ITINERIS

Geoelectrical monitoring: measurement principles and properties

IR0000032 – ITINERIS, Italian Integrated Environmental Research Infrastructures System
(D.D. n. 130/2022 - CUP B53C22002150006) Funded by EU - Next Generation EU PNRR-Mission 4 “Education and Research” - Component 2: “From research to business” - Investment 3.1: “Fund for the realisation of an integrated system of research and innovation infrastructures”

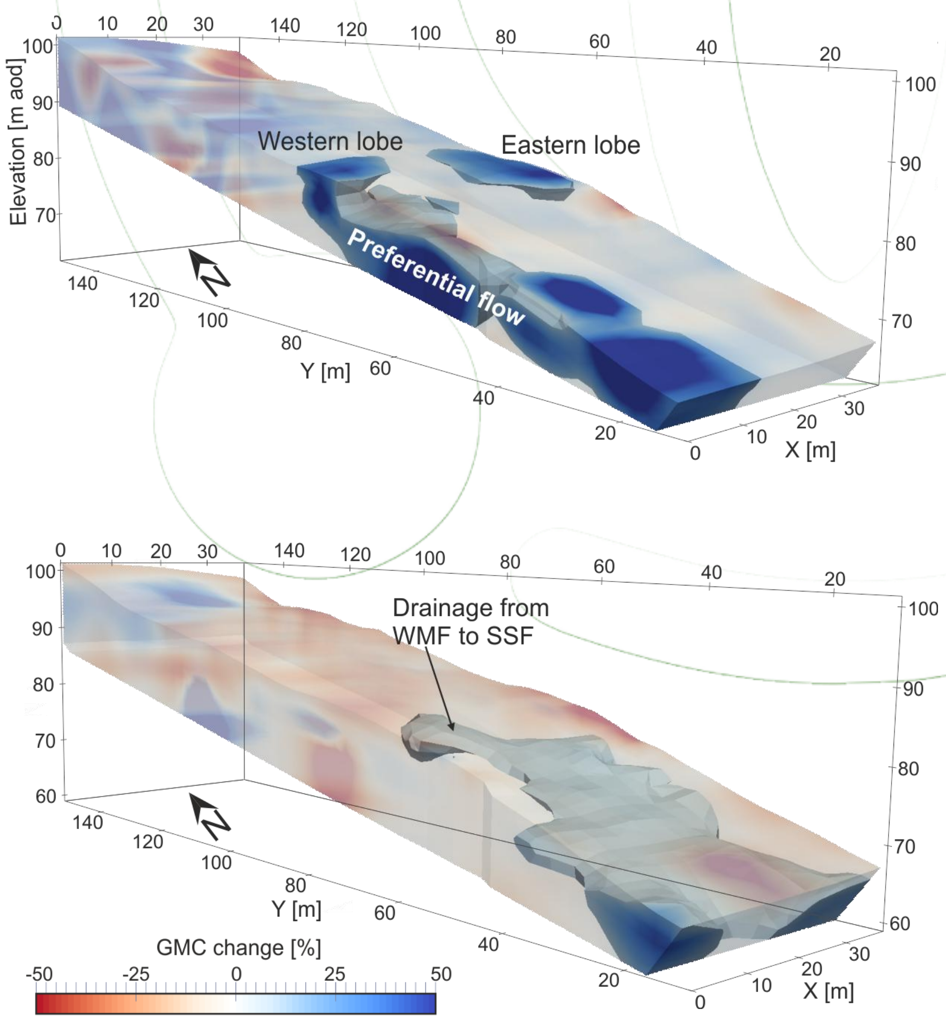
Finanziato dall'Unione europea NextGenerationEU

Ministero dell’Università e della Ricerca

Italiadomani

Outline of the day

- **Fundamentals of electrical resistivity measurements**
  - Electrical properties of soils and rocks
- **Geoelectrical monitoring: measurement principles and properties**
  - Basic principles, inversion approaches
  - Practical considerations
  - Examples
- **Quantitative analysis of geoelectrical monitoring data**
  - Limitations & opportunities
  - Applications
- **Examples of integrated landslide monitoring**

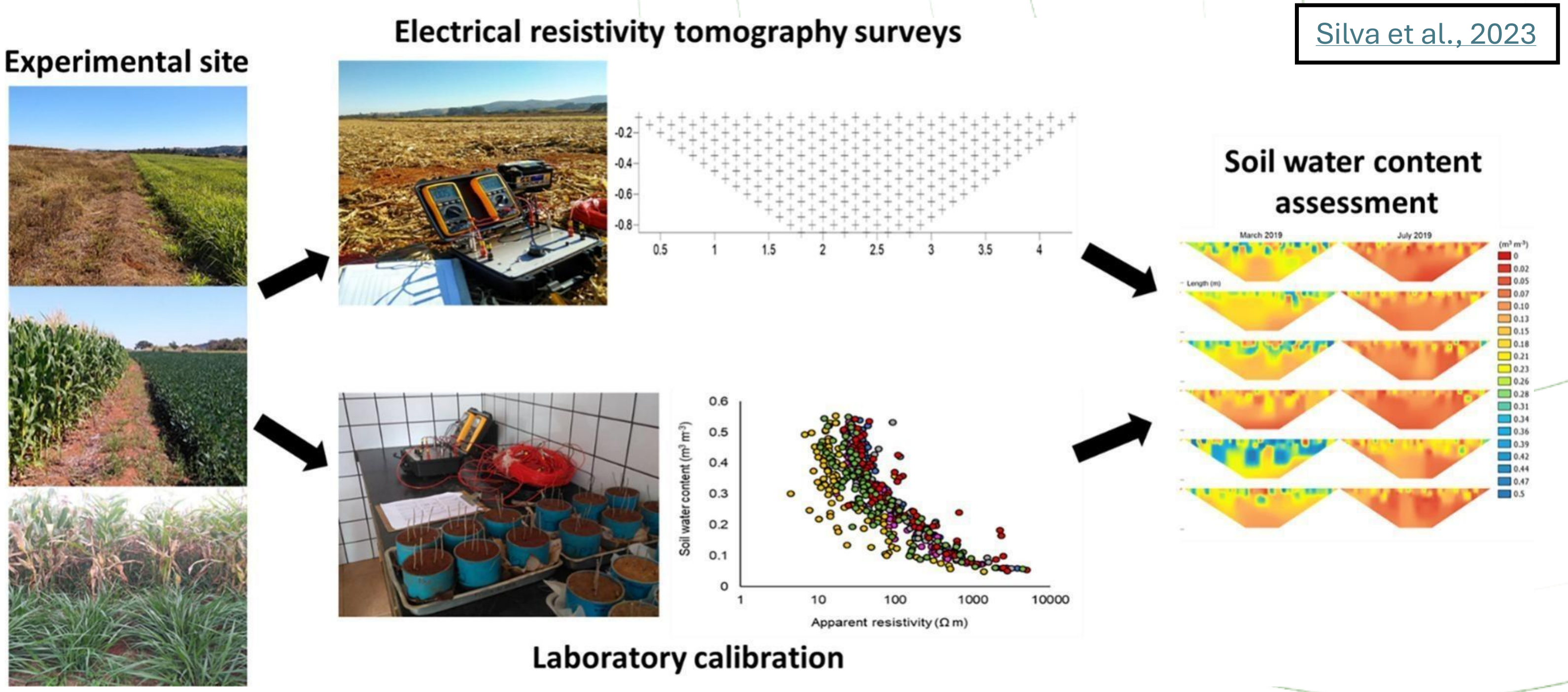


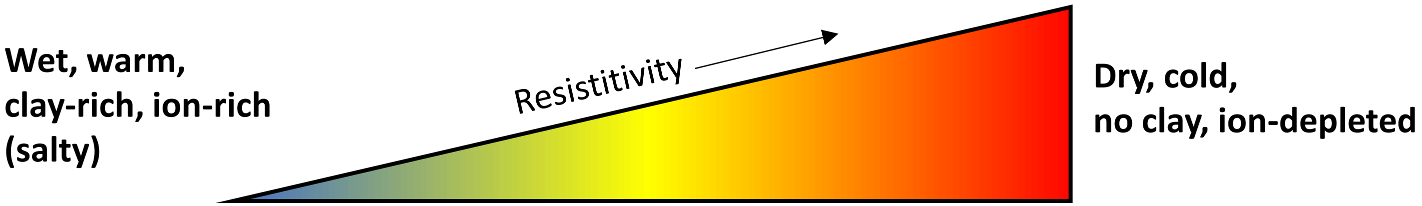
Why electrical and electromagnetic methods?

The electrical resistivity of Earth materials is highly sensitive to variations in the hydraulic properties of the subsurface:

- **Porosity**
- **Saturation**
- **Grain size distribution (hydraulic conductivity)**
- **Pore fluid conductivity**

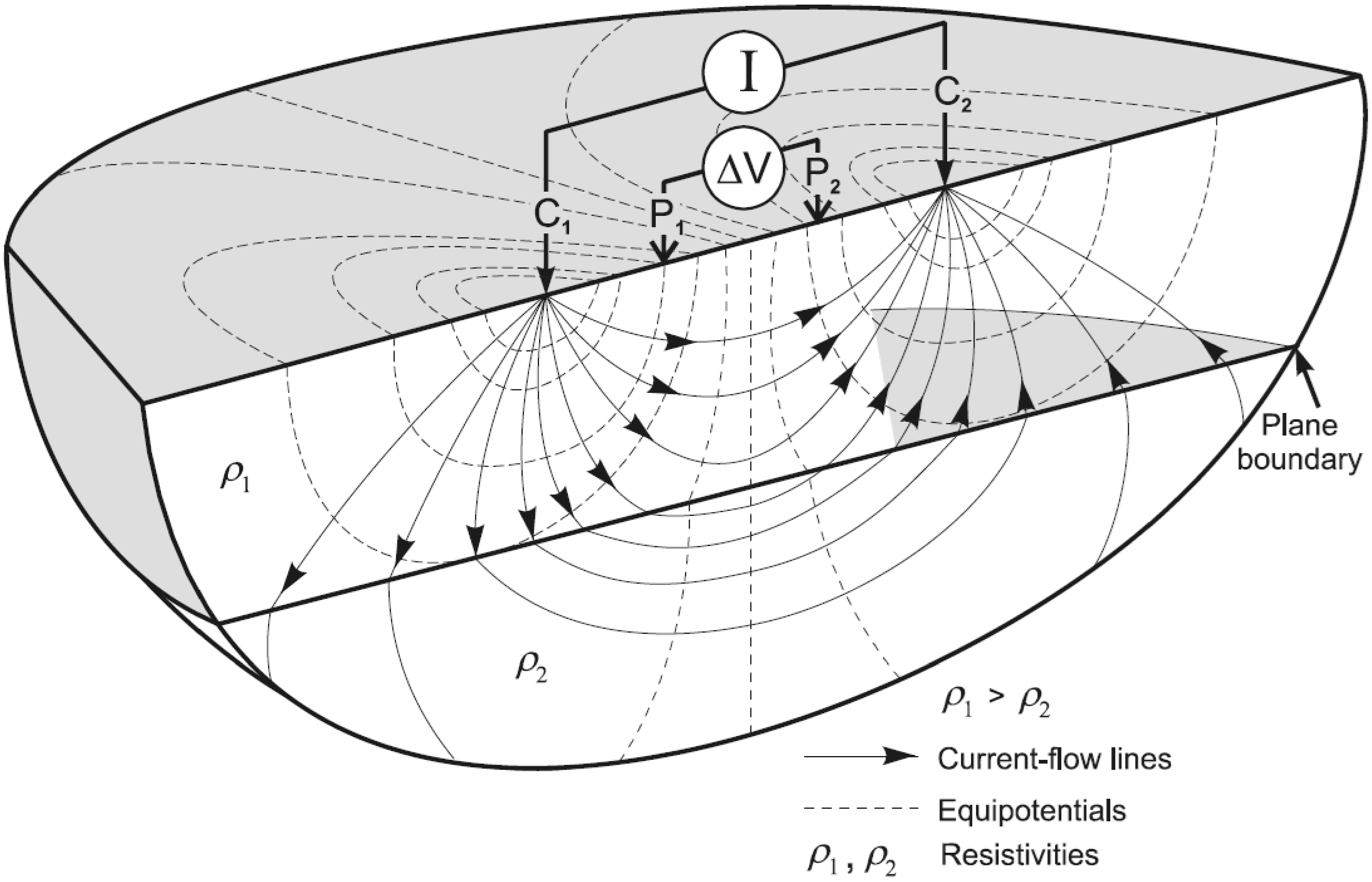
Silva et al., 2023





Electrical resistivity

Measurement principle



Electrical resistivity
Measurement principle

Ohm's Law describes the electrical potential:

$$\Delta V = IR$$

Electrical resistance R depends on

- resistivity of the ground ρ

  and

- the geometry of the electrodes (geometric factor K)

  Resistance [Ω]: $R = \rho / K$

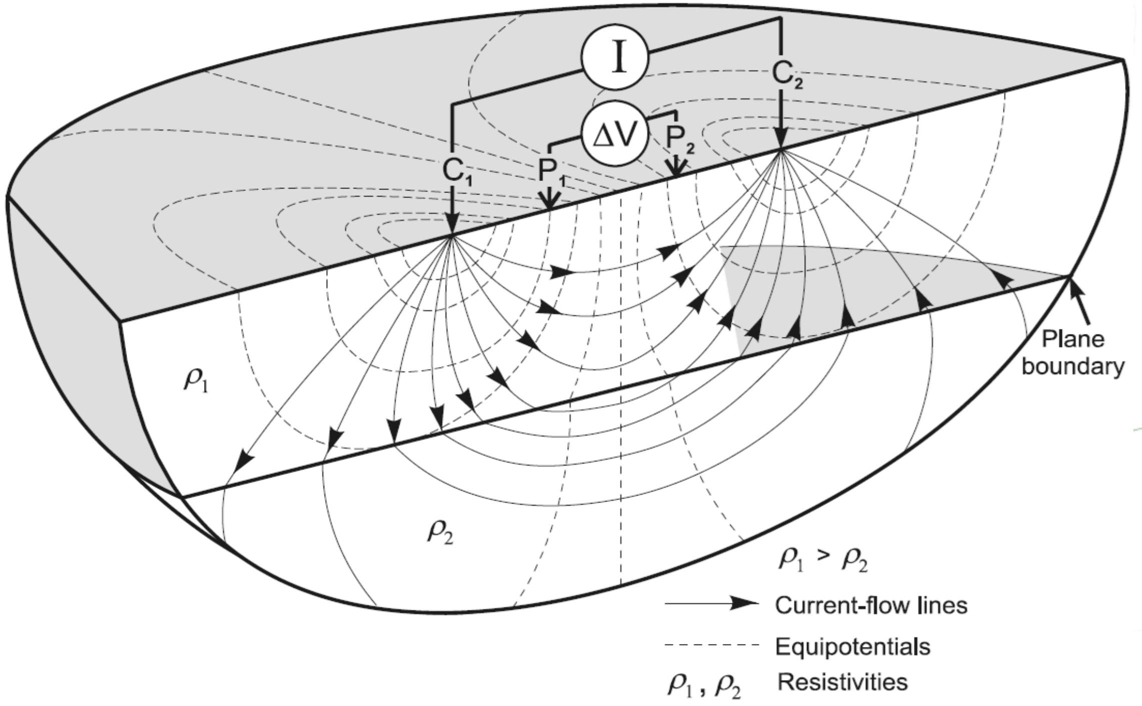
  Resistivity [Ωm]: $\rho = K\,R = K\frac{\Delta V}{I}$

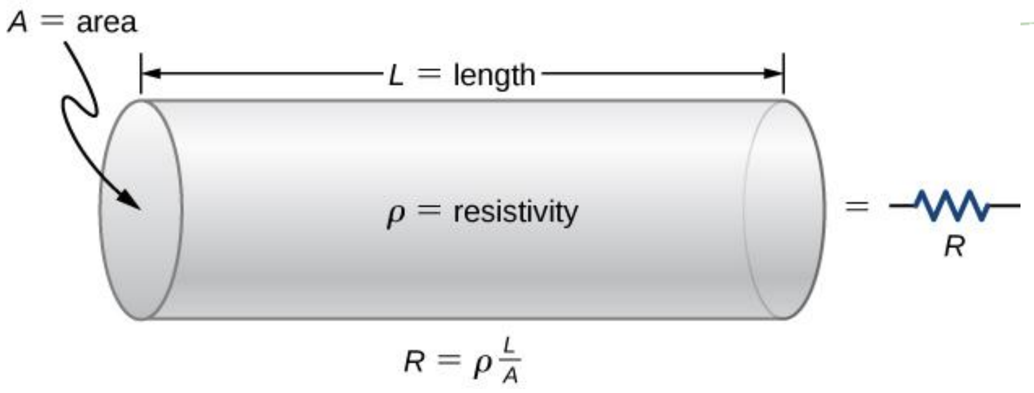
- **Units are important!** R has units of [Ω] (ohms), K has units of [m] (metres), ρ has units of Ωm (ohm-metres)

- **Note:** Electrical resistivity ρ and electrical conductivity σ are related

$$\sigma = 1/\rho$$

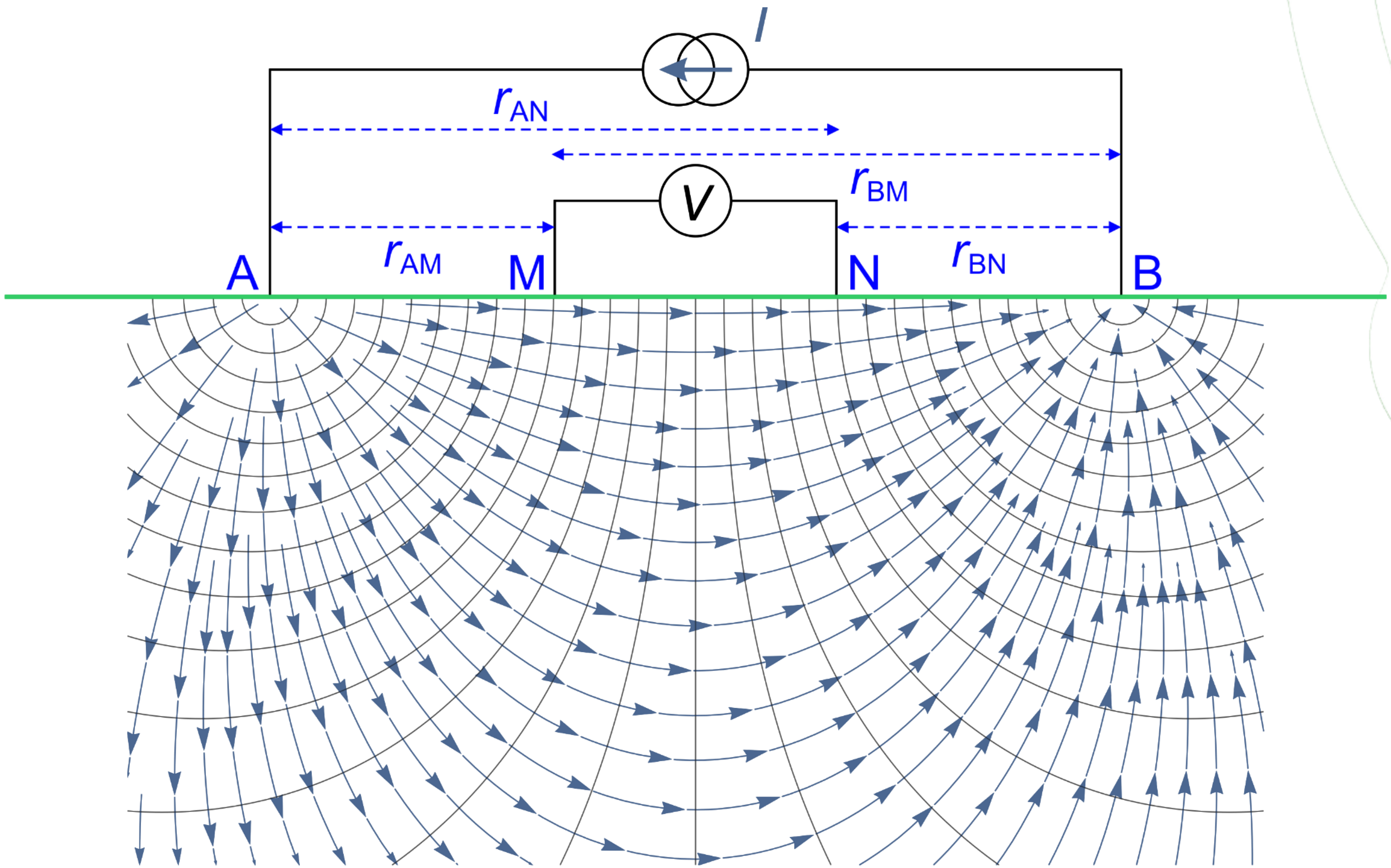
- σ has units of S/m (Siemens per meter)





Electrical resistivity

The geometric factor K



The geometric factor can be calculated based on the known distances between:

1. **the injection (A, B) dipole and**
2. **potential measurement (M,N) dipole**

$$\rho = R\ K$$

$$K = 2\pi \left(\frac{1}{r_{AM}} - \frac{1}{r_{AN}} - \frac{1}{r_{BM}} + \frac{1}{r_{BN}} \right)^{-1}$$

This is only valid for a homogeneous, flat half space

Electrical resistivity

Apparent resistivity

Field/Lab measurements:

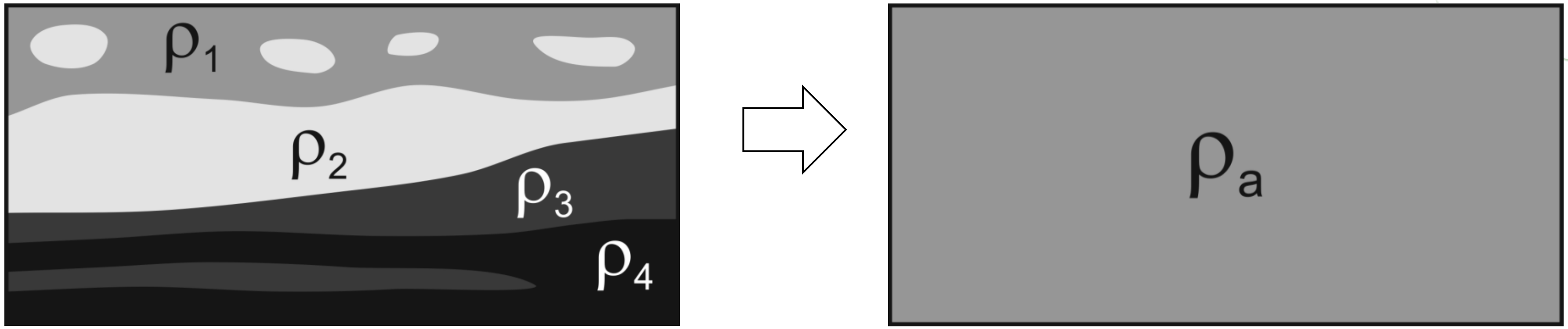
- Measured resistivity = ‘true’ resistivity **ONLY** over **flat homogenous** ground
- Subsurface is rarely completely homogenous

