthropiques



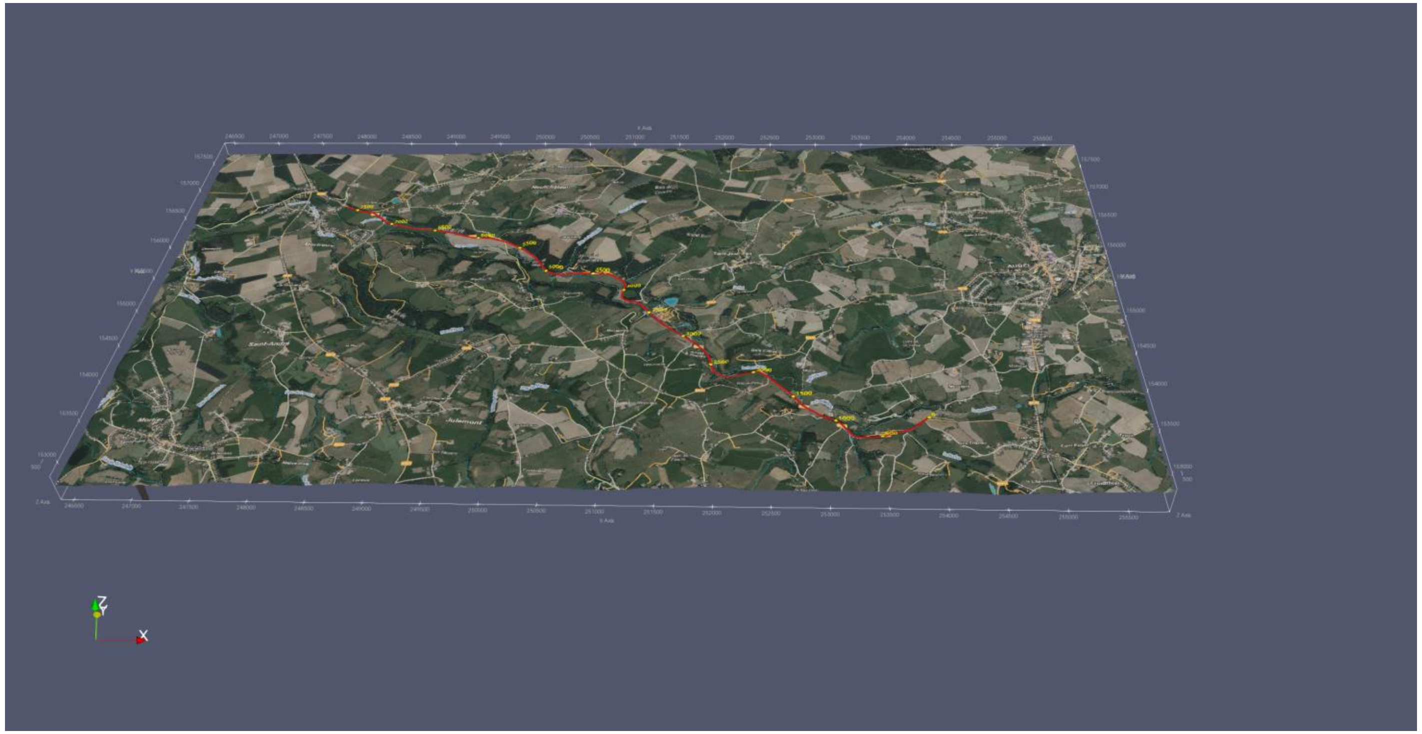


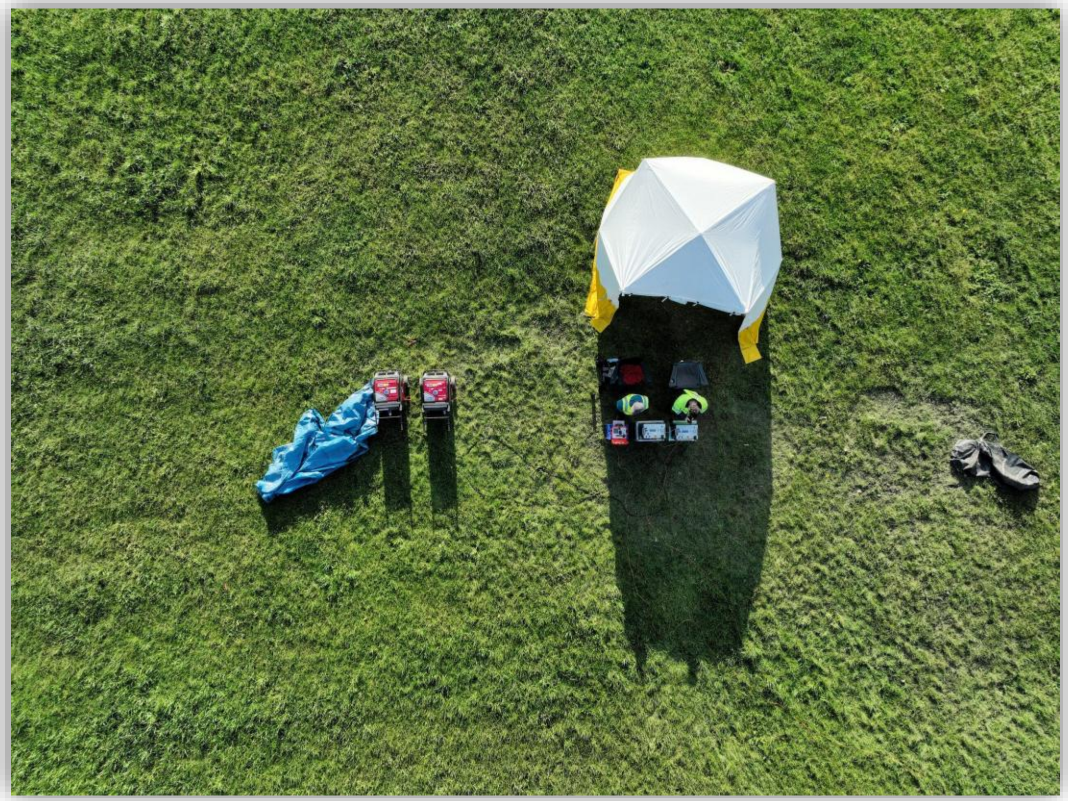
L’enjeu est de **prévoir** ces conditions pour minimiser les risques/coûts du génie civil et de s’assurer des exigences « vibratoires »



Imagerie géophysique

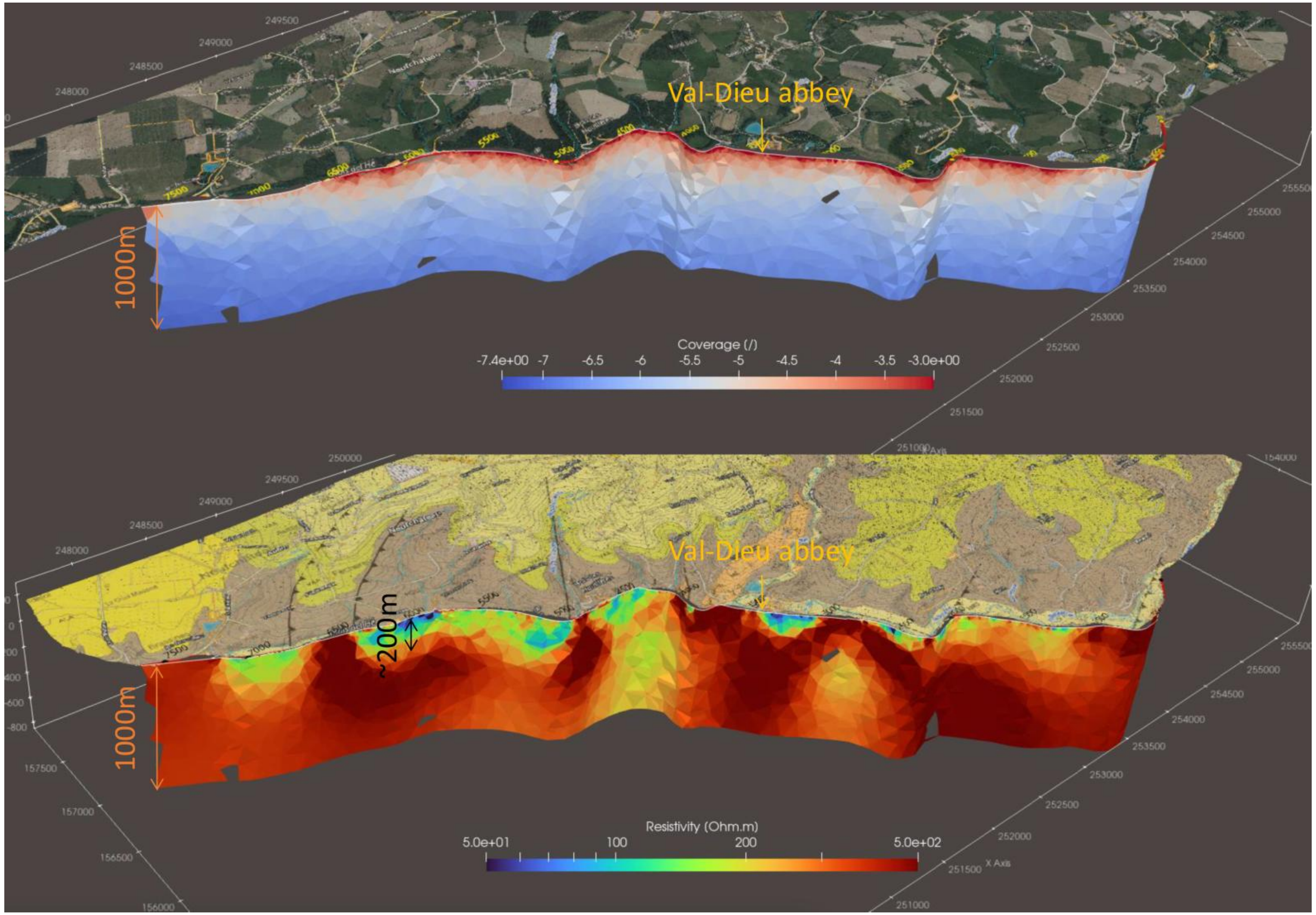
- « Tomographie électrique » à grande échelle (7km de long, 500m prof.)
- Permet de compléter l'information entre les forages et de faire ressortir les **contrastes** **électriques**

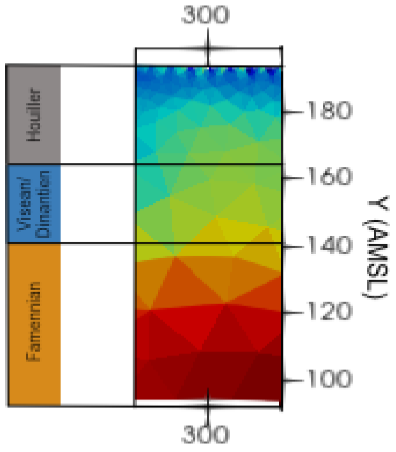




IRIS ® fullwaver unité d'acquisition GPS-PPS

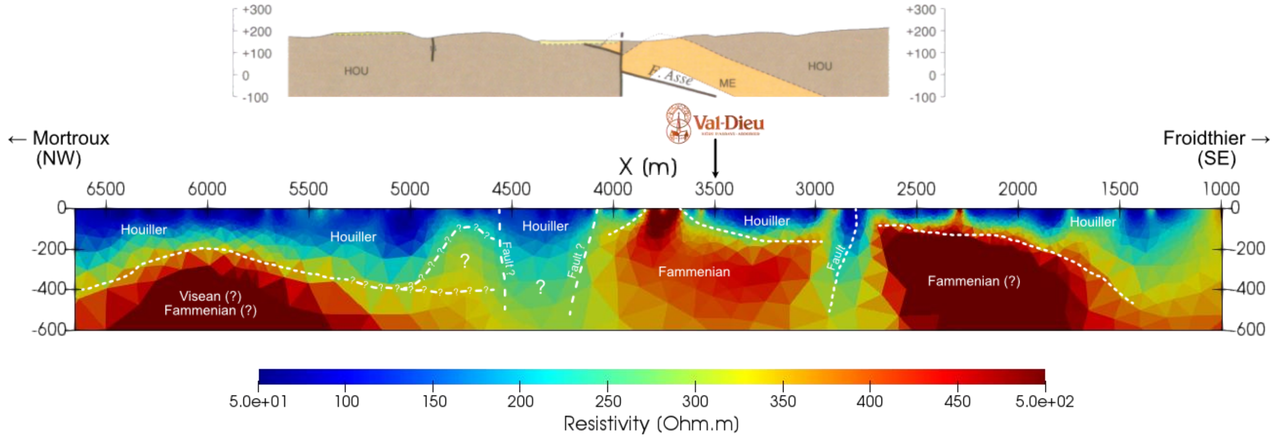
Correlation with geological maps and borehole data





Next steps in terms of the ERT imaging

- Interpretation in terms of structural information

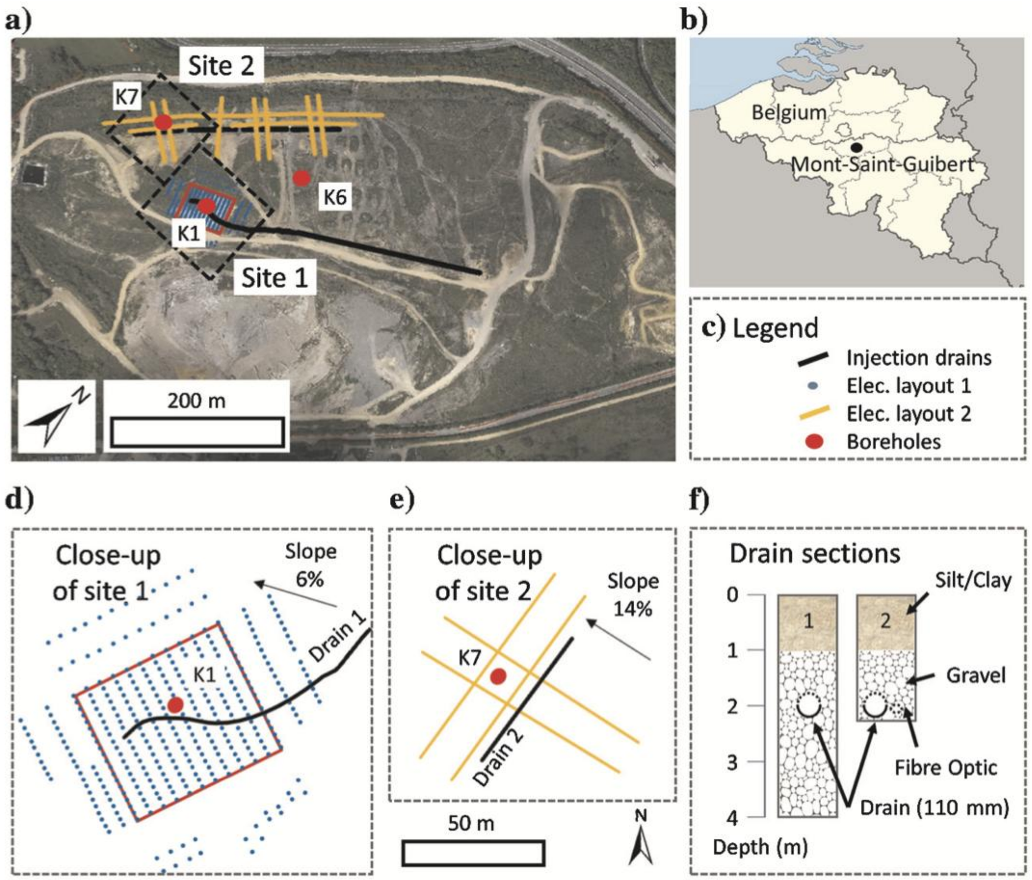


- Quantitative integration of geophysical logs from boreholes
- Integration with gravity, and seismic data
- Additionnal profiles in order to have 3D data sets

