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Ground and airborne geophysical characterization

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”

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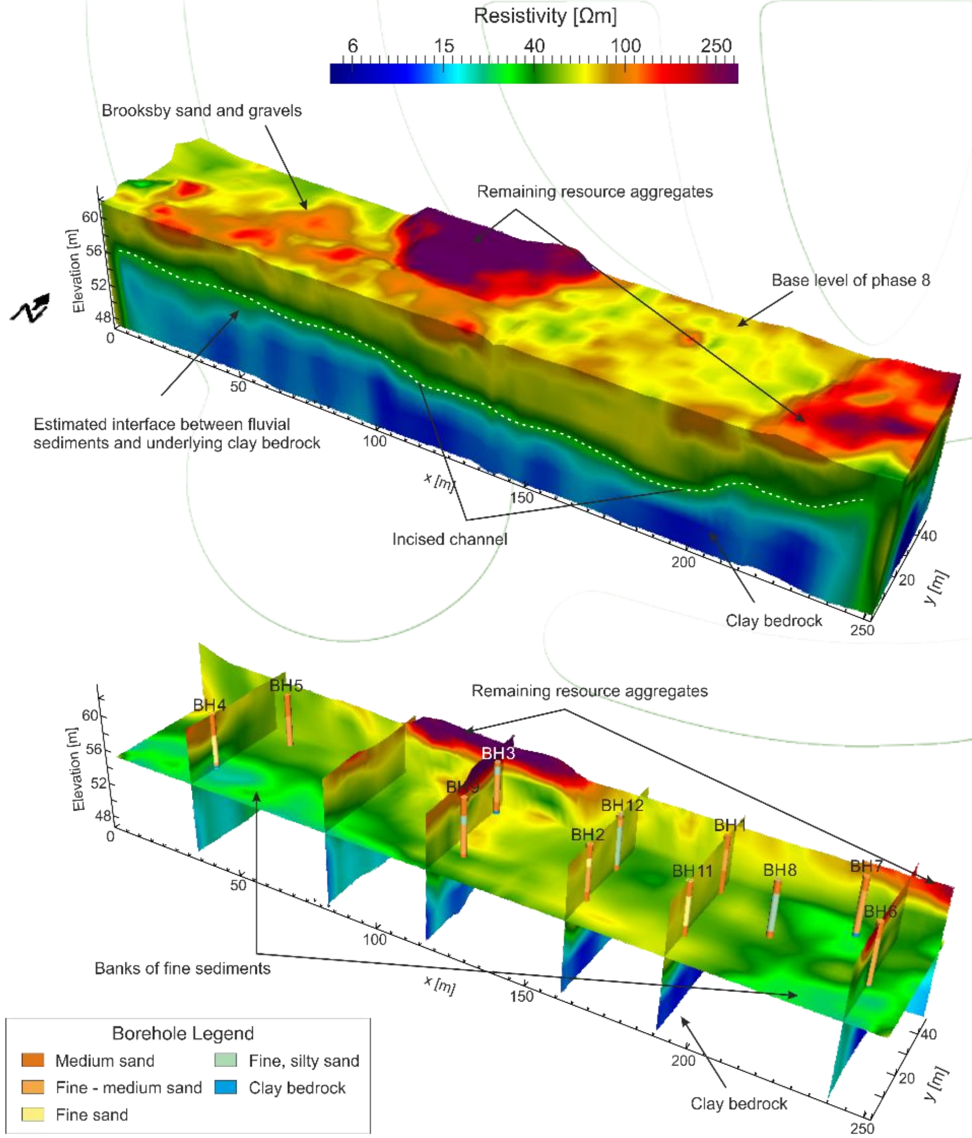
Outline of the day

- **Fundamentals of electrical resistivity measurements**
  - Electrical properties of soils and rocks
  - Translating geoelectrical data into hydrogeomechanical properties
- **Principles of Electrical Resistivity and Electromagnetic Measurements**
  - Applications to ground and airborne geophysical characterization
- **Geoelectrical monitoring: Principles and applications**
  - Inversion approaches, practical considerations
  - Monitoring applications
- **Machine Learning for exploiting and assimilating environmental data**

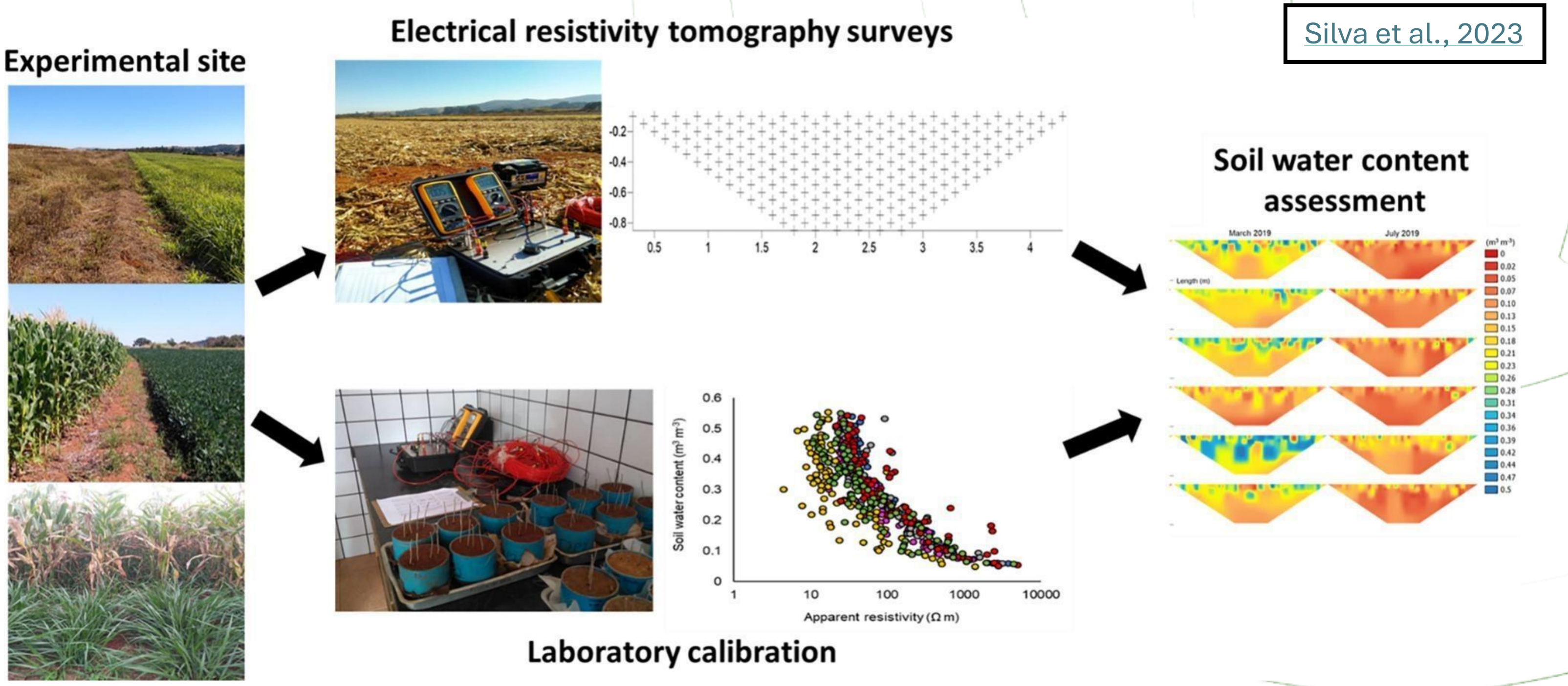


Why electrical and electromagnetic methods?

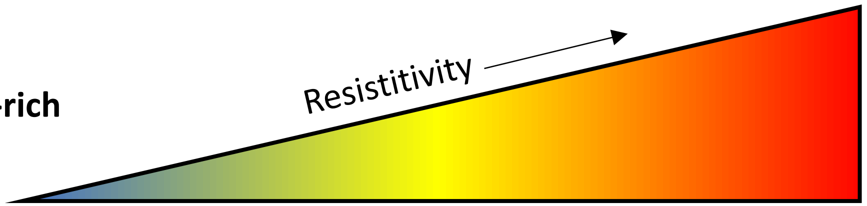
Silva et al., 2023

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

Electrical and electromagnetic methods

Different methods to measure the electro(magnetic) properties

4 different types of measurements to measure electrical and electromagnetic properties of Earth materials:

Geoelectrics: Changes in electrical resistance or conductivity (the reciprocal of resistivity) are measured by generating an electric current that flows through the soil using connected electrodes.

Electromagnetics (EM) respond to almost the same targets as geoelectrics, but they use time-varying electromagnetic fields rather than electrodes in the ground. This enables, for example, use from the air.

Magnetotellurics (MT) uses naturally induced currents (e.g. thunderstorms) whose propagation is measured by EM and resistance methods. This means that the results go much deeper than EM and geoelectrics.

Ground Penetrating Radar (GPR) records radar waves - a type of electromagnetic wave - that are reflected from surfaces and provide a more direct picture of the subsurface - similar to reflection seismology. However, it is usually limited to the uppermost meters of the ground.

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Ground-based Exploration

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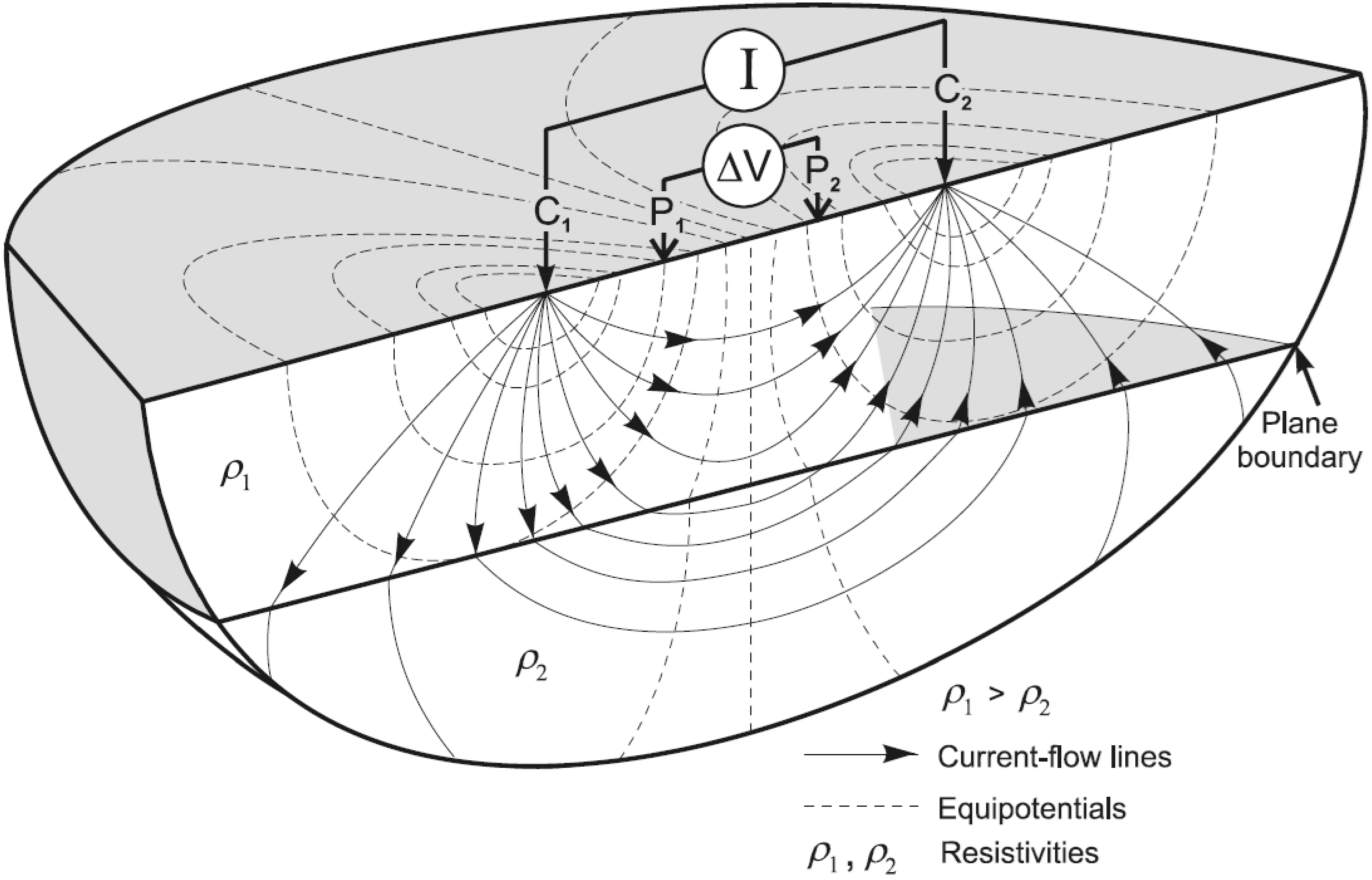
Electrical resistivity

Measurement principle



Electrical resistivity

Measurement principle

Ohm's Law describes the electrical potential:

$$\Delta \boldsymbol{V} = \boldsymbol{IR}$$

Electrical resistance *R* depends on

- resistivity of the ground ρ

  and

- the geometry of the electrodes (geometric factor *K*)

  Resistance [Ω]: $R = \rho / K$

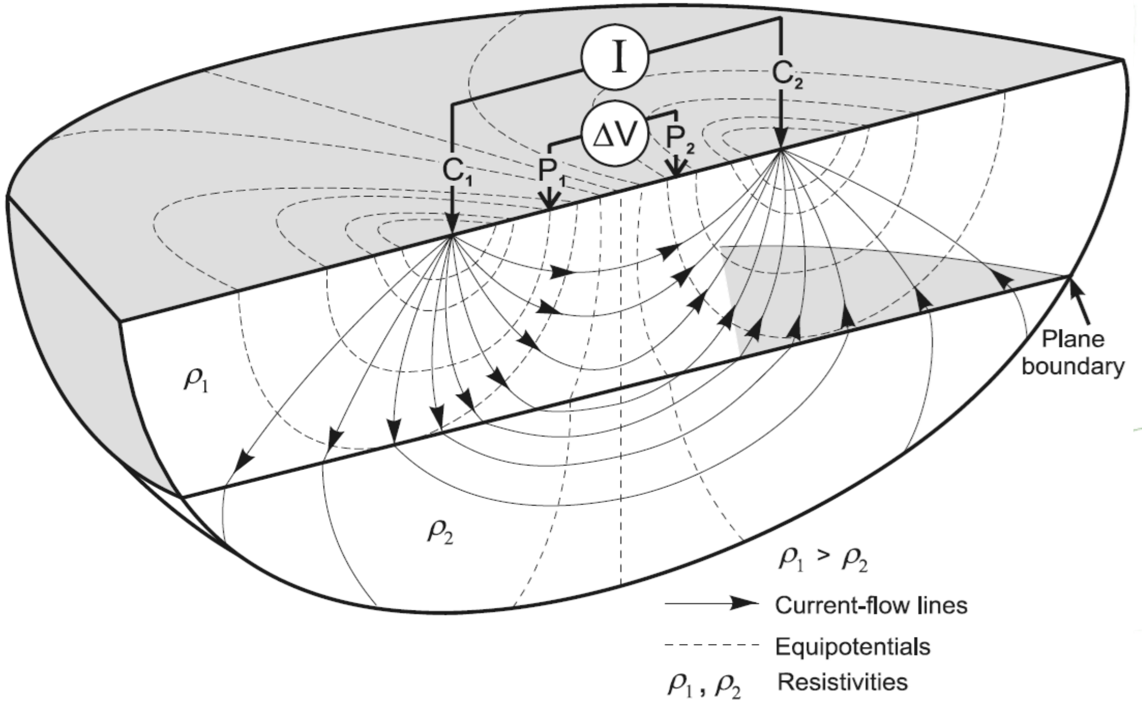
  Resistivity [Ωm]: $\rho = K\ R = K\frac{\Delta V}{I}$

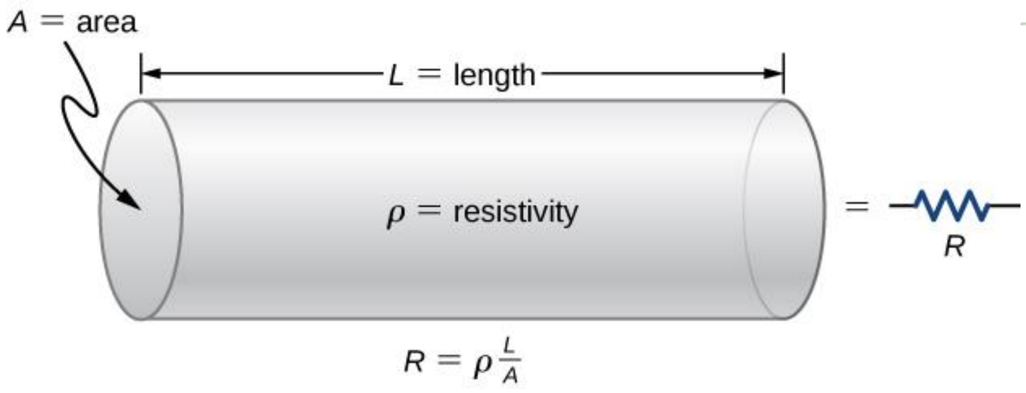
- **Units are important!** *R* has units of [Ω] (ohms), *K* has units of [m] (metres), ρ has units of Ωm (ohm-metres)