→ Measurements of **“apparent resistivity”**

In simple terms: The apparent resistivity is a weighted average of all the resistivities present in the area of the measurement

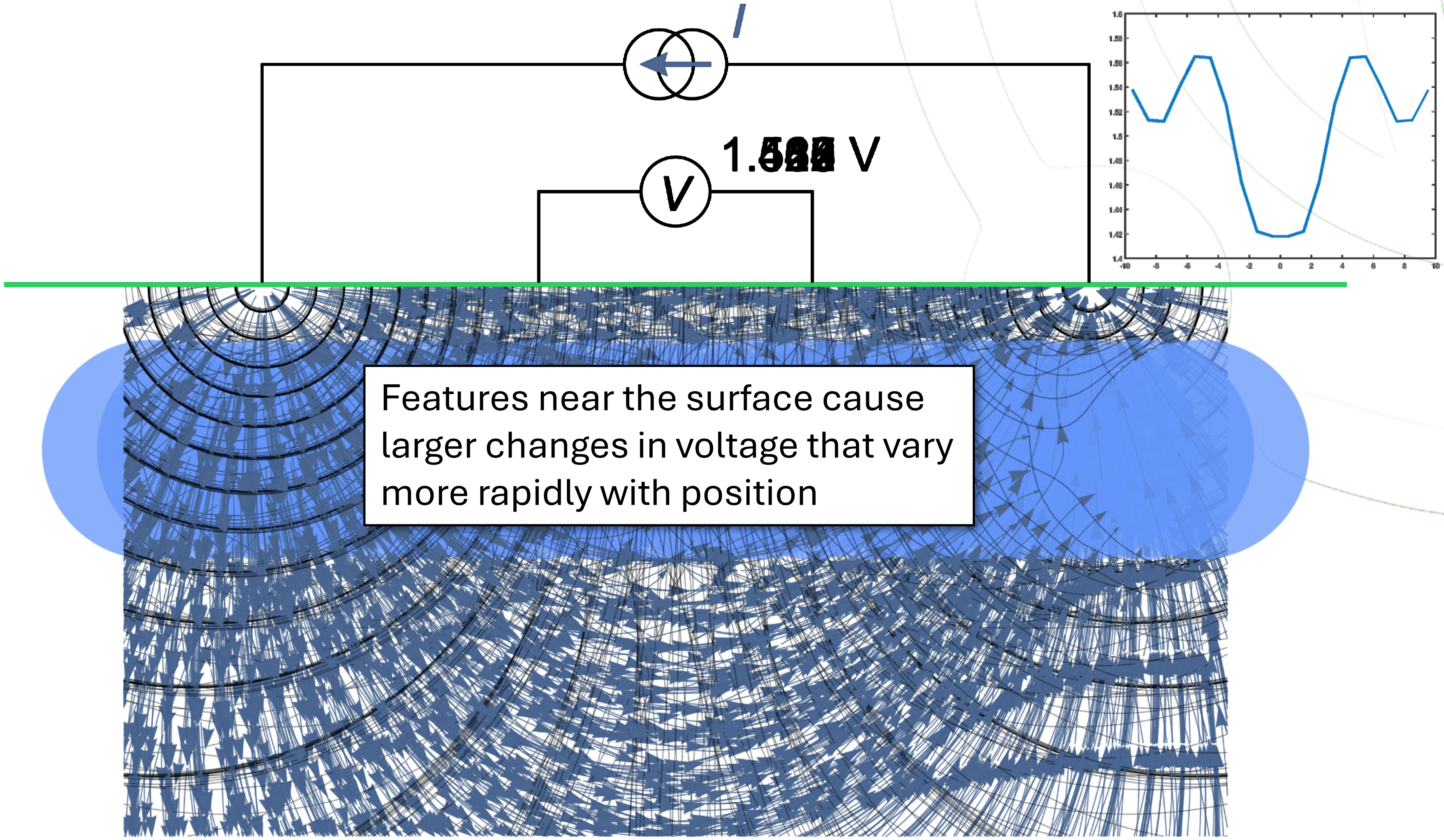
Real resistivity distribution

Apparent resistivity



Measurement sensitivity

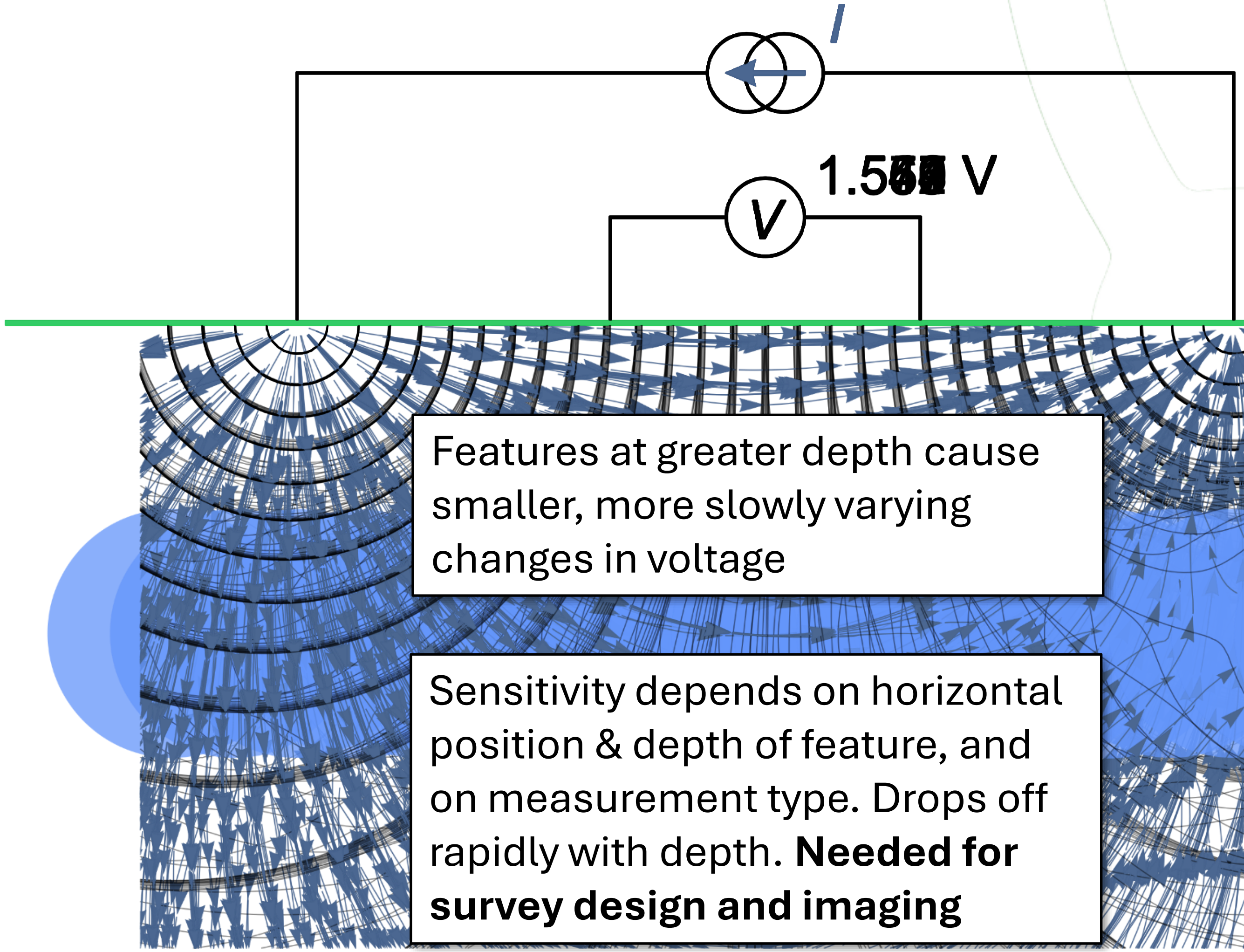
Voltages change with position

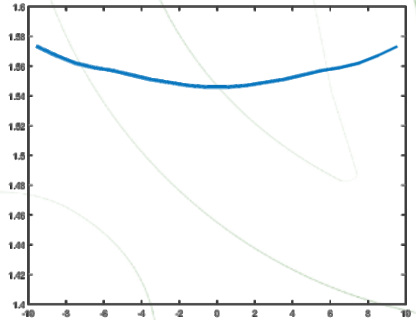


Features near the surface cause larger changes in voltage that vary more rapidly with position

Measurement sensitivity

Voltages change with position and depth





Features at greater depth cause smaller, more slowly varying changes in voltage

Sensitivity depends on horizontal position & depth of feature, and on measurement type. Drops off rapidly with depth. **Needed for survey design and imaging**

Measurement sensitivity

Sensitivity distributions for different configurations

Each measurement array is sensitive to different parts of the subsurface → spatial sampling of the subsurface

Areas of high sensitivity and changes in sign result in high resolution

Wenner:

- Good signal to noise ration
- High horizontal resolution

Pol-Dipole:

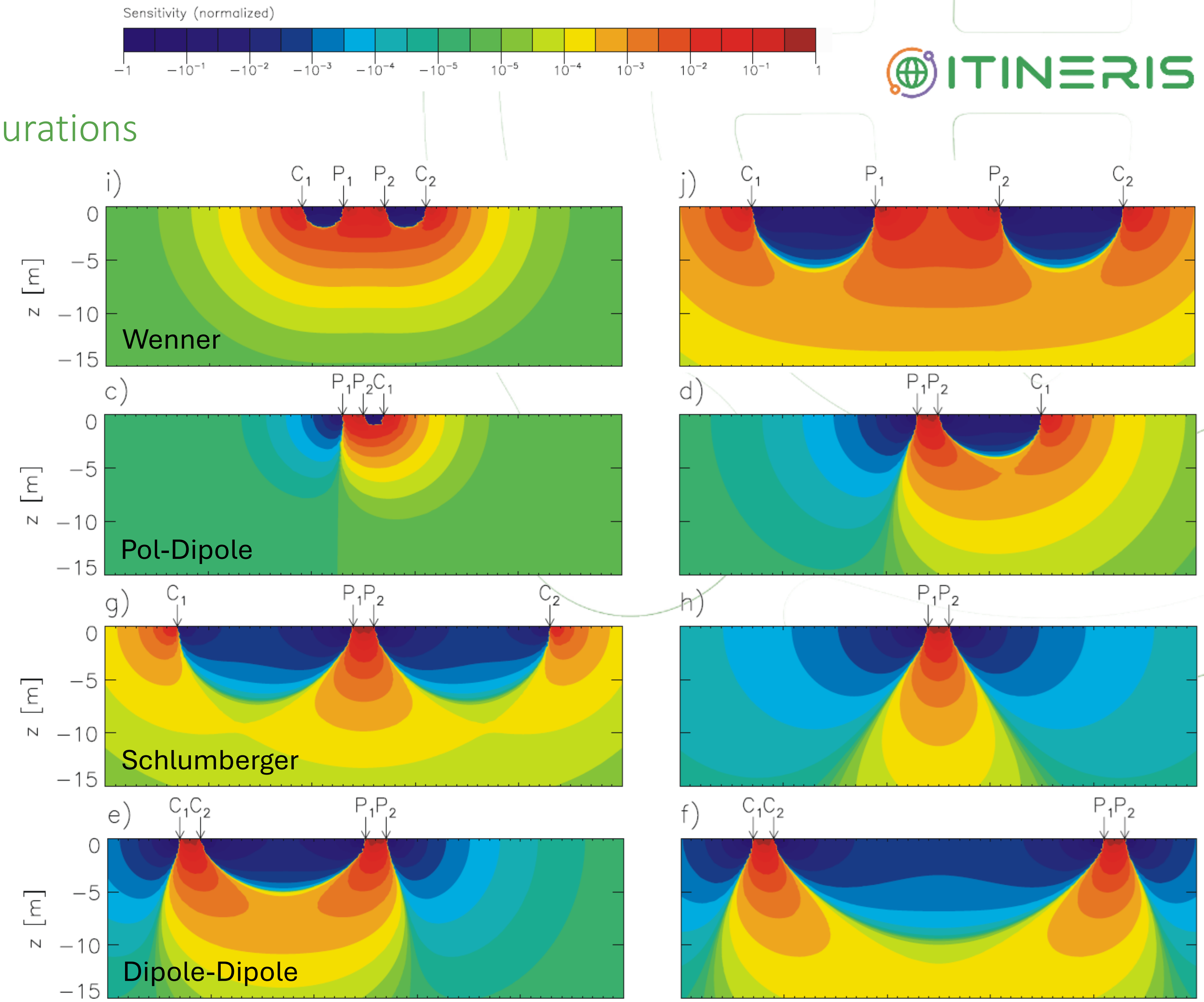
- Very good lateral resolution

Schlumberger

- mainly influenced by resistivity distribution underneath potential electrodes → Vertical electrical sounding

Dipole-Dipole

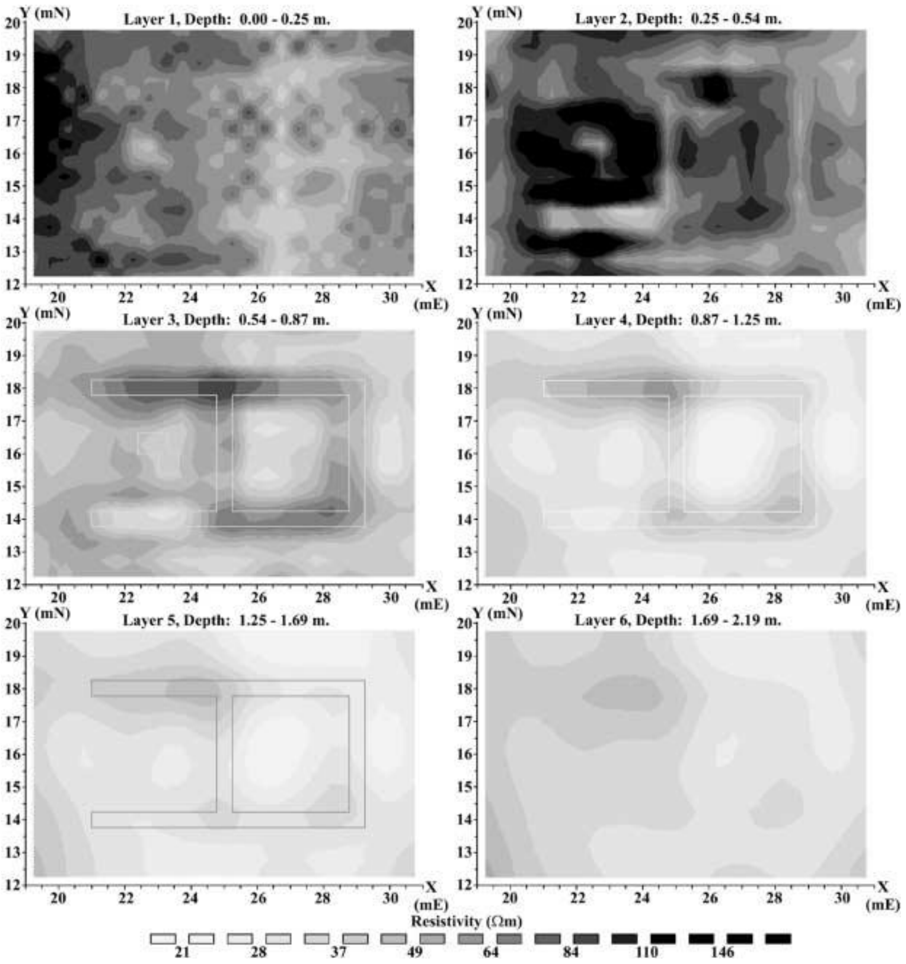
- Good lateral resolution, large depth of investigation
- High resolution
- Affected by variations close to electrodes



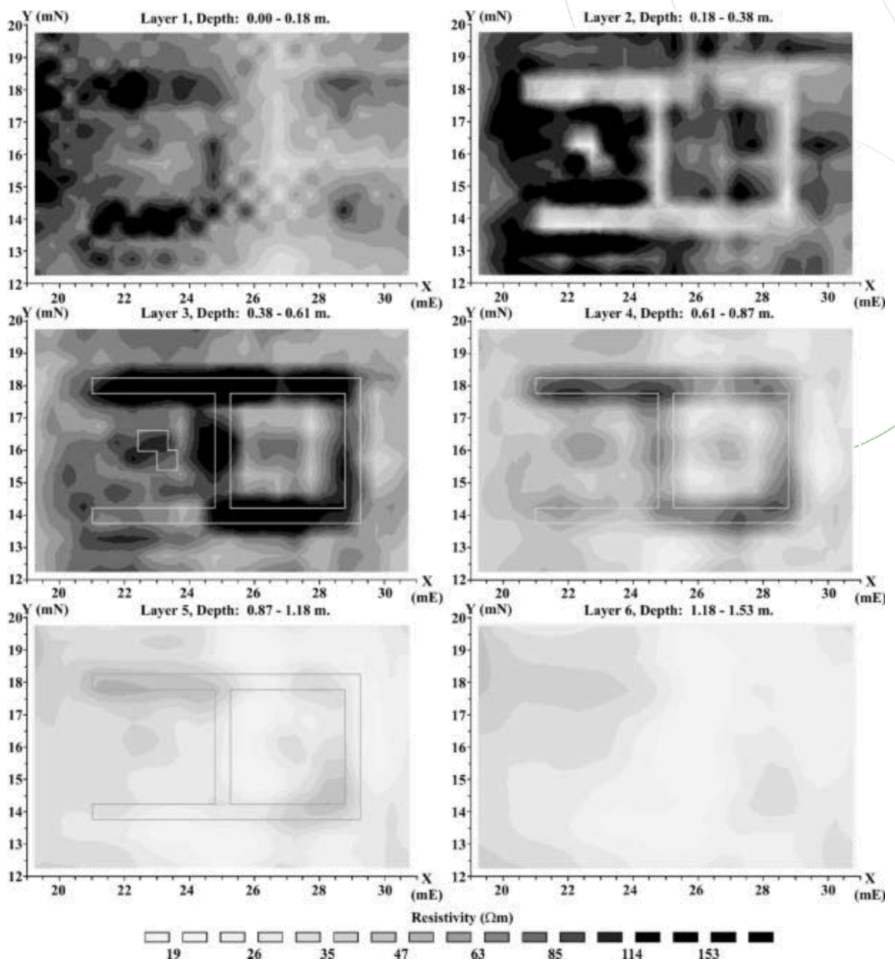
Measurement sensitivity → Model Resolution

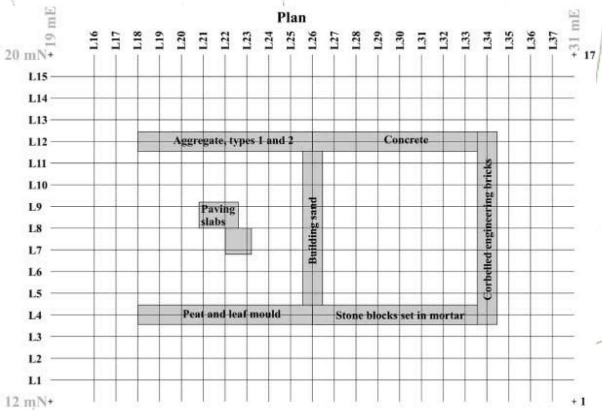
The type of measurement determines the model resolution

Wenner



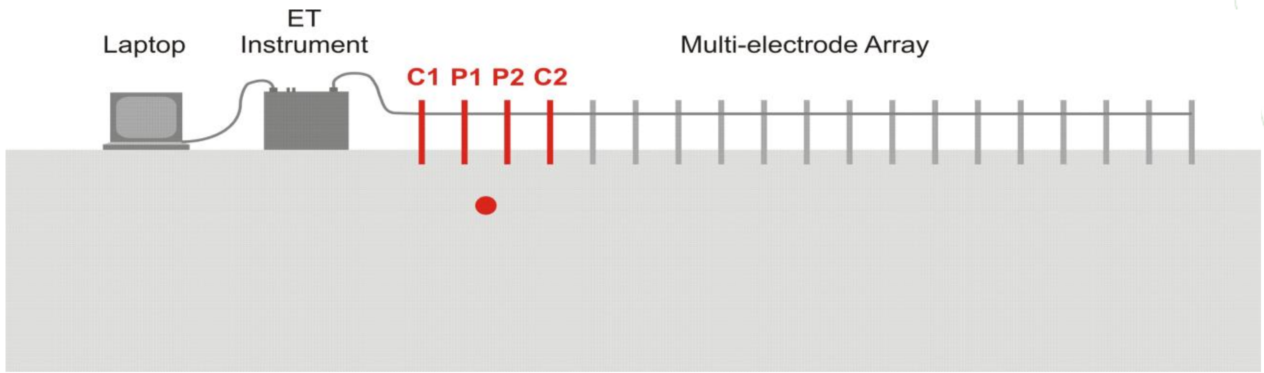
Dipole-Dipole



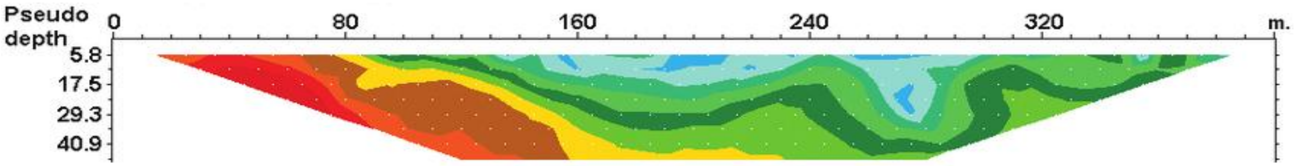


Imaging the resistivity distribution

2D Electrical Resistivity Tomography (ERT)