Time-lapse monitoring for **environmental geotechnics**

Automated remote control allows mapping preferential flowpath

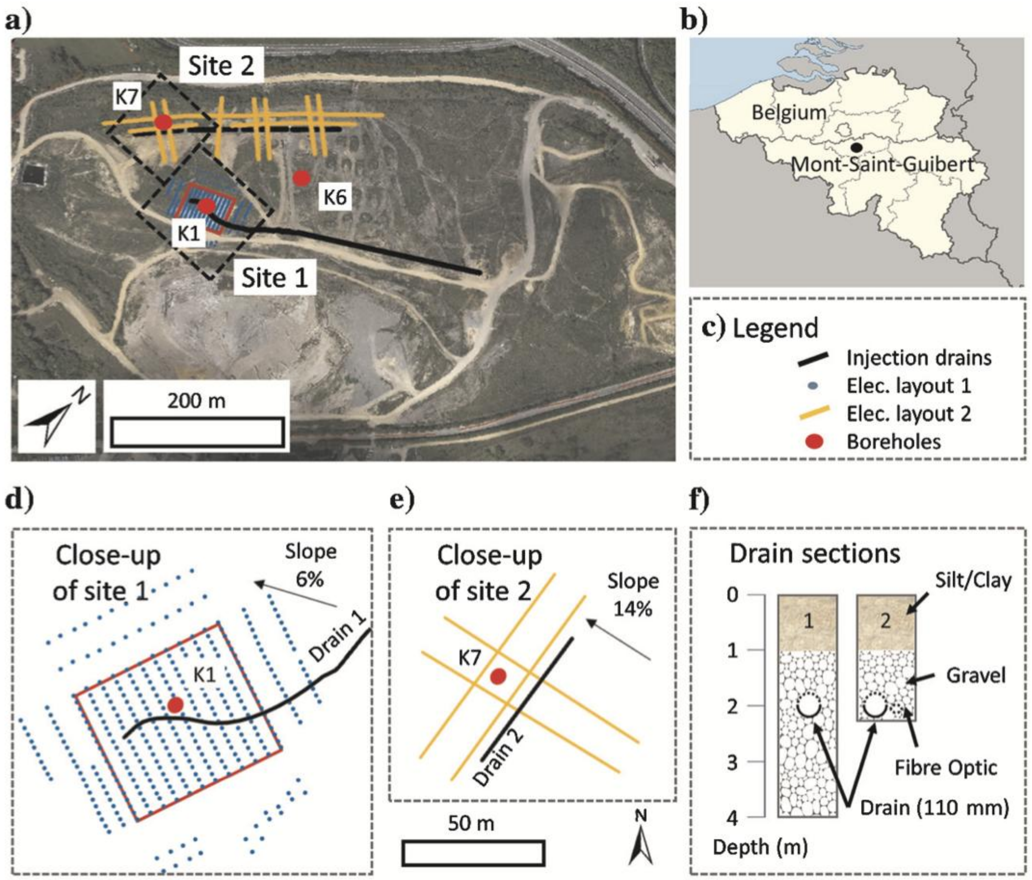
Water recirculation in engineered landills

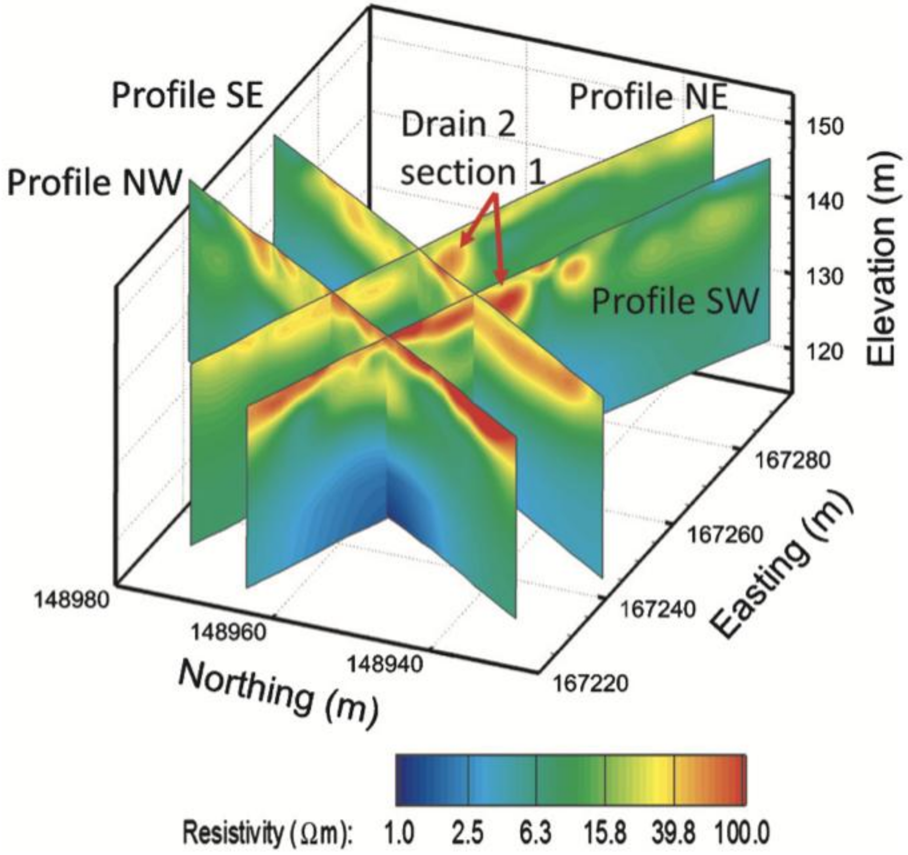


Dumont et al., 2018

Site 2 (drain section 1)
110 mm perforated tube, 4 m depth
50 m long
100–120 m^3/h injection
Pump test: 120 m^3
(late 6/2014)
Individual injection experiment: 60 (30/7/2014) and 275 m^3 (11/8/2014)
Along injection drain
Four lines of 32 electrodes (2.5 m spacing)
1152 data points
Hourly (30/7/2014–19/8/2014)

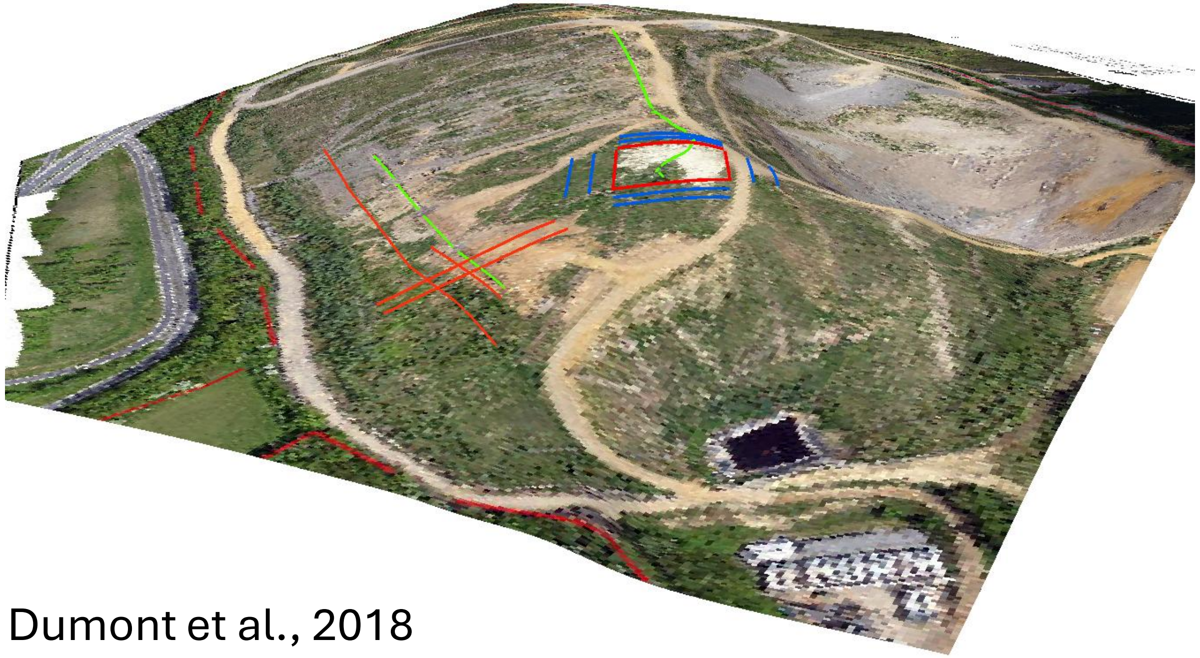
Water recirculation in engineered landills



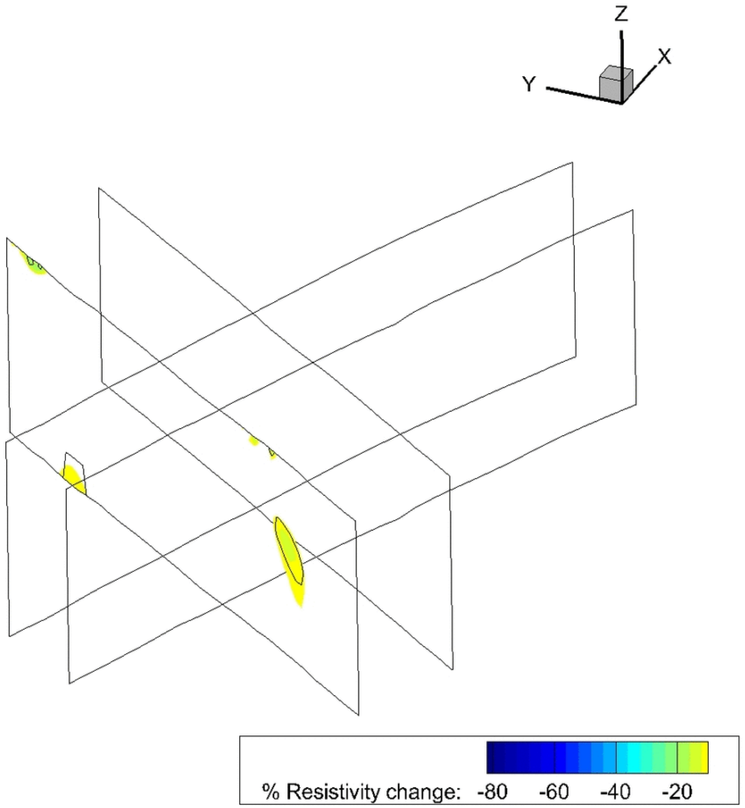


Dumont et al., 2018

Mapping preferential infiltration flowpath

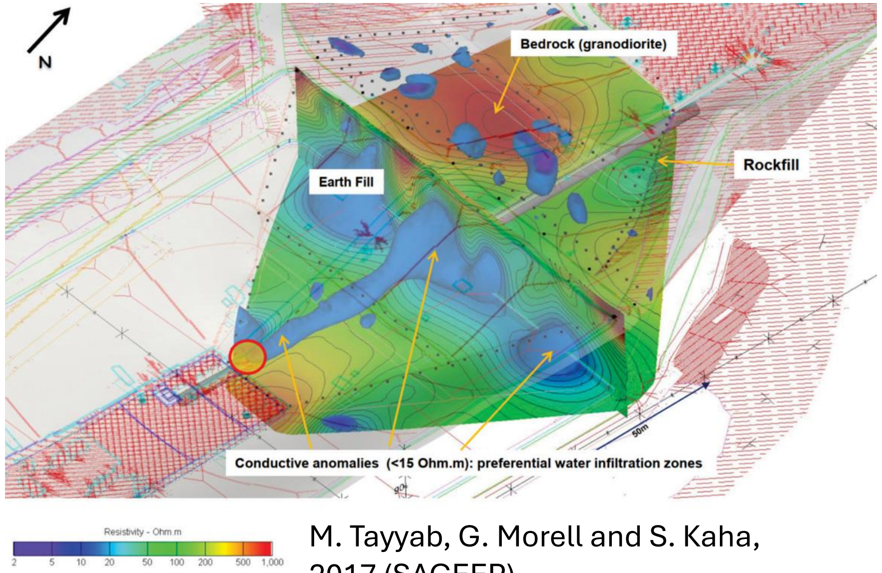


Dumont et al., 2018



Mapping preferential flowpath

- Low residence time of water in the landfill
- Optimize the injection frequency
- Strong flow anisotropy consistent with waste compaction
- Other potential applications: dams or embankments monitoring for seepage