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

$$\sigma = 1/\rho$$

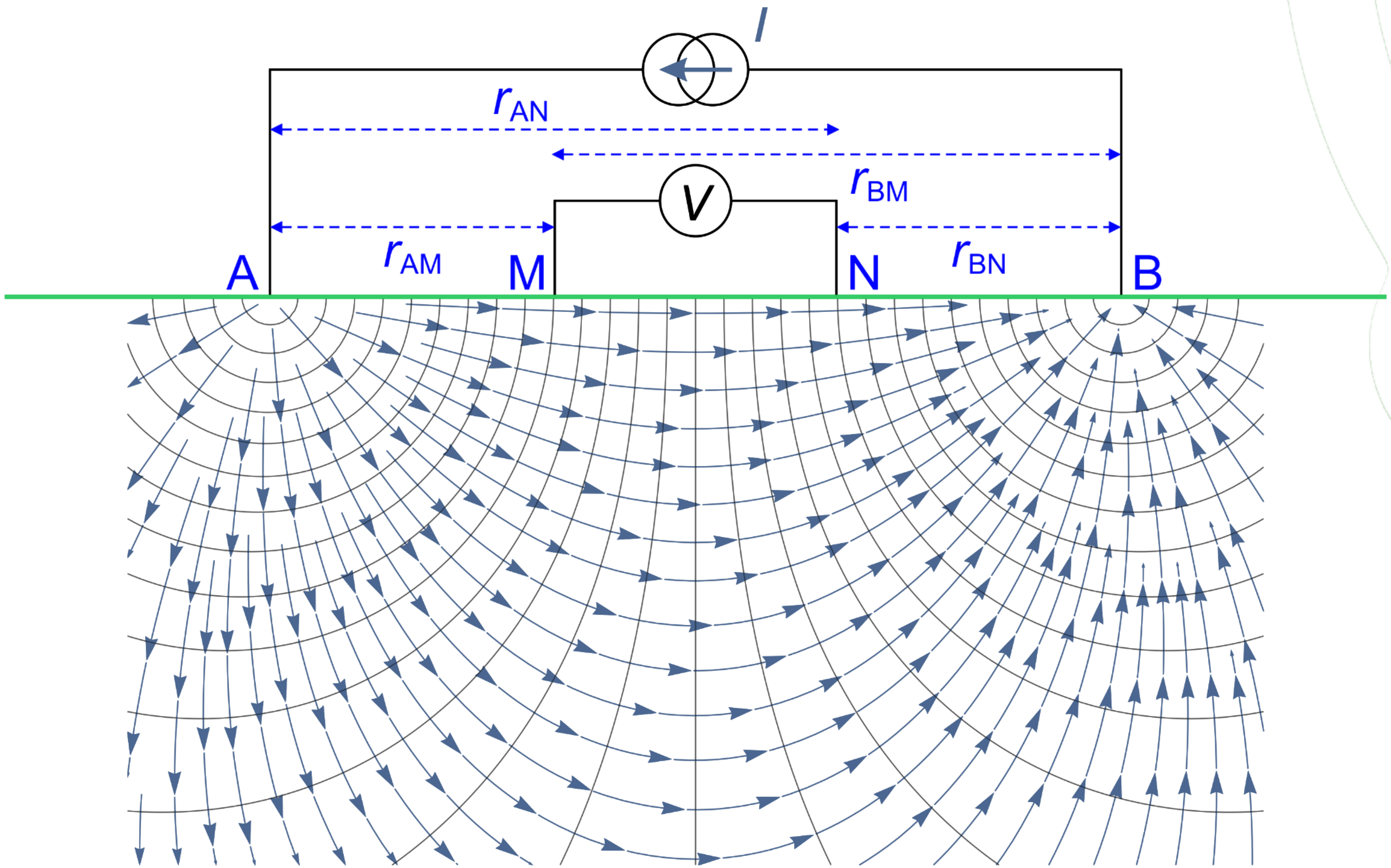
- σ has units of S/m (Siemens per meter)





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:

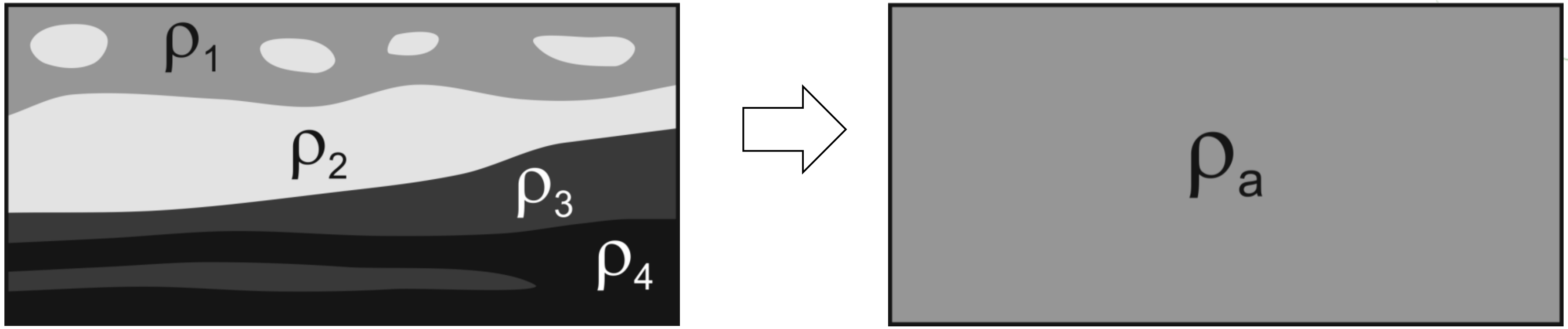
- Measured resistivity = ‘true’ resistivity **ONLY** over **flat homogenous** ground
- Subsurface is rarely completely homogenous

→ 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

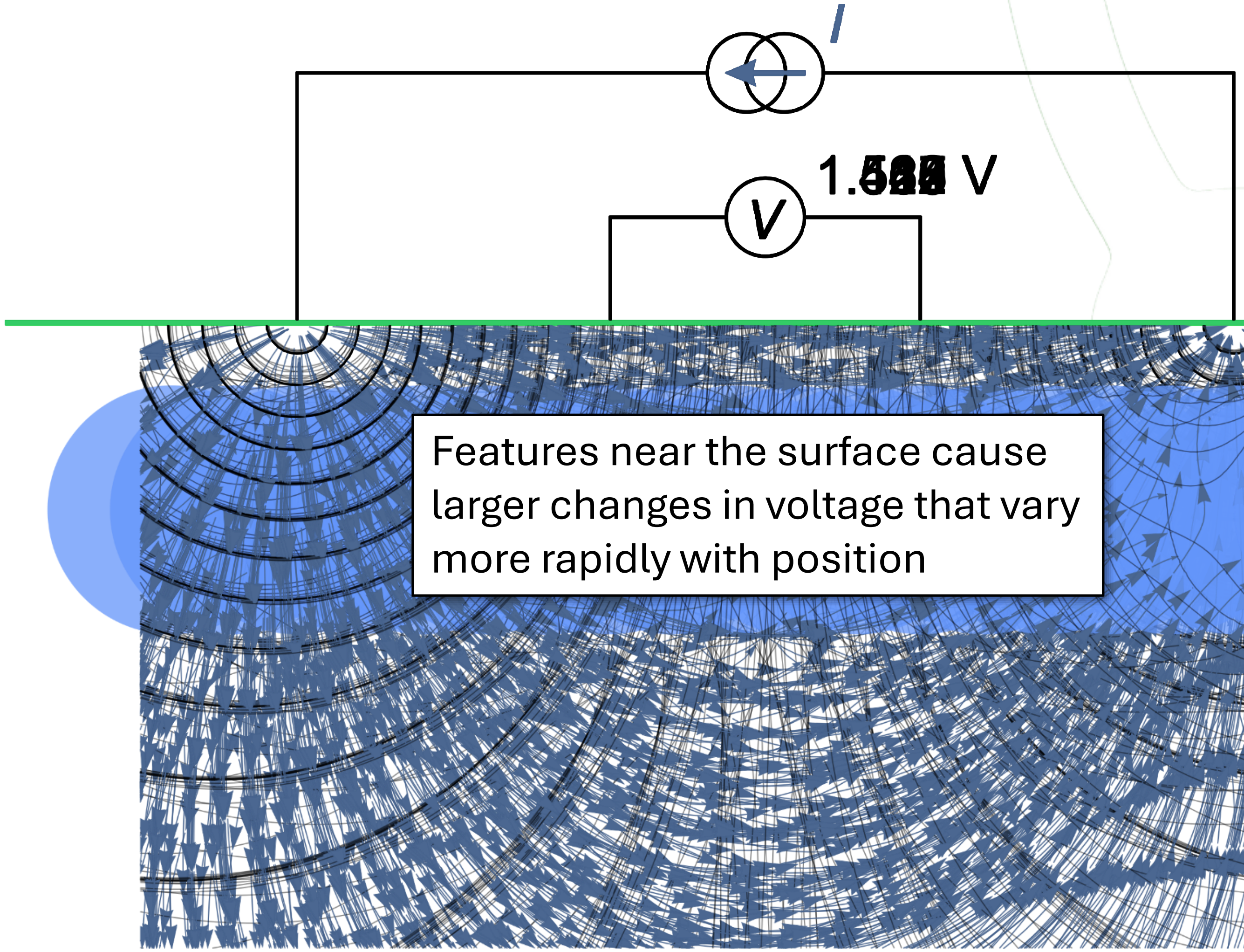
Real resistivity distribution

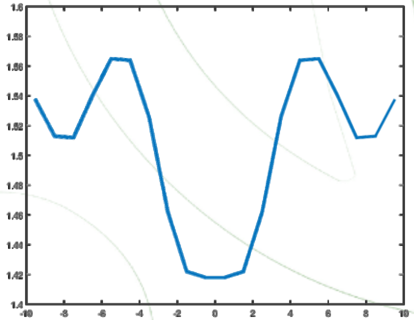
Apparent resistivity



Measurement sensitivity

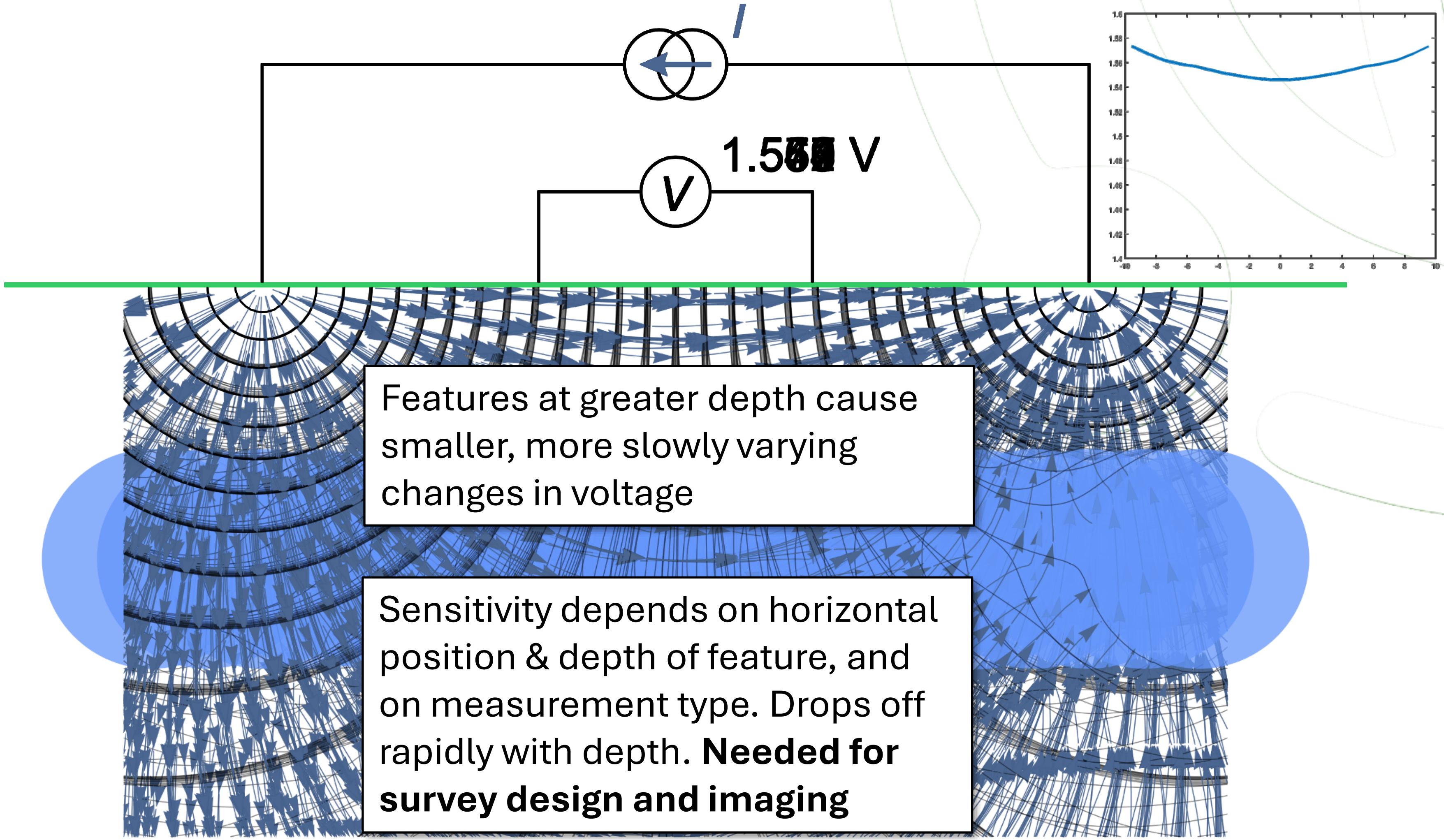
Voltages change with position





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:

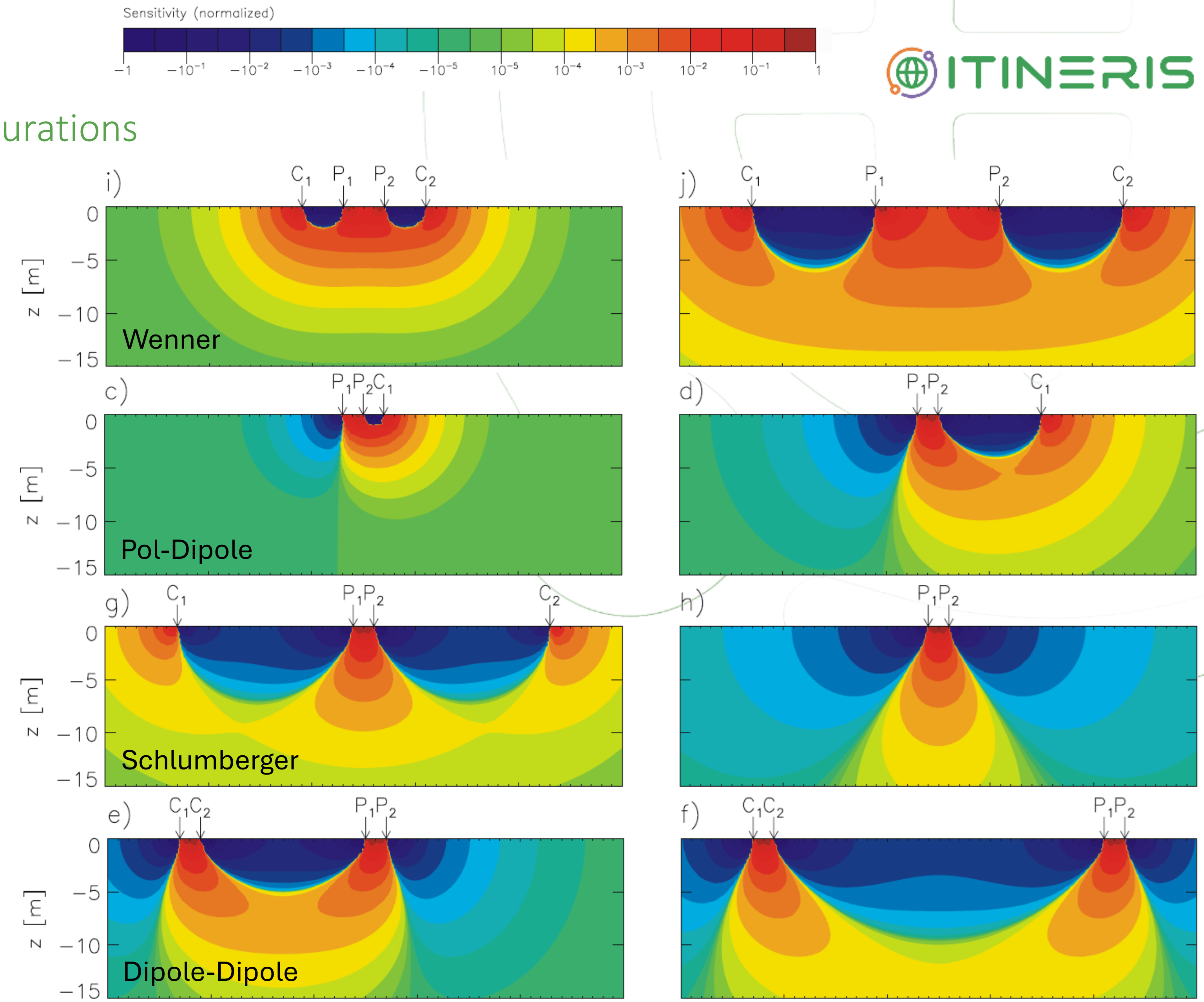
- Very good lateral resolution

Schlumberger

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

Dipole-Dipole

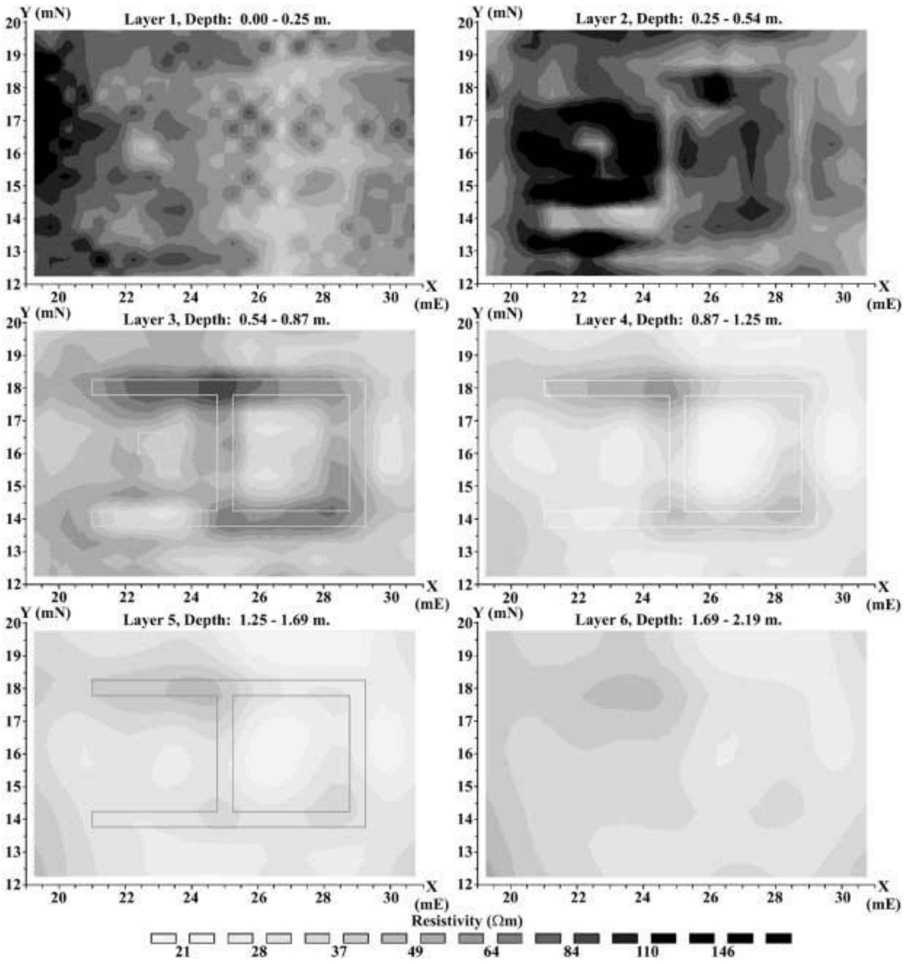
- Good lateral resolution, large depth of investigation
- High resolution
- Affected by variations close to electrodes