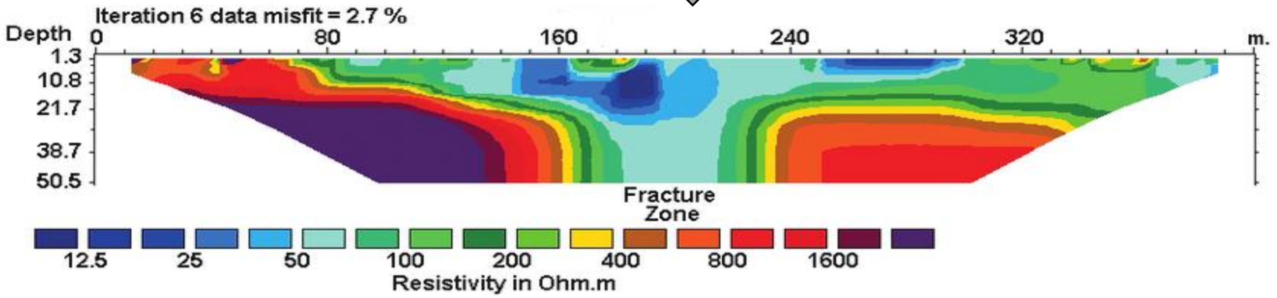
Resistance measurements (raw data)



Apparent resistivity pseudosection

Forward modelling & inversion

Measurements (type, number) and measurement quality define image resolution



Recovered **model** of the subsurface **resistivity distribution**

Forward modelling

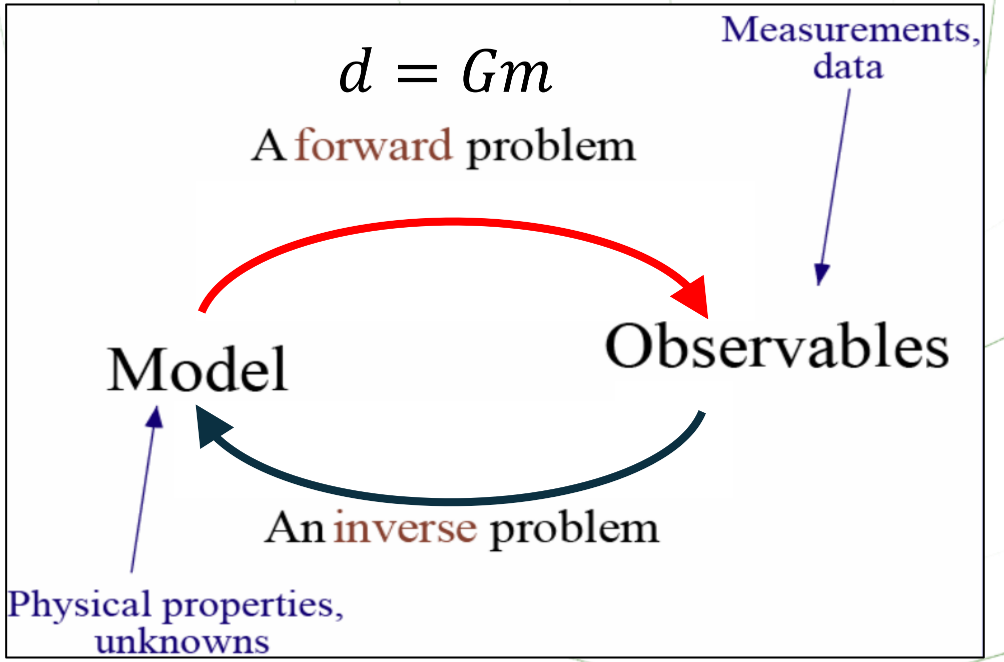
Predicting the response of the subsurface – simulating synthetic measurements

<u>**Forward modelling**</u>:

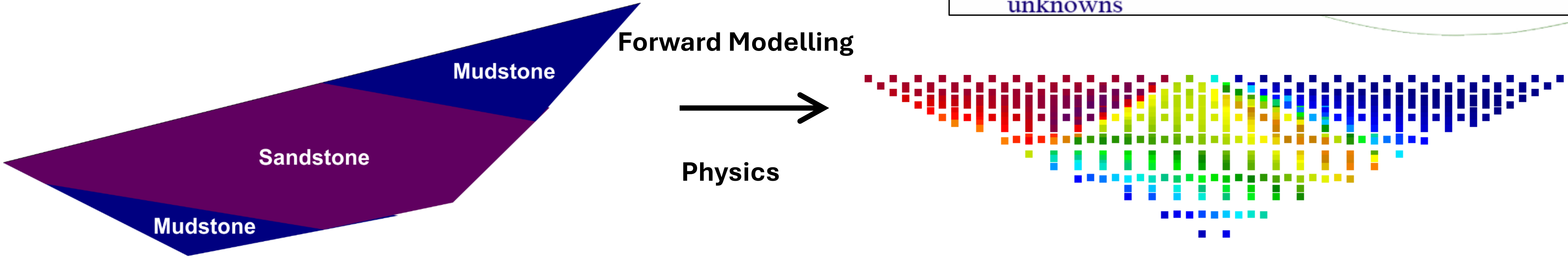
starting with an assumed (usually simplified) **model** of the geophysical ground properties, predict/**simulate the data** that will be measured

<u>**Useful for:**</u>

- survey design
- assessing technique suitability
- *qualitative* / *semi-quantitative* analysis of survey data.



Relatively easy!

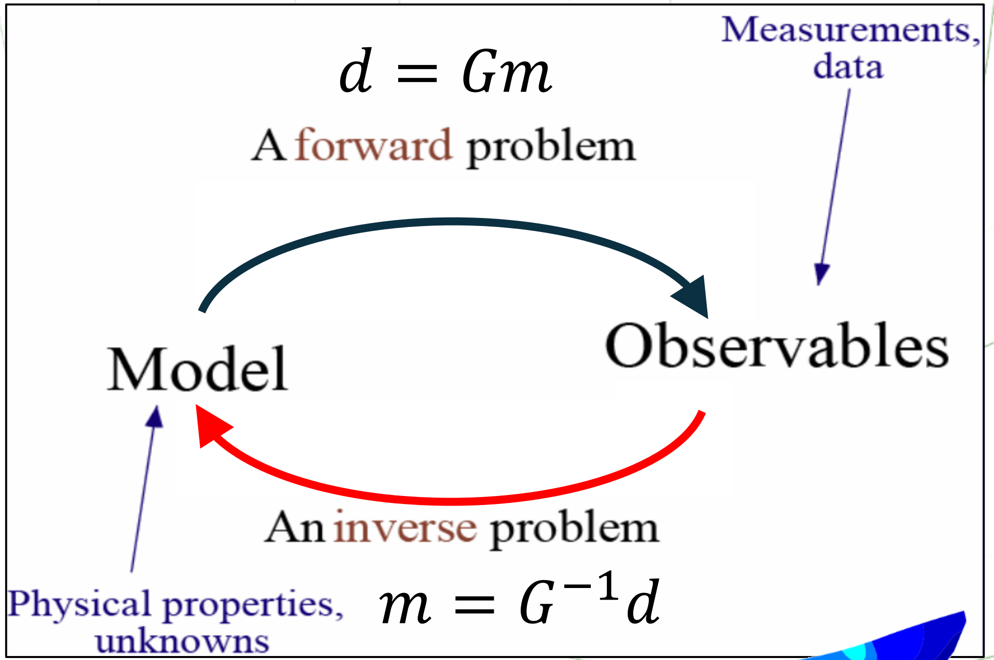


Subsurface Model

Geophysical Measurements

Inverse modelling

Predicting the subsurface model from real measurements



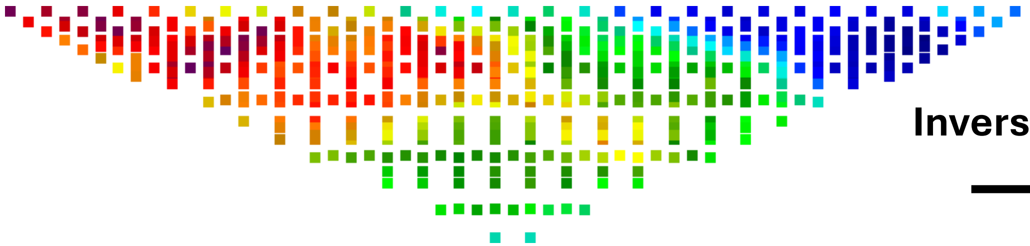
Inverse modelling

starting with the measured data, predict the geophysical properties of the ground (tomographic imaging/subsurface model)

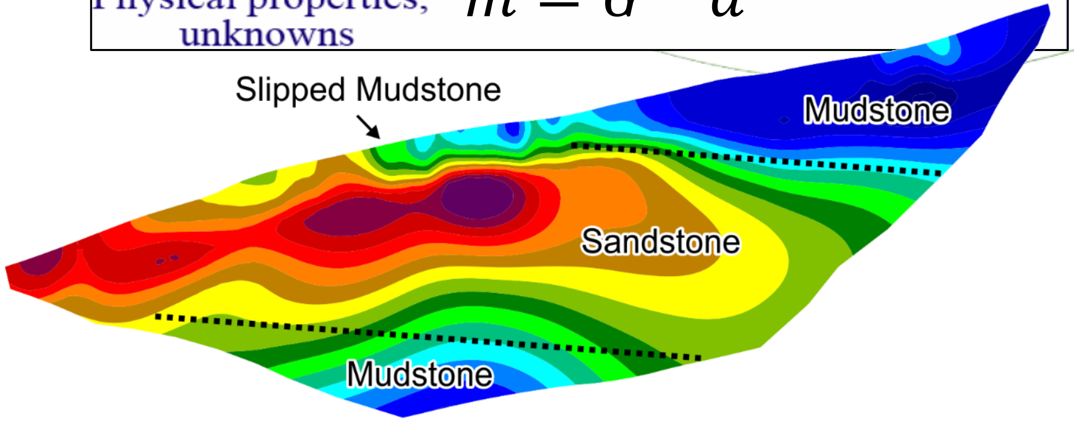
Useful for:

- *quantitative* analysis of survey data
- Visualisation
- assessing uncertainties
- survey design.

Relatively difficult!



Inverse Modelling →



Geophysical Measurements

Subsurface Model

Inverse modelling

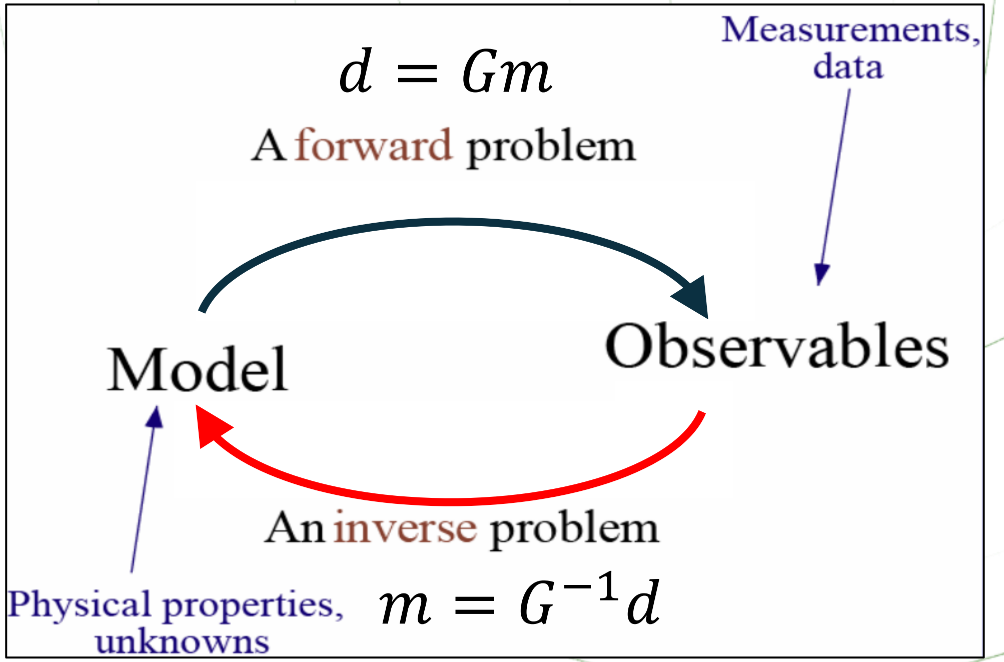
The inverse problem

Aim: Find a model of the electrical properties of the ground that is consistent with the data

With data covering the whole region of interest, can we work out the true resistivity distribution of the ground?

- In theory, yes!
- It has been *proven* that this inverse problem has a unique solution.

- But…



Inverse modelling

Uniqueness (or lack of…)

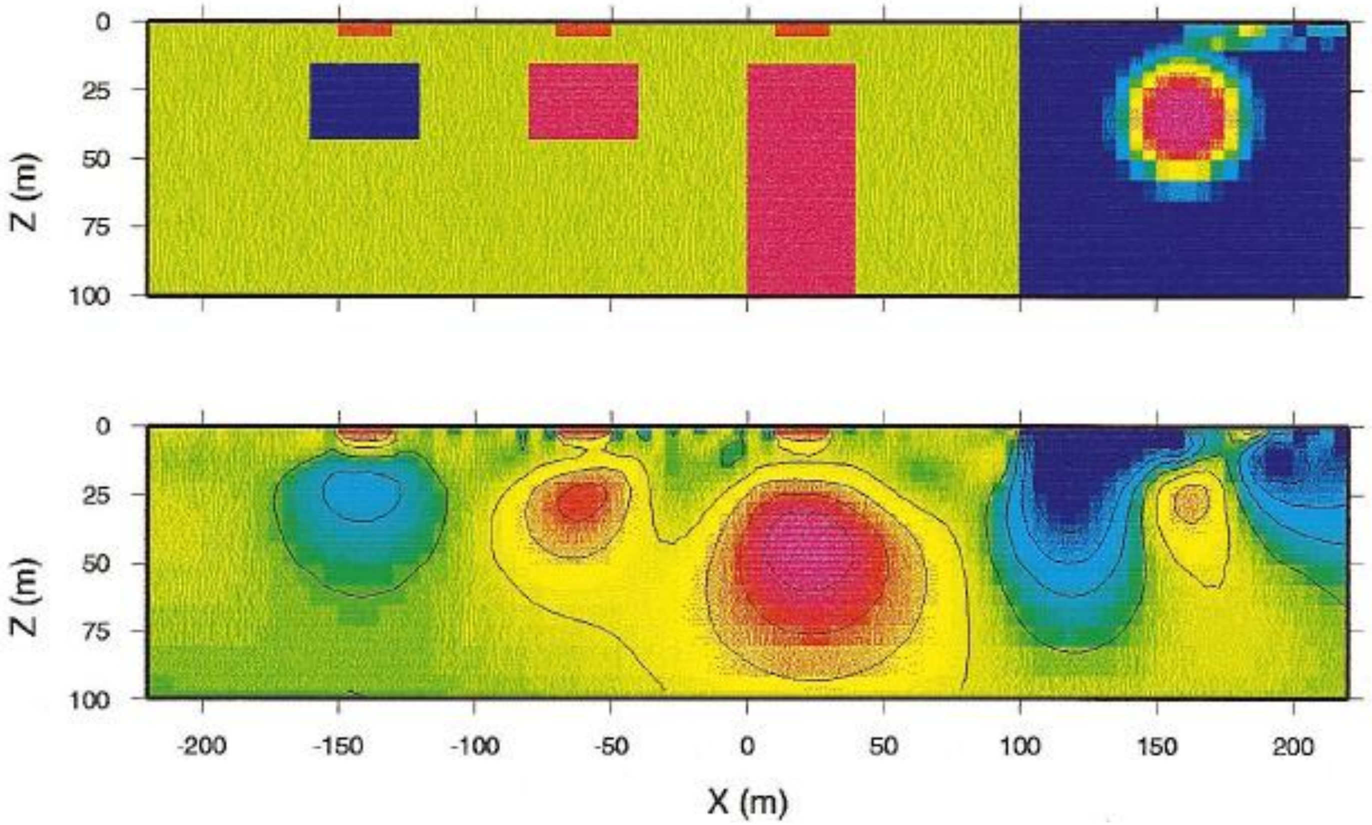
Conditions for the unique solution are very demanding:

- Must know the voltage distribution across the boundary of the whole region with infinite accuracy…impossible in Earth Science applications
- For every possible set of current electrodes!

In practice:

- Only cover **part** of the boundary
- Only use a **limited number** of electrodes
- Only measure with a **limited accuracy** (due to noise and instrument limitations)
- Causes ***non-uniqueness*** – there are an ***infinite*** number of models that fit the data equally well

Inverse modelling
Uniqueness (or lack of...)

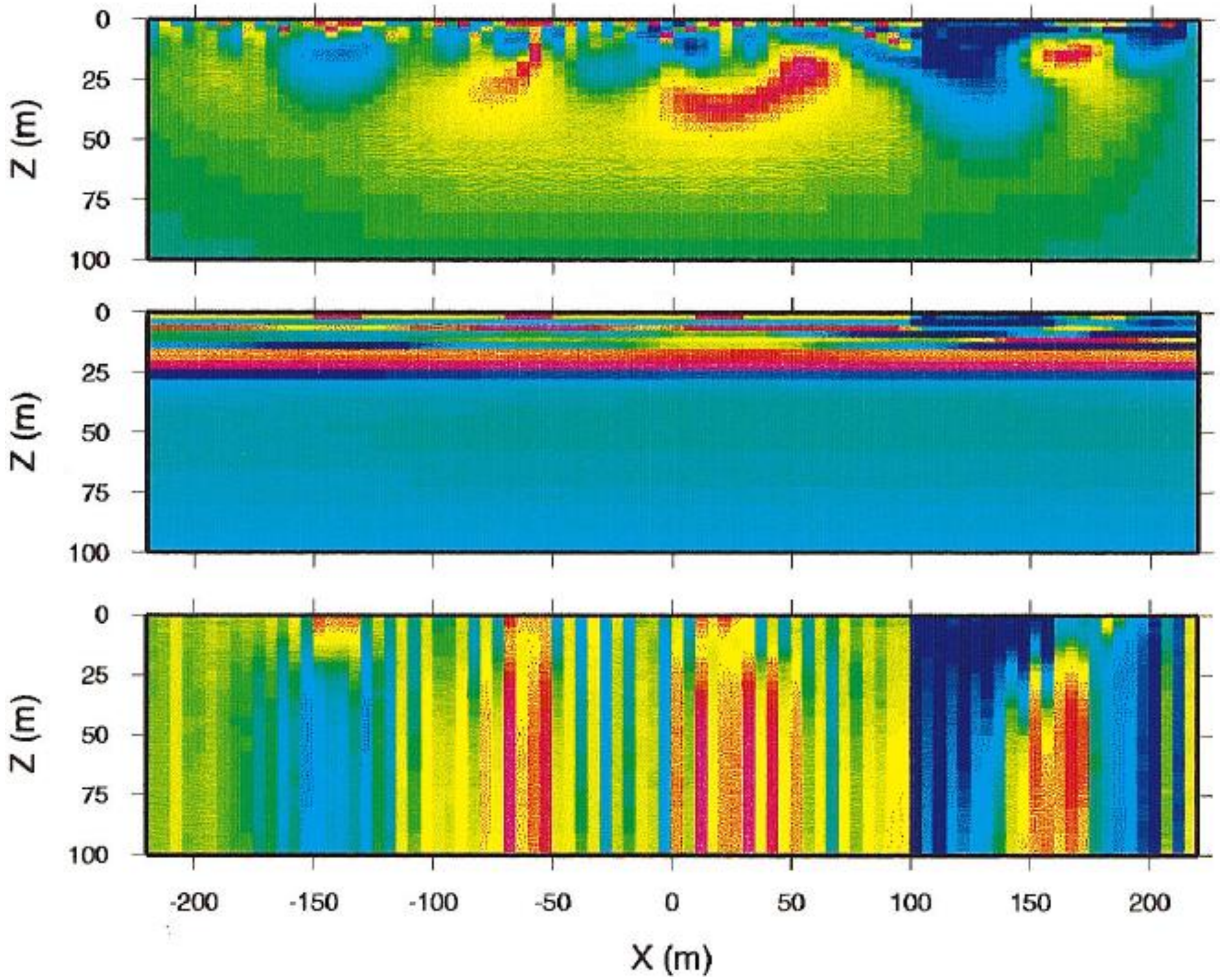


Forward model

Inverse model (note the lack of resolution)

Inverse modelling

Non-uniqueness – extreme example



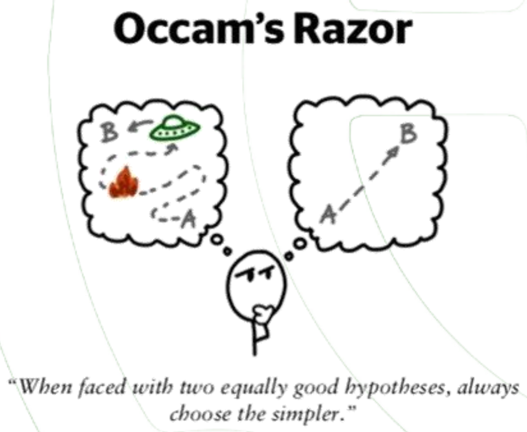
All these inverse models fit the data just as well!