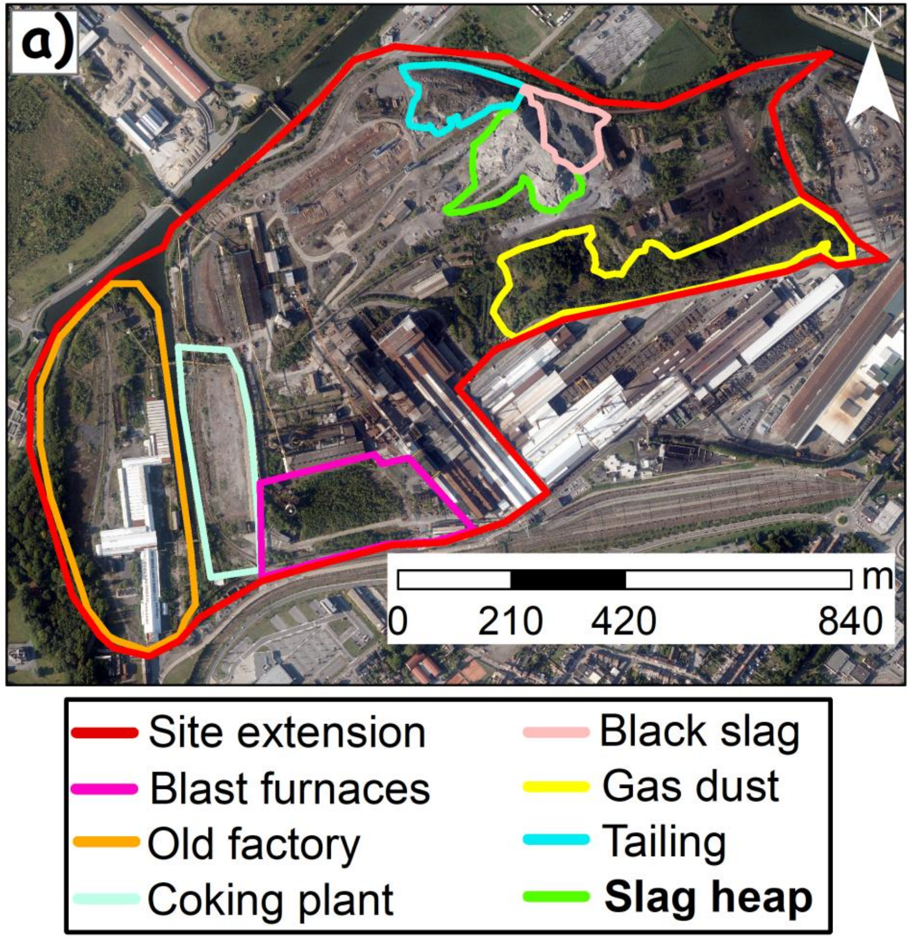


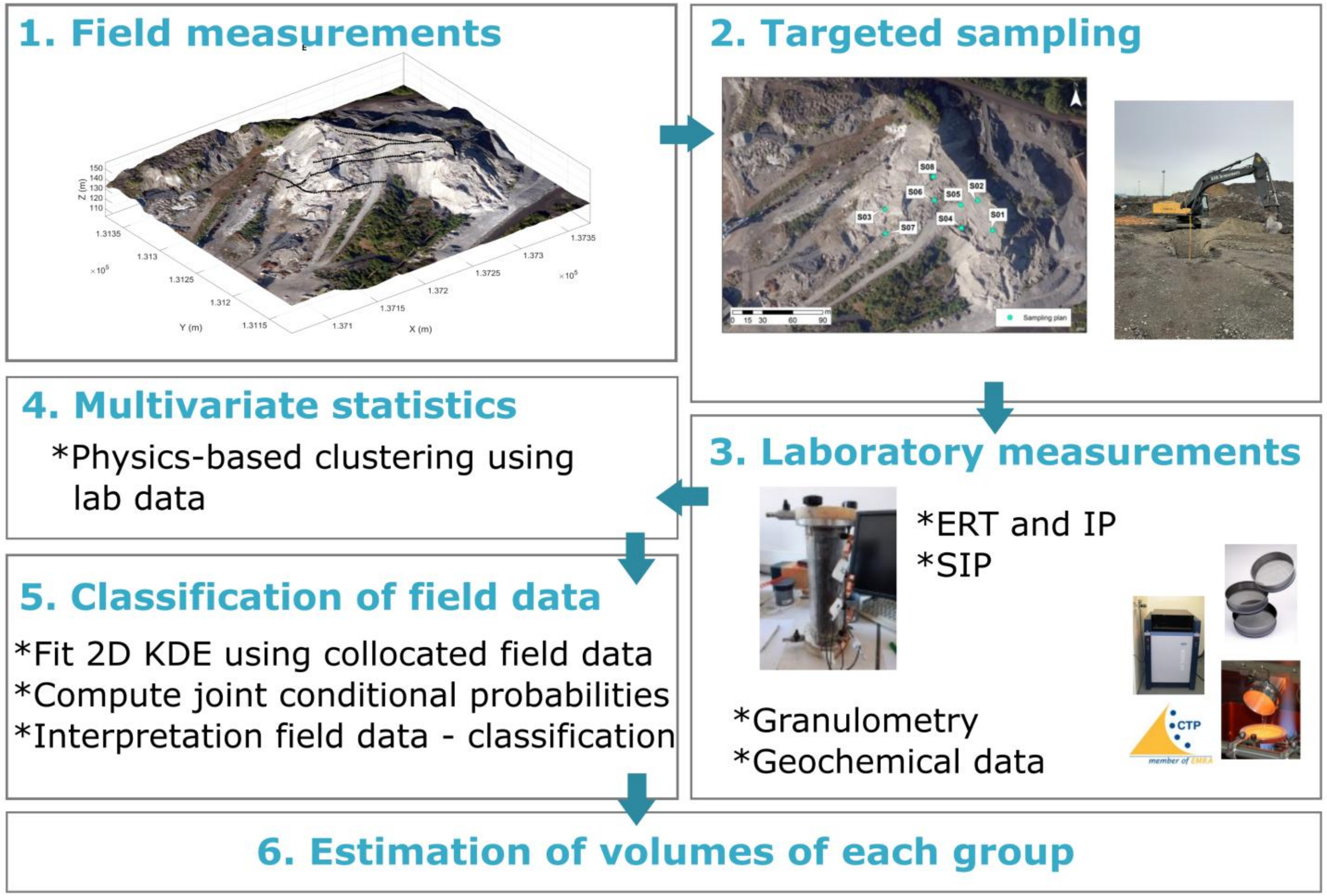
M. Tayyab, G. Morell and S. Kaha, 2017 (SAGEEP).

Urban geophysics: machine learning to mapping **backfills**

Itzel Isunza Manrique, Thomas Hermans, David Caterina, Damien Jougnot, Benoît Mignon, Antoine Masse, Frédéric Nguyen, Integrated methodology to link geochemical and geophysical-lab data in a geophysical investigation of a slag heap for resource quantification, Journal of Environmental Management, Volume 349, 2024, 119366, ISSN 0301-4797, https://doi.org/10.1016/j.jenvman.2023.119366.

Methodology to integrate lab and field data



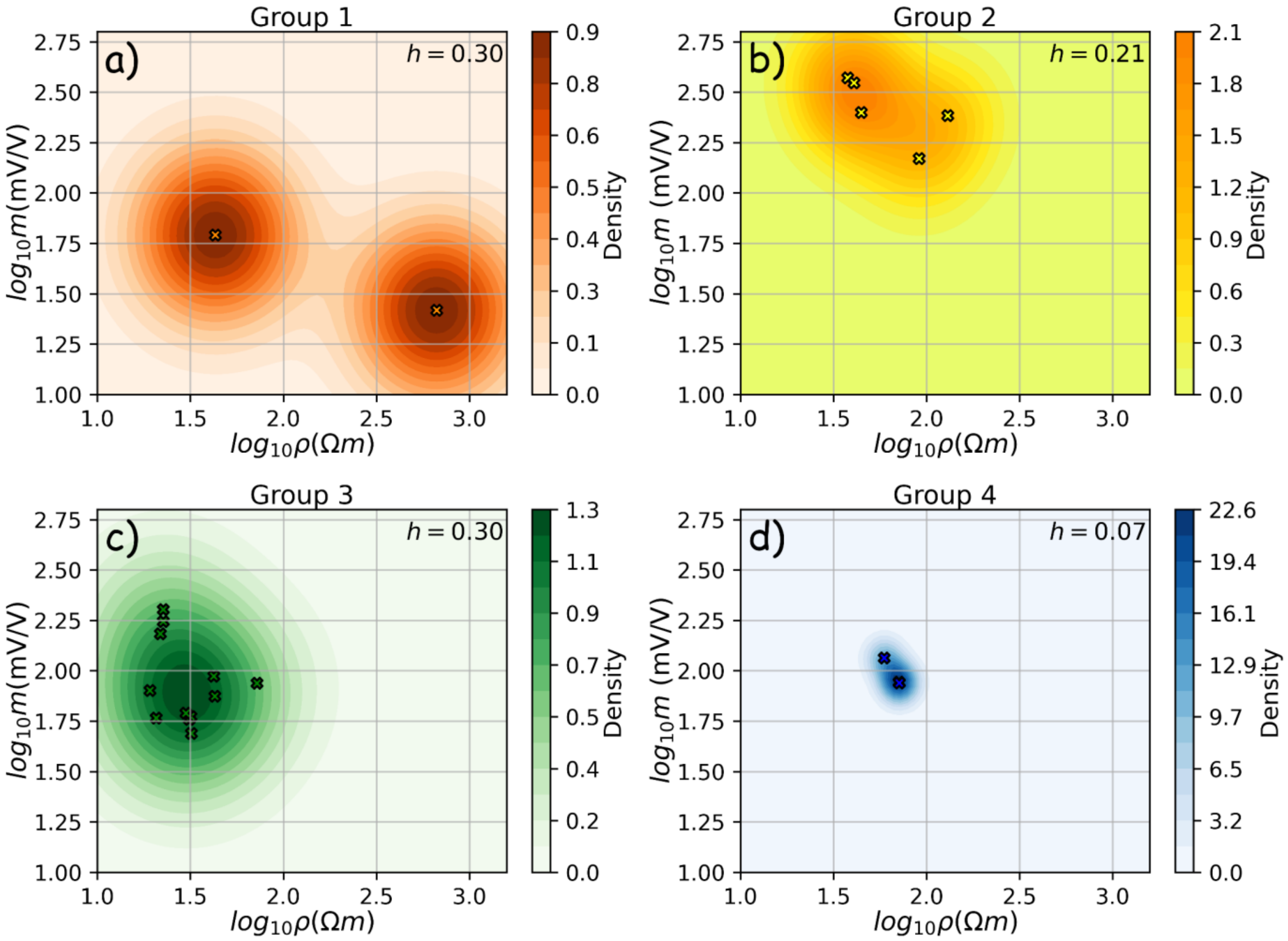


Lab analysis yielded 4 groups

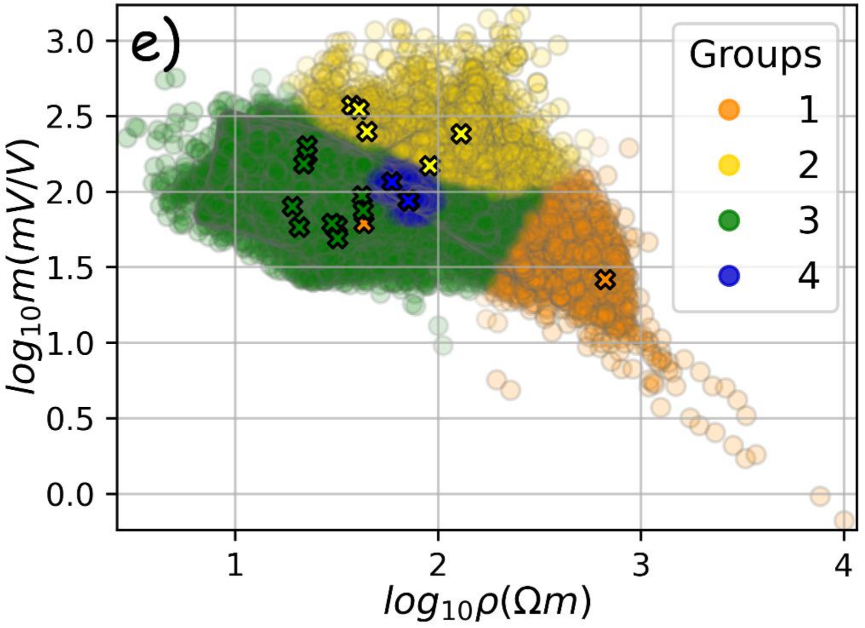
Group identifier	Samples	σ_{lab} (mS/m)	m_{lab} (mV/V)	Group composition	Metallic concentration
Group 1	S04_5, S05_3	< 20	< 20	Si-Ti-K	Low
Group 2	S02_3, S02_5, S06_1, S06_3, S06_5	> 20	> 100	Fe-Mn-V-Cr	High
Group 3	S01_1, S01_3, S01_5, S03_1, S03_3, S03_5, S04_1, S04_3, S07_1, S07_3, S07_5, S08_5	> 14	< 90 > 20	Fe-Mn-V-Cr	Low-intermediate
Group 4	S02_1, S08_1, S08_3	< 25	> 70	Fe-Mn-V-Cr	Intermediate-large

Groups supported using PCA & clustering (unsupervised learning)

Classification of field data using Kernel density estimation

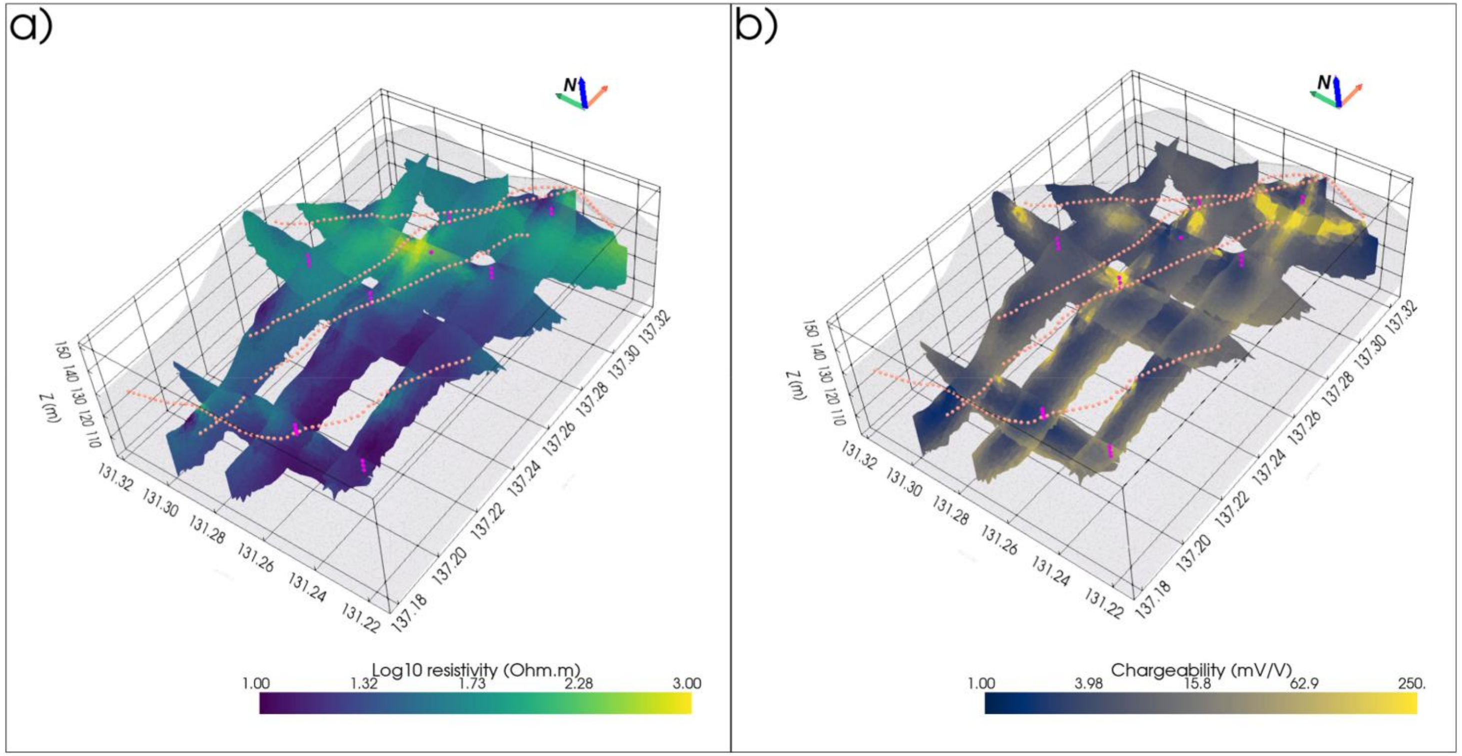


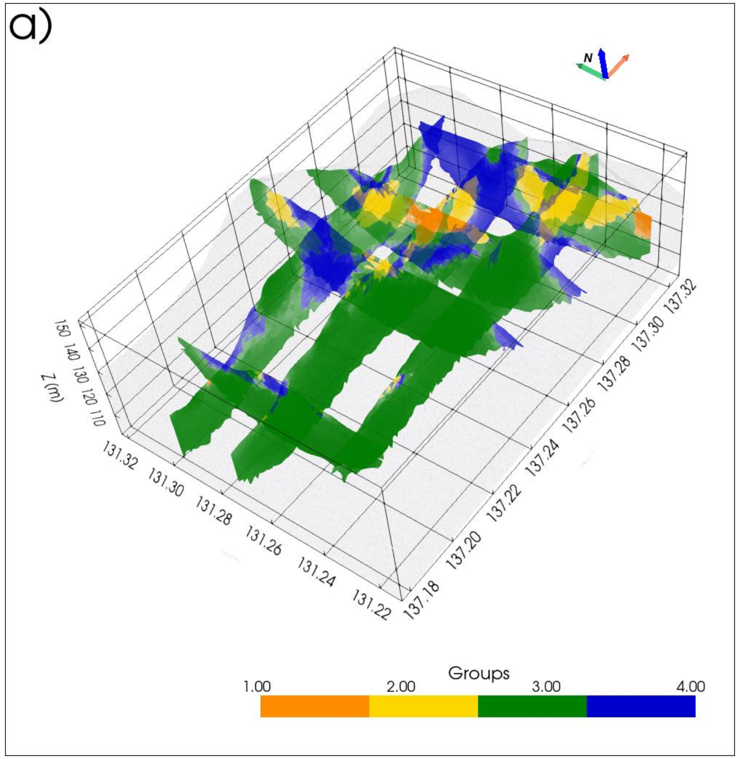
2D KDE’s visualization for a regular grid & collocated field data