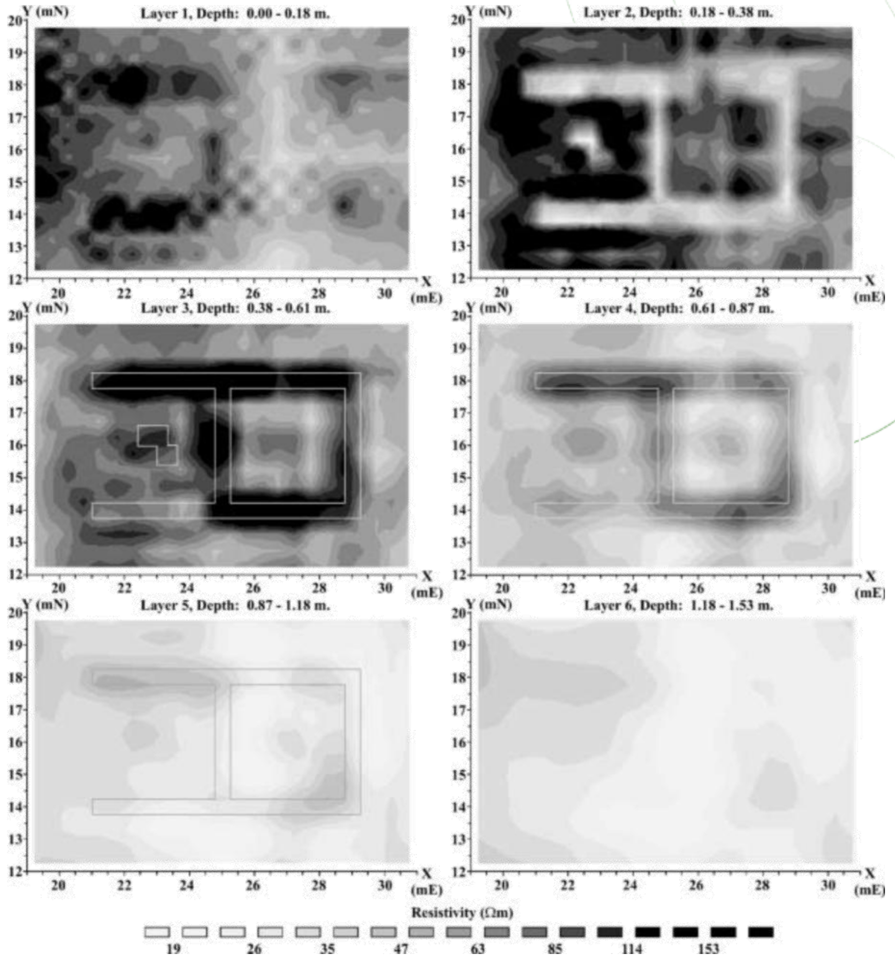
Measurement sensitivity → Model Resolution

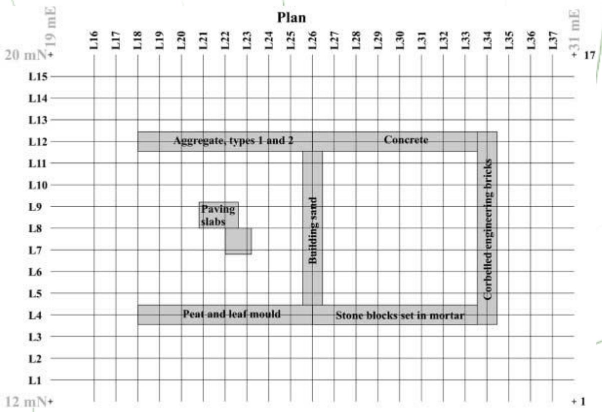
The type of measurement determines the model resolution

Wenner



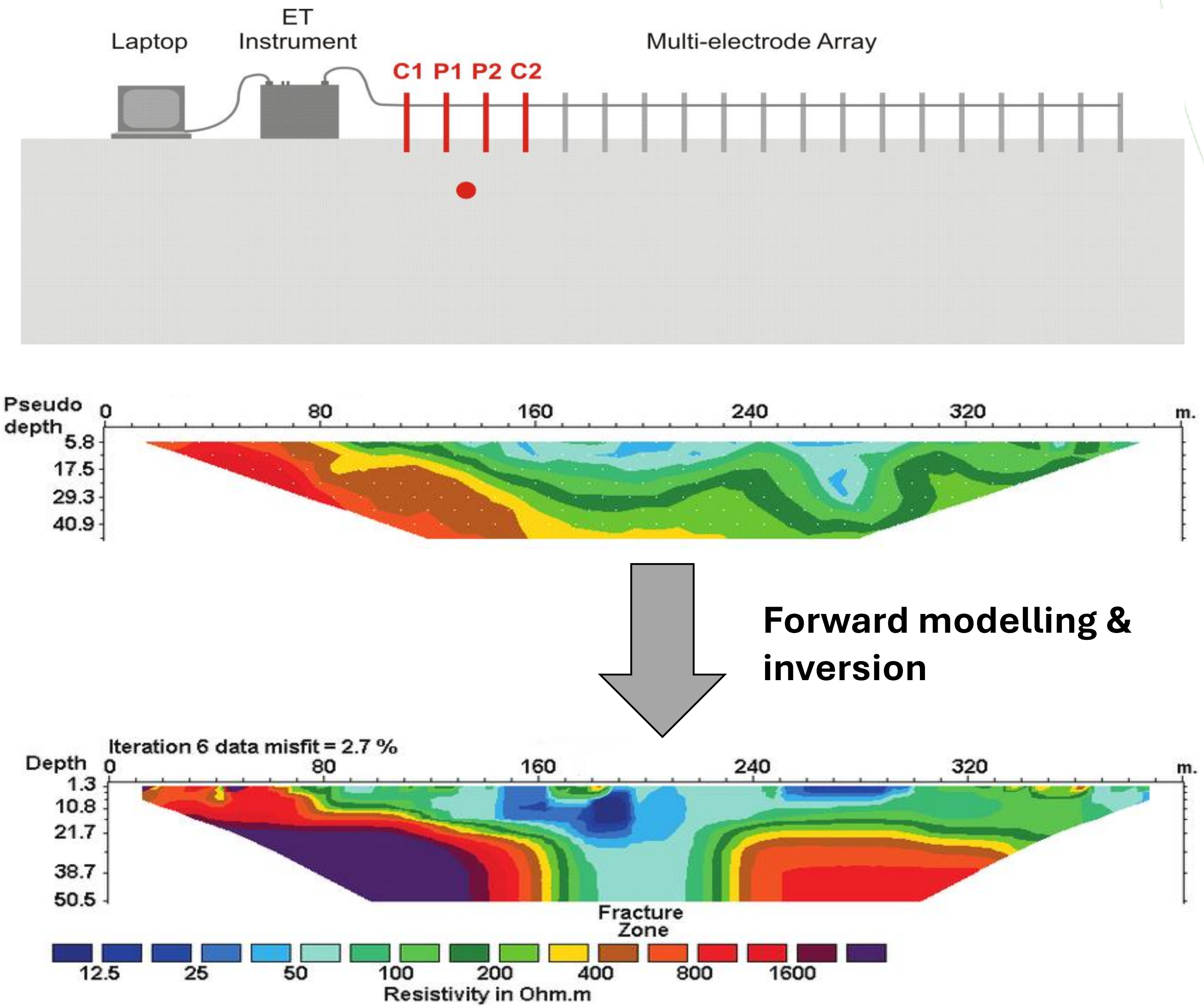
Dipole-Dipole





Imaging the resistivity distribution

2D Electrical Resistivity Tomography (ERT)



Resistance measurements
(raw data)

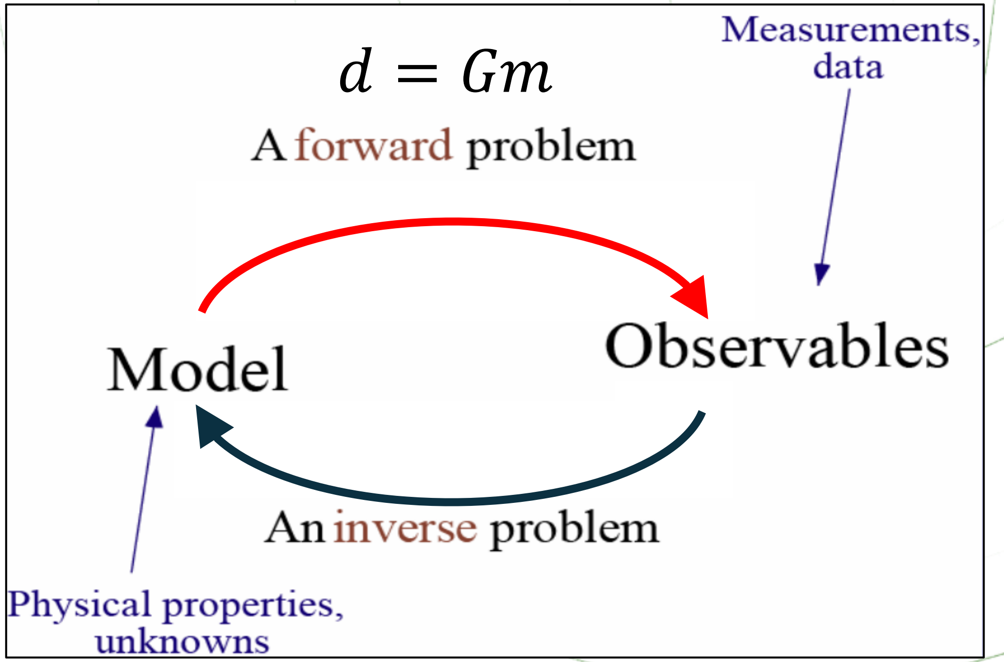
Apparent resistivity pseudosection

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



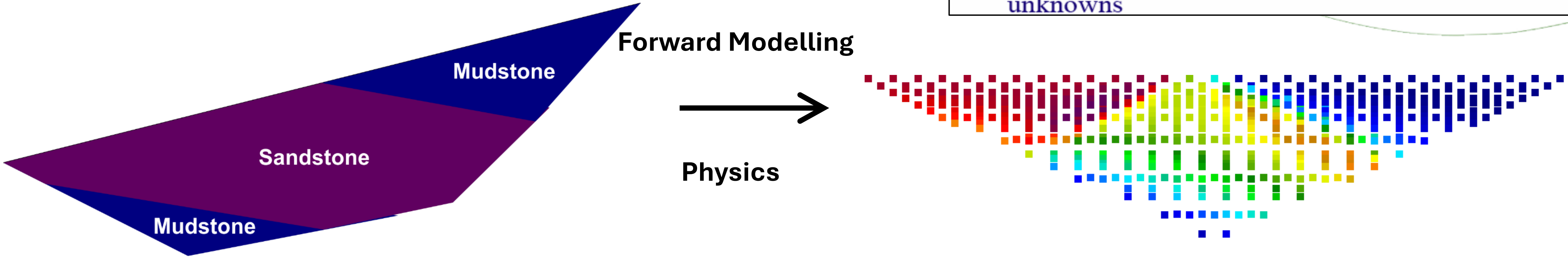
<u>**Forward modelling**</u>:

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

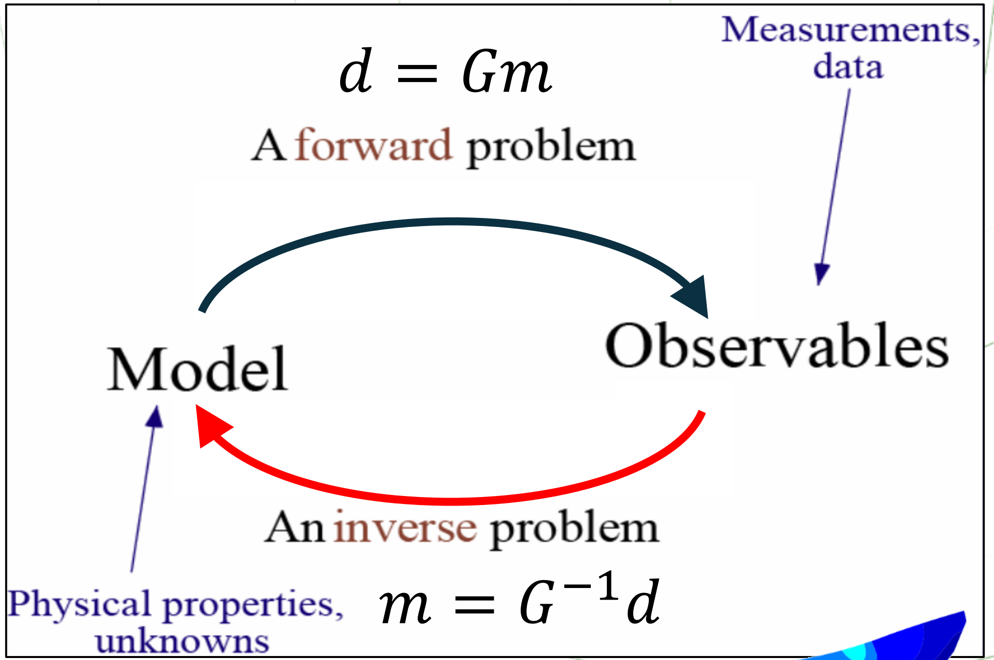
Predicting the subsurface model from real measurements

Inverse modelling

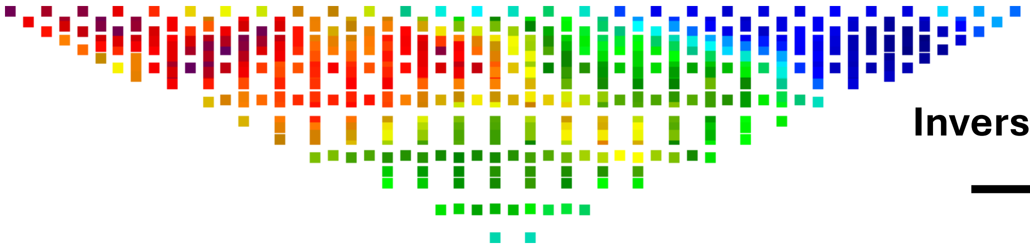
starting with the measured data, predict the geophysical properties of the ground (tomographic imaging/subsurface model)

Useful for:

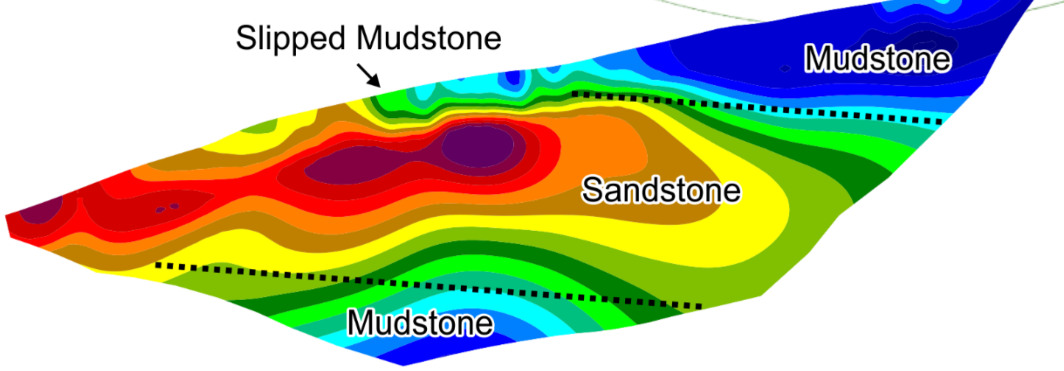
- *quantitative* analysis of survey data
- Visualisation
- assessing uncertainties
- survey design.



Relatively difficult!



Inverse Modelling →



Geophysical Measurements

Subsurface Model

Inverse modelling

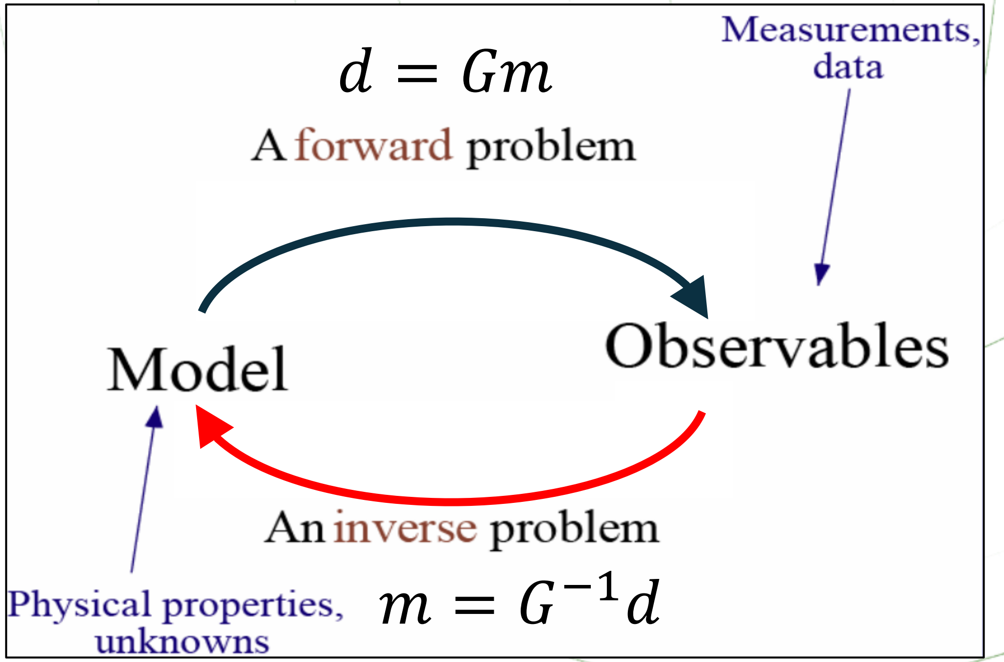
The inverse problem

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…)

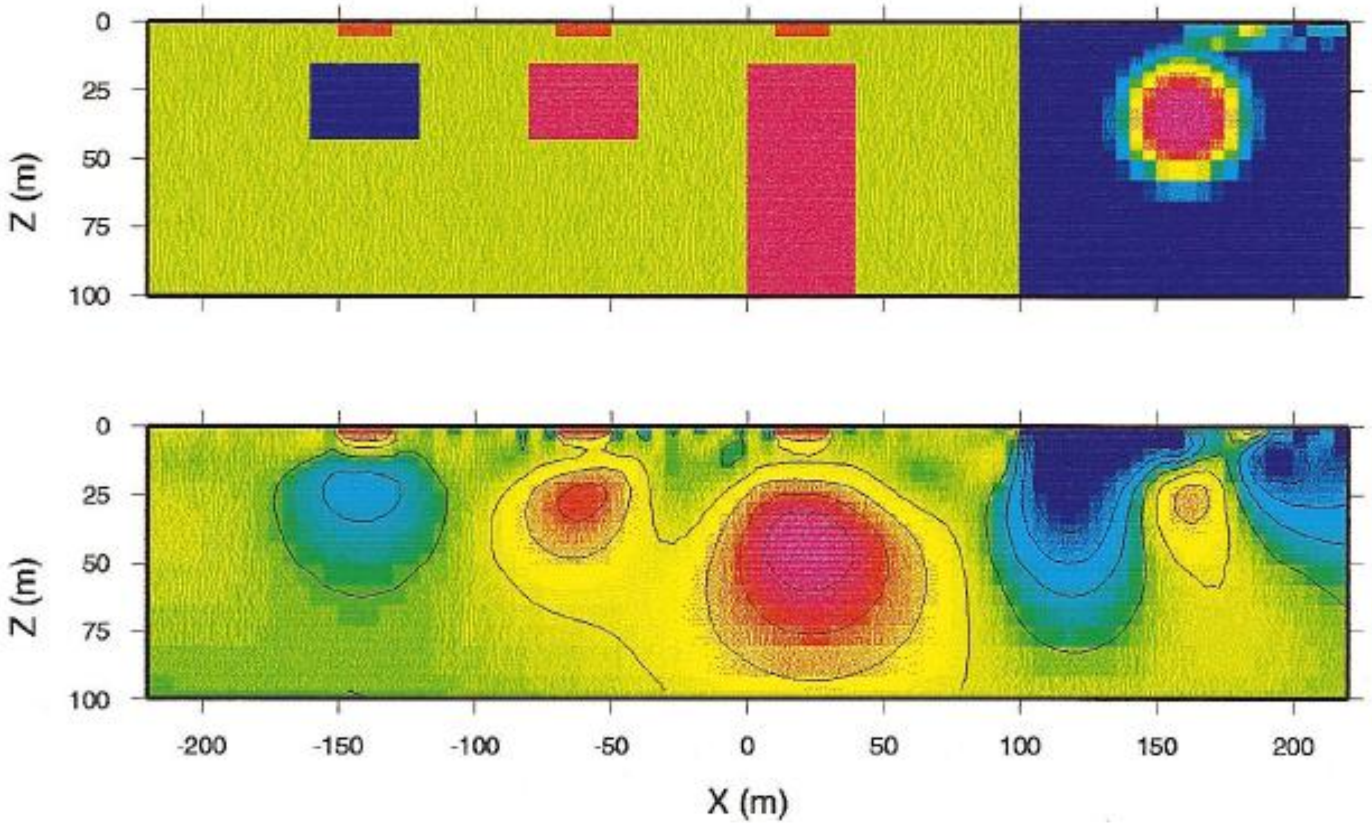
Conditions for the unique solution are very demanding:

- 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...)