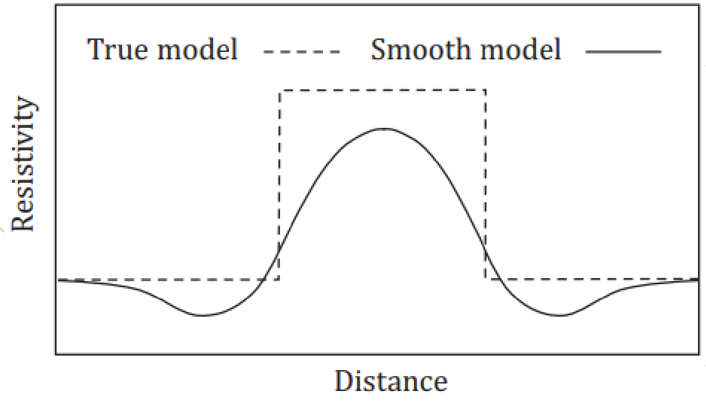
Inverse modelling

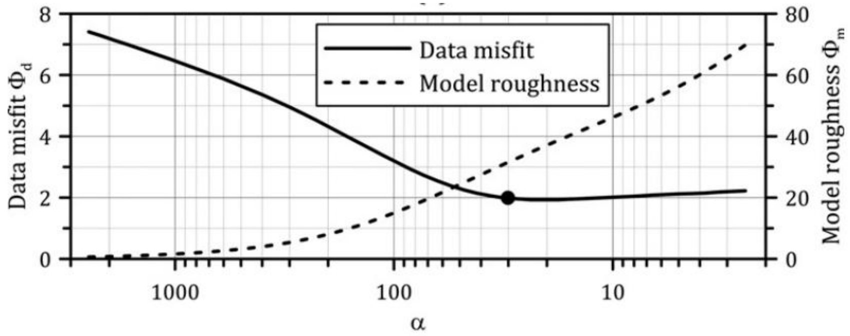
Constraints

- To find a stable solution, apply prior information / constraints
  - specific information (e.g. a borehole log, or information on the location of a feature like a fault or interface)
  - global characteristics like simplicity or smoothness (Occam's razor)

- Most common constraints are **smoothness-based:**
  - blocky models (tending to have continuous regions with sharp edges, **L1**)
  - smooth models (properties varies smoothly across regions and edges are gradational, **L2**)



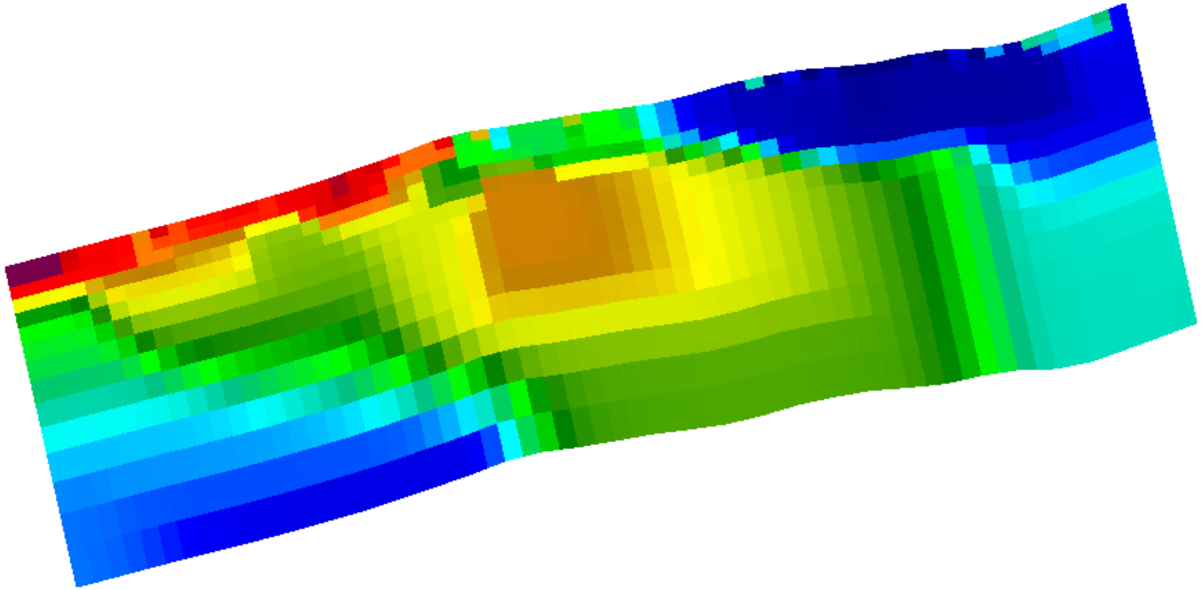




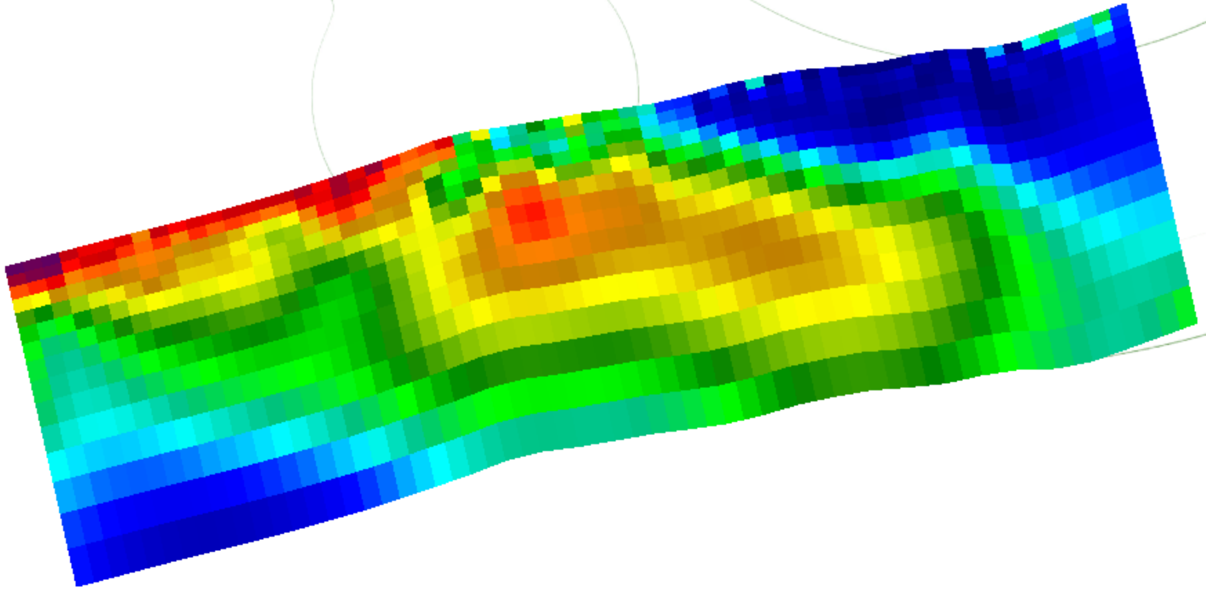
Inverse modelling

Constraint examples

Blocky model

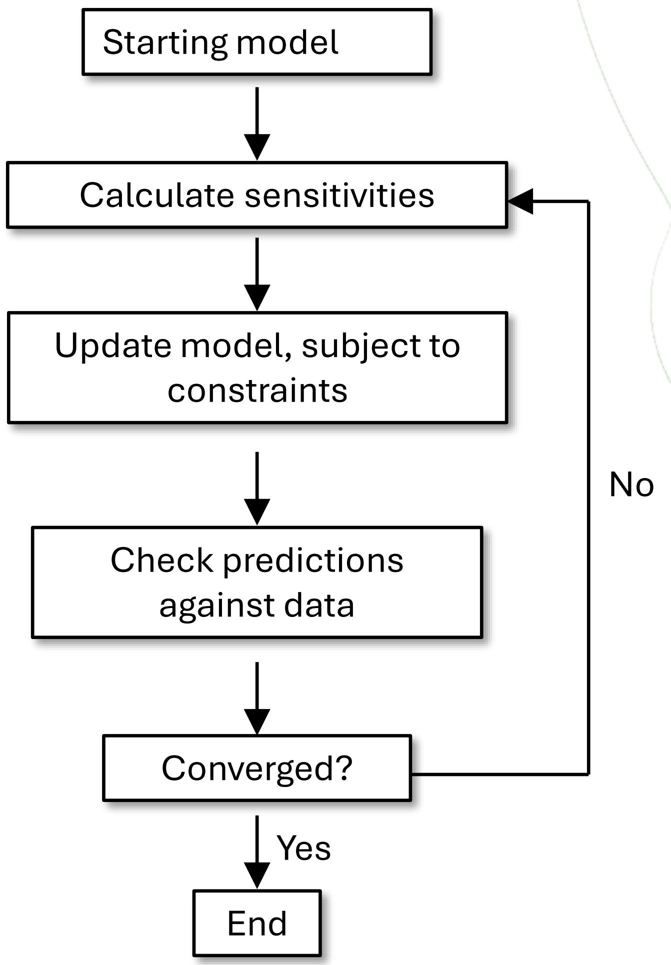


Smooth model



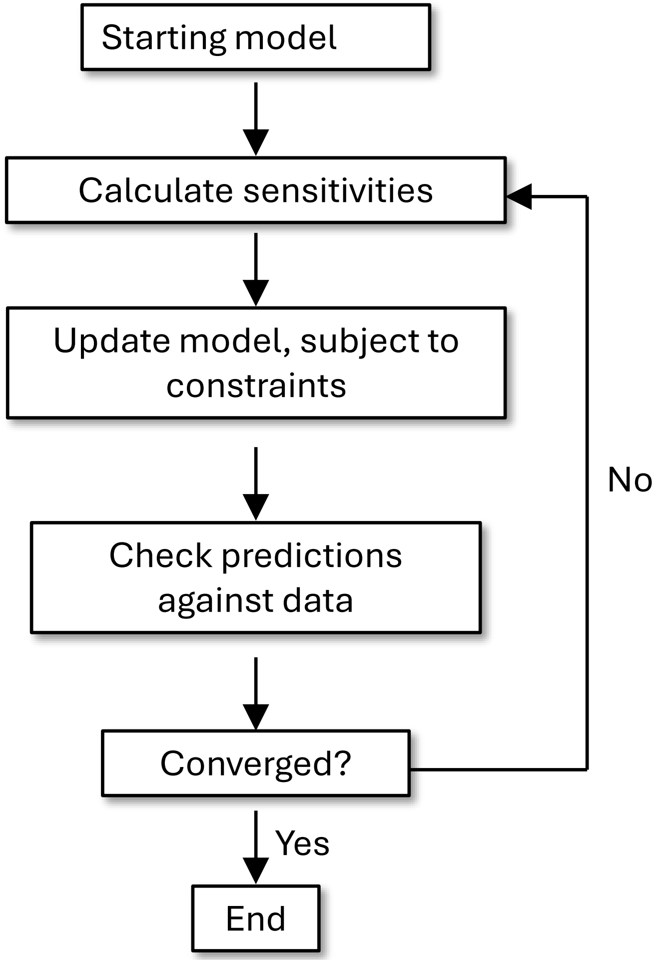
Inverse modelling

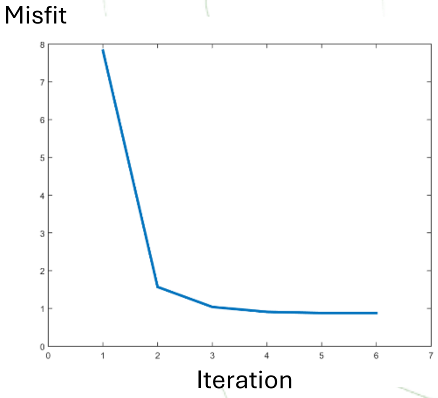
Iterative process

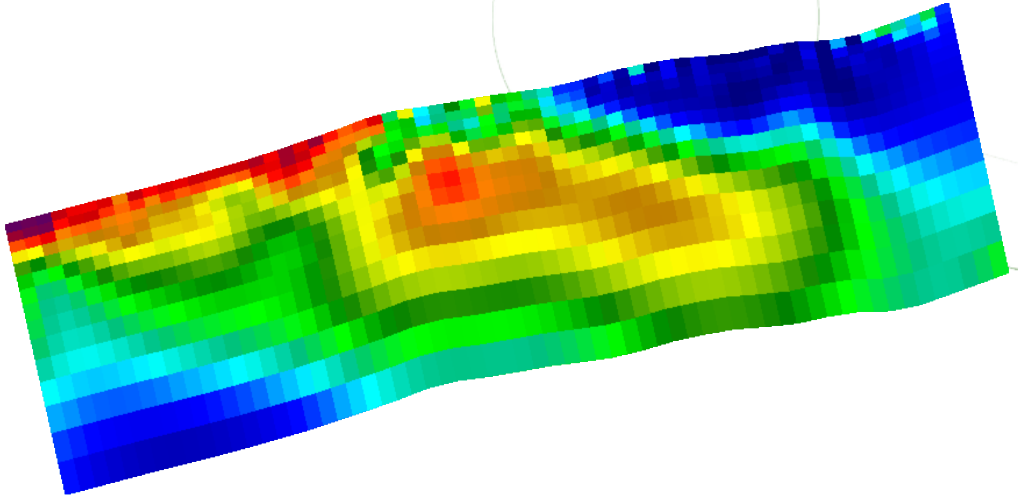


Inverse modelling

Example





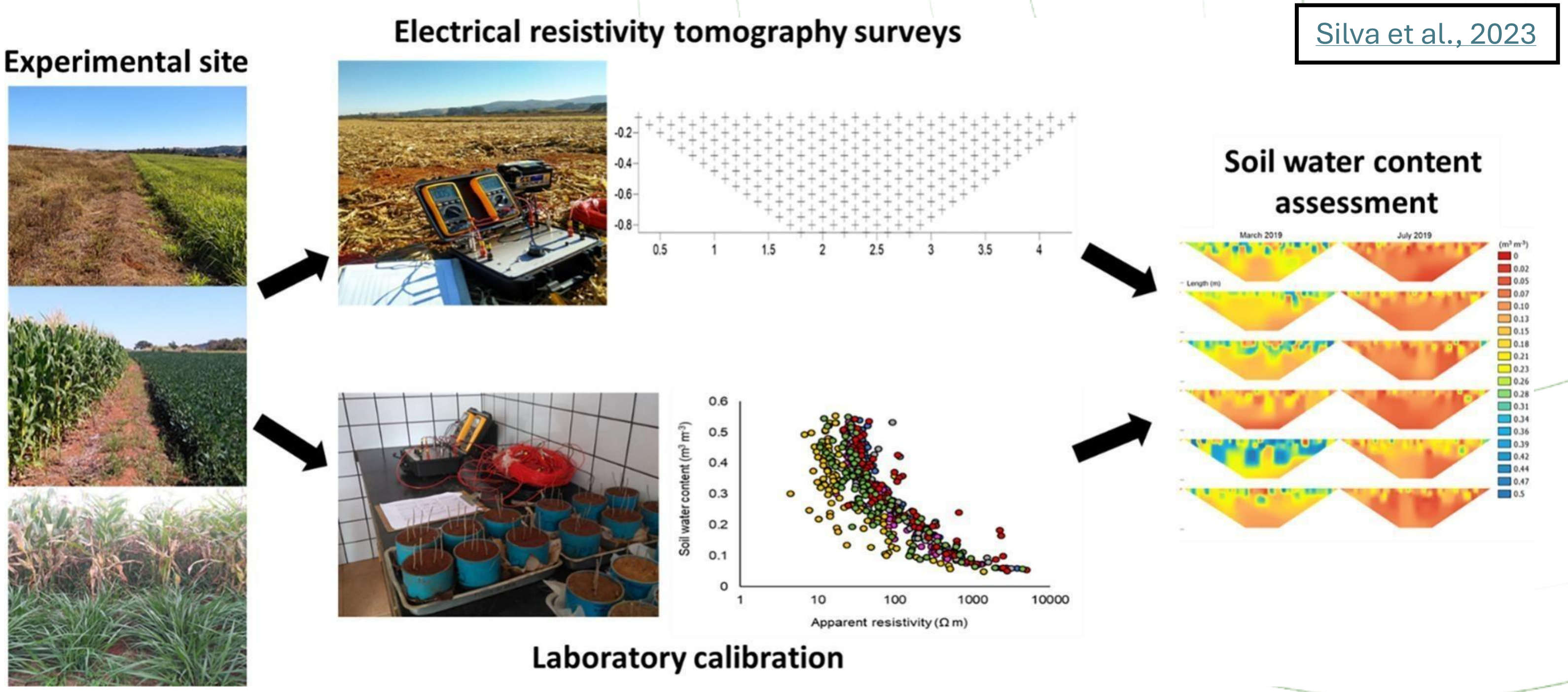


Why electrical and electromagnetic methods?

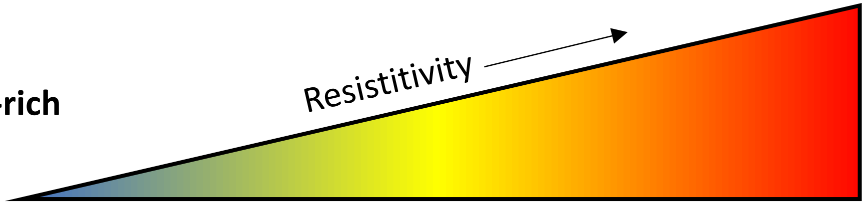
Silva et al., 2023

The electrical resistivity of Earth materials is highly sensitive to variations in the hydraulic properties of the subsurface:

- **Porosity**
- **Saturation**
- **Grain size distribution (hydraulic conductivity)**
- **Pore fluid conductivity**



Wet, warm, clay-rich, ion-rich (salty)



Dry, cold, no clay, ion-depleted

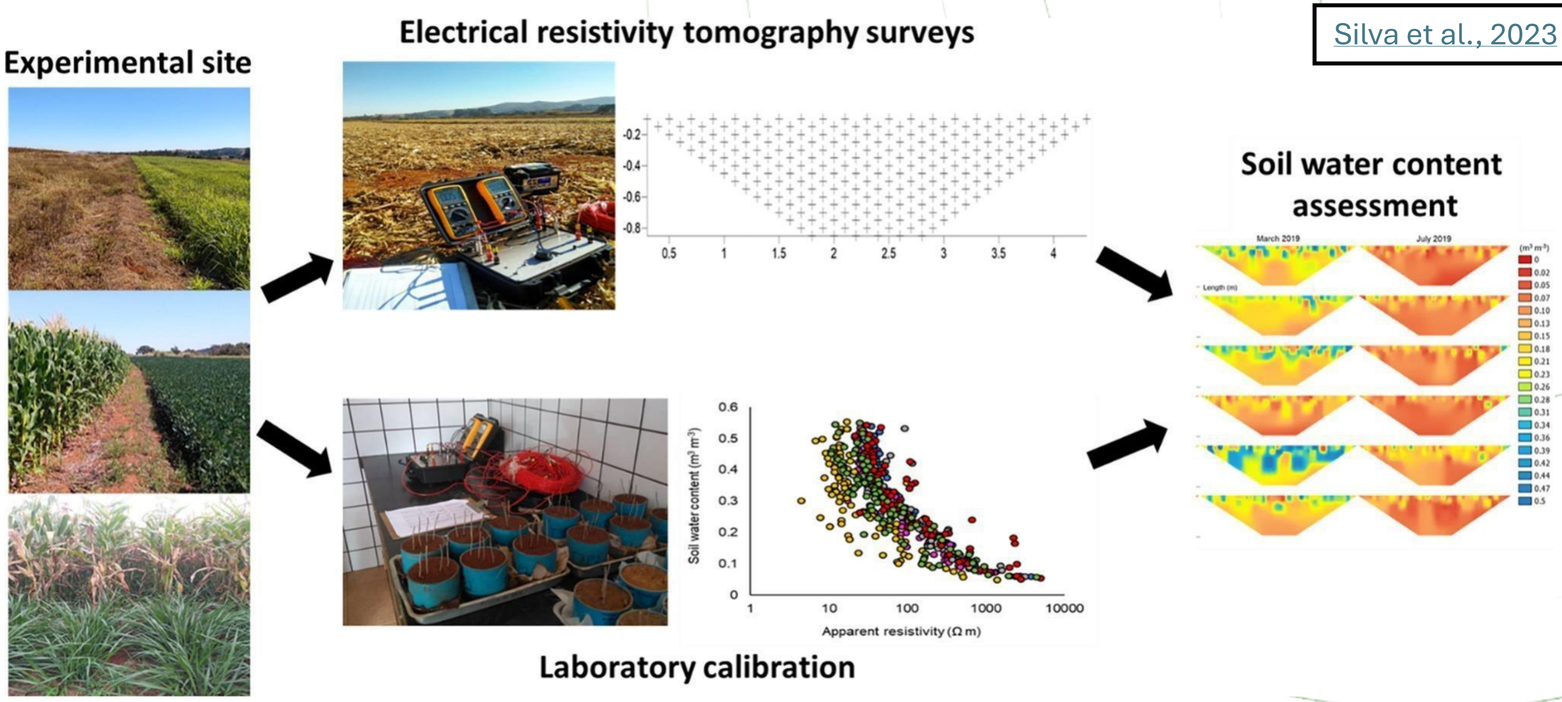
Why electrical and electromagnetic methods?

Silva et al., 2023

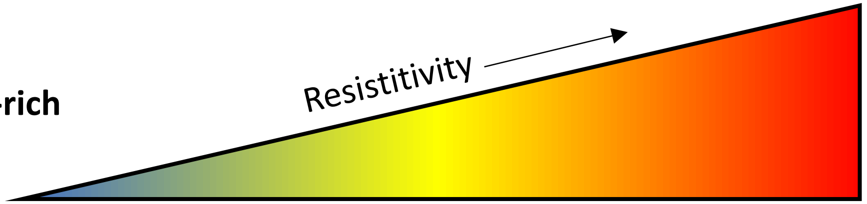
The electrical resistivity of Earth materials is highly sensitive to variations in the hydraulic properties of the subsurface:

- **Porosity**
- **Saturation**
- **Grain size distribution (hydraulic conductivity)**
- **Pore fluid conductivity**

Relatively constant



Wet, warm, clay-rich, ion-rich (salty)



Dry, cold, no clay, ion-depleted


Process-monitoring

Field deployment

Components and examples – short term deployment

Considerations:

- Required resolution
- Available instrument capability
  - System capability (no of channels/electrodes)
  - Available cables & electrodes
- Measurement time vs. process-dynamics

Field deployment

Components and examples – long term deployments

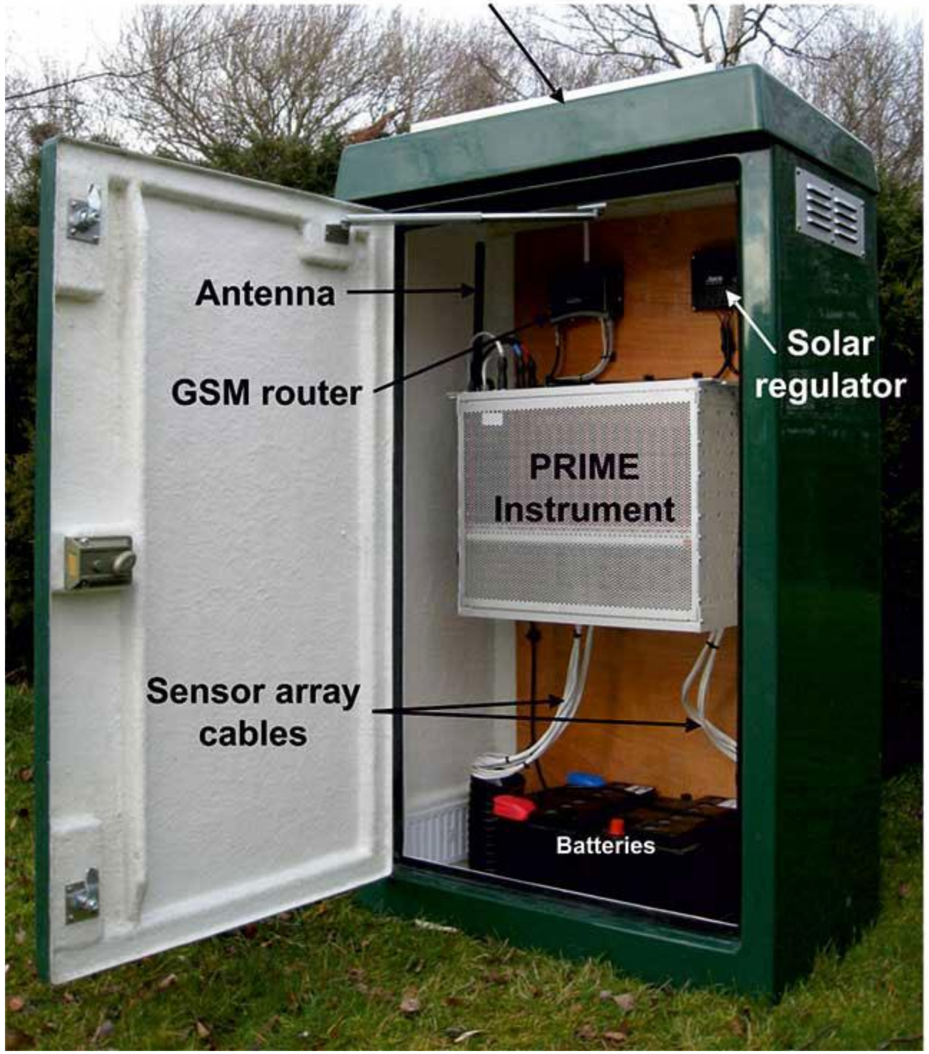
Considerations:

- Power requirements of ERT system
  - The smaller the better, but sometimes higher power systems are needed
- How to get the power?
  - Solarpanels, wind turbines, fuel cells
  - Backup battery power
- Reliability of ERT system
- Real-time data transmission or storage?
- Safety?