Probability of a point in the tomography to belong to a group > 33%

Classification of field data





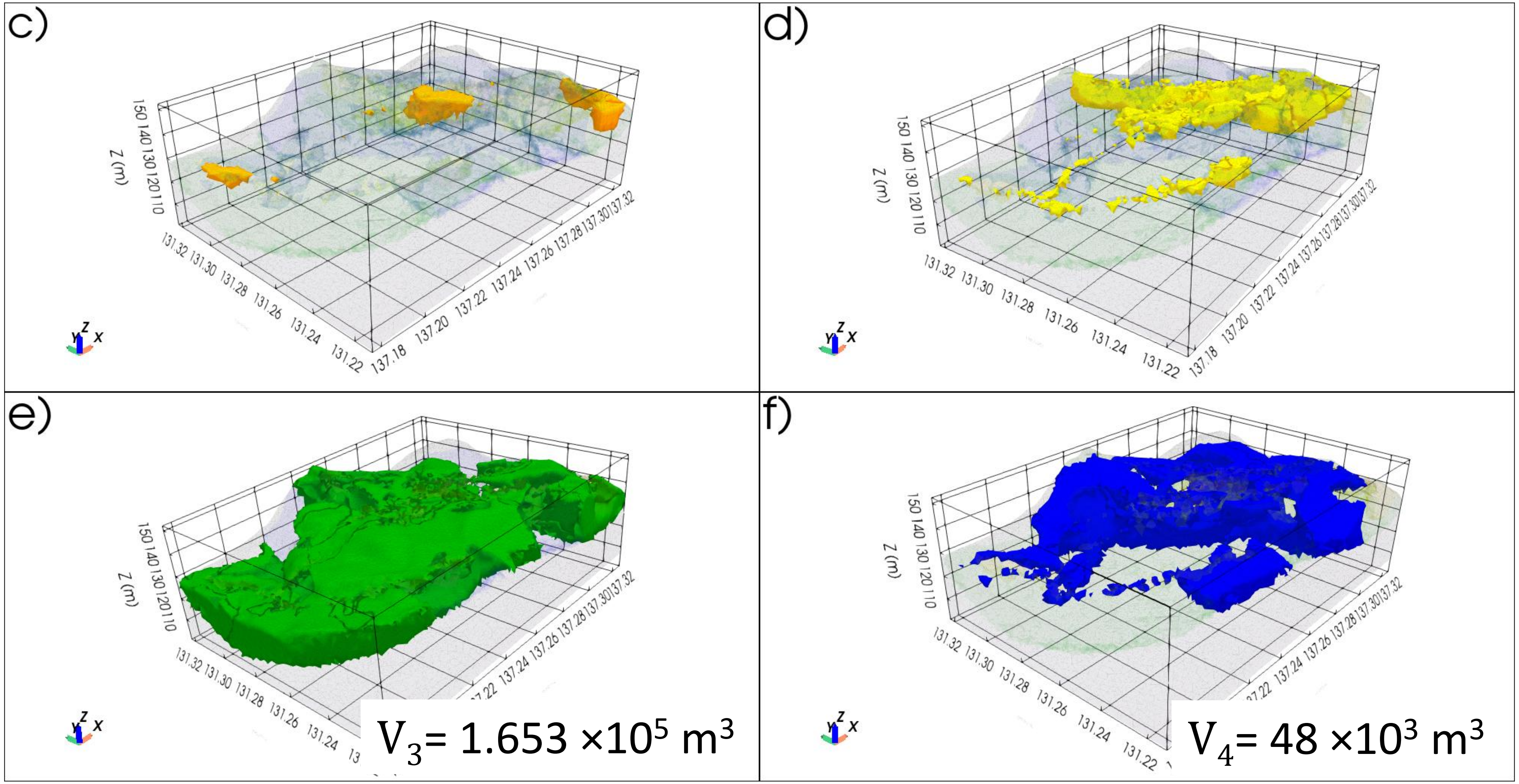
Volume estimation

The volumes of individual cells in the mesh v were weighted by corresponding probability values and added

$$V_i = \sum_{j=1}^{n} P(A_i|\boldsymbol{y})\, v$$

V_1= 3.66 ×10^3 m^3

V_2= 1.81 ×10^4 m^3



Conclusions

- Methodology that **links** a physics-based clustering at **lab** scale to **field** data and can be used to derive a quantitative interpretation of field data through a probabilistic classification that integrates **uncertainty**.

- Can be updated with additional data type

Geophysics in an **open** world

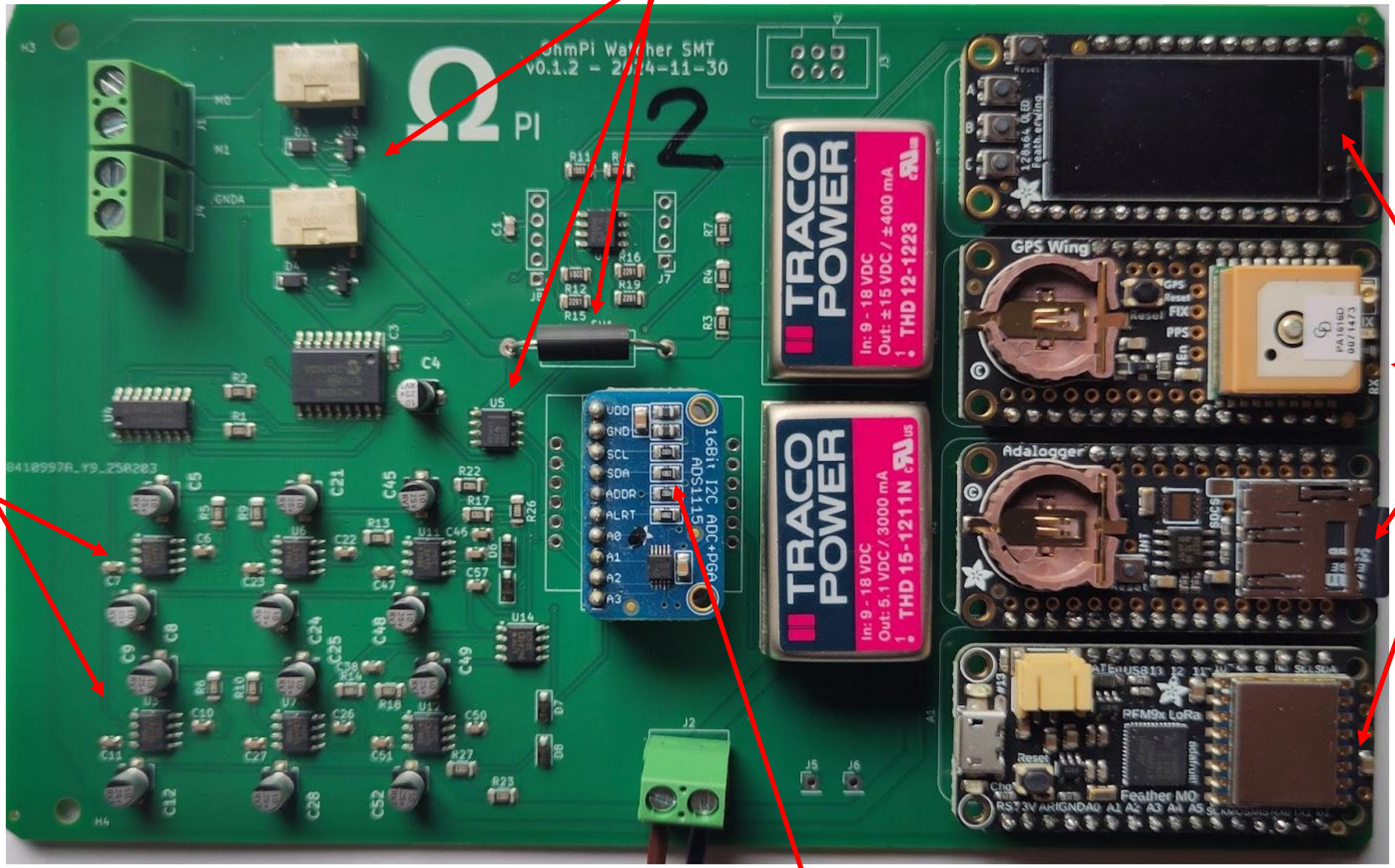
Work of G. Blanchy, H. Michel, D. Caterina and T. Debouny

Driving the survey cost down

OhmPi-Watcher v0.1.0

Relays, shunt resistor and current amplifier for contact resistance check

Signal conditionning with 3 stages op-amp

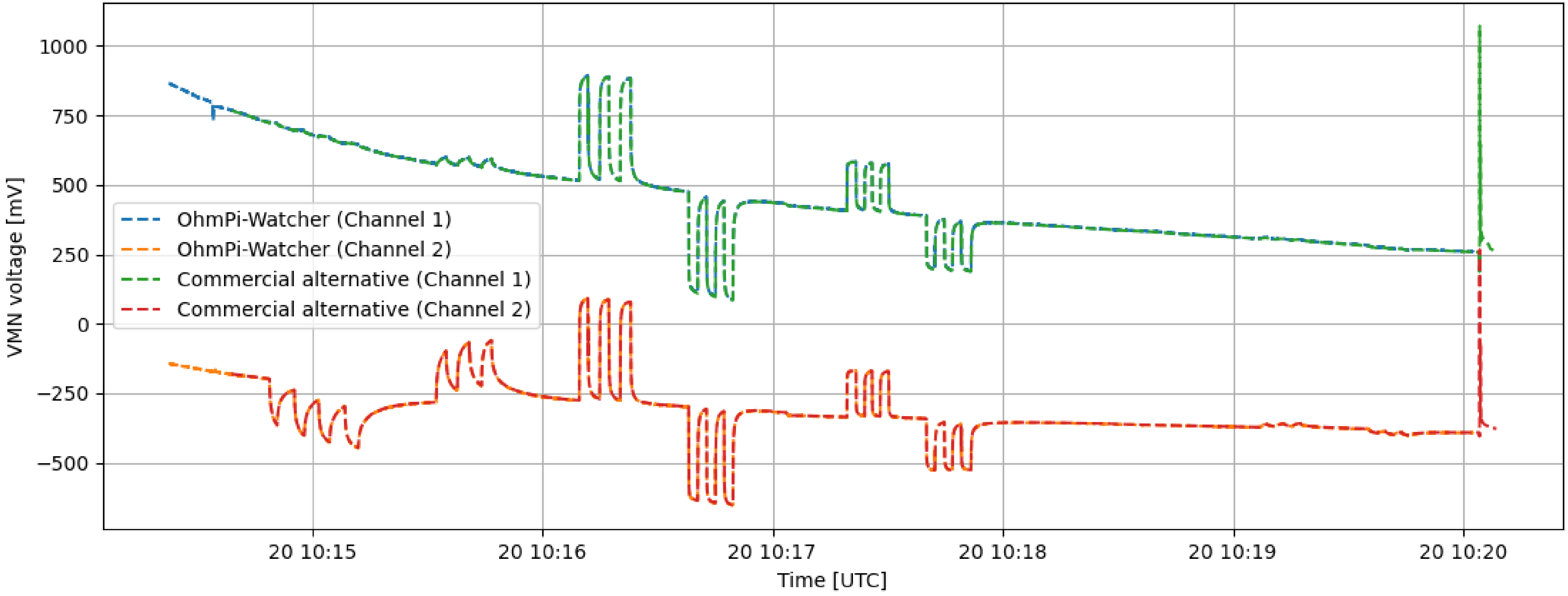


Using adafruit feathers (OLED, GPS, RTC/SD card, LoRa radio)

ADC 16 bits (24 bits optional)

https://ohmpi.org

OhmPi-Watcher



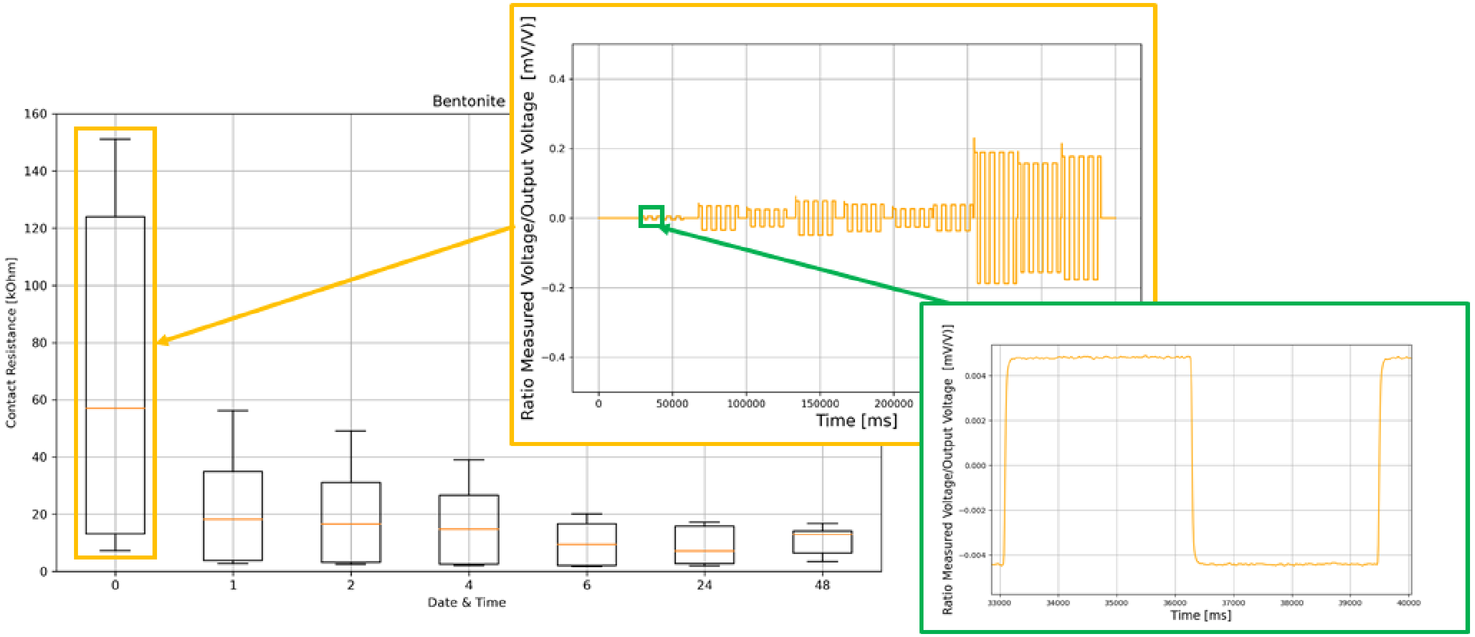
The Watcher perform very well compared to commercial alternative and can be used for resistivity monitoring. Main limitations are noise levels slighly higher on the Watcher (due to cheaper ADC) and no hardware frequency filtering.