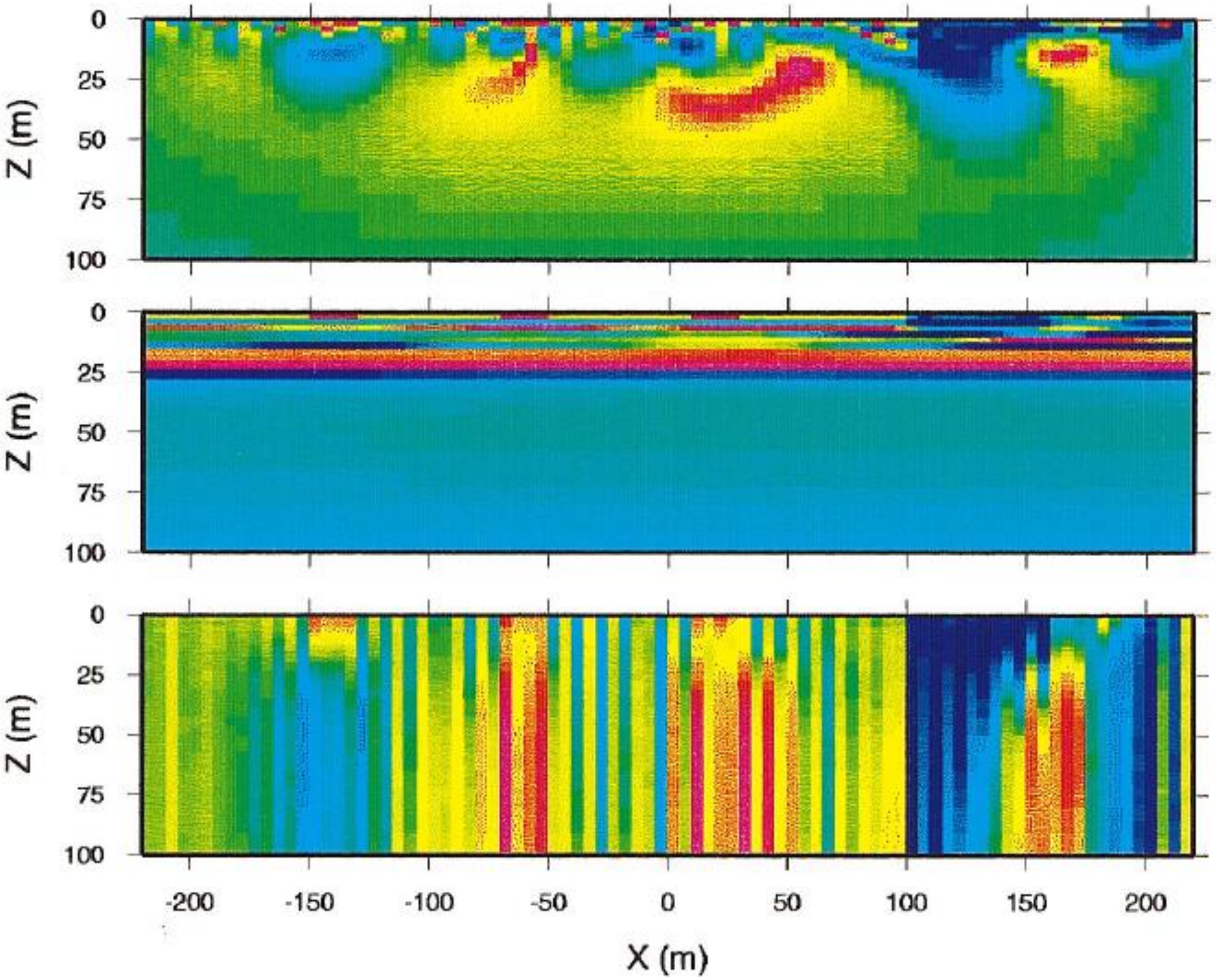


Forward model

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
Gauss-Newton optimization

Aim: minimize the data-model misfit

$$\Phi_d = \left(\boldsymbol{d} - F(\boldsymbol{m})\right)^T W_d^T W_d \left(\boldsymbol{d} - F(\boldsymbol{m})\right)$$

data weight matrix: W_d; measured data: $\boldsymbol{d}$; model response: $F(\boldsymbol{m})$

Since the forward model is a function of parameters m, a linearization process is required for inverse modelling. This is normally achieved using the Gauss-Newton approach:

$$\left(\boldsymbol{J}^T W_d^T W_d \boldsymbol{J}\right)\Delta\boldsymbol{m} = \boldsymbol{J}^T W_d^T \left(\boldsymbol{d} - F(\boldsymbol{m}_k)\right),$$
$$\boldsymbol{m}_{k+1} = \boldsymbol{m}_k + \Delta\boldsymbol{m},$$

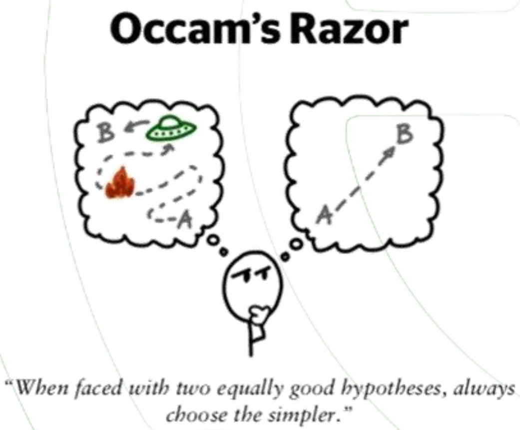
Of limited practical use due to convergence to a local minimum or instability of the solution. Hence, addition of damping and regularization:

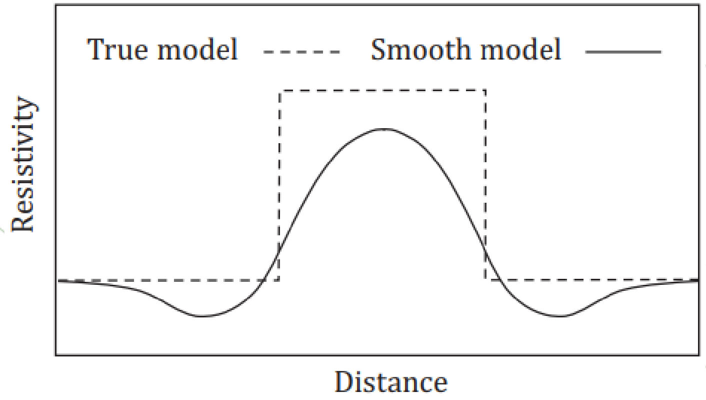
$$\left(\boldsymbol{J}^T W_d^T W_d J + \alpha \boldsymbol{R}\right)\Delta\boldsymbol{m} = \boldsymbol{J}^T W_d^T W_d \left(\boldsymbol{d} - F(\boldsymbol{m}_k)\right) - \alpha \boldsymbol{R}\boldsymbol{m}_k$$

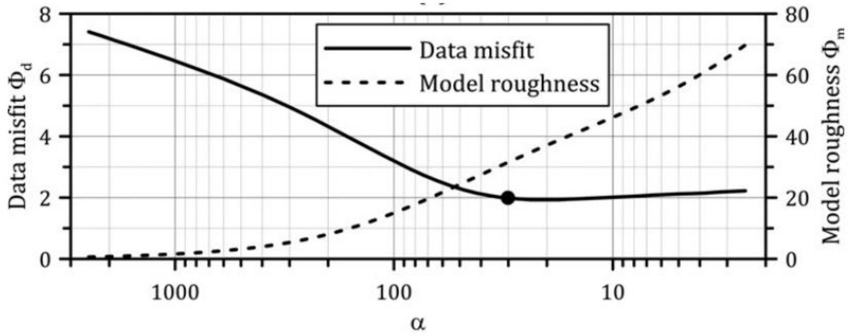
Inverse modelling
Constraints

- 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**)