Field deployment

Components and examples – long term deployments – systems

Solar array, 20W



PRIME Instrument:
Site installation

Natural Environment Research Council

ERT Monitoring system from **Subsurface Insights**

Field deployment

Components and examples – long term deployments – installation

Buried cables and electrodes for automated measurements

- **Protection against damage by wildlife or humans**
- **Making sure that electrodes stay in place**

For repeat measurements (no permanent installation) mark electrode locations!

Field deployment

Components and examples – long term deployments – installation

Field deployment

Components and examples – long term deployments

Remote/automated monitoring is great!

BUT: Systems and components may need maintenance

Need a maintenance strategy – and money!

Timelapse-inversion strategies

Overview

Full 4D Inversion

- Invert the entire time series as one dataset
- Enables implementing true smoothness constraints across time
- Requires the entire data set to be acquired

Windowed 4D Inversion

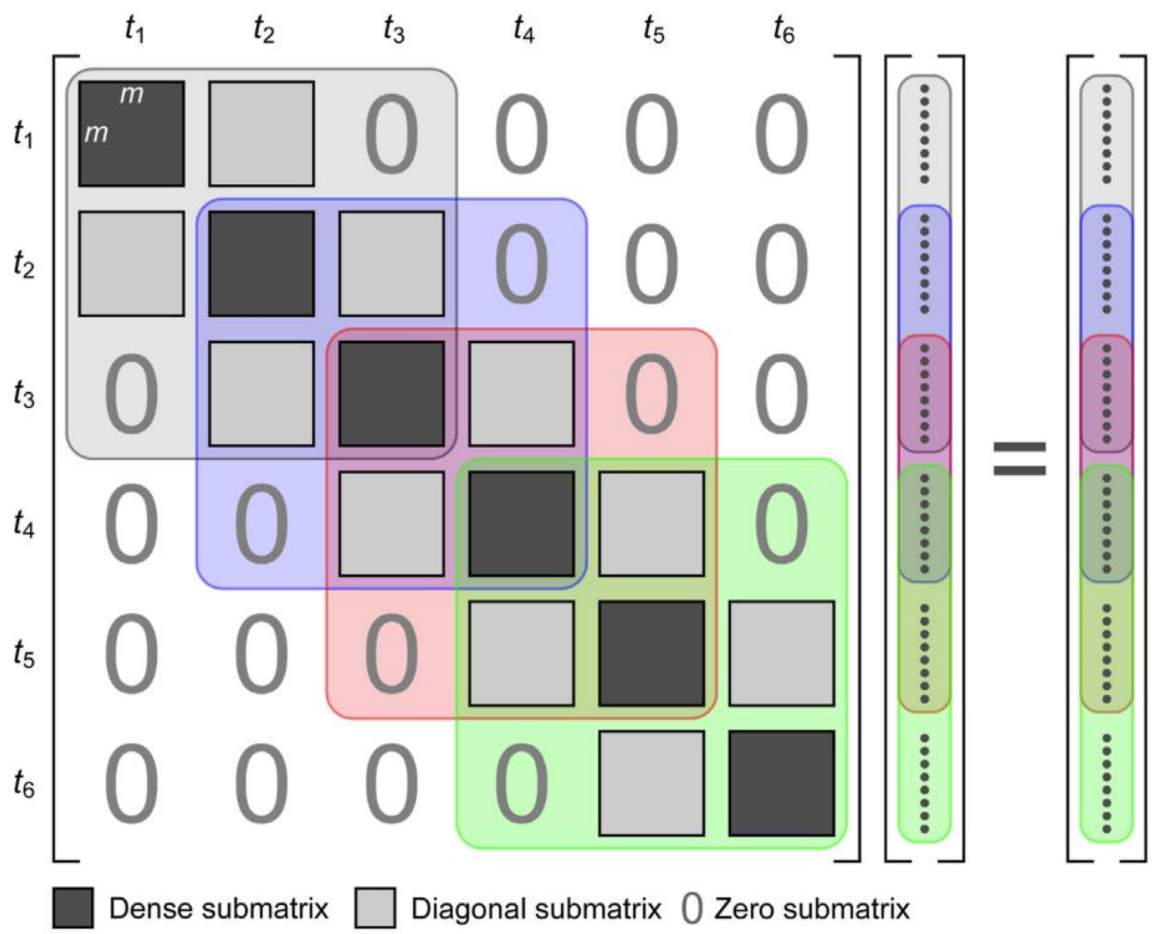
- Full 4D Inversion of data subsets
- Allows for near real-time results (no need for entire time series to be acquired)

Timelapse inversion

- Invert one timestep against a baseline
- Constraints to minimize the difference between two resistivity models

Difference inversion

- Only invert for the differences in the acquired data
- Baseline: invert ρ_a → timesteps: invert $\Delta\rho_a$



Timelapse-inversion strategies

Overview

Full 4D Inversion

- Invert the entire time series as one dataset
- Enables implementing true smoothness constraints across time
- Requires the entire data set to be acquired

Windowed 4D Inversion

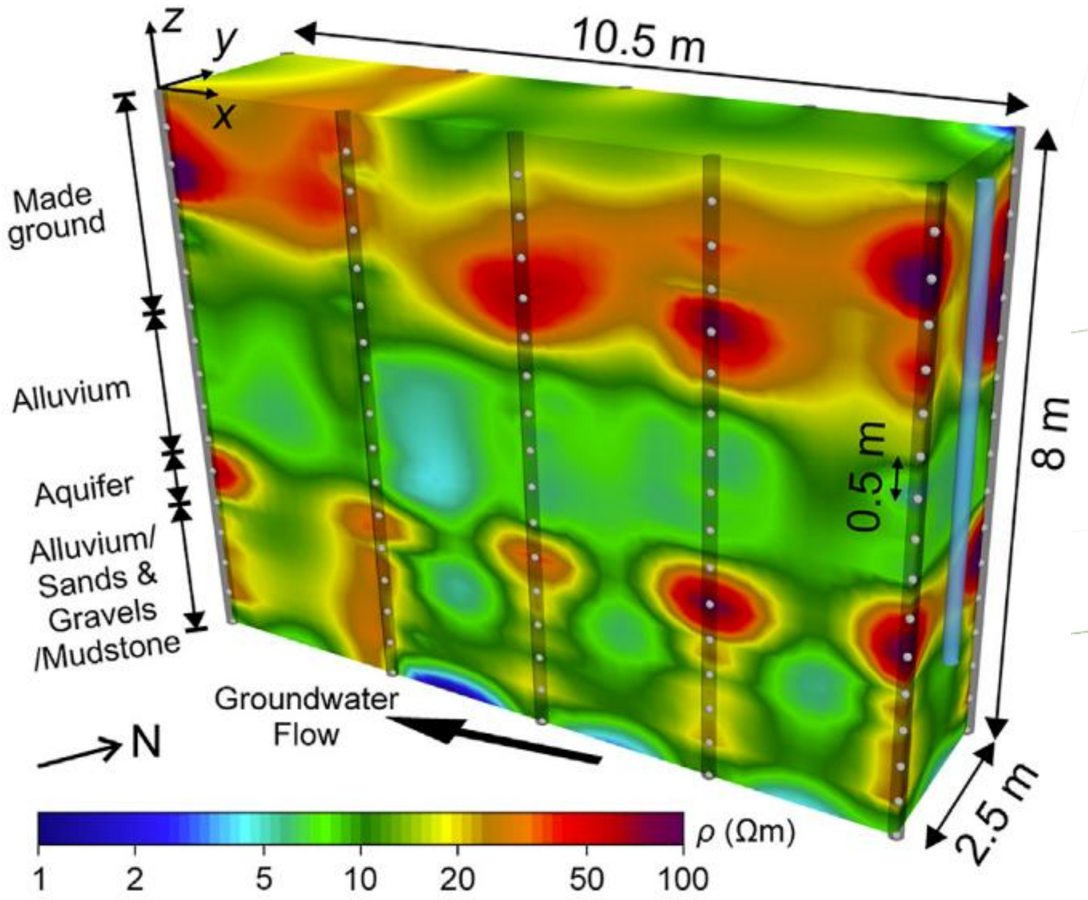
- Full 4D Inversion of data subsets
- Allows for near real-time results (no need for entire time series to be acquired)

Timelapse inversion

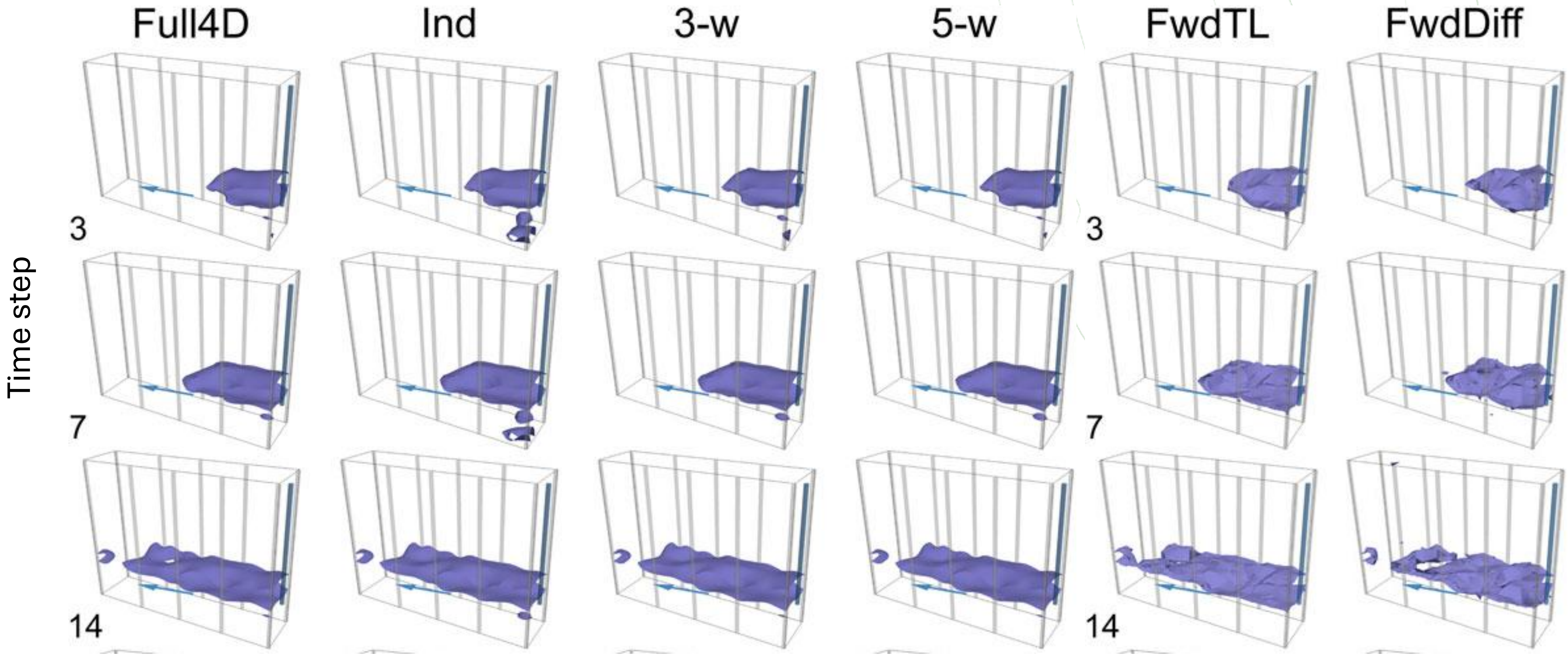
- Invert one timestep against a baseline
- Constraints to minimize the difference between two resistivity models

Difference inversion

- Only invert for the differences in the acquired data
- Baseline: invert ρ_a → timesteps: invert $\Delta\rho_a$

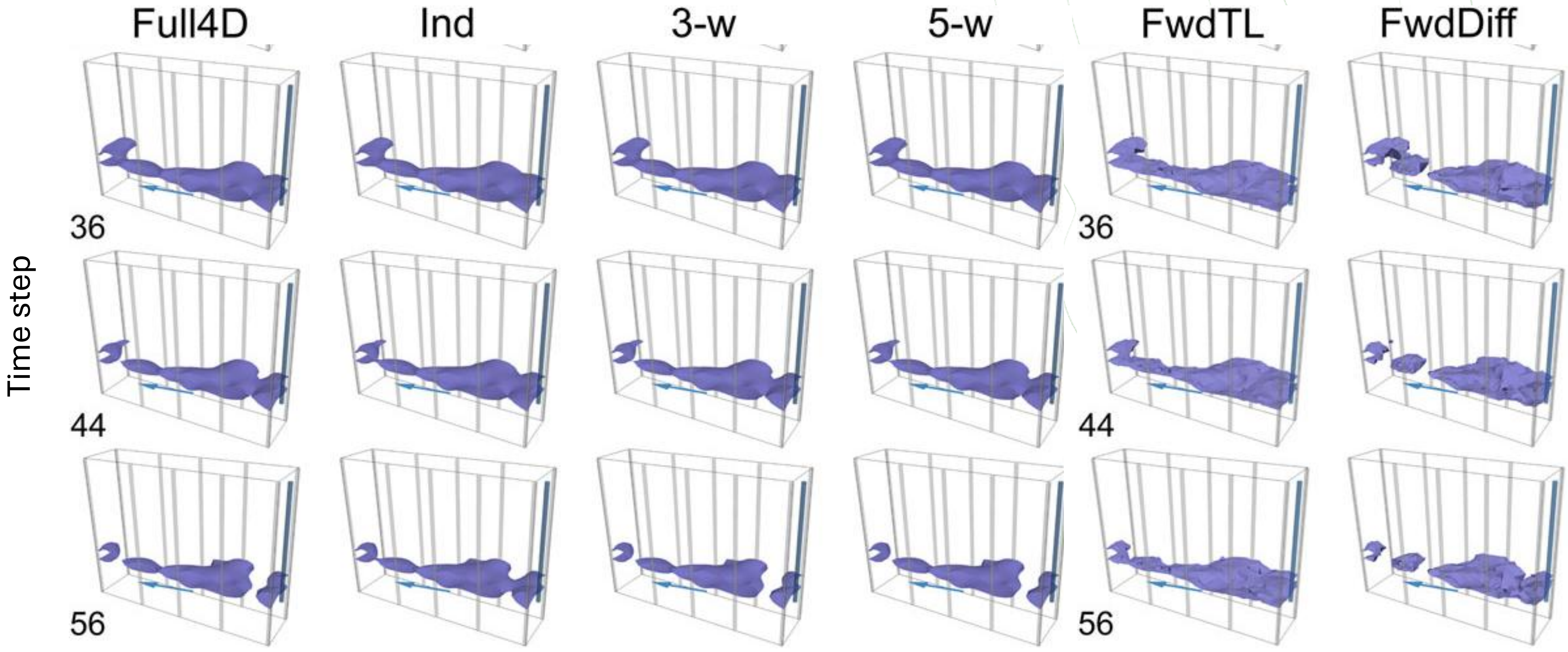


Timelapse-inversion strategies
Overview



Timelapse-inversion strategies

Overview



Timelapse-inversion strategies

Overview

Full 4D Inversion

- Invert the entire time series as one dataset
- Enables implementing true smoothness constraints across time
- Requires the entire data set to be acquired

Windowed 4D Inversion

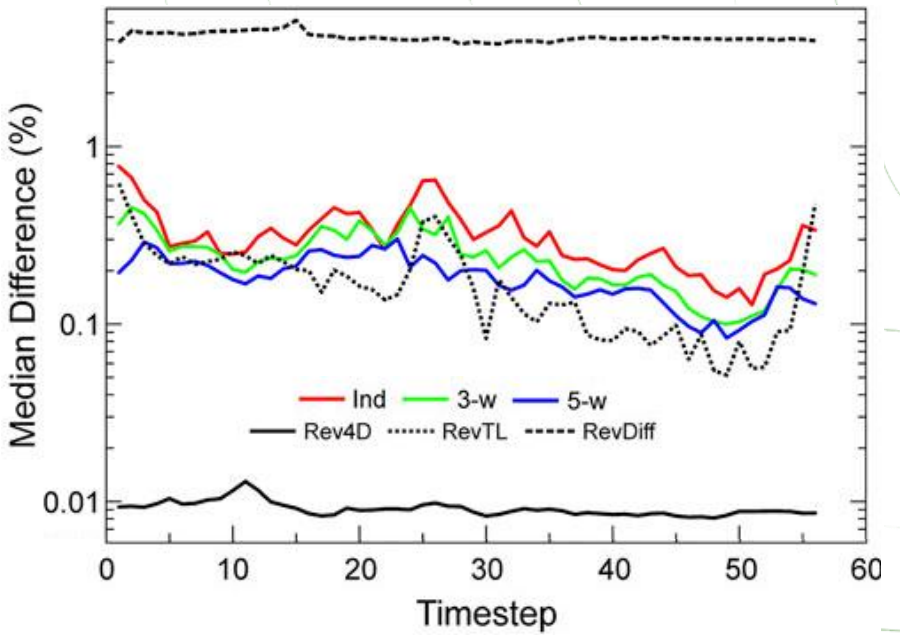
- Full 4D Inversion of data subsets
- Allows for near real-time results (no need for entire time series to be acquired)

Timelapse inversion

- Invert one timestep against a baseline
- Constraints to minimize the difference between two resistivity models

Difference inversion

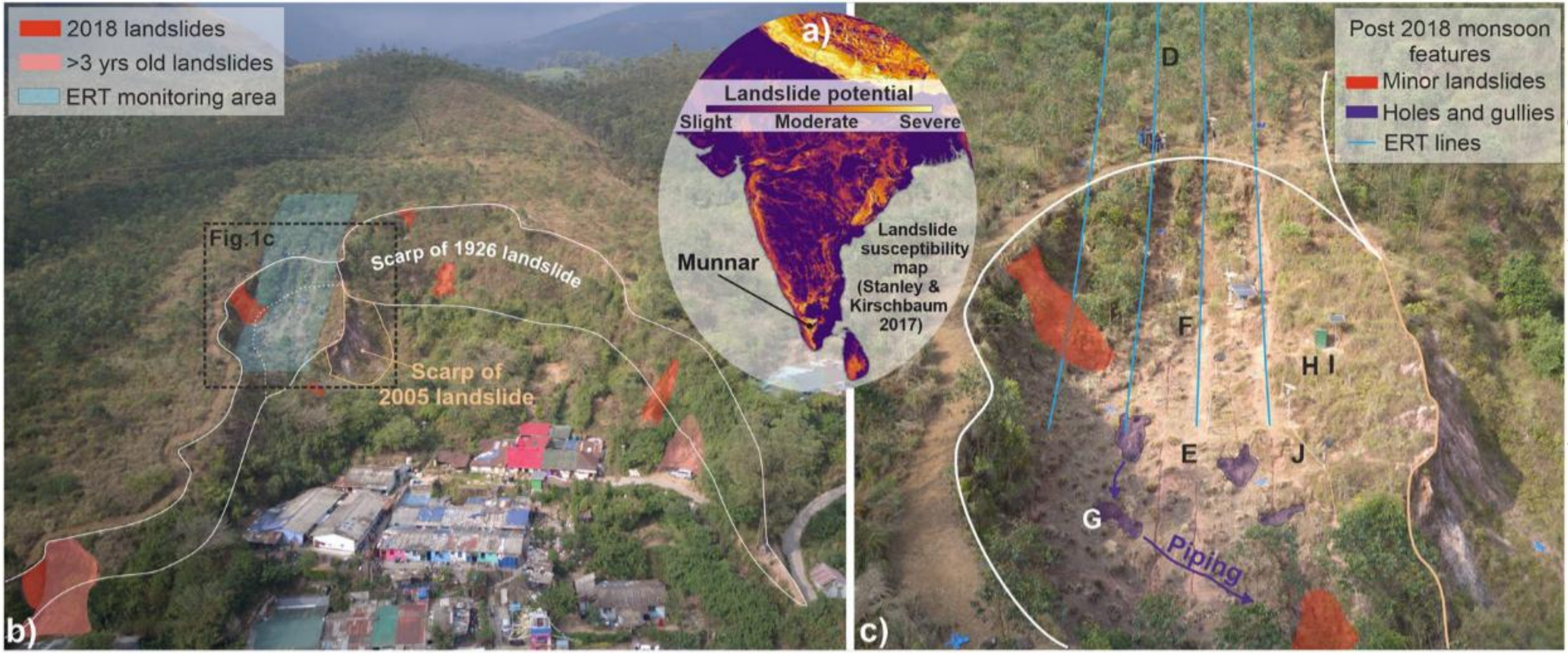
- Only invert for the differences in the acquired data
- Baseline: invert ρ_a → timesteps: invert $\Delta\rho_a$



- Full4D shows best performance
- Windowed and timelapse approach similar
- Difference inversion comparatively bad