Designing and testing electrode type

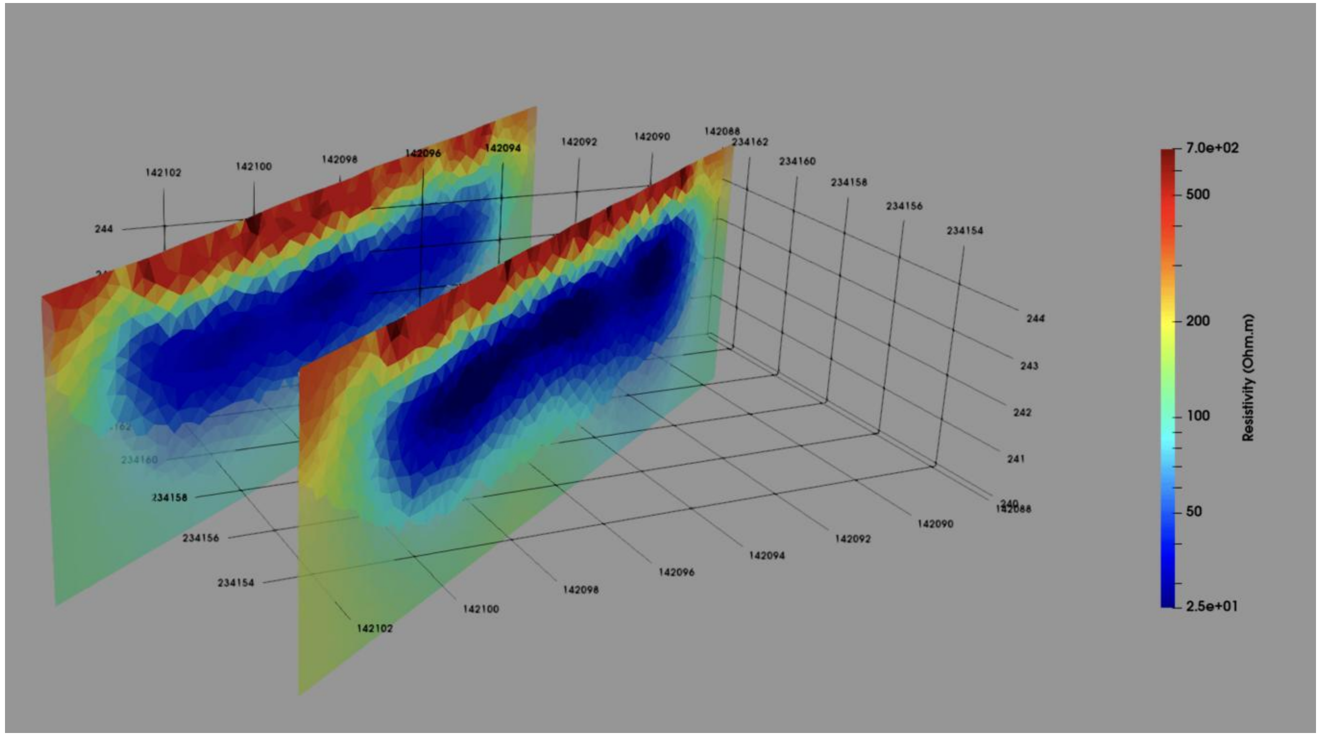
4 types of electrode:
Agar powder gel
- NaCl (2M) & KCl (2M)
- Prepared the day before
- 2% of the liquid mass of agar powder

Salty saturated sponge
- Porous media
- Saturated only once with salty water with a NaCl concentration of 100 g/L

Salty Bentonite
- Mix of 250 g of bentonite and salty water with a NaCl concentration of 100 g/L



Testing in real-world conditions (electrodes only)



Next steps

OhmPi-Watcher

- Deployment in field conditions for deep ERT survey
- Validation through parallel measurements using commercial devices
- Open source publication for dissemination

Non-invasive electrodes

- Understanding monitoring behaviour (repeated injection)
- Design a towable system
- Demonstrate on additional cases

Take home message

- More flexible systems layout allows new applications (deeper, more complex geometries)
- Cheaper systems (open hardware) and remote control should make monitoring affordable e.g. to monitor water movement (slope instabilities ...)
- Machine learning algorithm allows to integrate various data sets and help the interpretation
- Open source software allows to tailor ERT to many applications

Thank you

Prof. Frédéric Nguyen

Logisticien de recherche : Dr. Eng. David Caterina

7 postdocs: Guillaume Blanchy, Hadrien Michel, Anne-Sophie Mreyen, Satoshi Izumoto, Lin-Lin, Neill Marshall, Foivos Karakostas

4 PhD: Tom Debouny, Yannick Forth, Giorgia Stasi (GSB), Russel Swift (BGS)

2 Master: Camille De Villers, Clément De Lanève

Research "philosophy"

- **Methods**

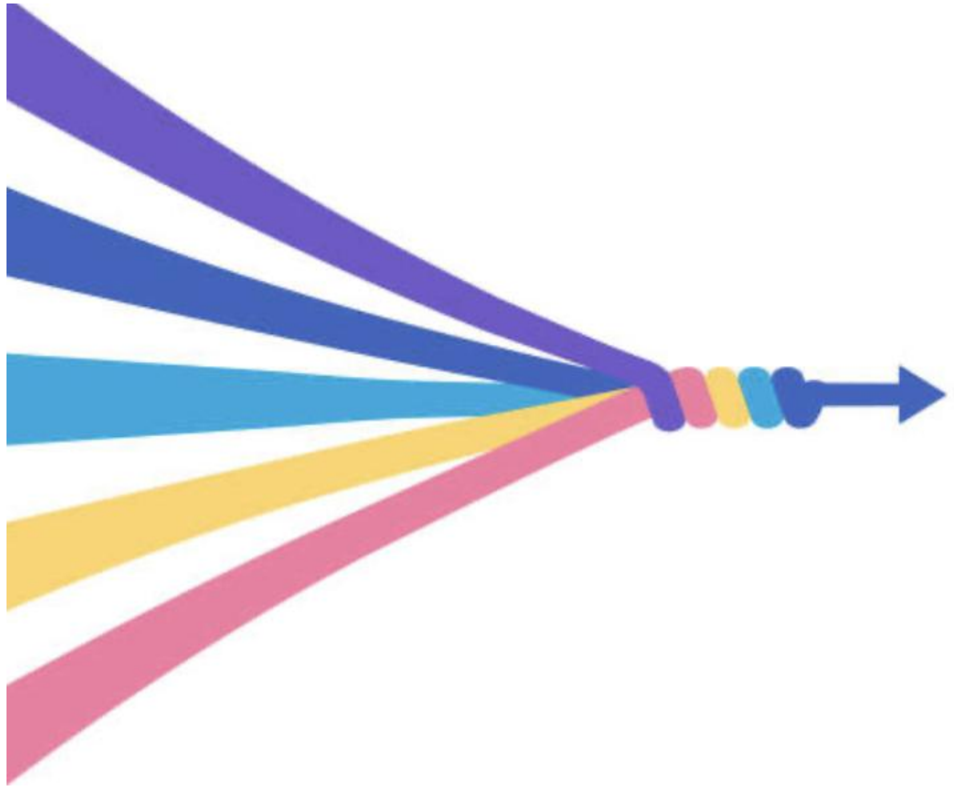
Observations are sparse and information is largely indirect and uncertain

- **Applications**

Looking and understanding new and best suited proxies depending on the needs

- **Users**

Applied Geophysics: trying to make an impact

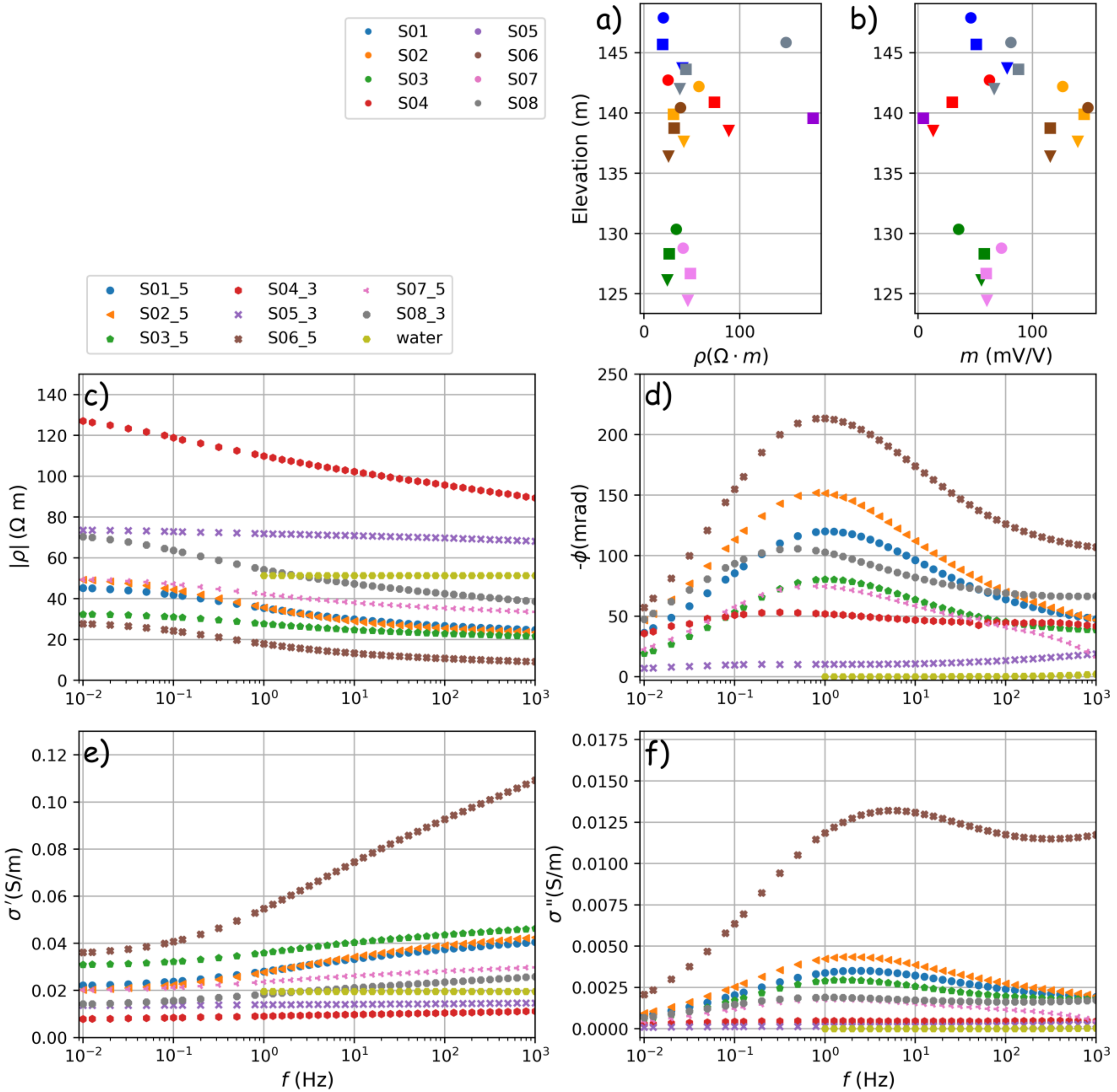


Additional slides

Laboratory measurements

Geophysical data

ERT (ρ_{lab}), IP (m_{lab}) and SIP ($\sigma', \sigma'', \phi, f$)
*Measurements in 22 samples, columns of 1.5 dm^3



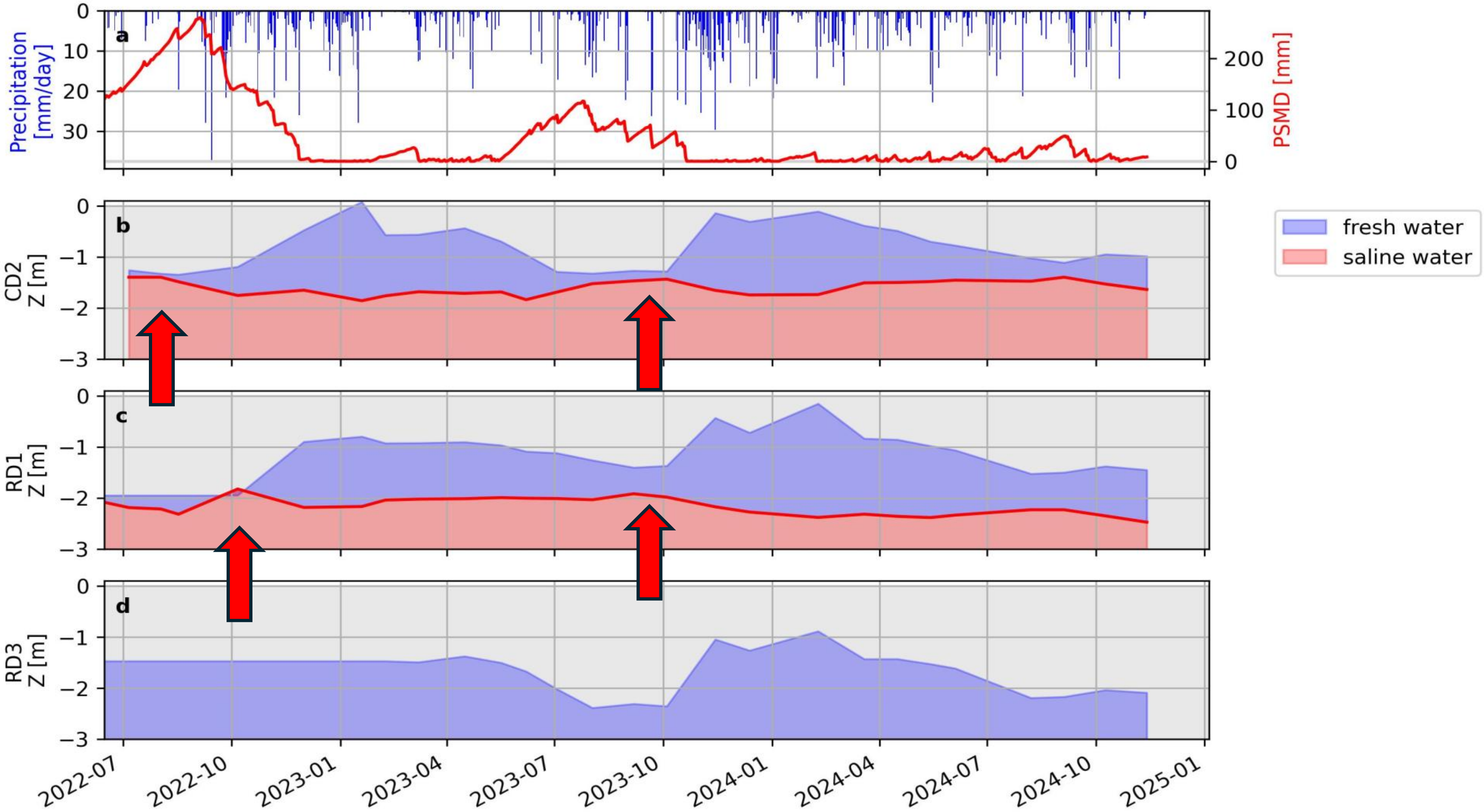
Geochemical data

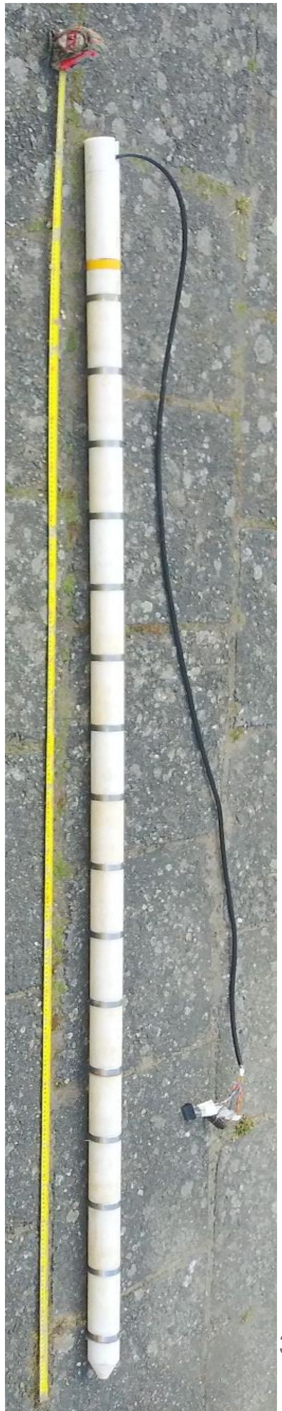
XRF analysis for major elements
Average content > 1 wt. %: Si, Ca, Fe, Mn, Mg & Al