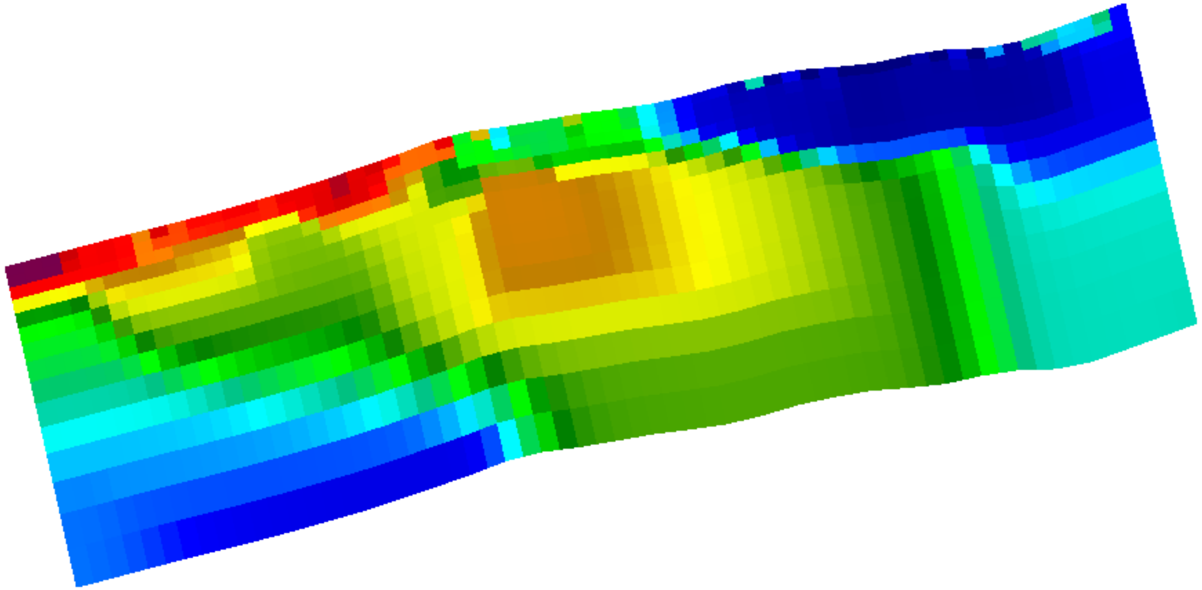




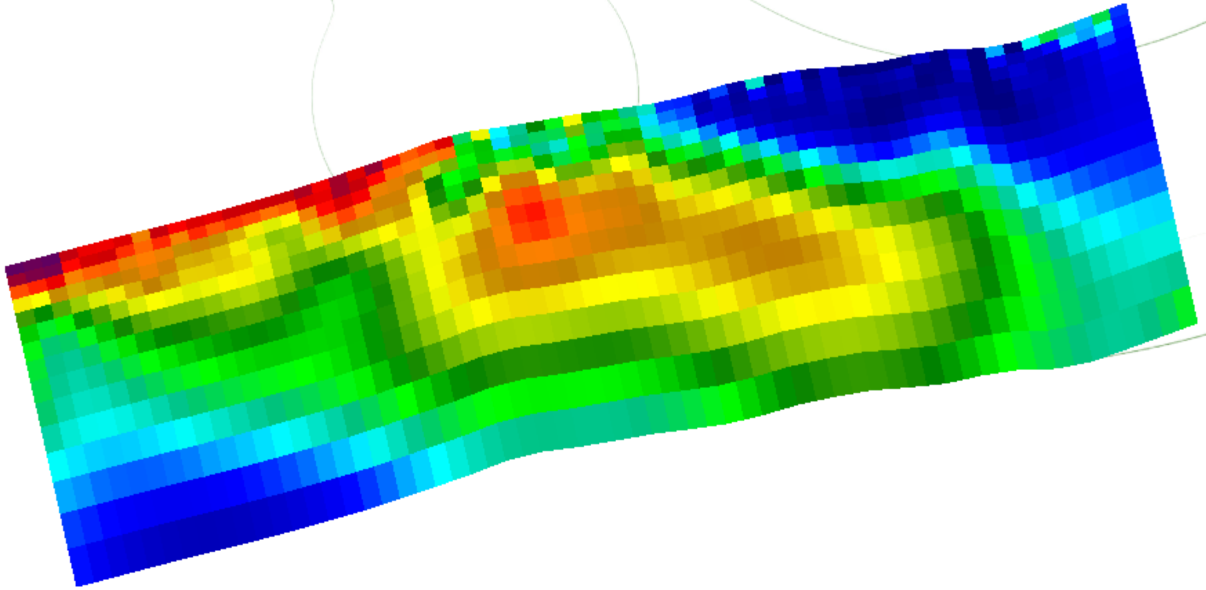
Inverse modelling

Constraint examples

Blocky model

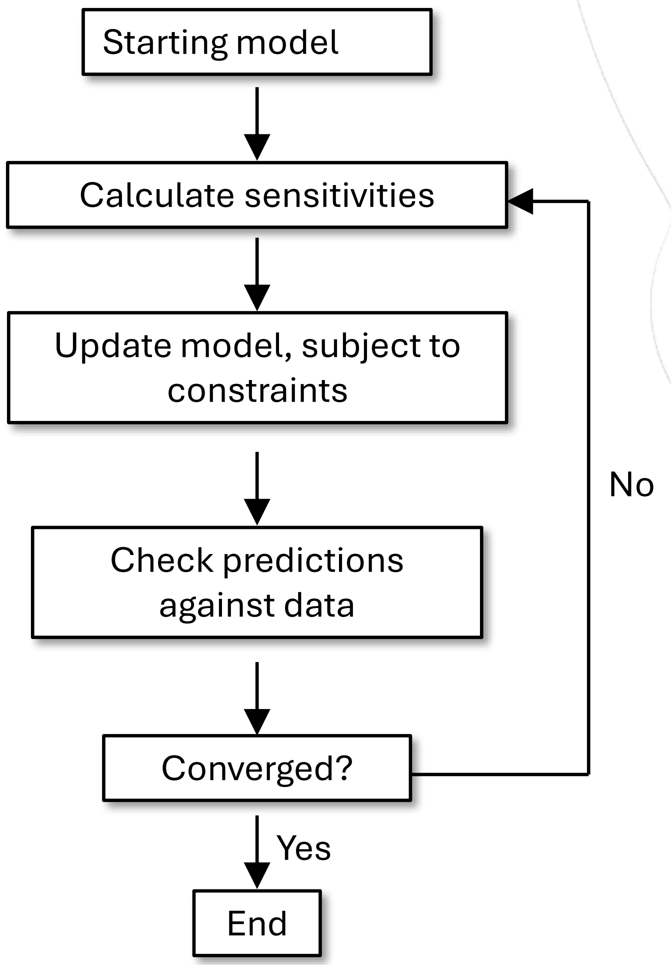


Smooth model



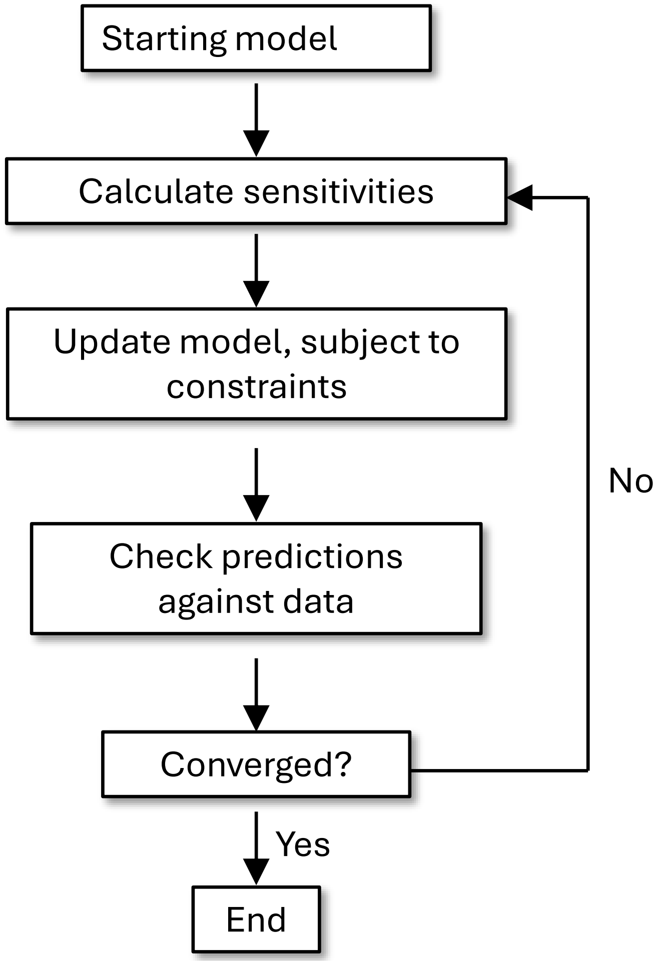
Inverse modelling

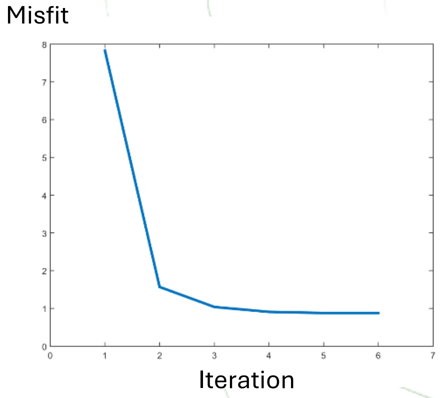
Iterative process

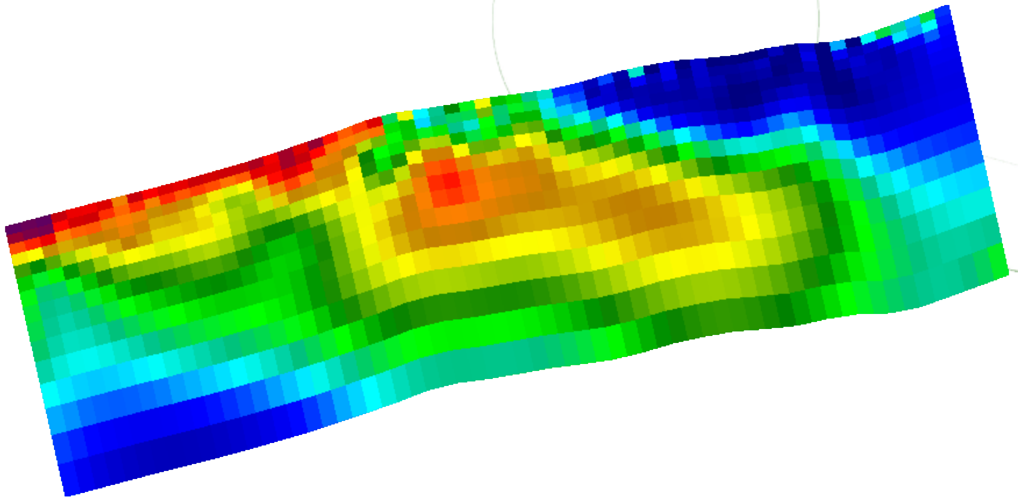


Inverse modelling

Example







Inverse modelling

Misfit and reliability of the model

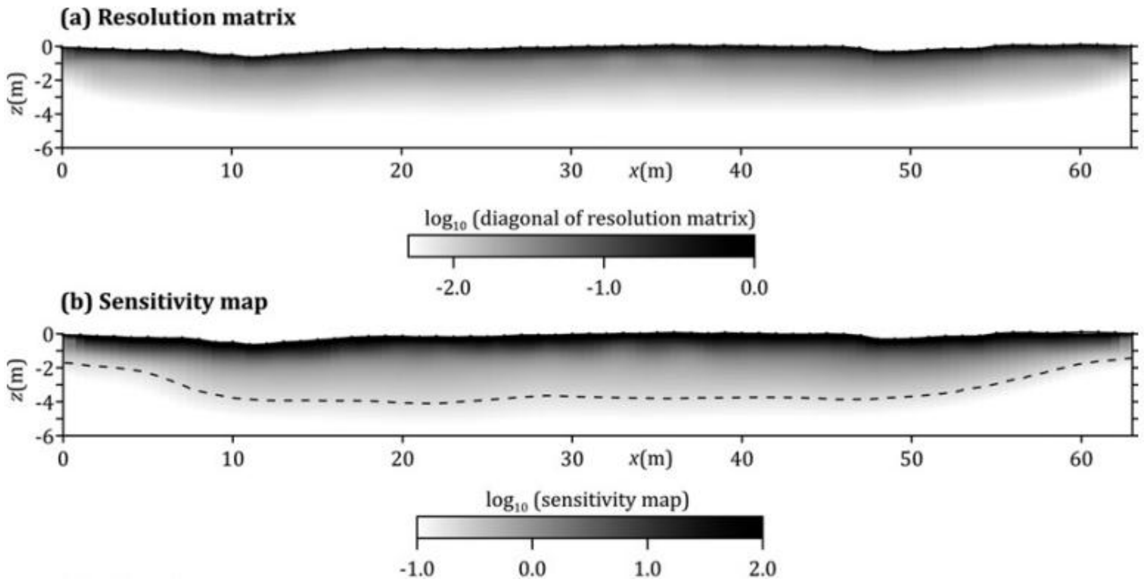
Misfit

- Inversion usually stops when either:
  - The fit to the data is similar to the level of error
  - The fit to the data no longer improves
- The fit to the data is usually reported as an average percentage or a “chi-squared” (χ^2) value
- The average percentage error misfit should be similar to the typical data error
- The average chi-squared value should equal 1

Reliability

- The reliability of the final resistivity model can be assessed based on
  - the sensitivity distribution (cumulative sensitivity)
  - the resolution matrix

$$m = R_m m_{true}$$



Summary

The electrical resistivity of Earth materials and forward & inverse modelling

Electrical resistivity of Earth materials

Main conduction pathways:

- Electrolytic and surface conduction
- Archie's equation can describe electrolytic conduction

Resistivity measurements

4 point measurements are usually used to measure the resistance of the ground

Apparent resistivity is a weighted average of the subsurface resistivity distribution

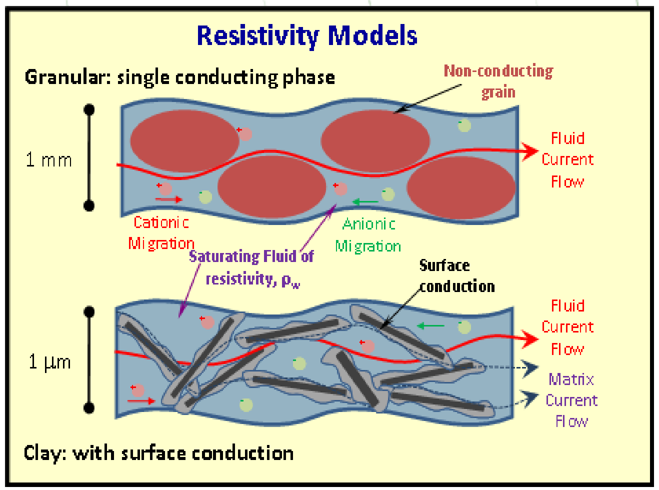
Different measurement configurations show different sensitivities and resolution

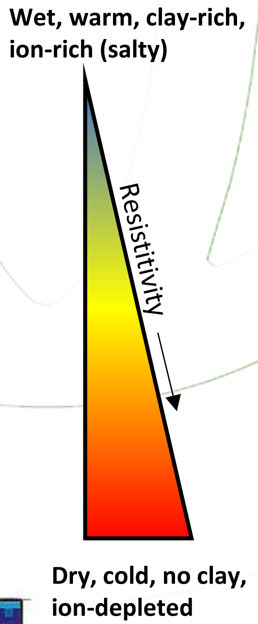
Forward modelling can be used to simulate measurements to:

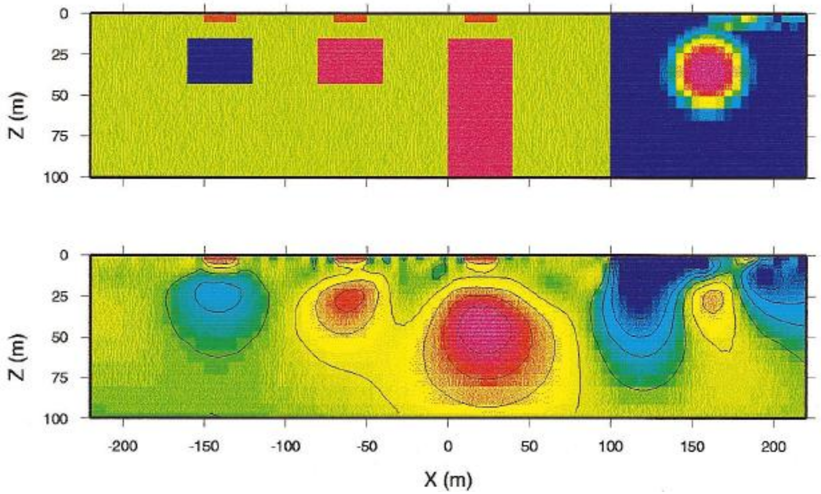
- Determine the most appropriate measurement configuration
- Assess how well subsurface features can be imaged

Inverse modelling required to get a subsurface resistivity model from the measured data

- Inversion is non-unique! An infinite number of models explains the data equally well
- Constraints are required to come a solution







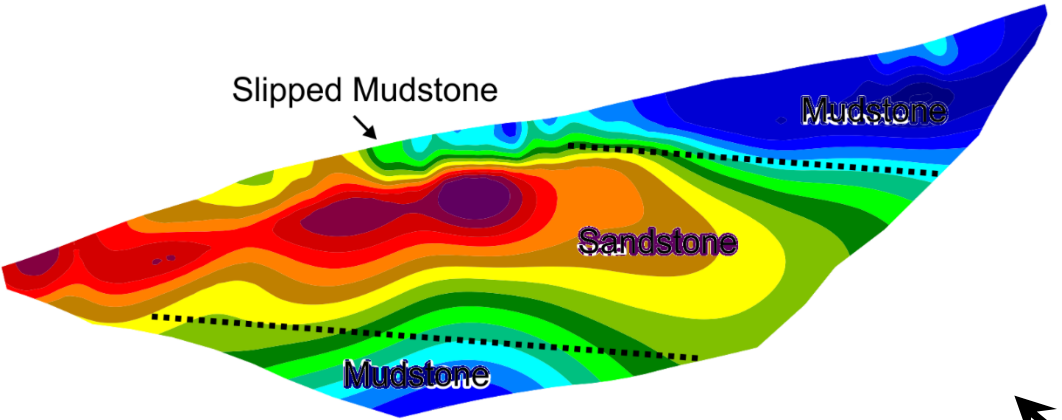
Crossroads

What do you want to do now?

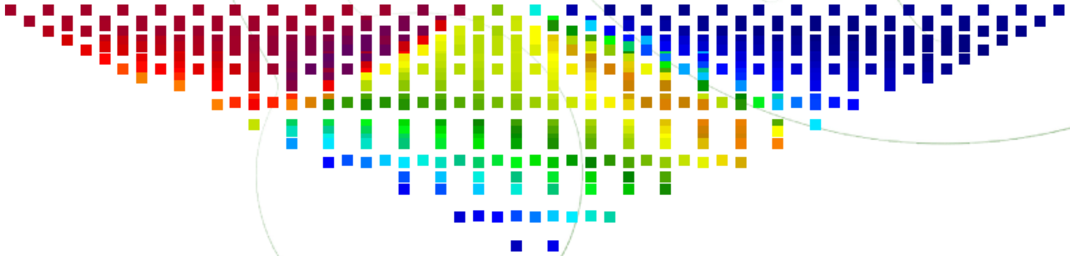
Resistivity forward modelling and inversion

Concept

Forward modelling

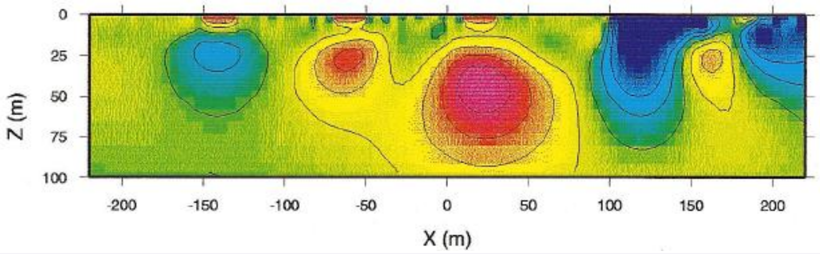


Subsurface resistivity model

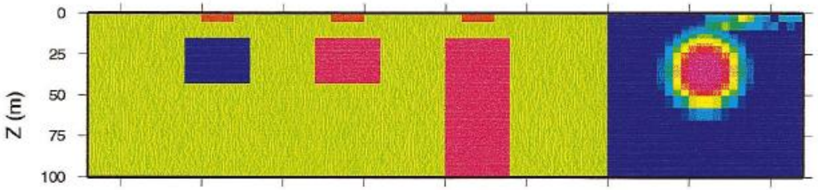


Geoelectrical measurement

Inversion



Non-uniqueness



Resistivity forward modelling and inversion

ResIPy example

Download ResIPy – no installation required

Forward modelling:

1. Choose option “Forward” under “Importing – Data”
2. Under „Electrodes (XYZ/Topo)“ define the number of electrodes (48) and their spacing (2 m)
3. Under „Mesh“ create a discretization of the subsurface – use a „Triangular mesh“ – forward modelling usually requires a relatively fine mesh (to minimize numerical errors) – set depth (Fine/Coarse boundary depth) to 30 m
4. Create a measurement sequence (Dipole-Dipole, Wenner, etc. with multiple a/n spacings)
5. Press “forward modelling” – once complete, you will see a pseudo section
6. Go back to the Mesh tab and create resistivity anomalies and repeat the step of the forward modelling

Inversion:

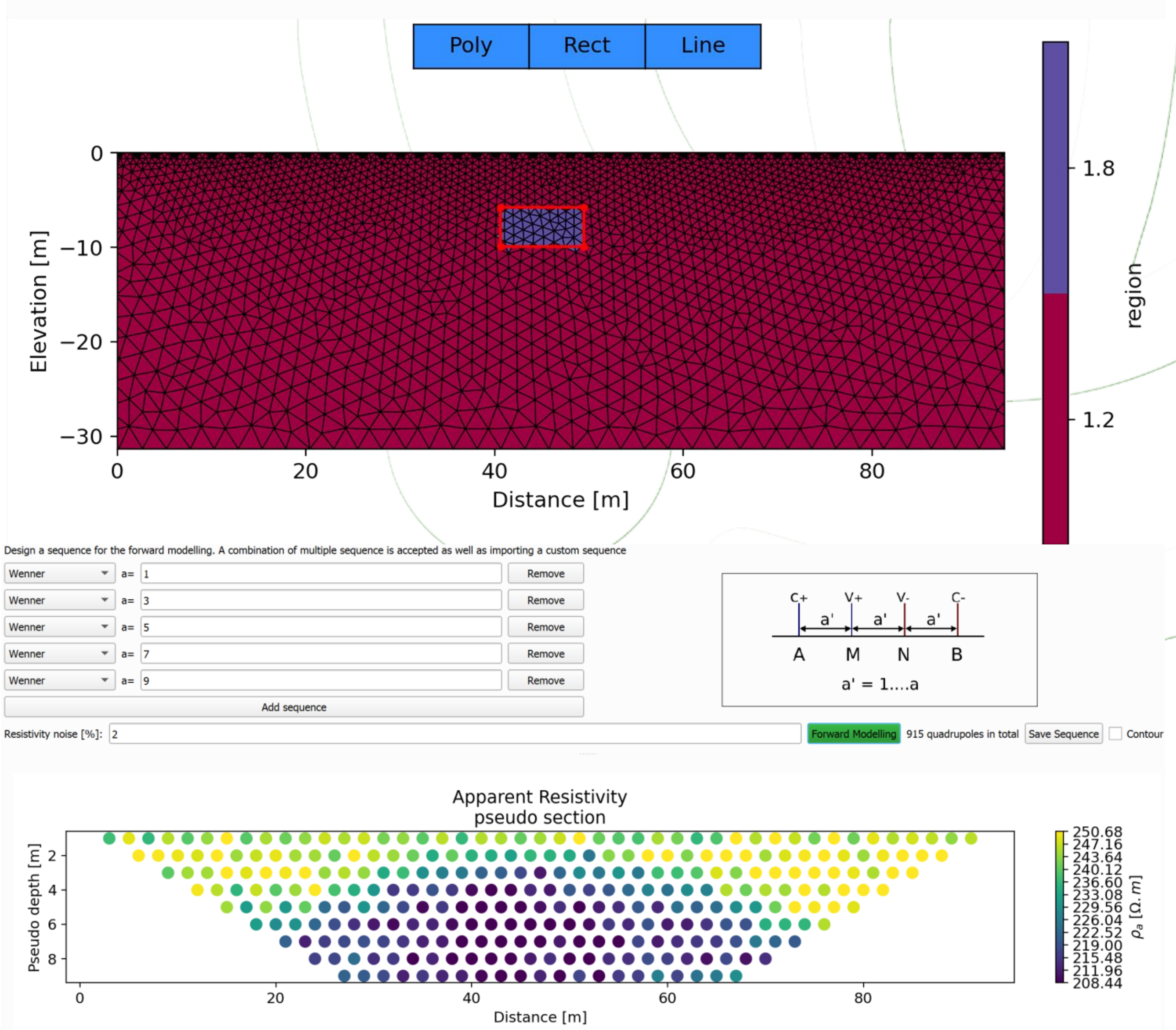
1. Go back to the „Mesh“ tab and press „Reset mesh“ and create a coarser mesh than used for the forward modelling
2. In the inversion settings, set “a_wgt” to 0.001
3. Start the inversion

Resistivity forward modelling and inversion

ResIPy example

Practical:

1. Create a forward model with 48 electrodes at 2 m spacing
2. Model a rectangular object with low resistivity (10 Ωm) in a resistive halfspace (250 Ωm). The upper edge of the anomaly should be no more than 5 m deep, and the size of the anomaly should be roughly 10 x 5m
3. Create a Wenner-Measurement with a = 1, 3, 5, 7, 9 and press “Forward Modelling”
4. Now you see the pseudosection
5. Go back to „Mesh“, press „Reset Mesh“ and create a new, coarser mesh with a depth of at least 20 m.
6. Under inversion settings, set a_wgt = 0.001
7. Run the inversion. When you plot the result, set the minimum and maximum resistivity values to 25 and 150 Ωm
8. Repeat everything with a dipole-dipole measurement (a = 1,3,5,7,9, n=8)
9. What is the difference between the two?
10. Repeat this for the two models on the website



Some practical considerations
(for a happy survey...)