Monitoring examples

Munnar landslide investigation

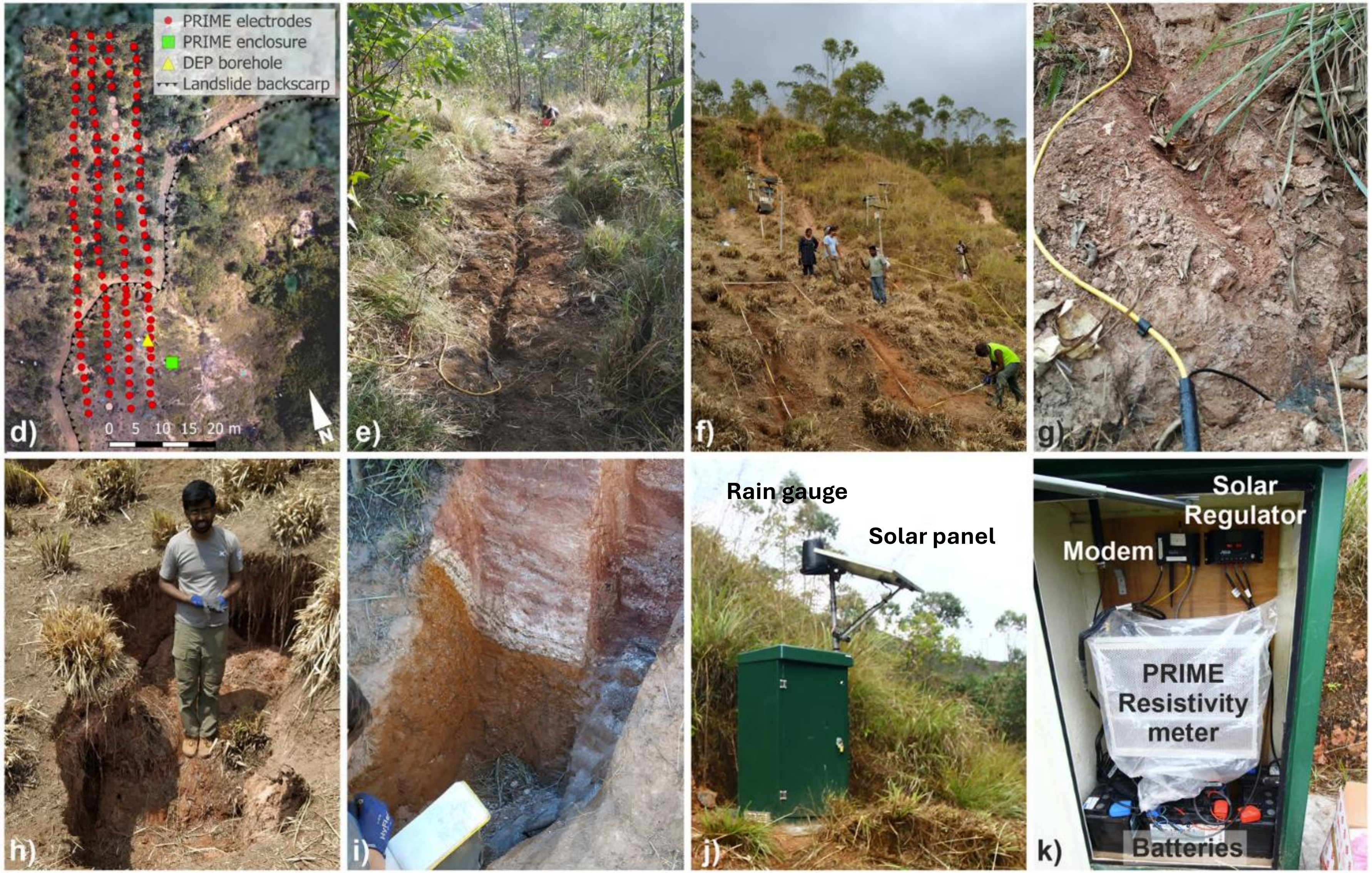


Monitoring examples

Munnar landslide investigation

Above backscarp **Within landslide**

„Dissolution“ cracks



Monitoring examples

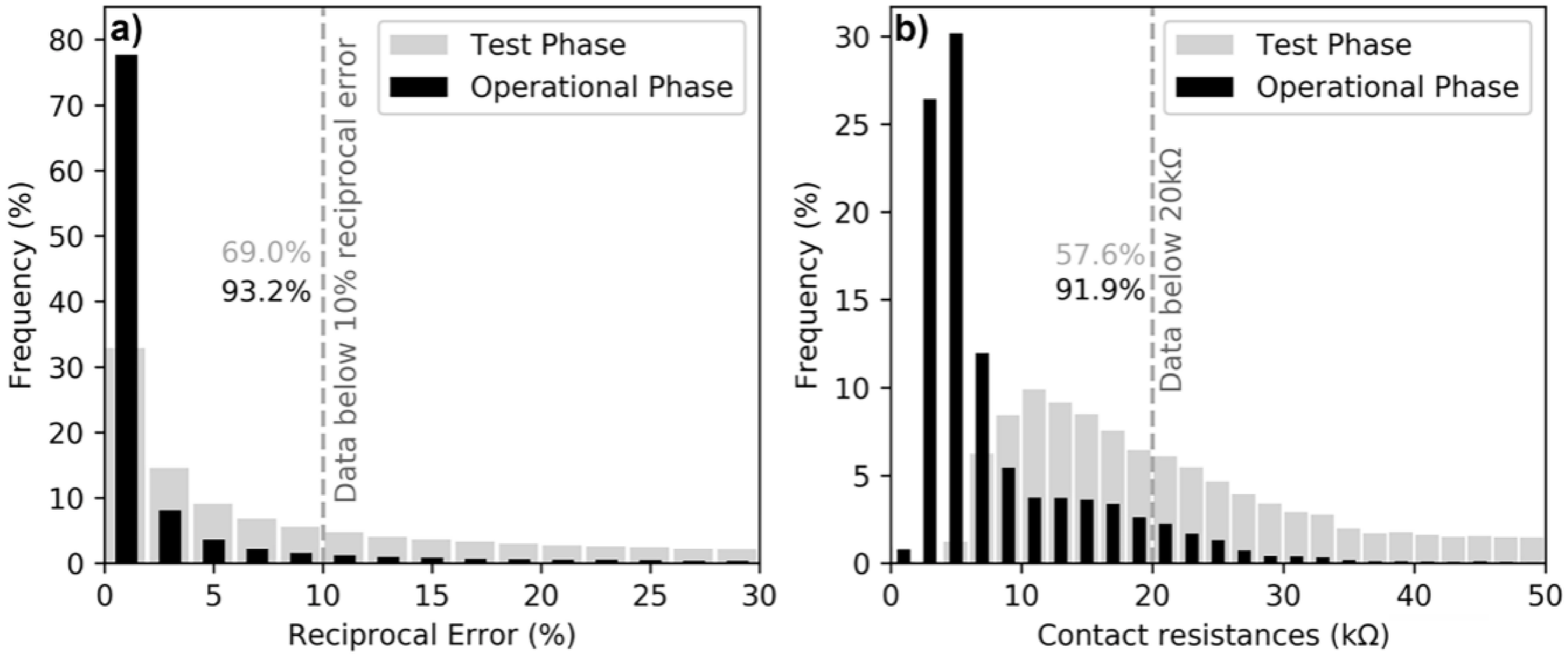
Munnar landslide investigation

Electrodes initially deployed in soil

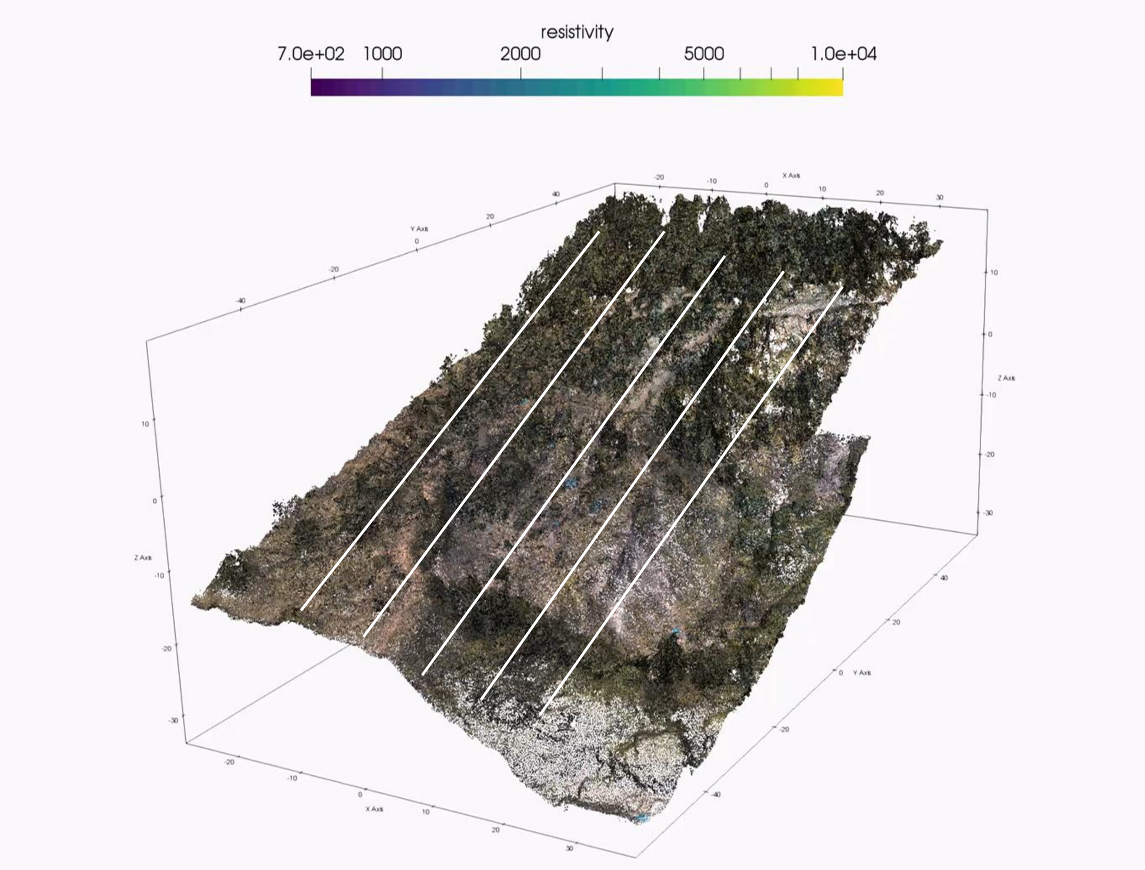
Tropical soil tends to be depleted of clay minerals

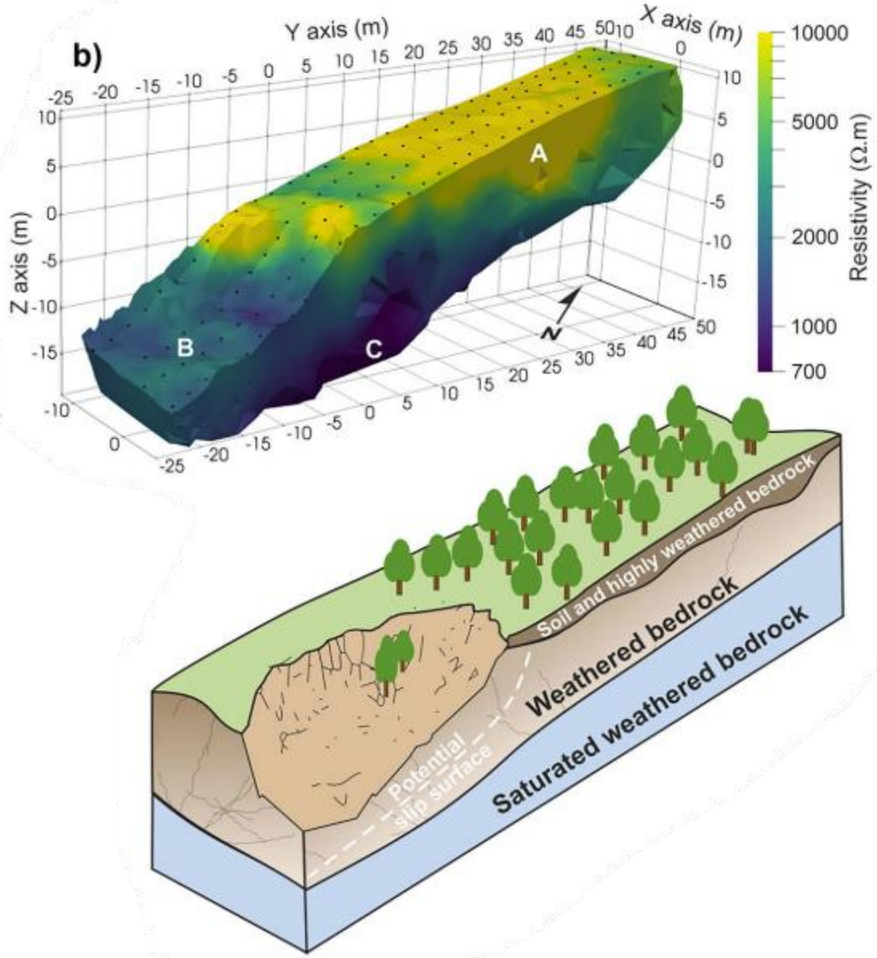
→ Very high contact resistances

During operational phase, electrodes installed in conductive graphite paste



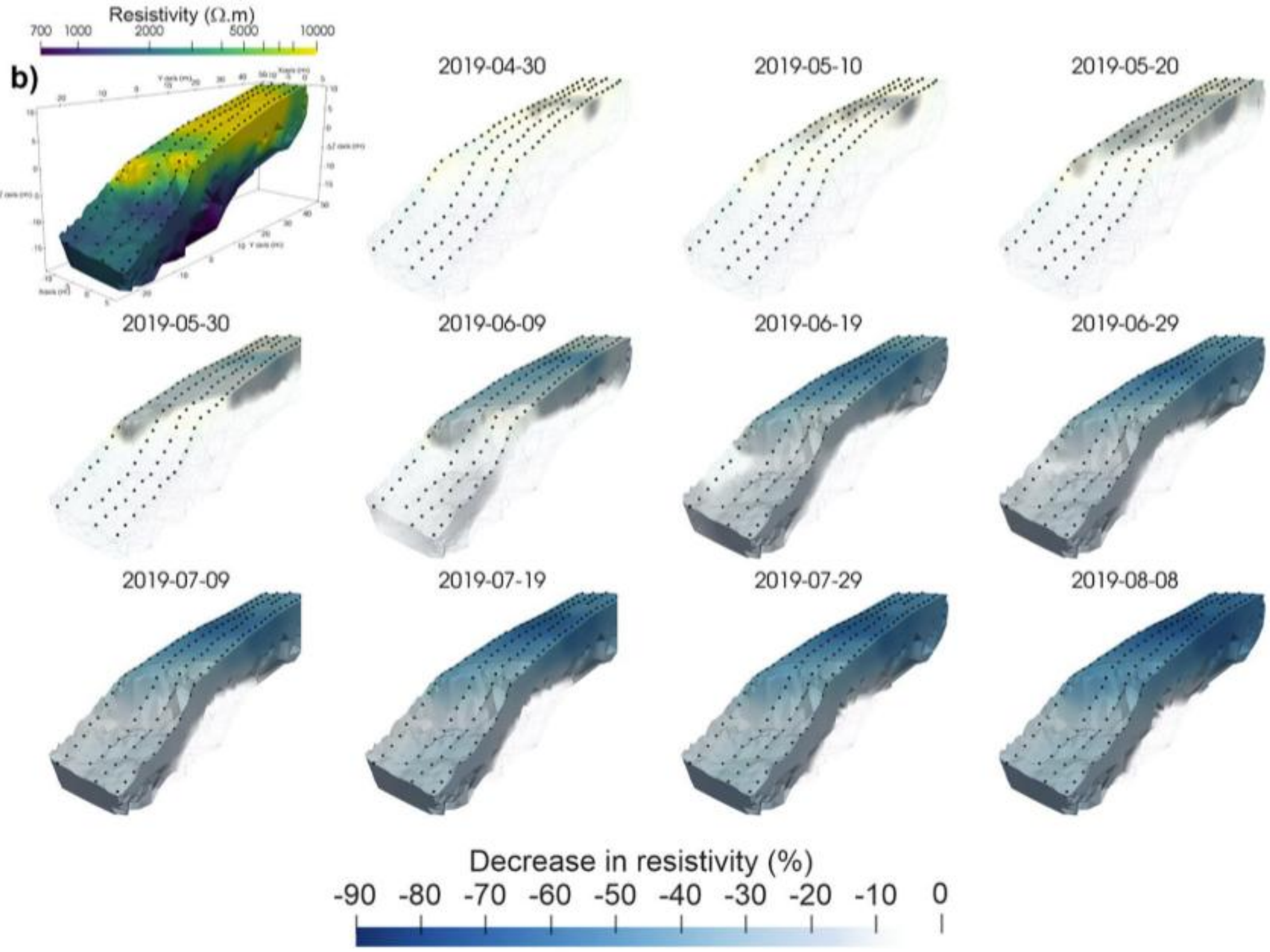
Monitoring examples
Munnar landslide investigation