Group identifier	**Samples**	**σ_{lab} (mS/m)**	**m_{lab} (mV/V)**	**Group composition**	**Metallic concentration**
Group 1	S04_5, S05_3	< 20	< 20	Si-Ti-K	Low
Group 2	S02_3, S02_5, S06_1, S06_3, S06_5	> 20	> 100	Fe-Mn-V-Cr	High
Group 3	S01_1, S01_3, S01_5, S03_1, S03_3, S03_5, S04_1, S04_3, S07_1, S07_3, S07_5, S08_5	> 14	< 90 > 20	Fe-Mn-V-Cr	Low-intermediate
Group 4	S02_1, S08_1, S08_3	< 25	> 70	Fe-Mn-V-Cr	Intermediate-large

Groups supported using PCA & clustering (unsupervised learning)

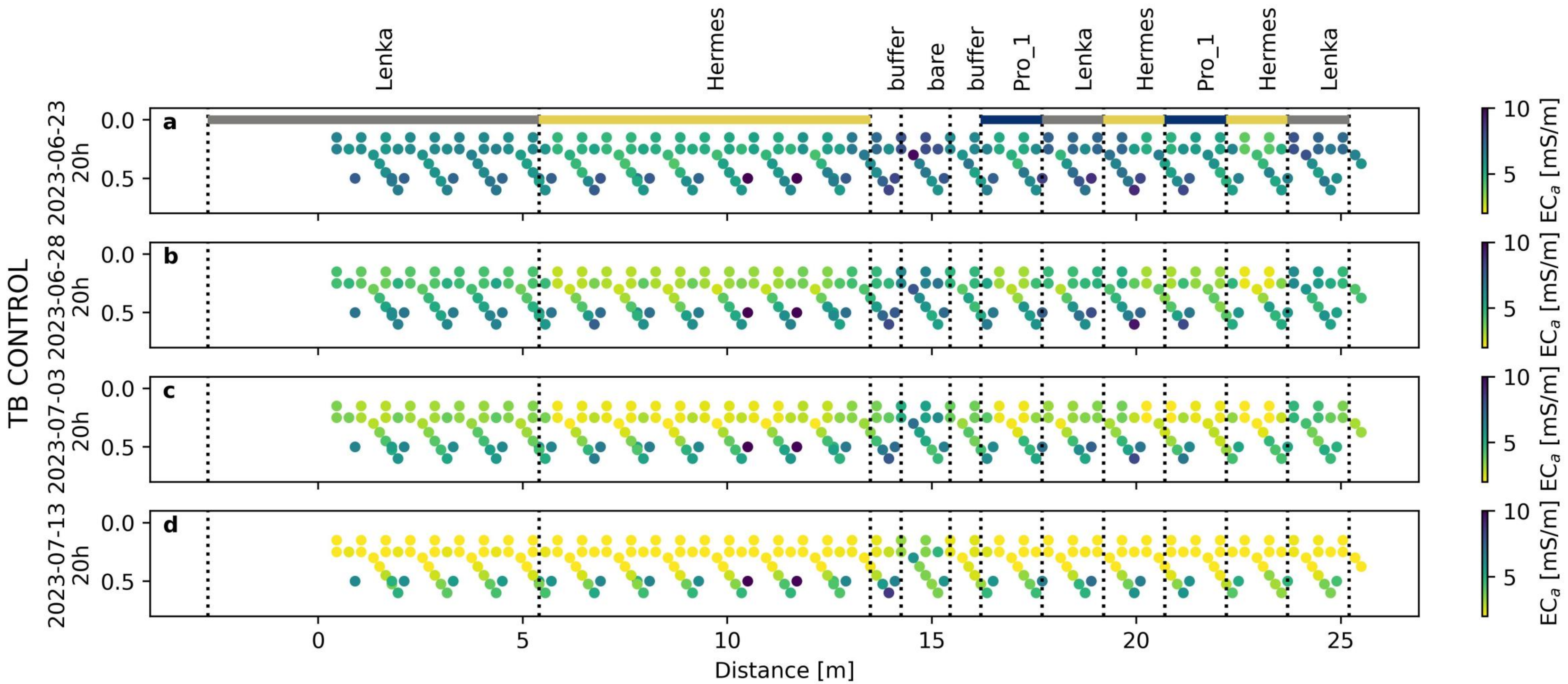
Monitoring saline-freshwater interface





1D electrical resistivity stick enable to follow the saline-freshwater interface in the Belgian polders under different drainage regimes. We can observe that during summer, the freshwater lens decreases and the saline water rises up, potentially endangering yield.

Imaging crop water uptake to select drought resistant varieties



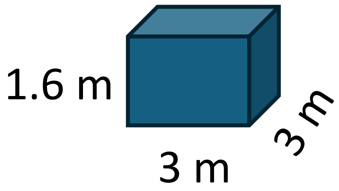
Lenka, Hermes and Pro_1 are soja varieties. Hermes and Pro_1 dries the soil earlier compared to Lenka. Lenka will be more sensitive to later drought compared to Hermes and Pro_1.

Classification of field data

- Compute joint conditional probabilities of each group

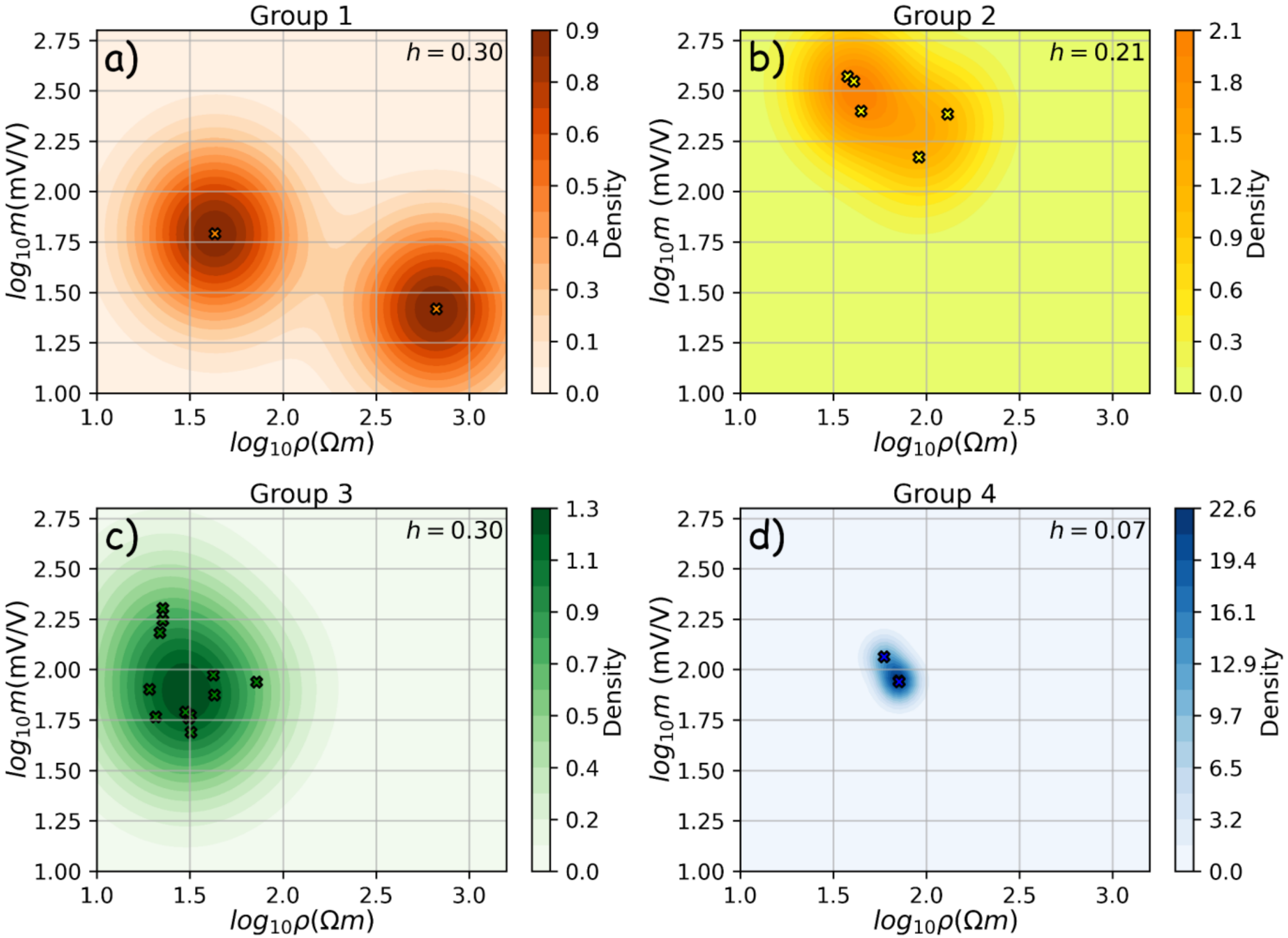
  → 2D Kernel Density Estimator (KDE)

  → volume-averaged field data $(\rho, m)_j$ collocated with sampling



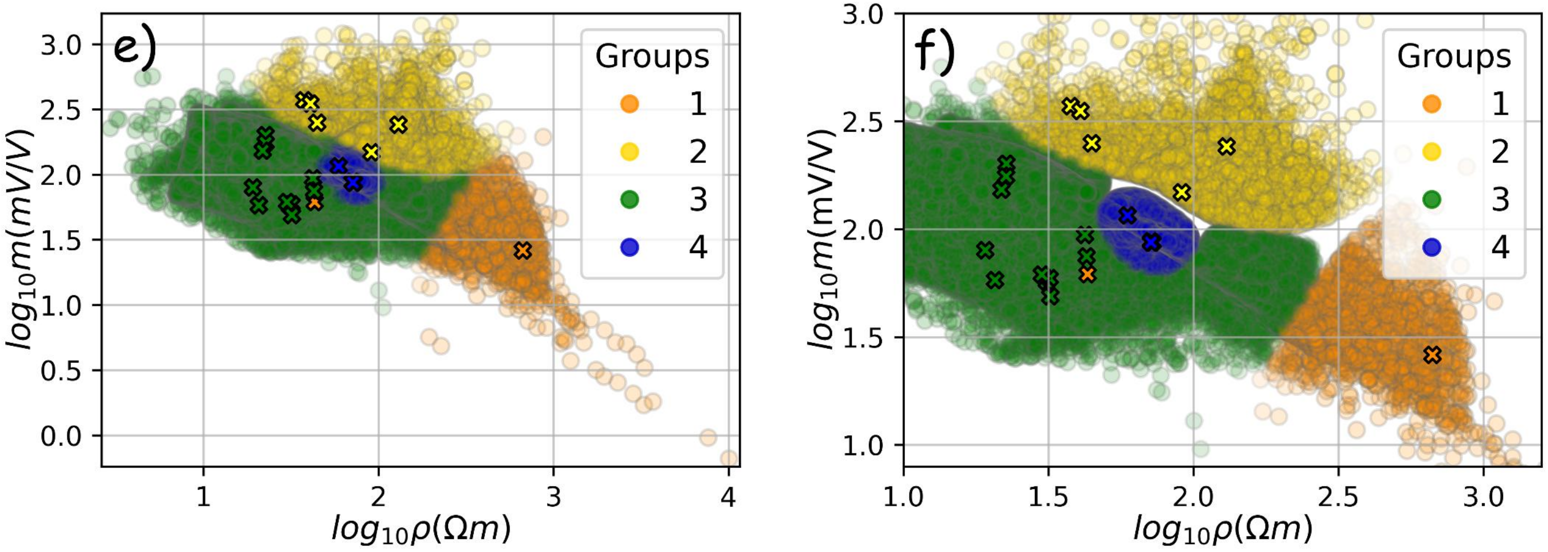
  → $f_{KDE}(y) = \sum_{j=1}^{N} K\left(y - x_j; h\right)$ for a Gaussian kernel $K \propto \exp(-x^2/2h^2)$ with a bandwidth h

2D KDE's visualization for a regular grid & collocated field data

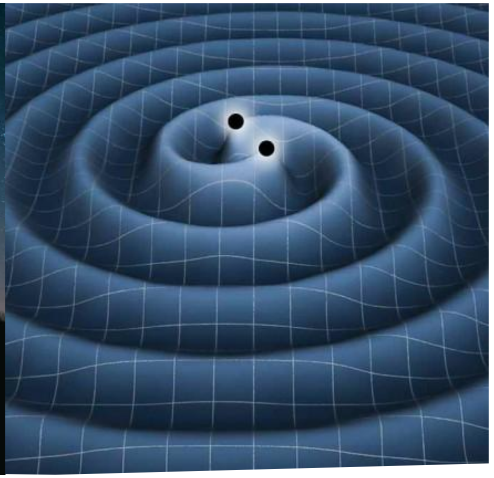


Classification of field data

- Estimate 2D KDE's at the resistivity and chargeability values of the whole inverted model, i.e., $\boldsymbol{y} = (\boldsymbol{P}, \boldsymbol{M})$
- Estimate $P(A_i|\boldsymbol{y})$ using Bayes' Rule and $P(A_i)$ from sampling
- Comparing $P(A_i|\boldsymbol{y})$ and derive a classification model



Probability values > 50 %

Le **Télescope** Einstein : une infrastructure scientifique remarquable **souterraine**

L’Euregio Meuse Rhin comme site candidat

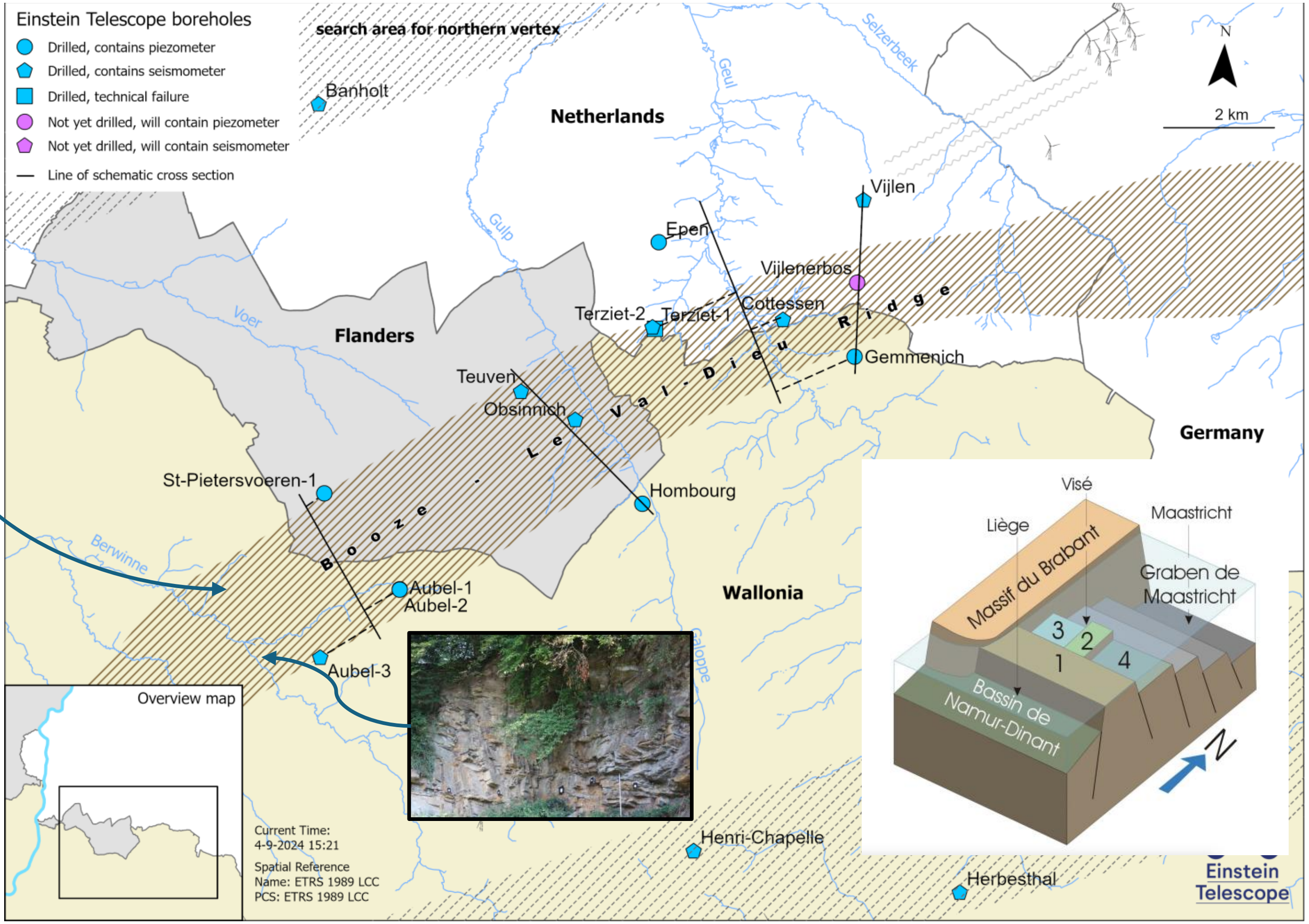
! Données limitées!