Conducting resistivity measurements

2D measurements

2D Electrical Resistivity Tomography

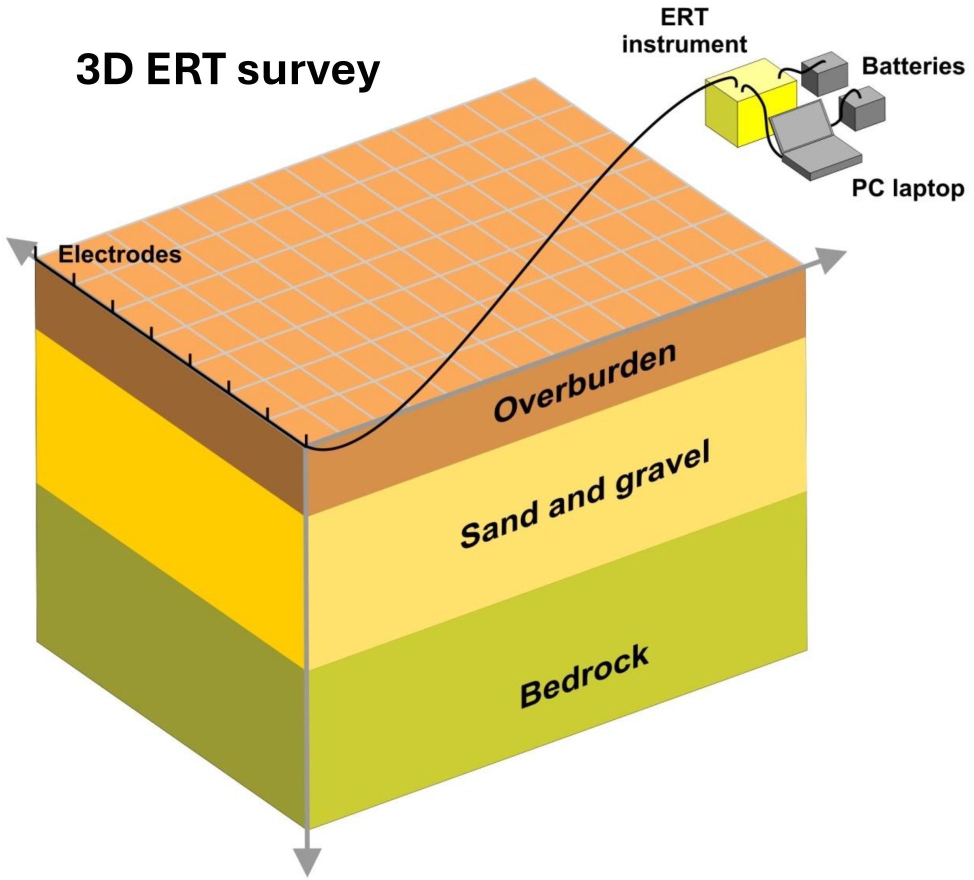
- Linear lines of electrodes (usually between 48 and 96)
- Stainless steel pins or plates
- Connected via multicore cables to automated resistivity meter
- **Important:** Measure electrode location (distance & elevation)


Reduce contact resistance to improve measurement quality
Measurement system
• Usually 10 – 250 W
• Battery powered
• Can have multiple measurement frequencies
Multi-core cable
• Numbered takeouts
• Direction important
Stainless steel electrodes

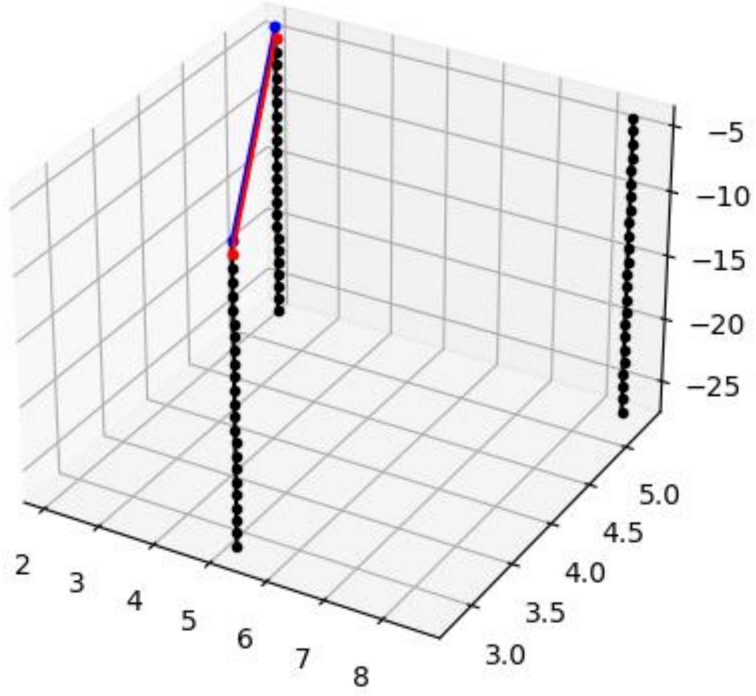
Conducting resistivity measurements

3D and borehole measurements

3D ERT survey

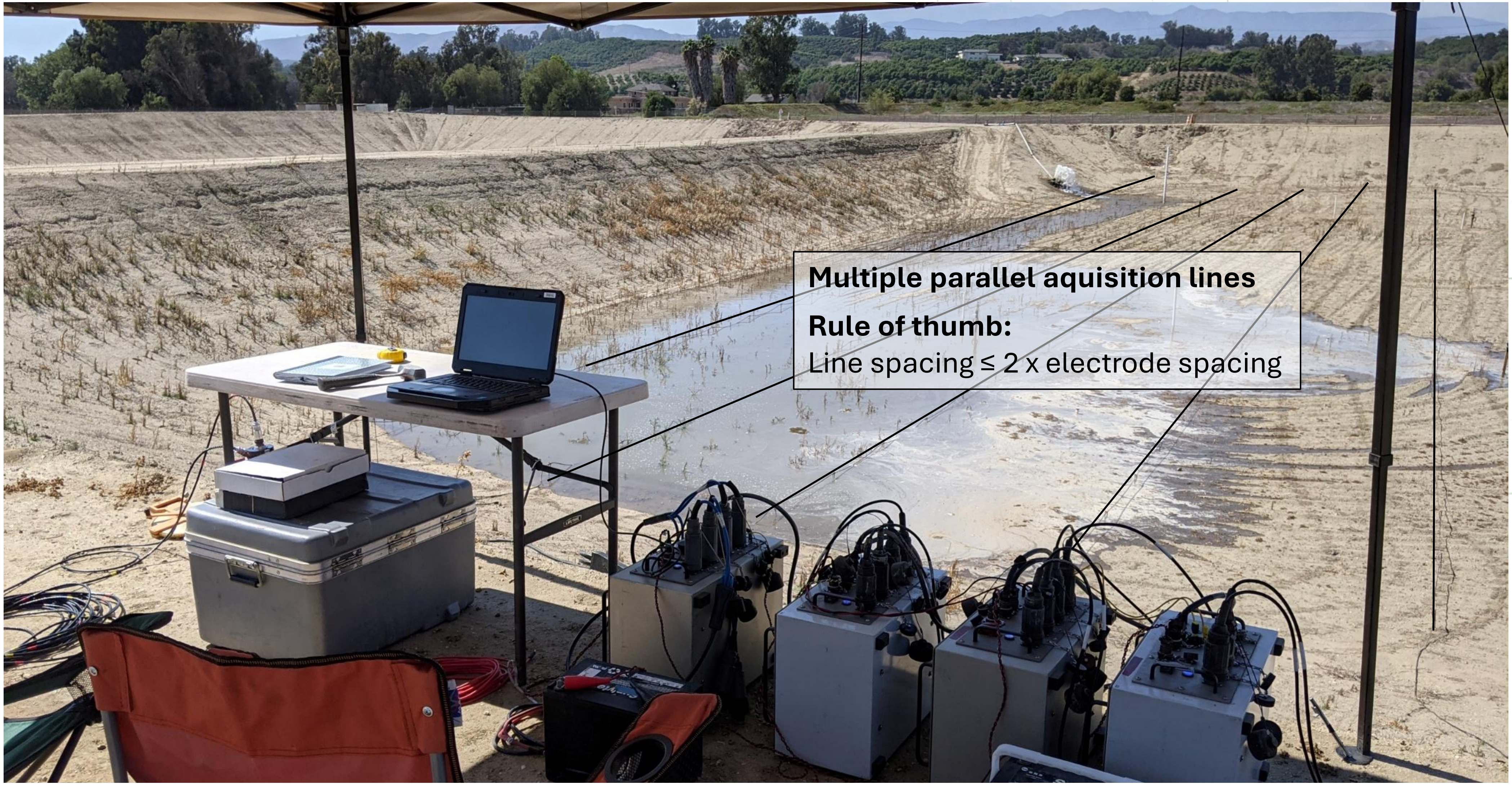


Cross-borehole ERT survey



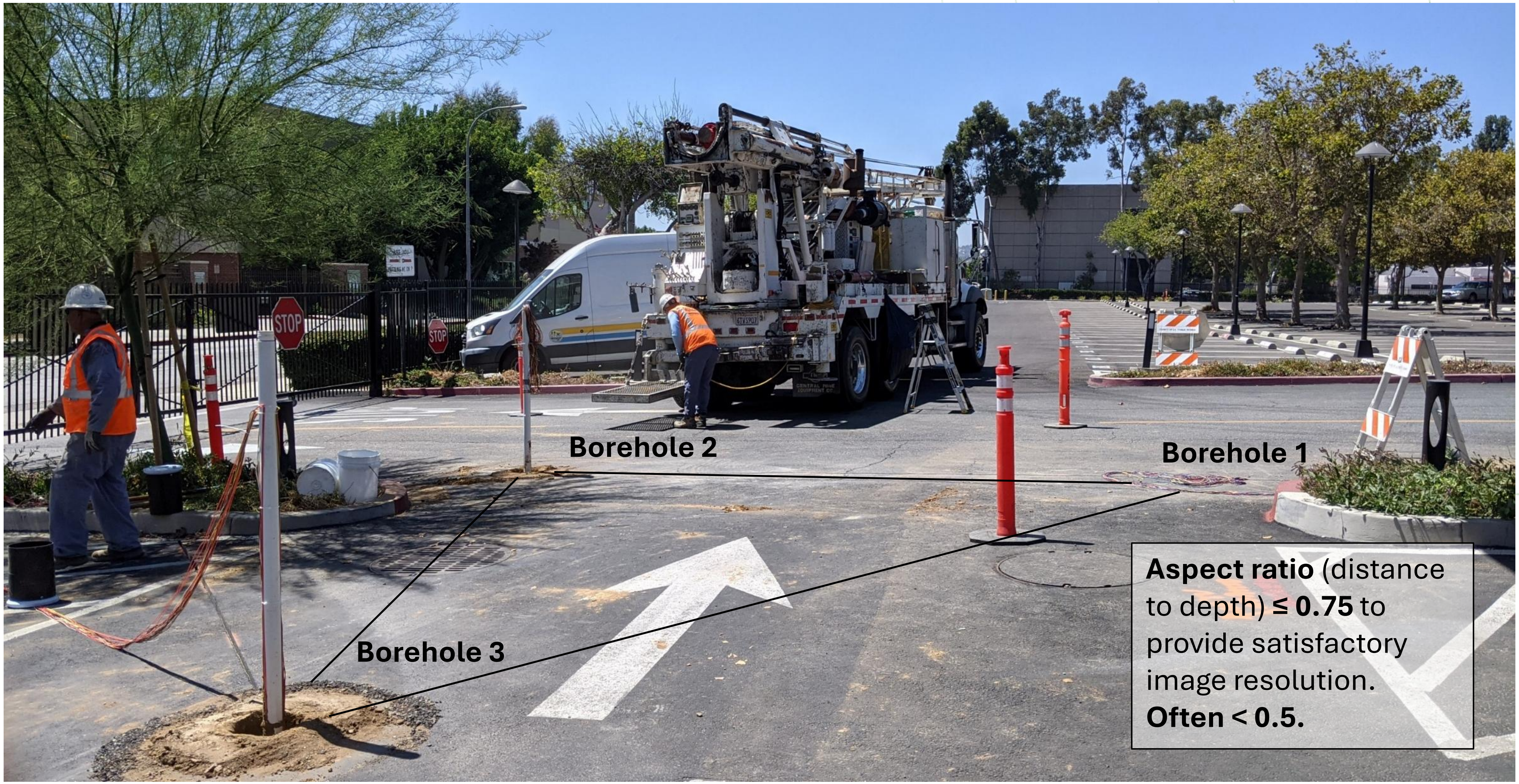
Conducting resistivity measurements

3D and borehole measurements



Conducting resistivity measurements

3D and borehole measurements



Assessing data quality

Measurement errors

<u>Measurement errors are important!</u>

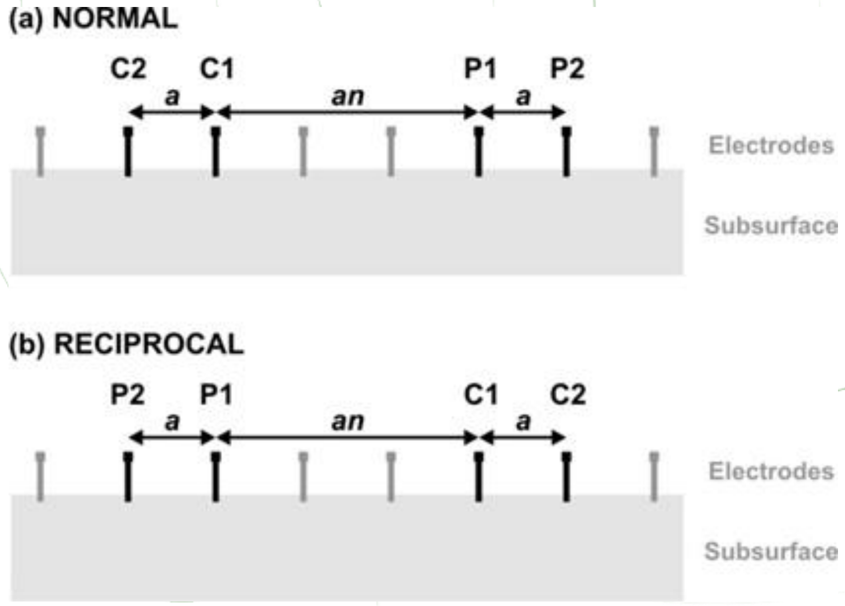
1. They provide information on the reliability/accuracy of the data
2. They define how data are weighted in the inversion

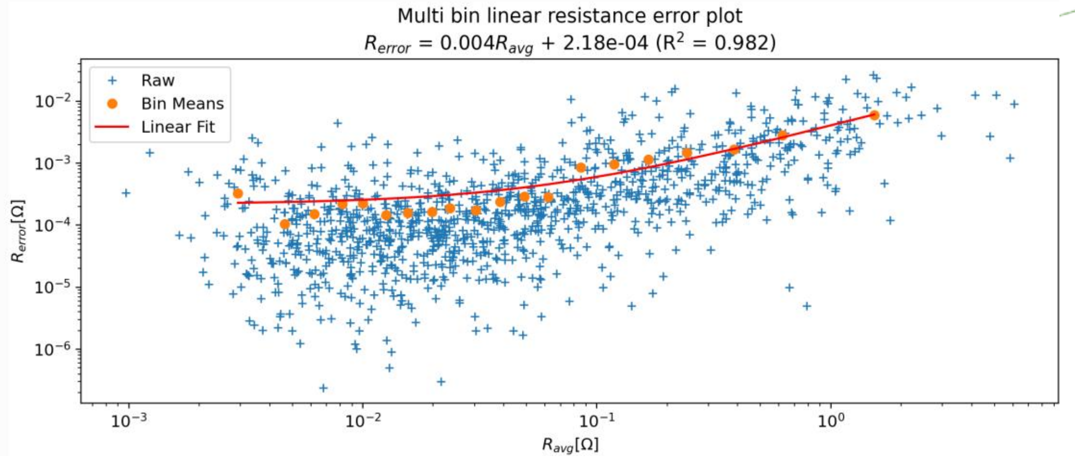
<u>Types of error estimates:</u>

- Stacking errors
- Repeat measurements (same configuration measured at different points in time)
- **Reciprocal errors** (= robust error estimate)

Reciprocity theory: Exchange of current injection and potential electrodes should, in theory, return the same measurement

Frequently used to develop a statistical representation of the measurement error – Error model





Pre-processing of ERT data

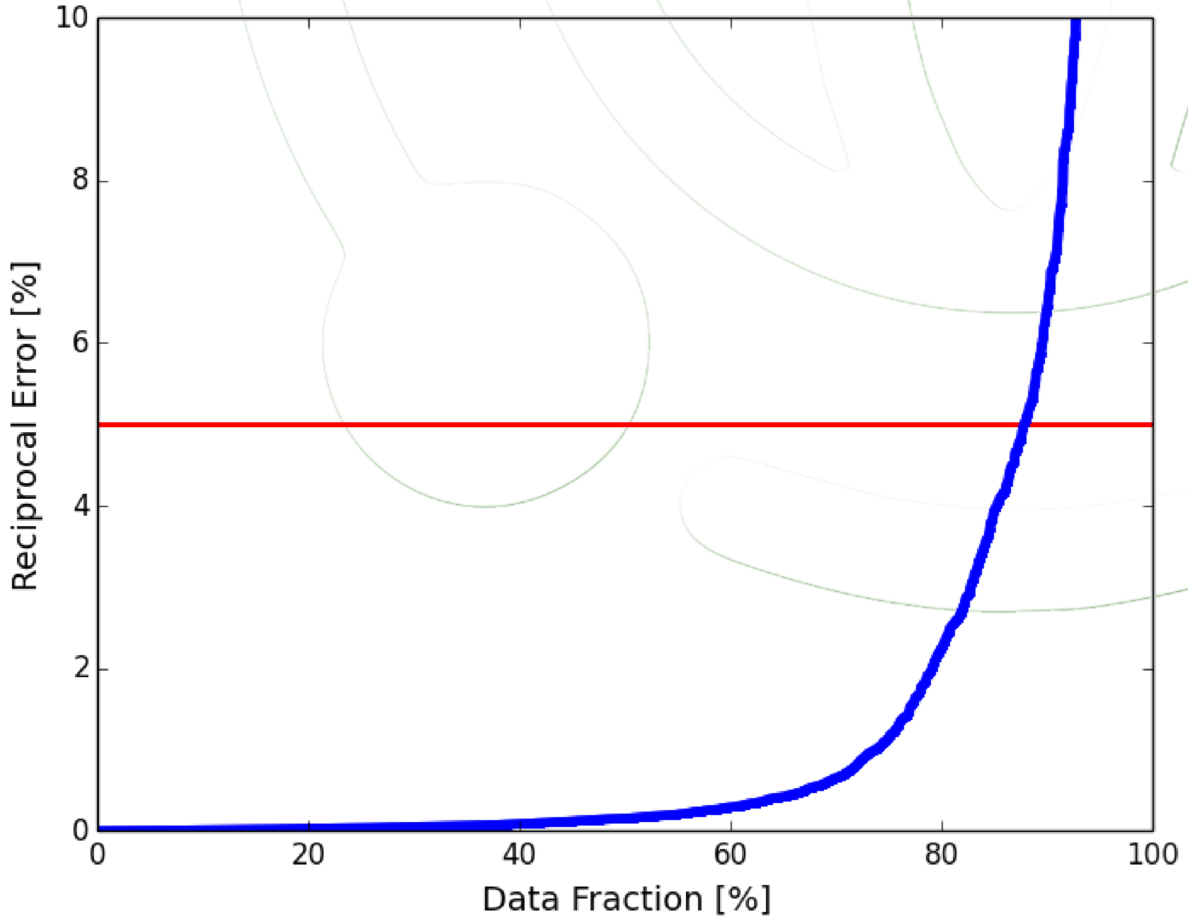
Filtering approaches

Data filtering commonly based on reciprocal errors, with thresholds of ~ 5% - 10 %

$$e_r = 100 \cdot \frac{|R_r - R_n|}{|R_r + \bar{R}|}$$

Additional filtering may be based on:

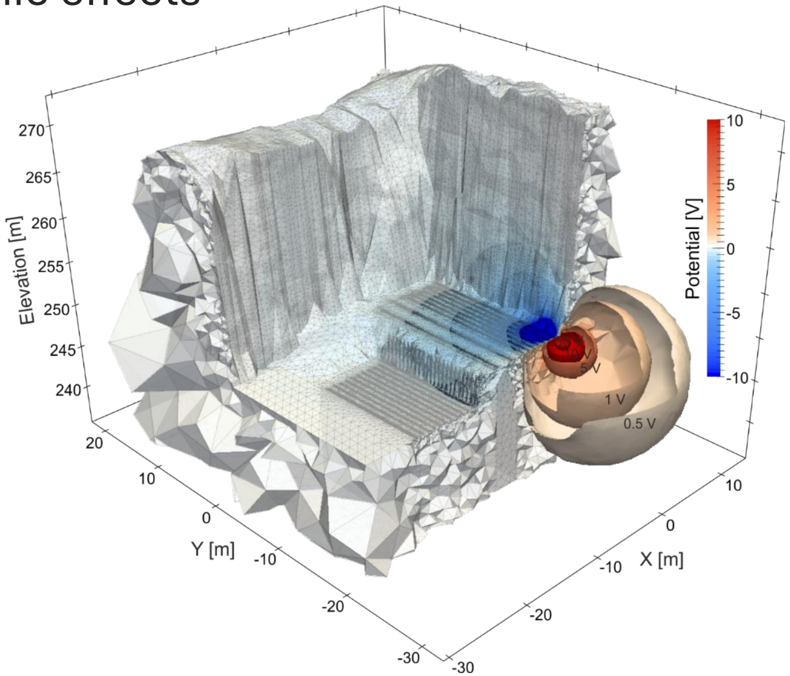
- Contact resistance
- Geometric factor
- Std of repeated measurements
- Voltage ratio
- Removal of outliers

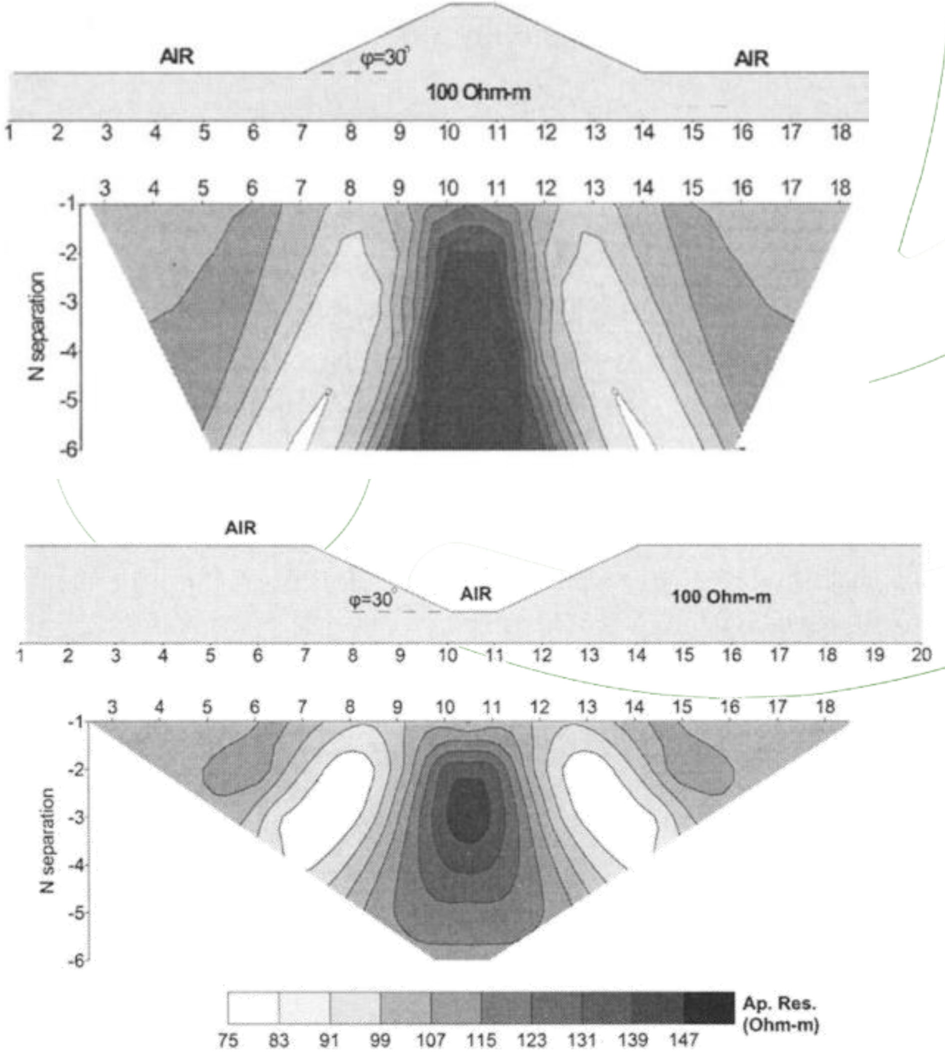


Topography is important!

Need to account for topography along and off measurement area

- Measured data depends not only on the subsurface resistivity distribution, but also on the electrode locations.
- Next to resistivity survey, also the topography needs to be determined
- Consider 3D topographic effects





Not all measurement systems are equal– choose carefully

Systems vary in speed, power, and accuracy

AGI SuperSTING R8/IP & Switchbox

8 channel system
~ 11 measurements/minute
Resistivity & time-domain IP
200W
Max. Voltage: 800V

Geolog2000 GeoTom

1 (up to 8) channel system
~ 10 - 25 measurements/minute
Resistivity & frequency-domain IP
100 W
Max. Voltage: 500V

Syscal Terra Switch

20 channel system
~ 10 - 25 measurements/minute
Resistivity & time-domain IP
250W
Max. Voltage: 2000V

Max. Voltage particularly important for high contact resistance areas

Multichannel acquisition can speed up measurement time

Dipole-Dipole or Multiple Gradient most applicable for multichannel systems

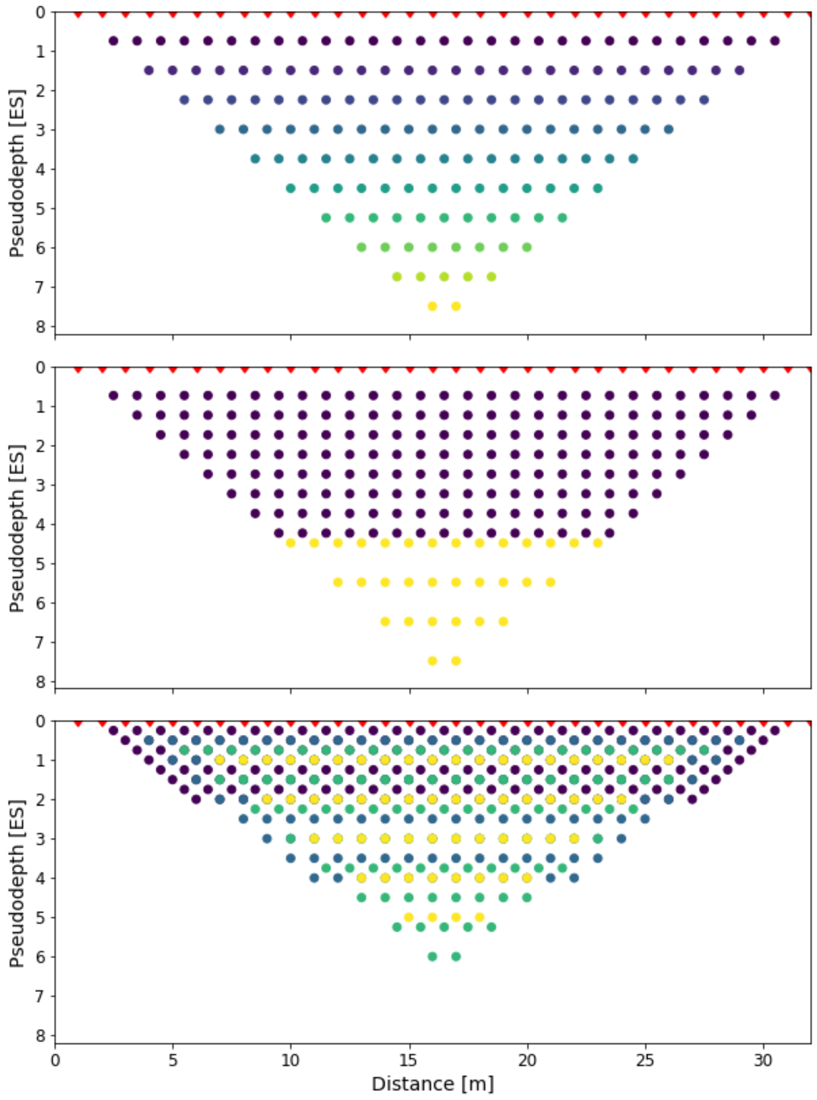
Example using AGI Supersting

Wenner
- Measurements: 155
- Time: 16 mins

Schlumberger
- Measurements: 208
- Time: 21 mins

Dipole-Dipole
- Measurements: 1108
- Time: 24 mins (112 min with 1 channel)

→ Effective use of multichannel instruments

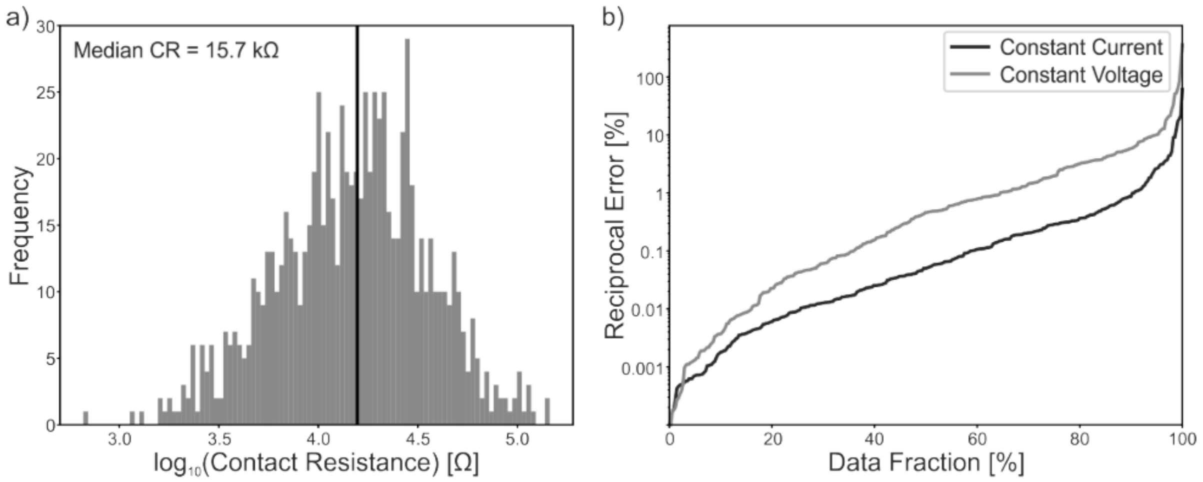


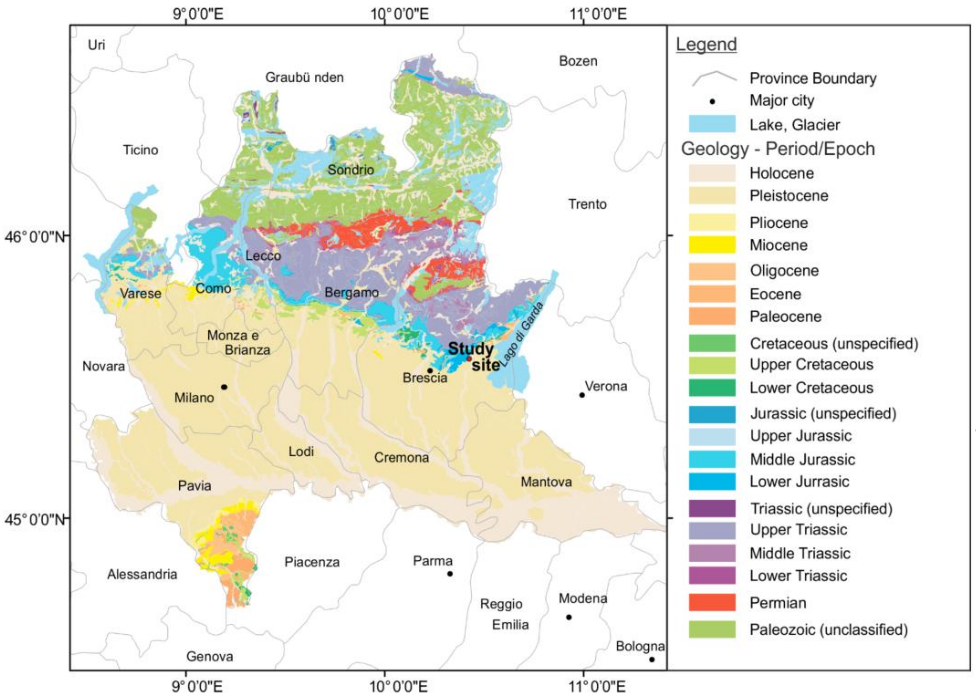
3D Survey Example

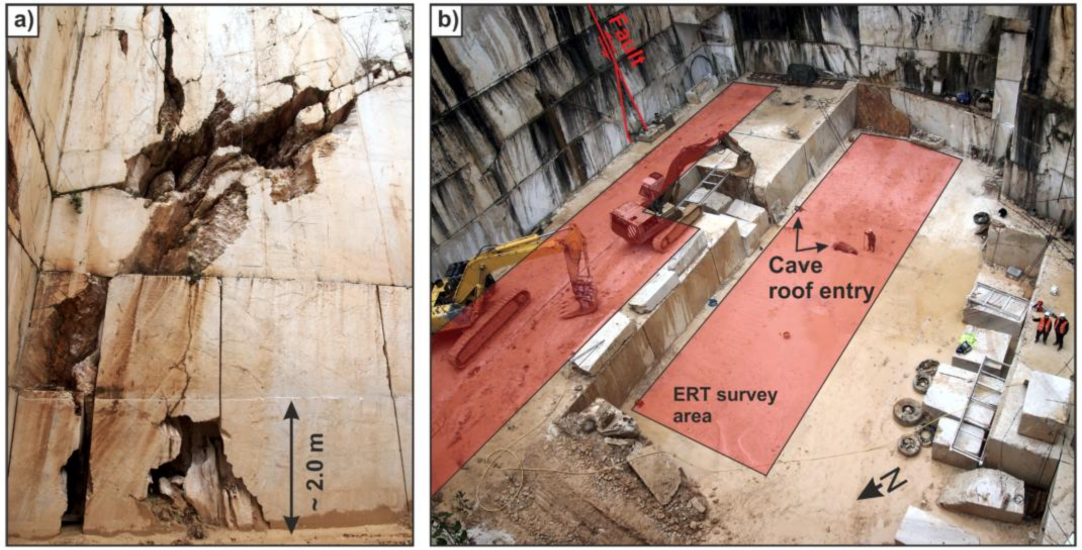
Geoelectrics to minimize mining risk

<u>Target:</u> Estimating the quality of natural stone and potential mining hazards

- Results of 3D dipole-dipole survey, 0.75 m electrode & line spacing, > 800 electrode locations
- > 18,500 Dipole-dipole survey measurement
- Challenging survey conditions
- Use stainless steel pin and plate electrodes







3D Survey Example

Measurement impressions

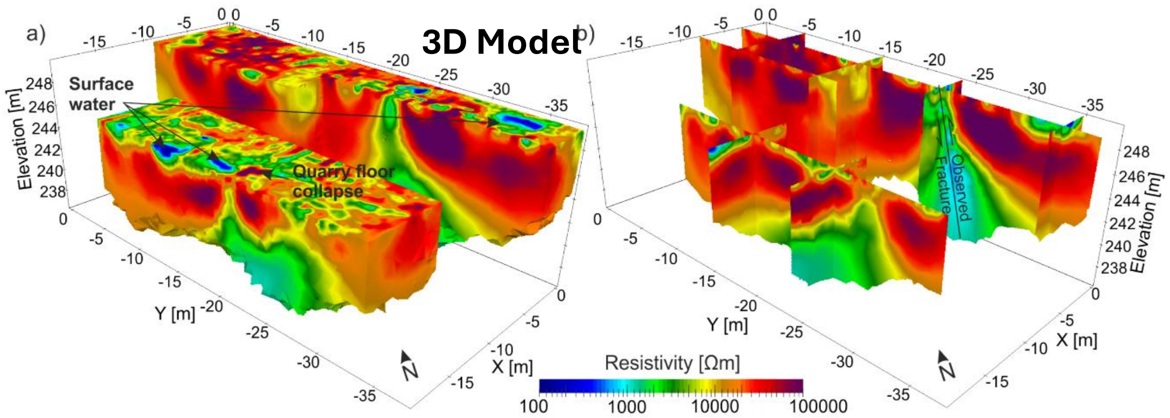
3D Survey Example

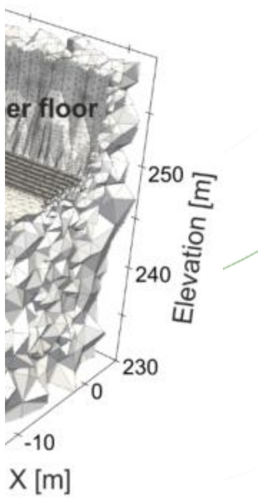
Resulting resistivity model

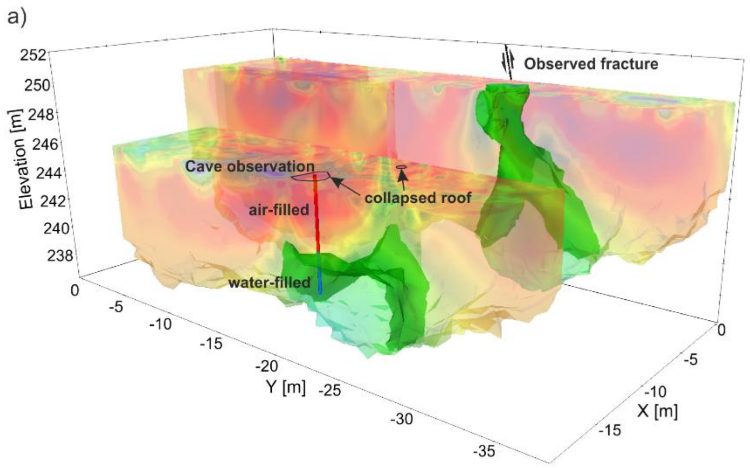
Target: Estimating the quality of natural stone and potential mining hazards