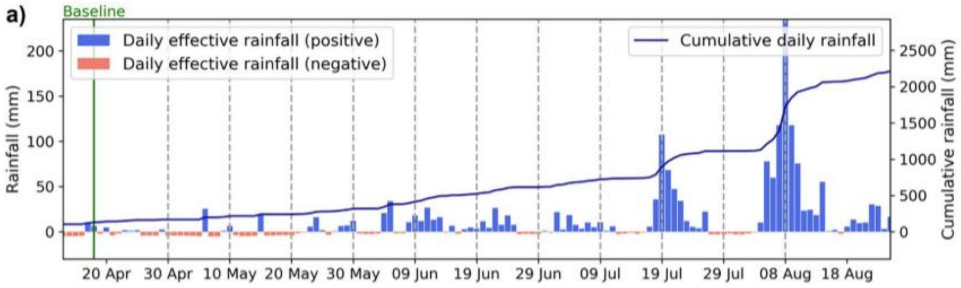




Monitoring examples

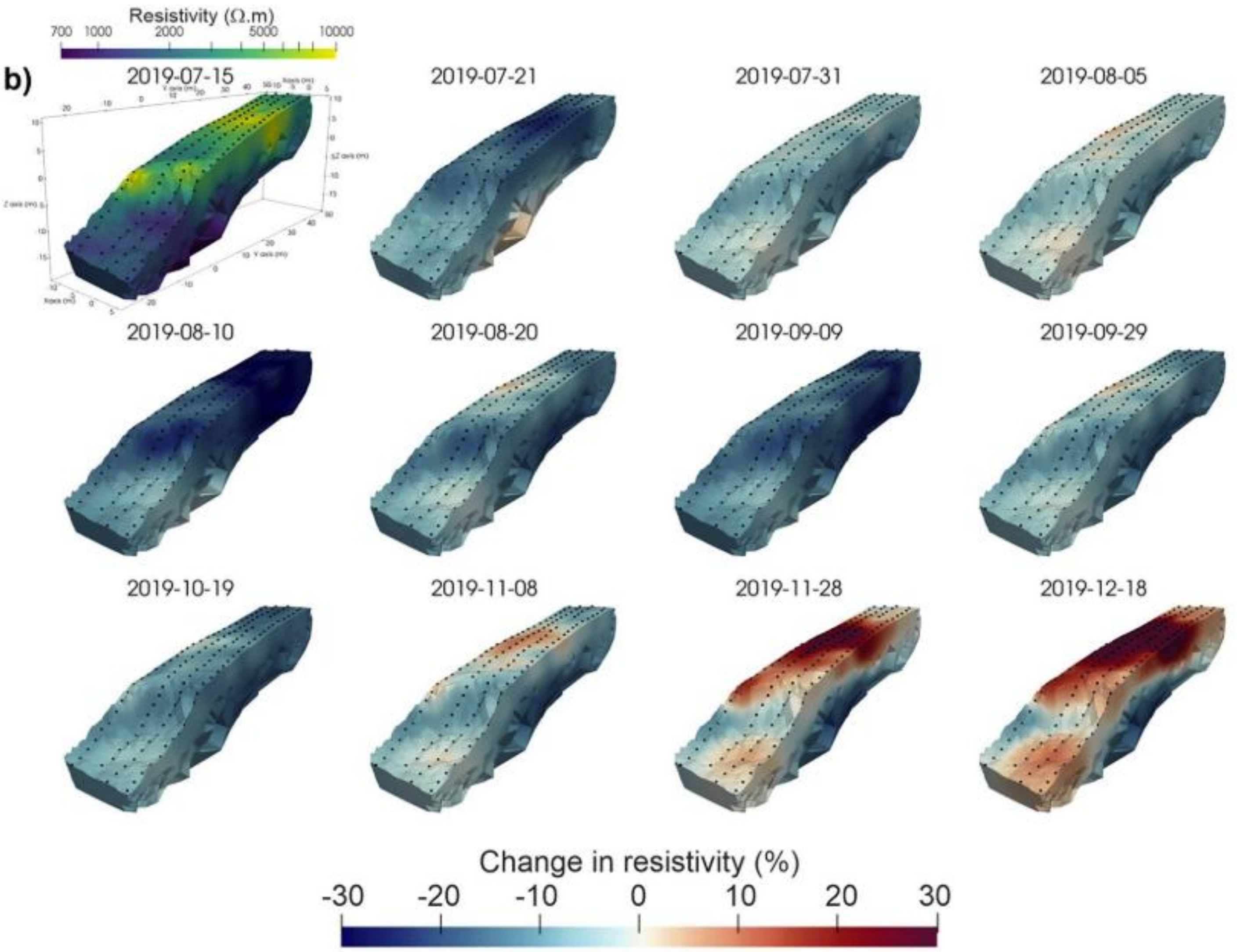
Munnar landslide investigation

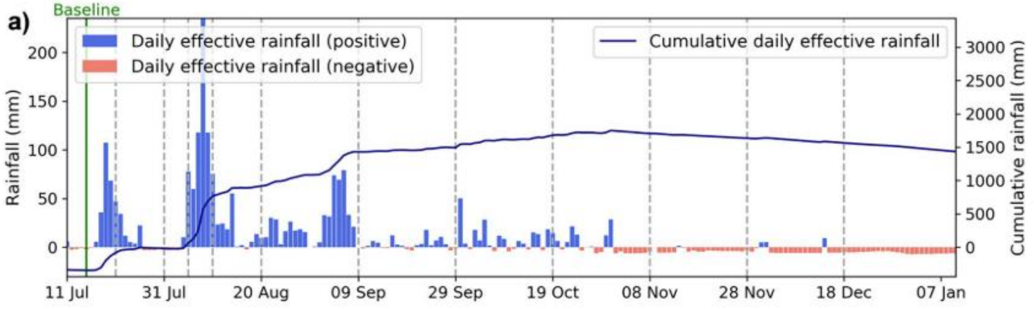




Monitoring examples

Munnar landslide investigation



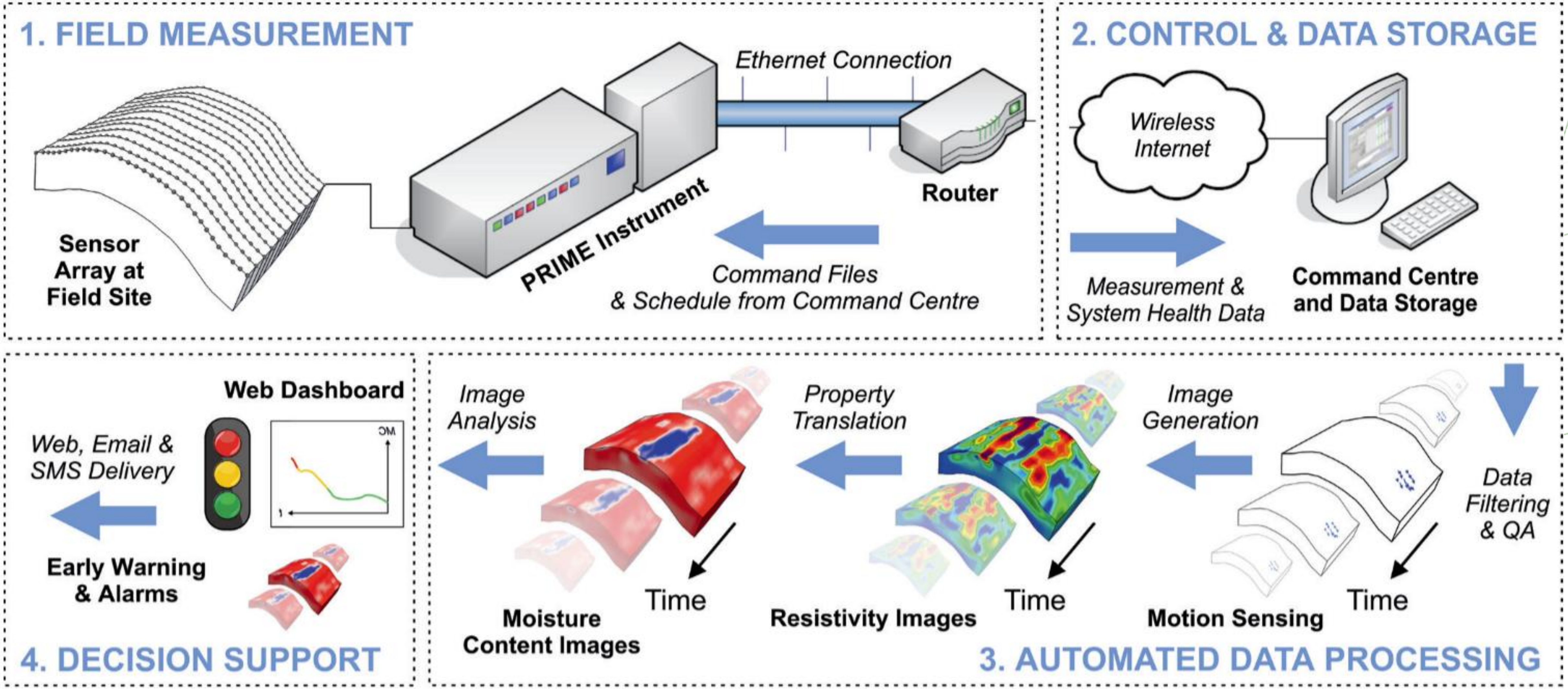


Geoelectrical monitoring shows pronounced wetting and drying patterns

Particularly above recent landslide domain
→ Increased weathering

High moisture levels reach depth of recent slip surface

Monitoring examples
Automated monitoring workflows



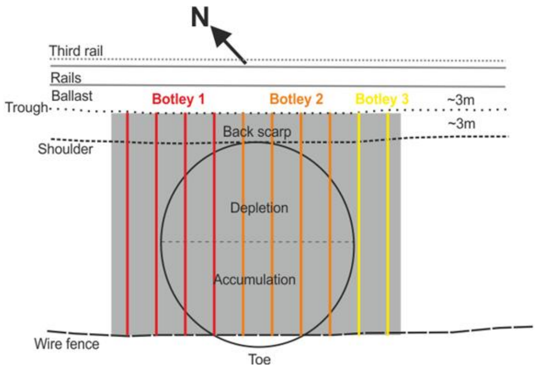
Monitoring examples

Monitoring the stability of railway infrastructure

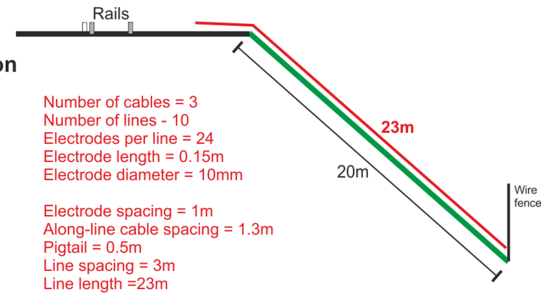
ITINERIS

Site Install

Plan



Section



Completed 4 - 5 days

Minimally invasive

NO Line block in place

Monitoring examples

Monitoring the stability of railway infrastructure

Railway embankment with a history of instability up to the present day

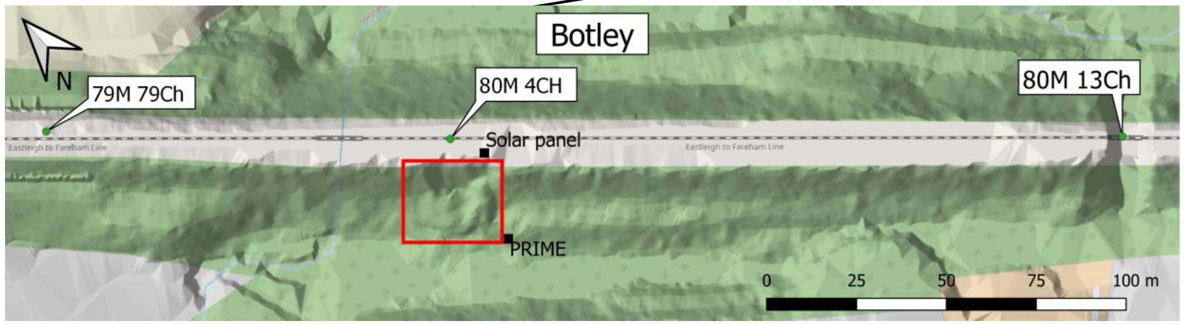
Located on major UK rail line

Botley

Local rotational failure (London Clay)

Purpose of monitoring:

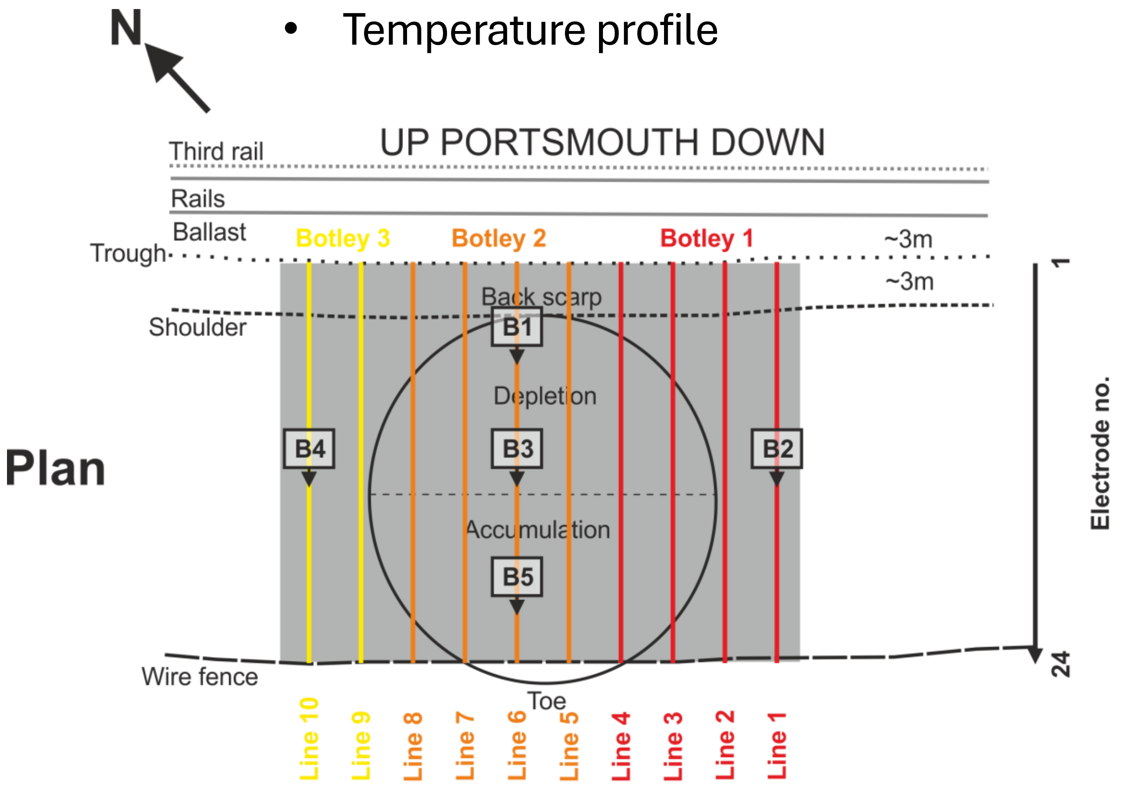
- 10s m scale
- 3D visualisation
- Moisture processes
- Electrode movements
- Increased chance of failure

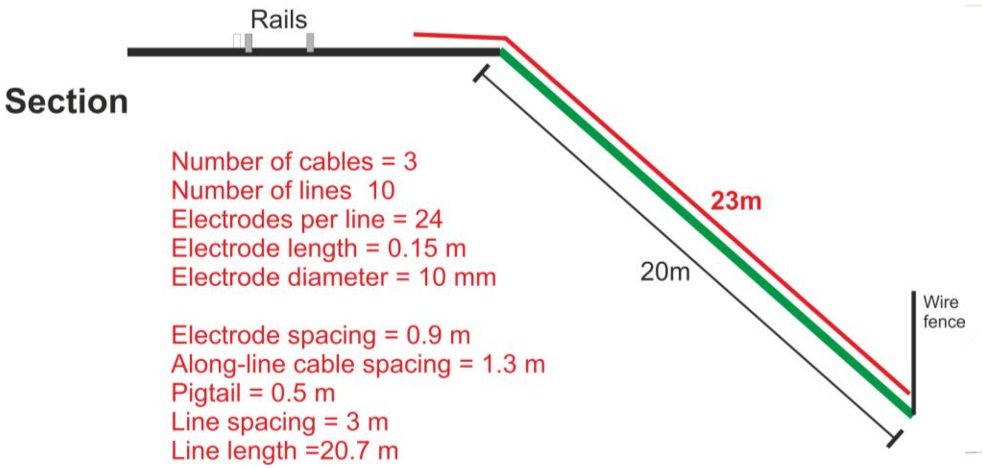


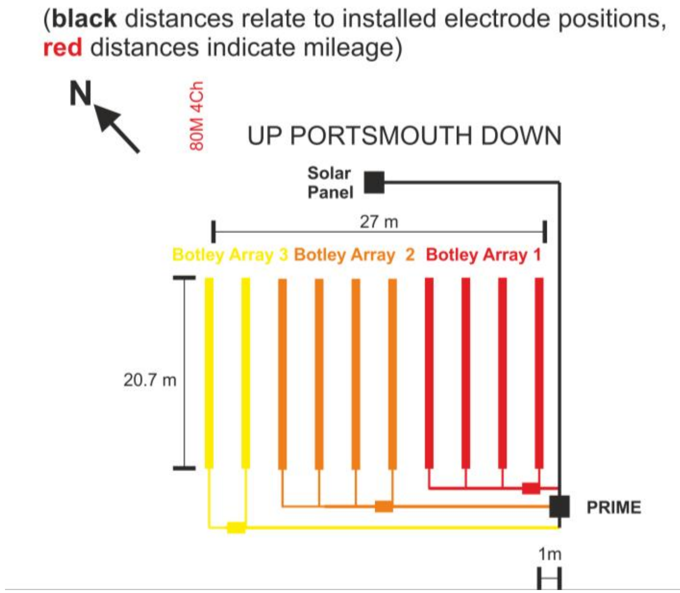
Monitoring examples

Monitoring the stability of railway infrastructure

- Grid of 10 ERT lines (20.7 x 27 m = ~560 m^2)
- 240 electrodes (24 per line)
- 5 clusters of geotechnical - hydrological sensors:
  - Tiltmeters, moisture and suction sensors
  - Temperature profile



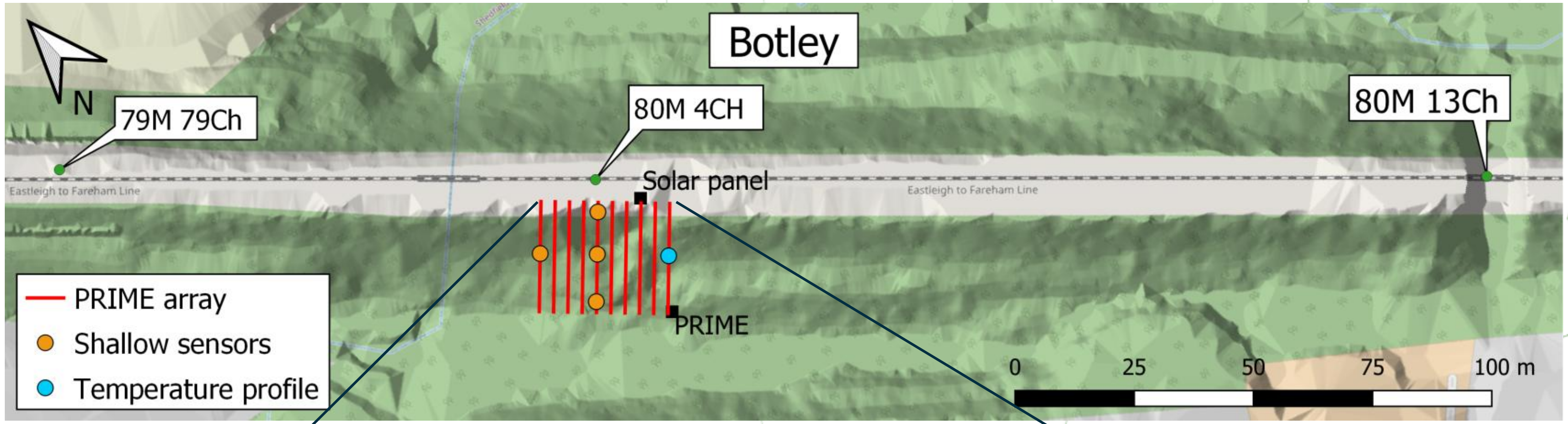


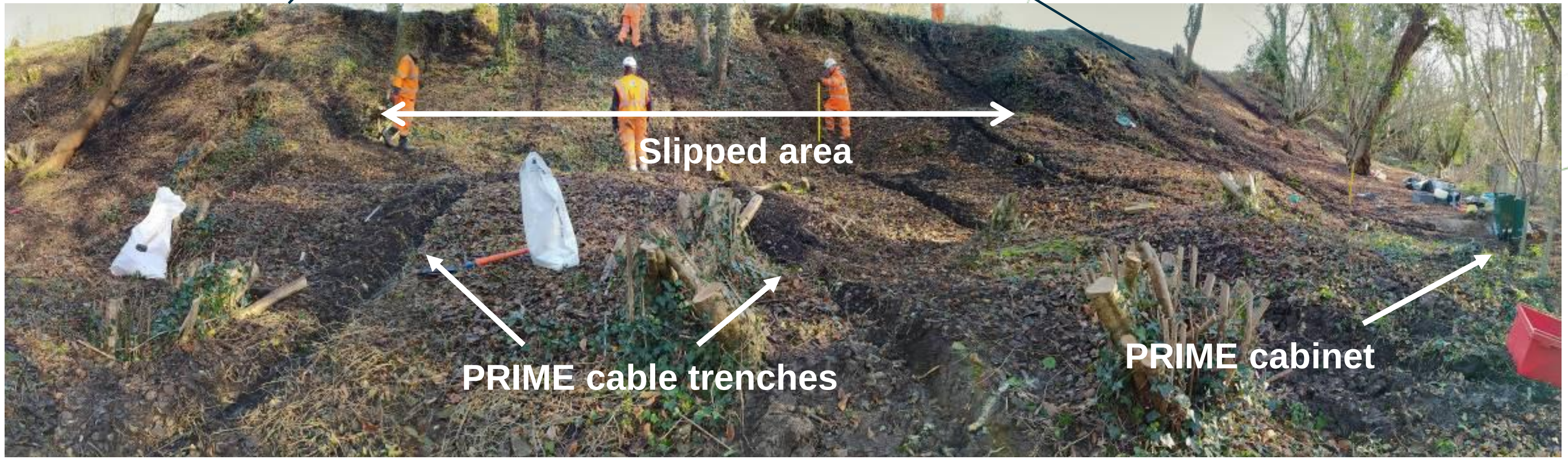


Monitoring examples

Monitoring the stability of railway infrastructure

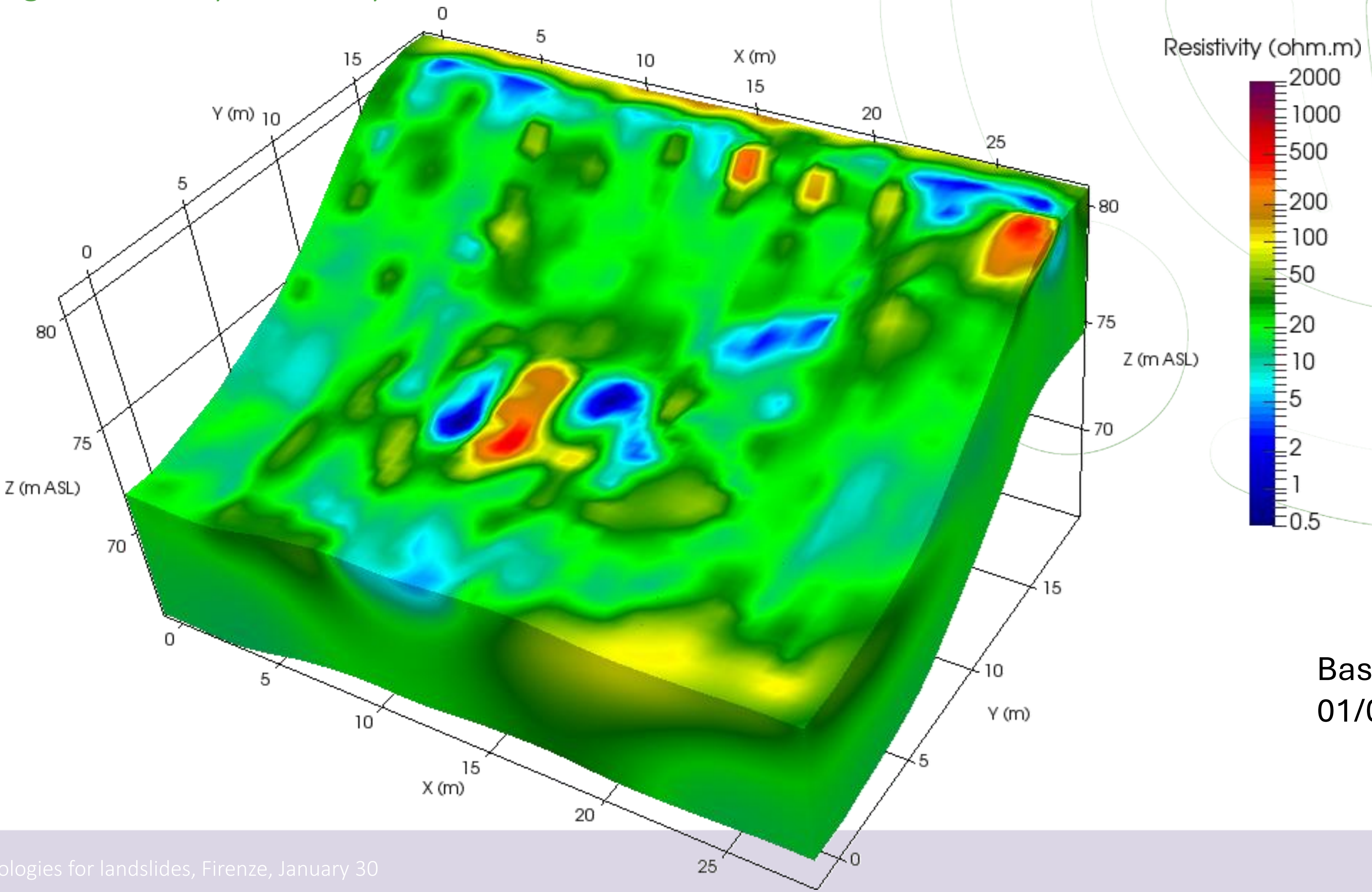
5 days
~2 NR staff
~5 Socotec staff
~3 BGS staff





Including total station survey of electrode positions (to be completed at regular intervals)