Les arguments géophysiques:

- Un niveau de vibration en profondeur « protégé » par des couches superficielles atténuantes
- Des conditions géotechniques à ce stade favorables

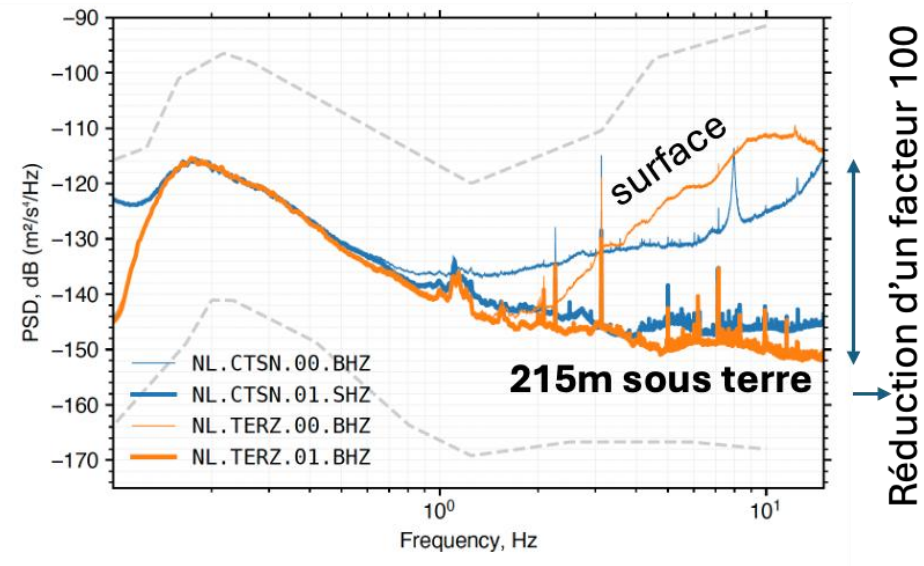
Le sous-sol est étudié à travers:

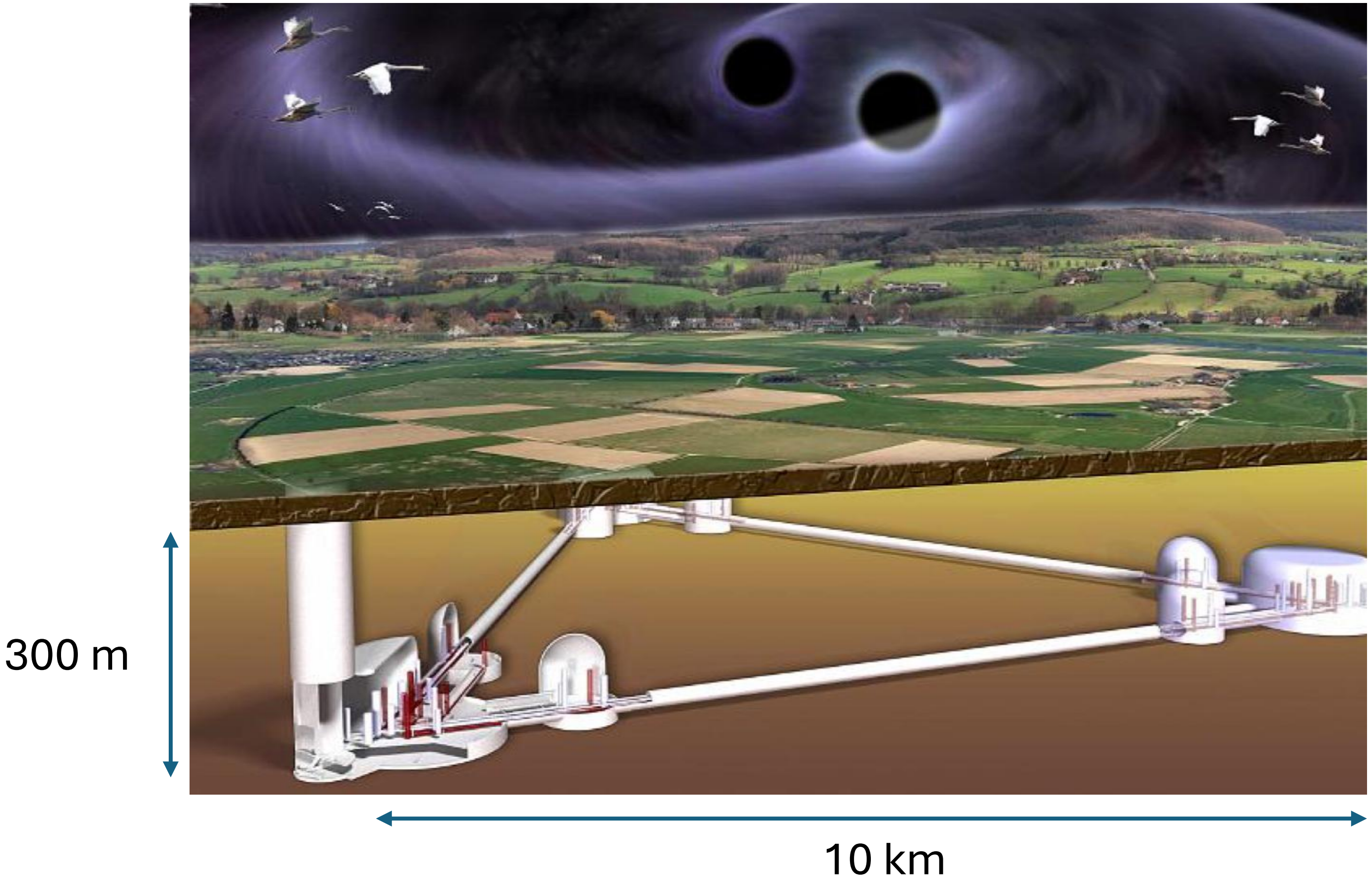
- Forages (14)
  - Succession verticale
  - Echantillons
  - Essais
  - Pose d’instruments (bruit sismique)
- Géophysique
  - Imagerie
  - Exigences en termes de vibration
- Modèles
  - Génie civil
  - Eau souterraine



Pourquoi s'intéresser au sous-sol alors que l'on cherche à comprendre l'univers lointain ?

✓S'enterrer permet de **s'affranchir (en partie) des vibrations** anthropiques



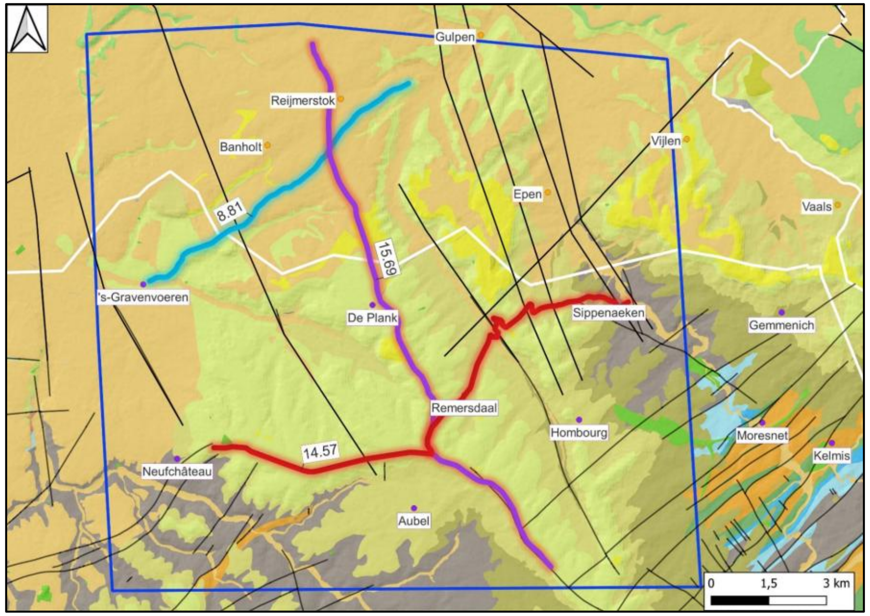


Pourquoi s’intéresser au sous-sol alors que l’on cherche à comprendre l’univers lointain ?

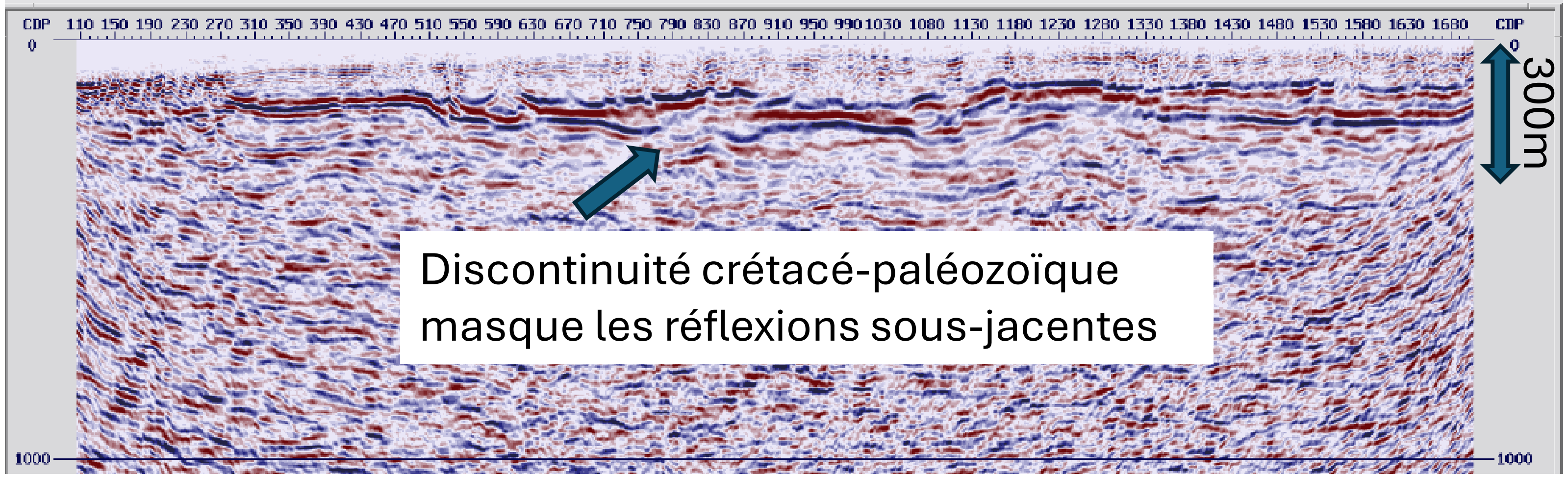
- ✓S’enterrer permet de **s’affranchir (en partie) des vibrations** anthropiques (>bruit Newtonien)
- ➢Augmenter le nombre de détections par an
- ➢Détections précoces
- ➢Détections de trous noirs massifs
- ➢…

Imagerie géophysique

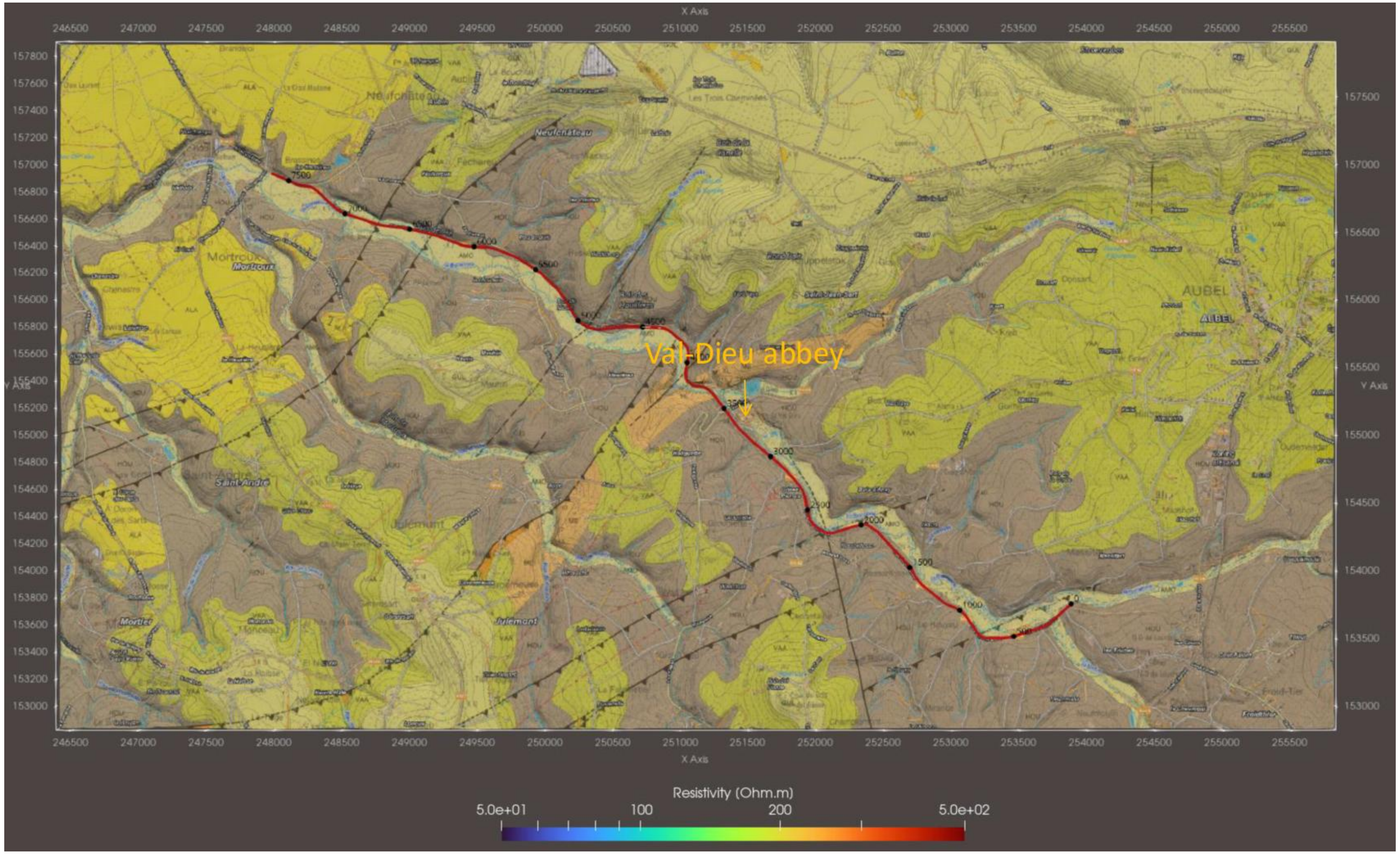
- « Echographie sismique » du sol pour l'instant limitée en information
- Permet de compléter l'information entre les forages et de faire ressortir les **contrastes mécaniques**



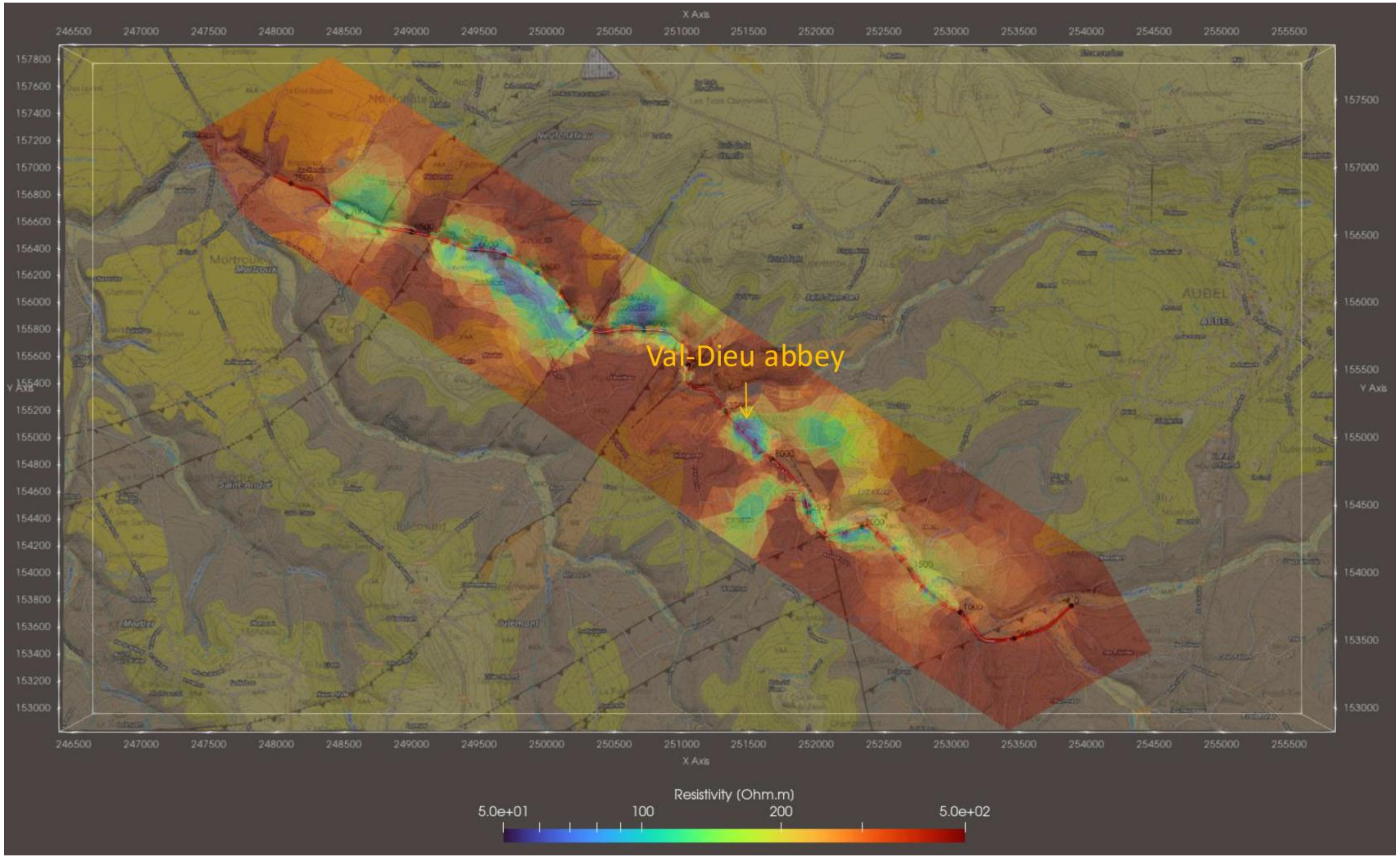
Shallow Processing Flow : Pre-Stack Time Migration



Correlation with geological maps

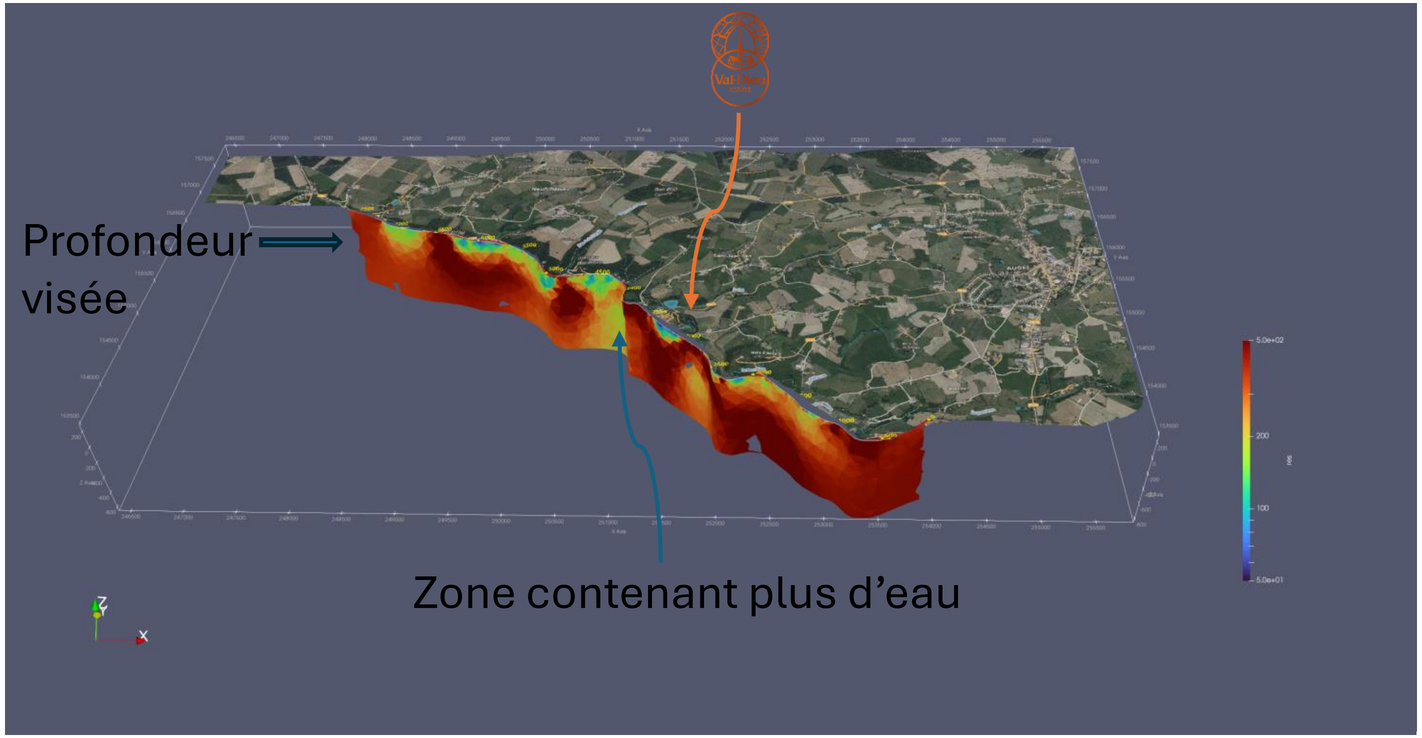


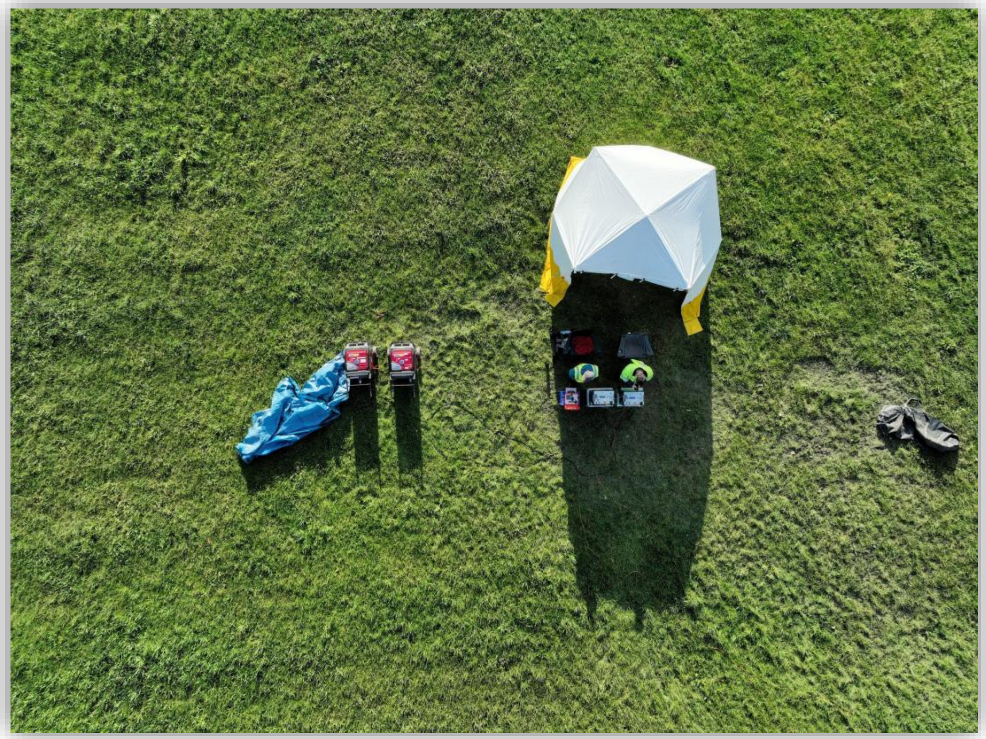
Correlation with geological maps



Imagerie géophysique

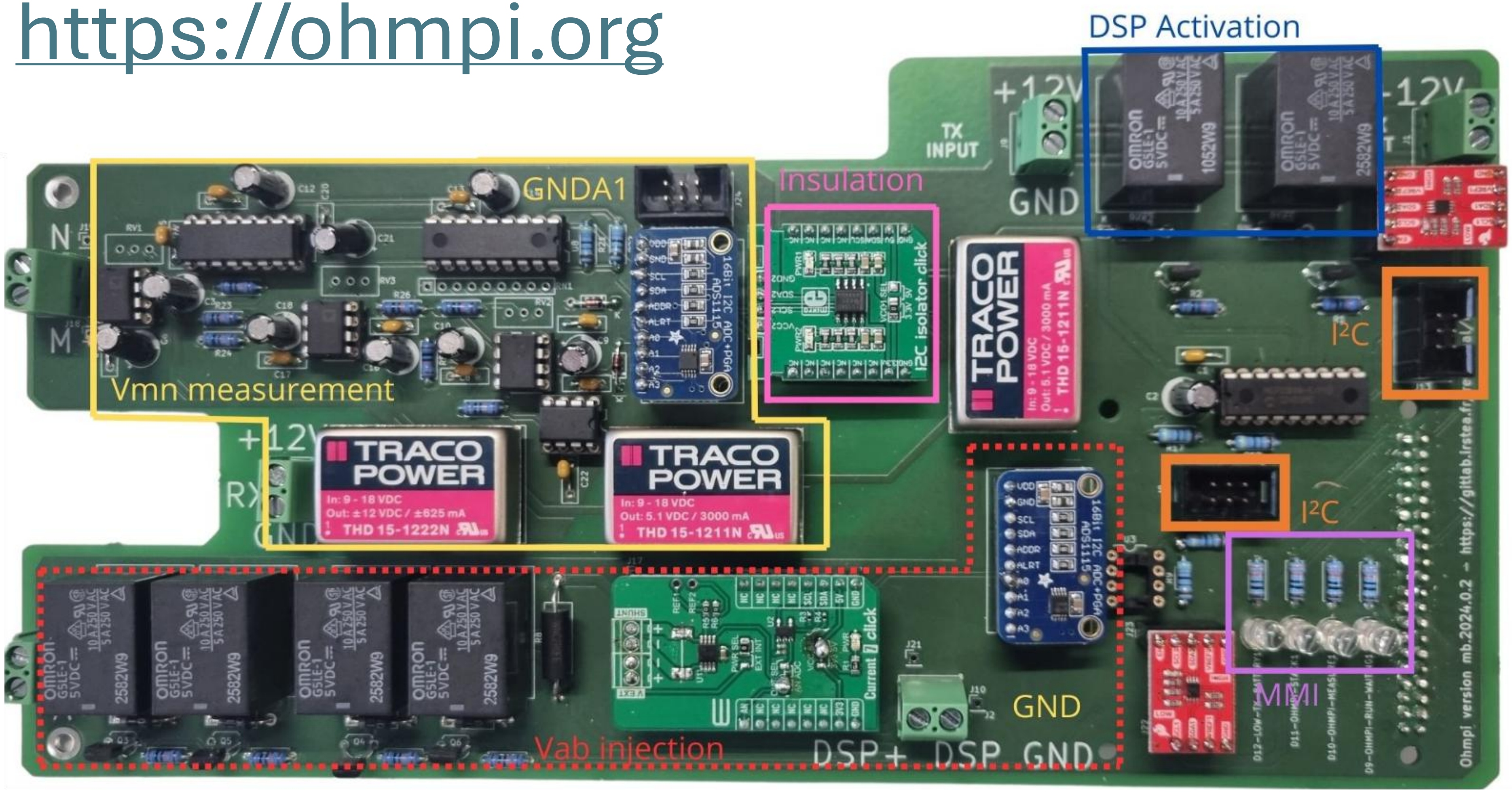
- « Tomographie électrique » à grande échelle
- Permet de compléter l'information entre les forages et de faire ressortir les **contrastes** **électriques**





OhmPi: Open-Hardware resistivity-meter

https://ohmpi.org



- Mono-channel resistivitymeter.
- Instructions and assembling guidelines can be found online.
- With multiplexer (also open-hardware), we tested up to 128 electrodes but more can be added.
- Design for monitoring applications
- Open-source Python code and Web interface available to operate the instruments.

Aim: Estimate volume(s) of different types of materials to assess potential resource recovery

Context: Idled factory of iron & steel production, La Louvière, Belgium
Materials: slags from electric arc and ladle refining furnaces + heterogeneous residues

Interreg
North-West Europe
NWE-REGENERATIS
European Regional Development Fund
EUROPEAN UNION