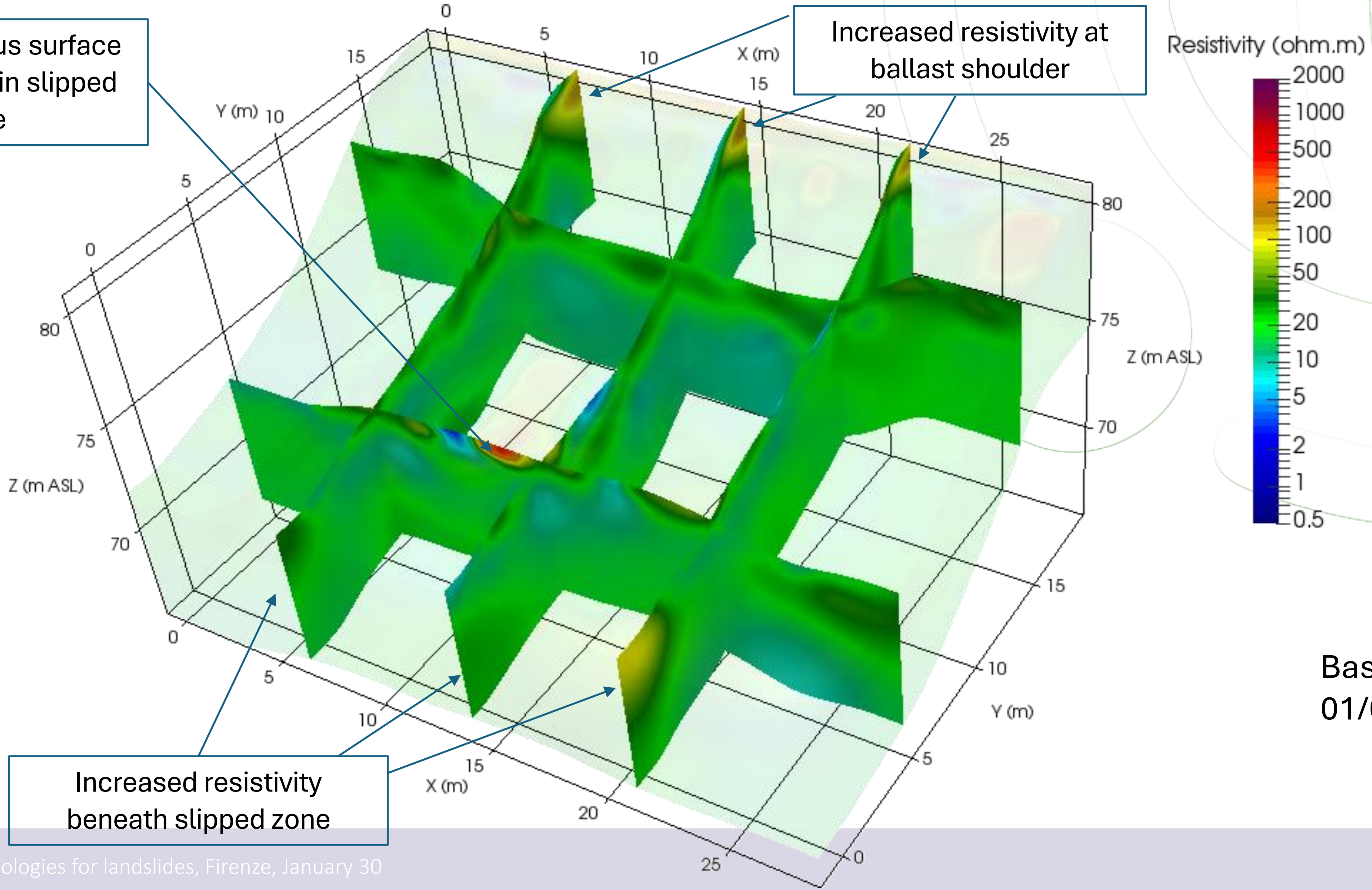
Monitoring examples
Monitoring the stability of railway infrastructure



Baseline model:
01/01/2021

Monitoring examples

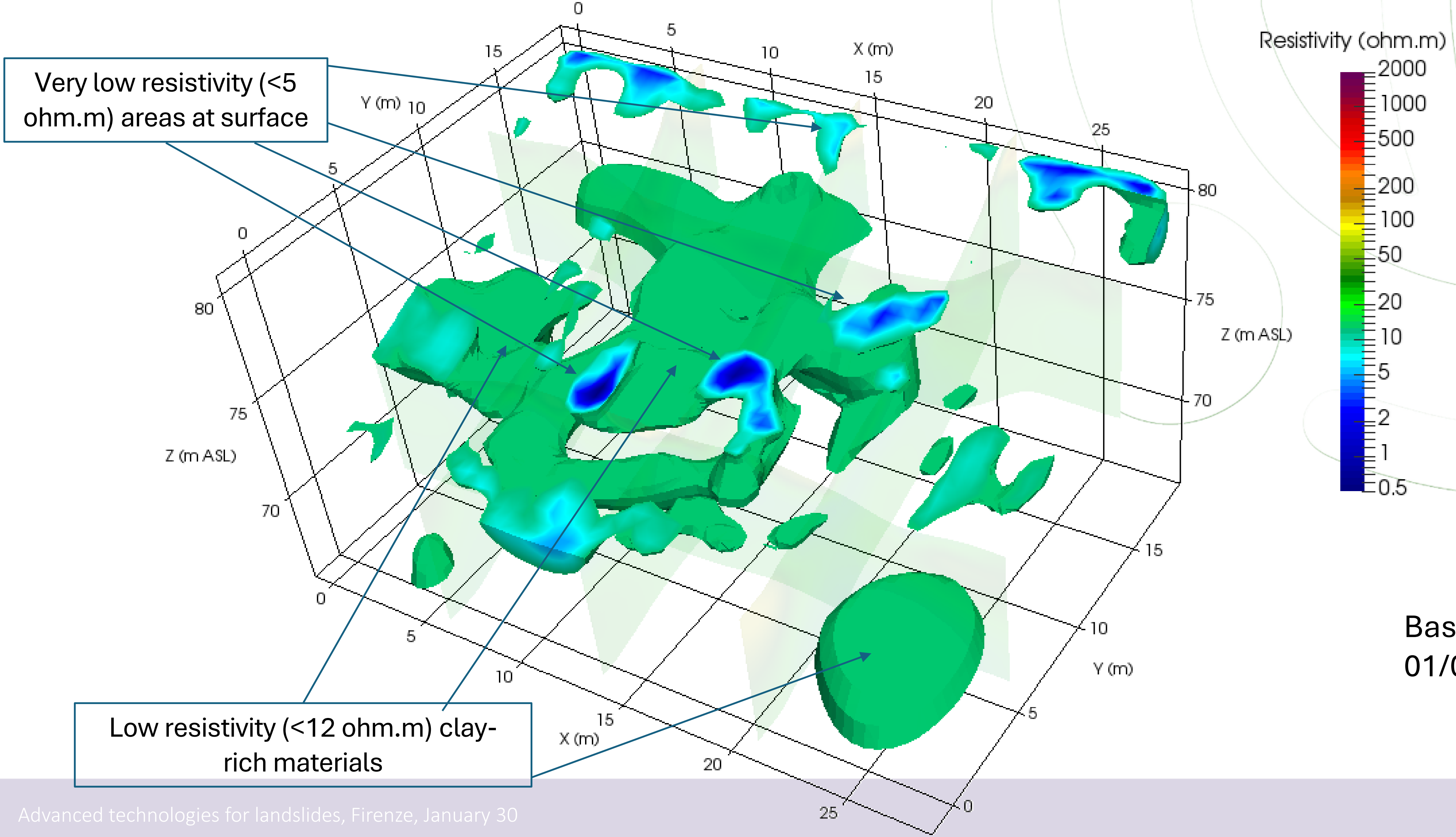
Monitoring the stability of railway infrastructure



Baseline model:
01/01/2021

Monitoring examples

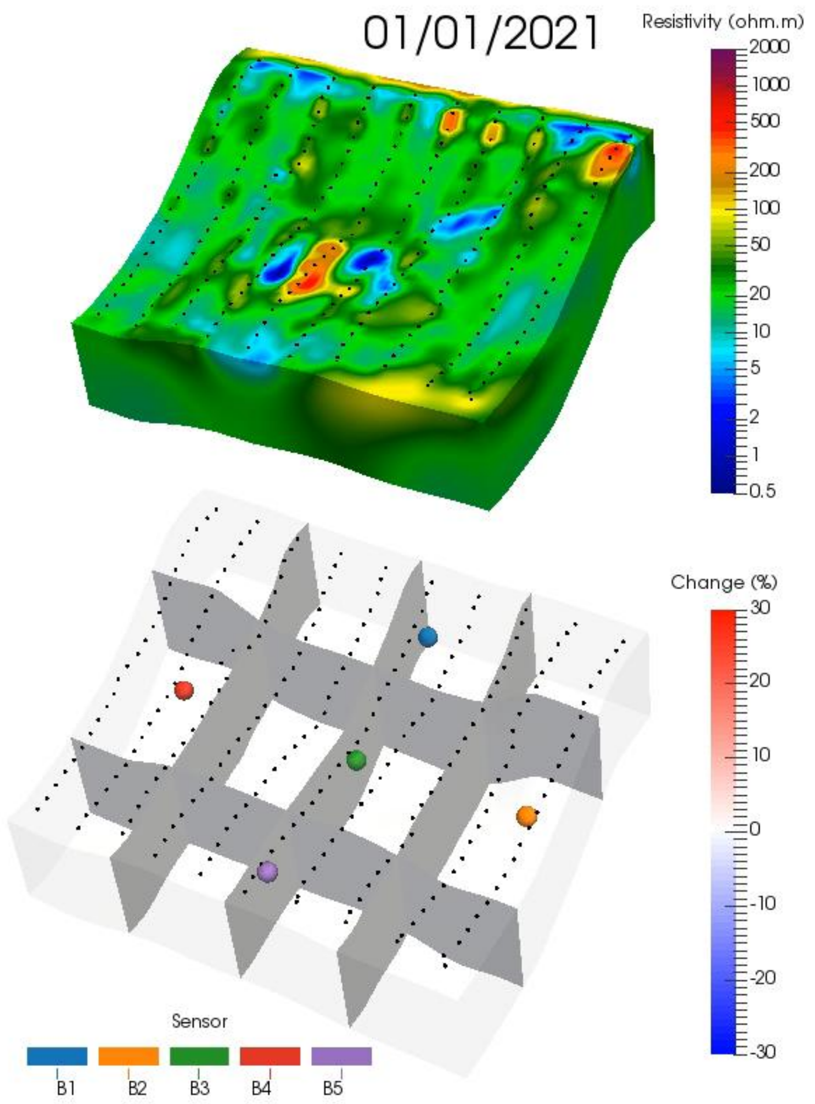
Monitoring the stability of railway infrastructure

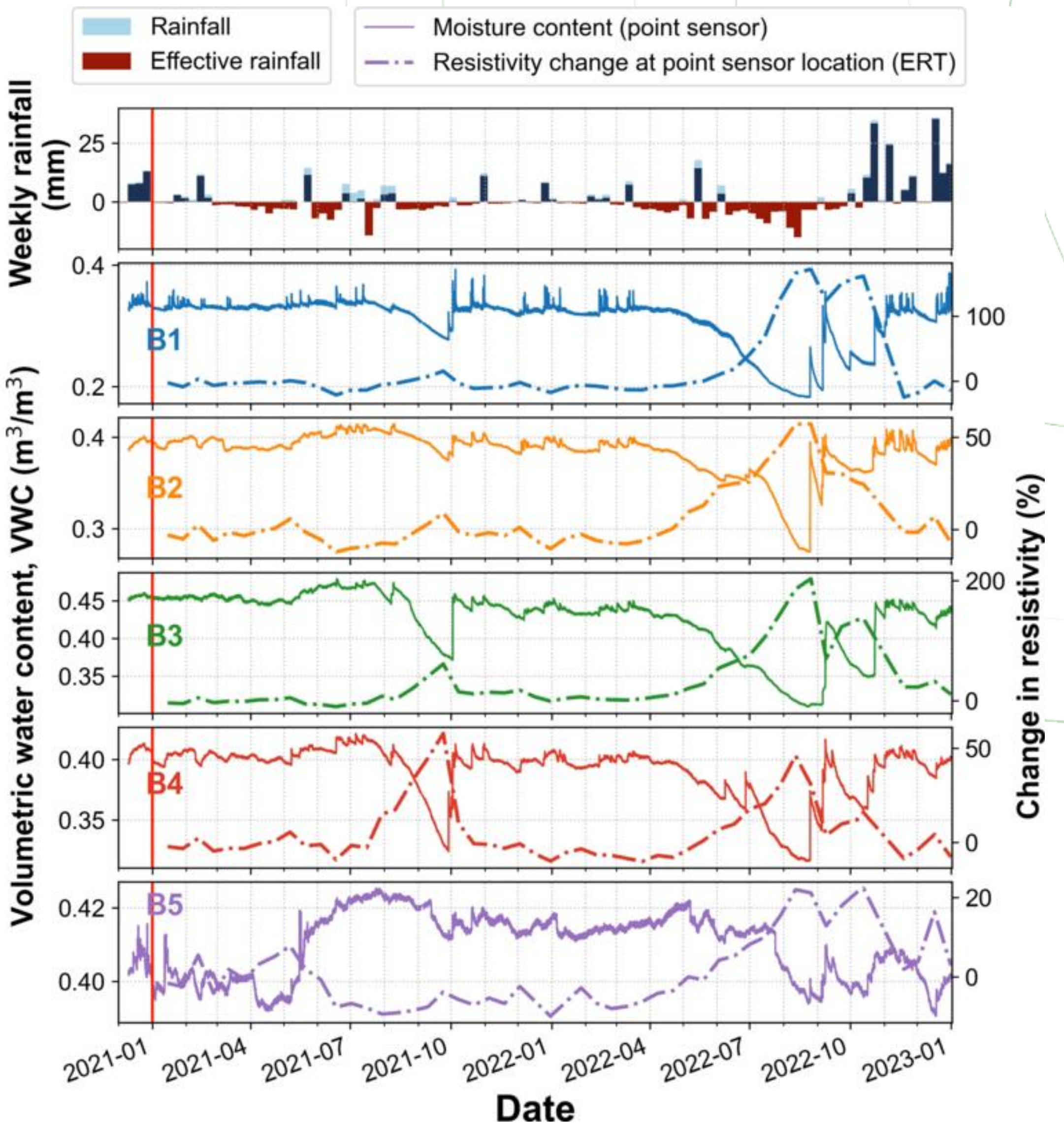


Baseline model: 01/01/2021

Monitoring examples

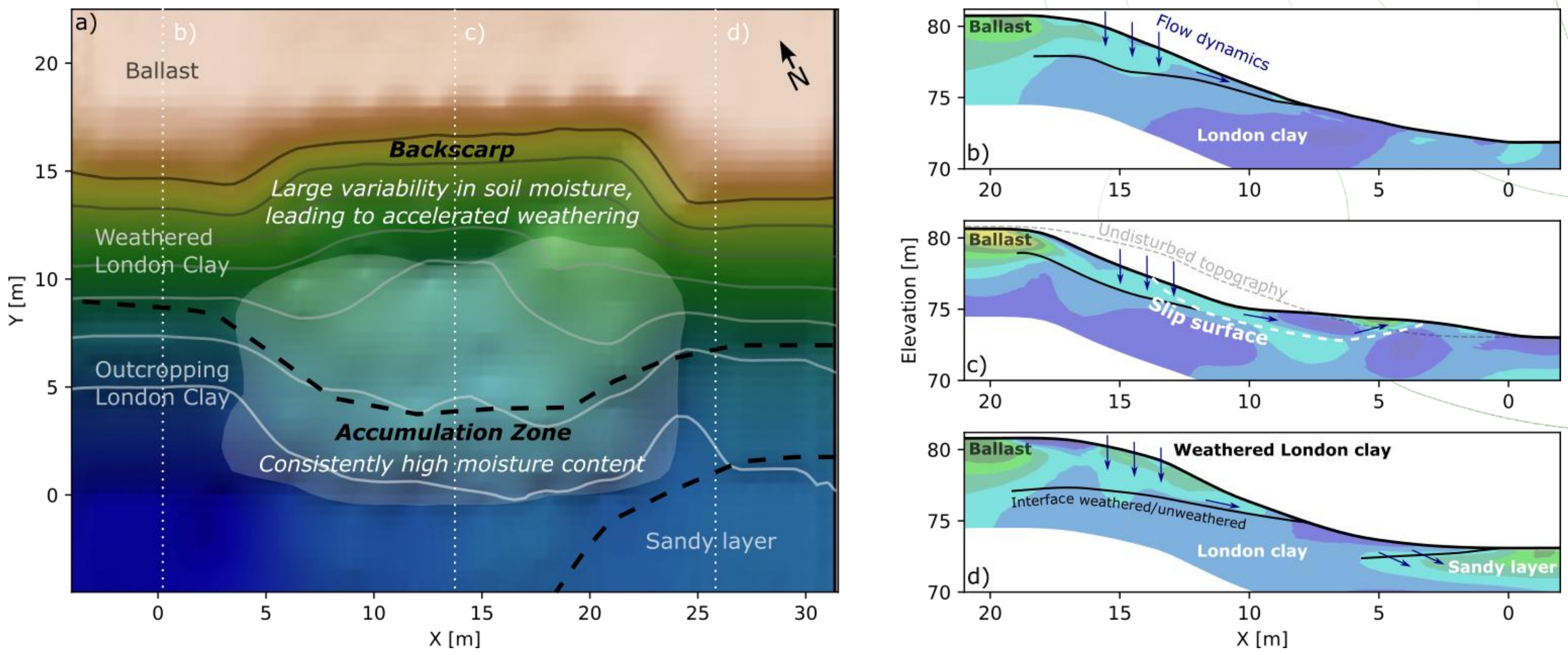
Monitoring the stability of railway infrastructure





Monitoring examples

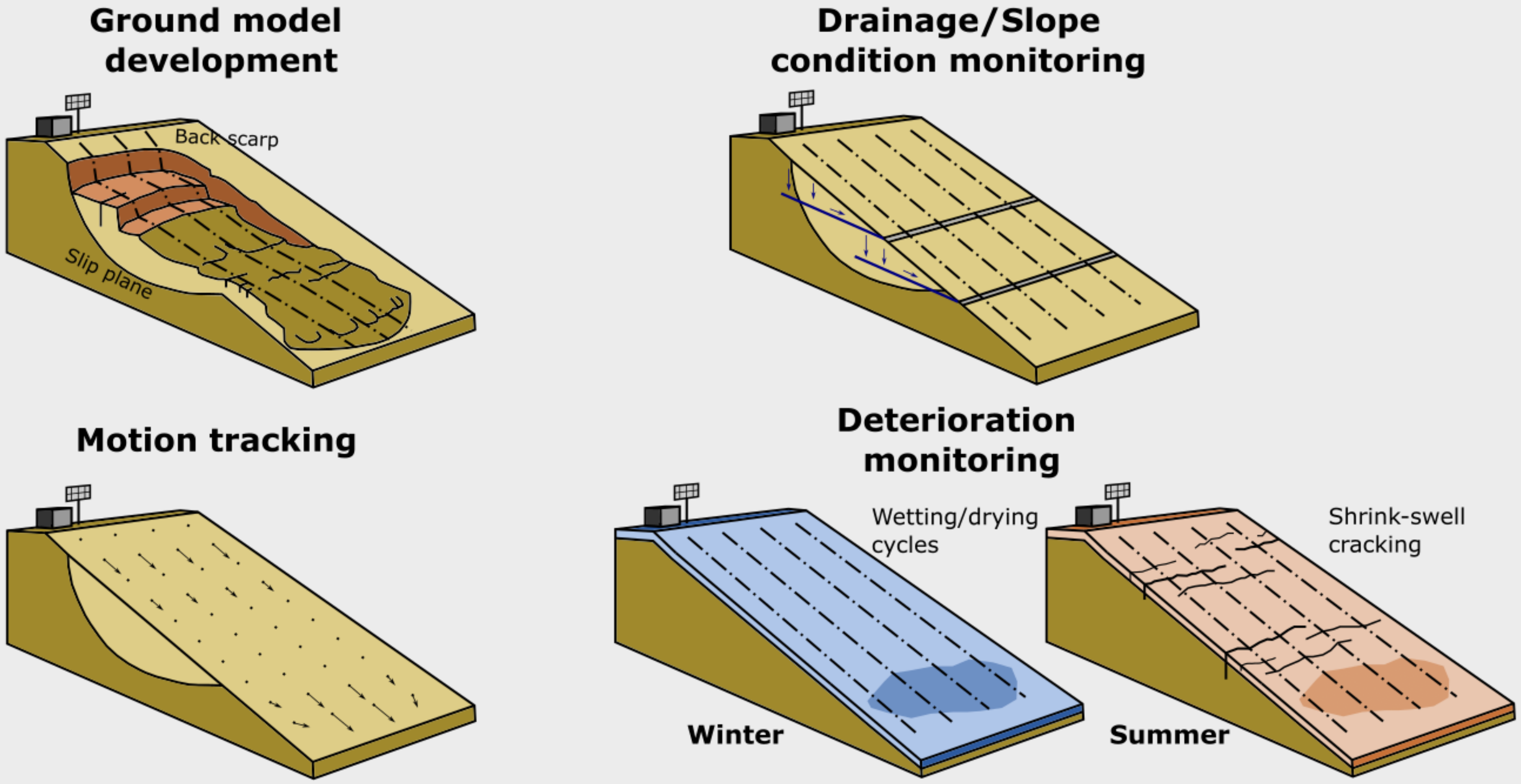
Monitoring the stability of railway infrastructure

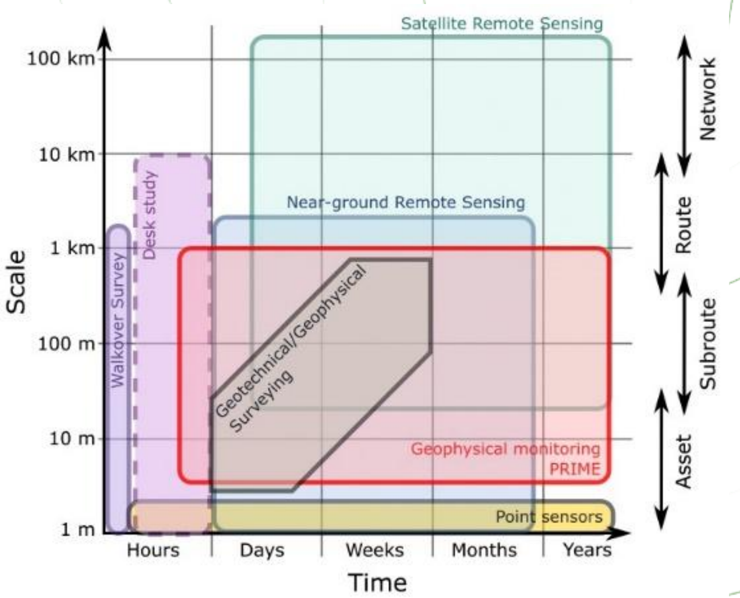


Monitoring examples

Monitoring the stability of railway infrastructure

Geoelectrical monitoring





ITINERIS

THANKS!

IR0000032 – ITINERIS, Italian Integrated Environmental Research Infrastructures System
(D.D. n. 130/2022 - CUP B53C22002150006) Funded by EU - Next Generation EU PNRR-Mission 4 "Education and Research" - Component 2: "From research to business" - Investment 3.1: "Fund for the realisation of an integrated system of research and innovation infrastructures"

Finanziato dall'Unione europea NextGenerationEU

Ministero dell'Università e della Ricerca

Italiadomani