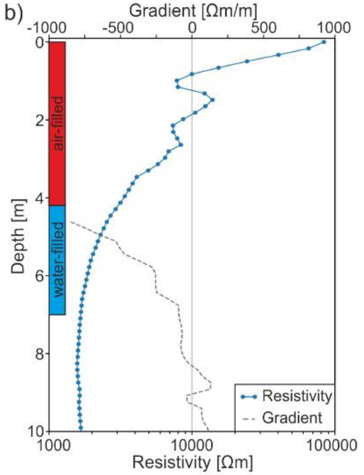
- **Complex inversion mesh (>1.5M cells)**
- Imaging of cave and fault system
- Good agreement with site observations

3D Model

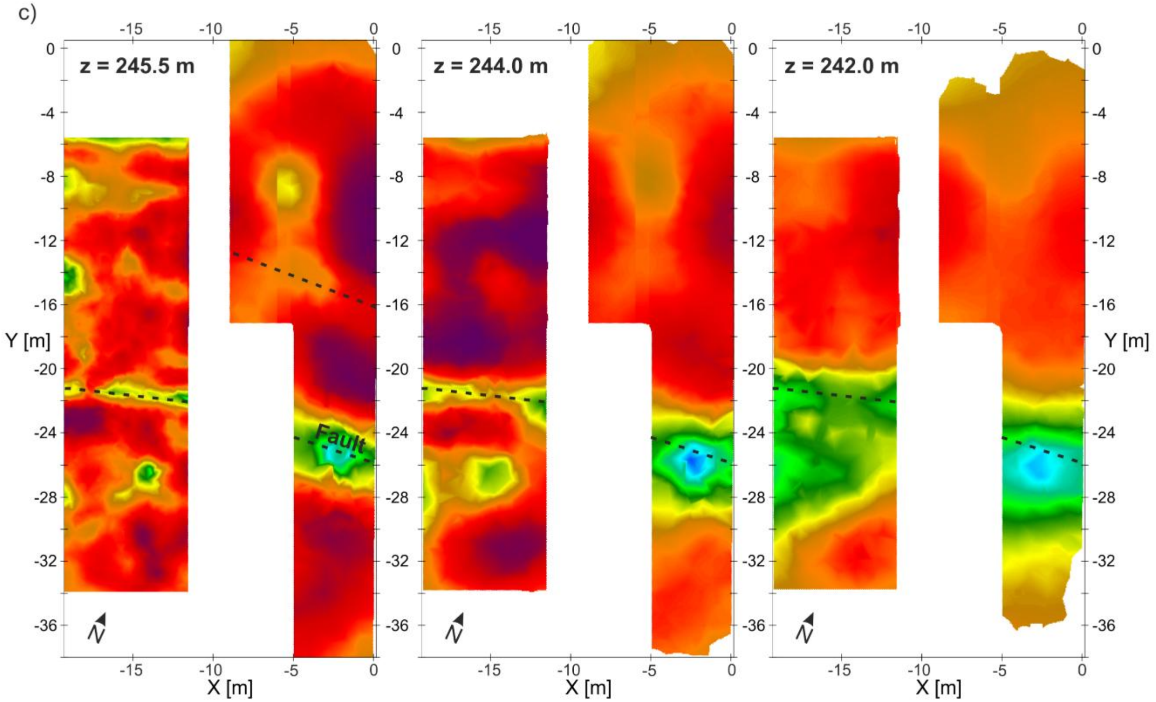






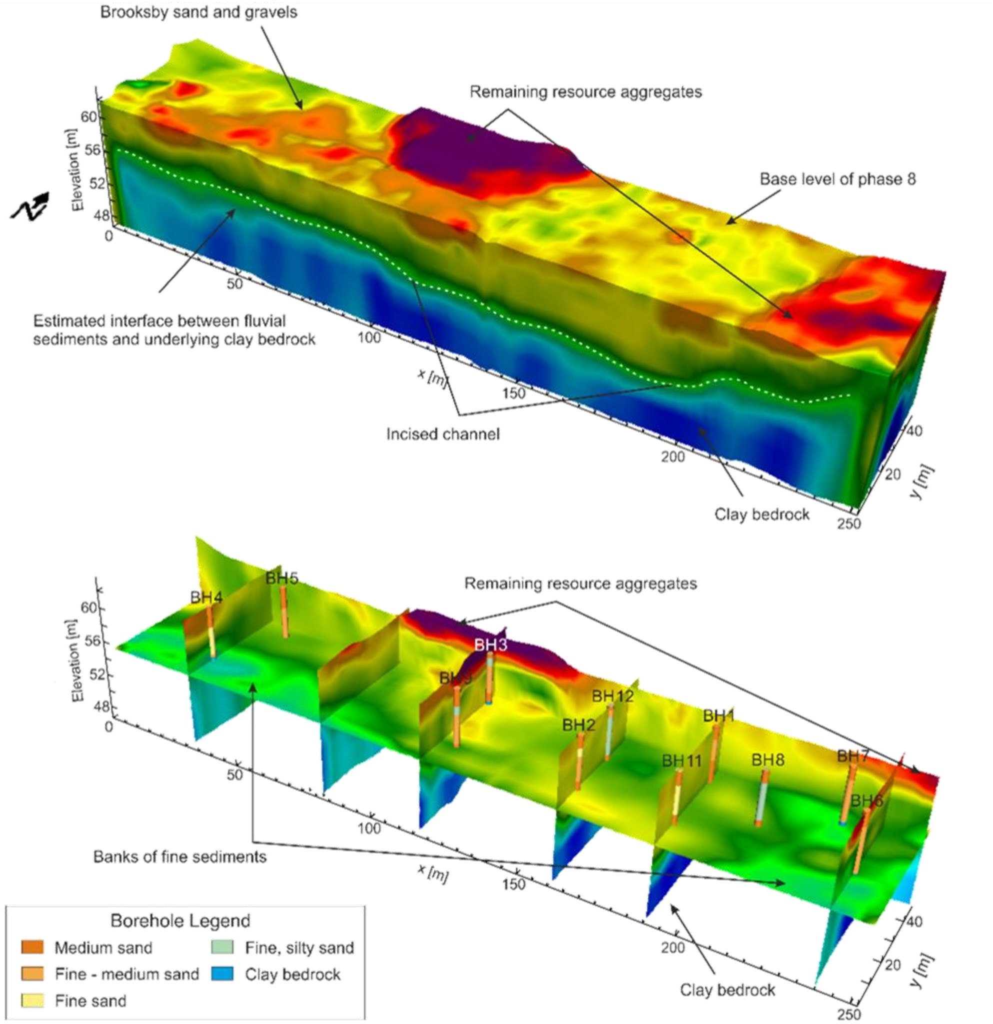


Resistivity at observation point



Horizontal slices through 3D model

Summary Resistivity Measurements



What you should have learned

1. We measure the electrical resistivity of the ground
   - Inject a current → measure the resulting potential
   - The resistance measurement depends on the location of the electrodes
   - Apparent resistivity assumes a homogeneous ground
2. Imaging uses modelling and inversion to create an image of the ground
   - Blurry, smooth boundaries
3. Interpreting the resistivity without additional information can be challenging

ITINERIS

Airborne Exploration

Electromagnetic Methods

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

Electromagnetic methods

Brief overview

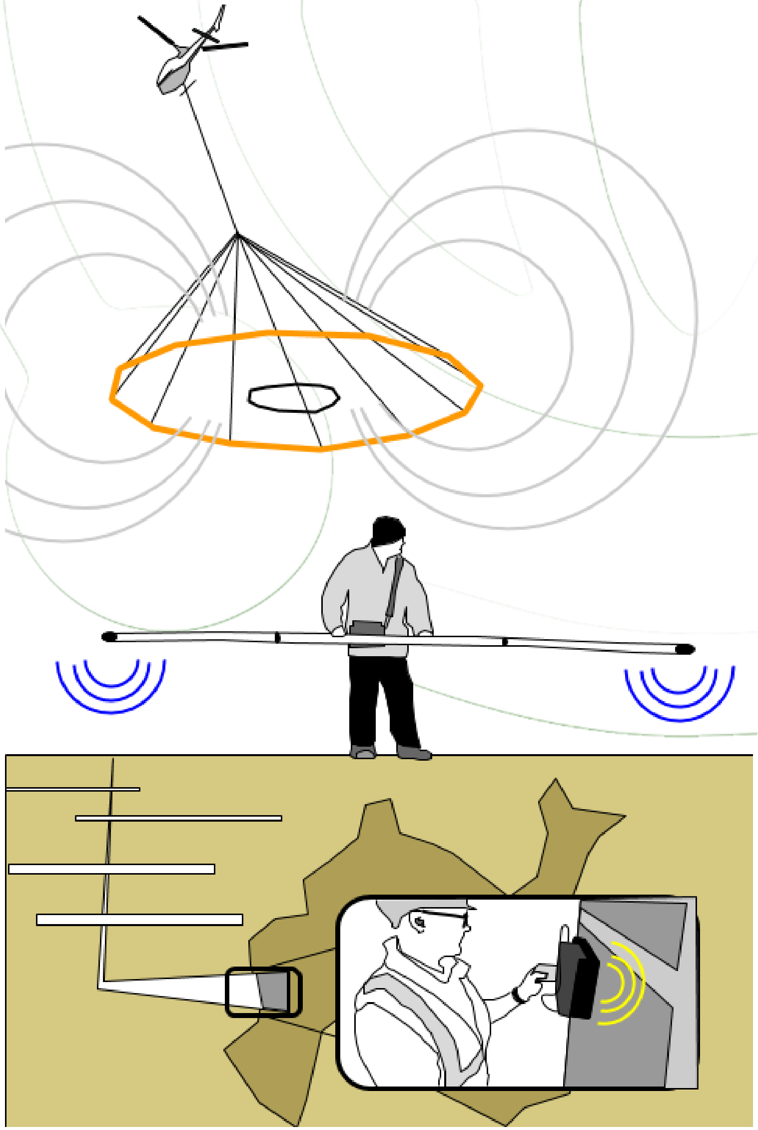
EM methods have played an important role in mineral exploration since at least the early 1960s.

A wide range of EM systems have been designed over the years, varying in size, source functions and receiver-transmitter configurations.

The great variety of surveys is reflective of the scalability EM methods

EM data can be acquired at the

- Centimeter scale (mine tunnels, structures)
- Meter scale (ground survey)
- Kilometers (airborne, towed & water borne)



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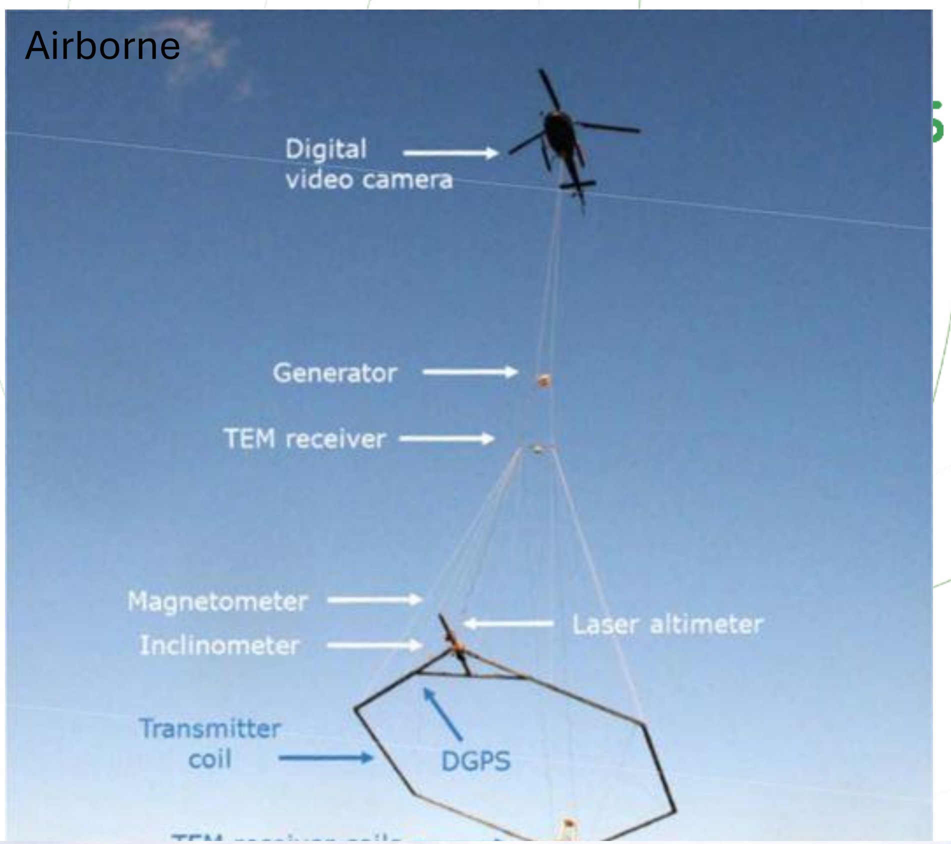
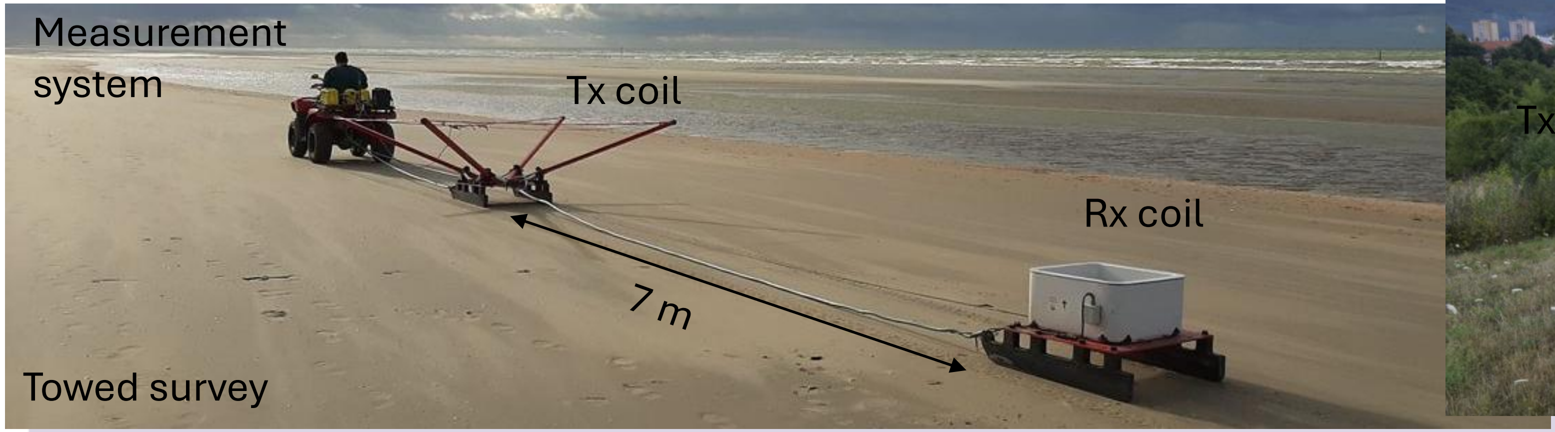




Electromagnetic surveys
Measurement principle

For geophysical applications, frequencies of the primary alternating field are usually less than a few thousands Hz

- Wavelength primary field: 10 – 100 km
- Typical source-receiver distance: 1 – 100+ m

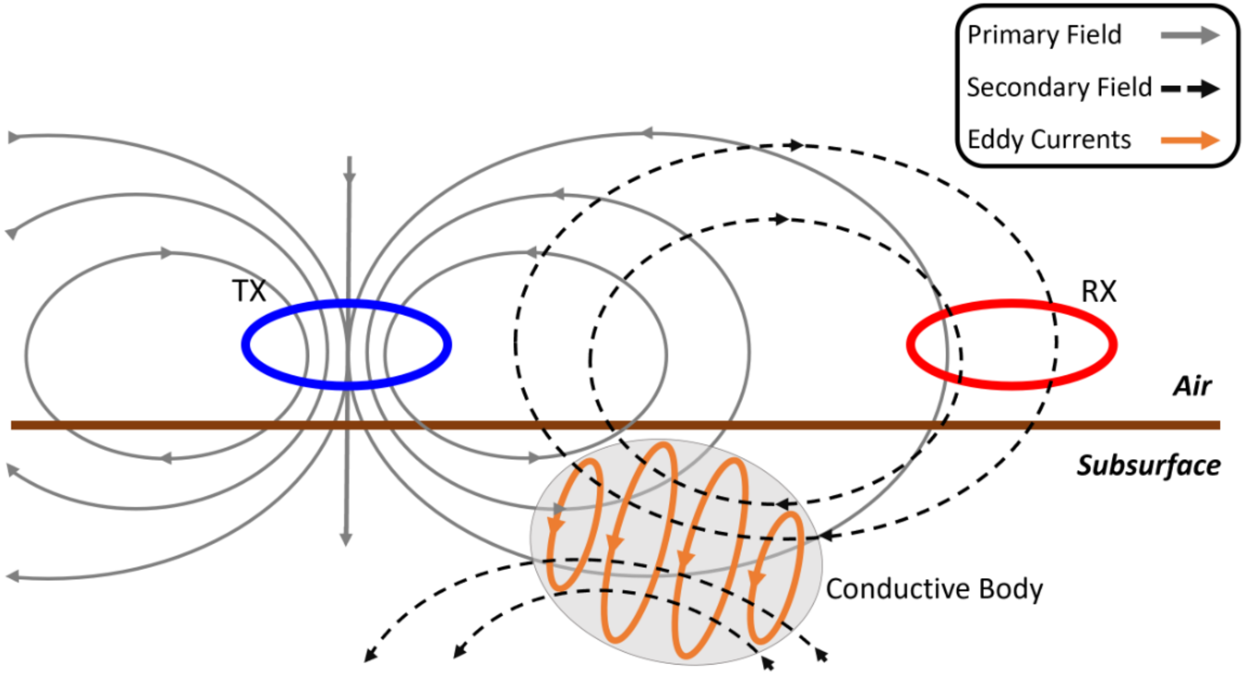
→ Propagation of primary wave and associated wave attenuation can be neglected

A transmitter coil is used to generate a primary EM field that propagates above and below ground

If a conductive body is present in the ground, the magnetic component of the primary EM field is inducing eddy currents within the conductor

These eddy currents generate their own secondary EM field

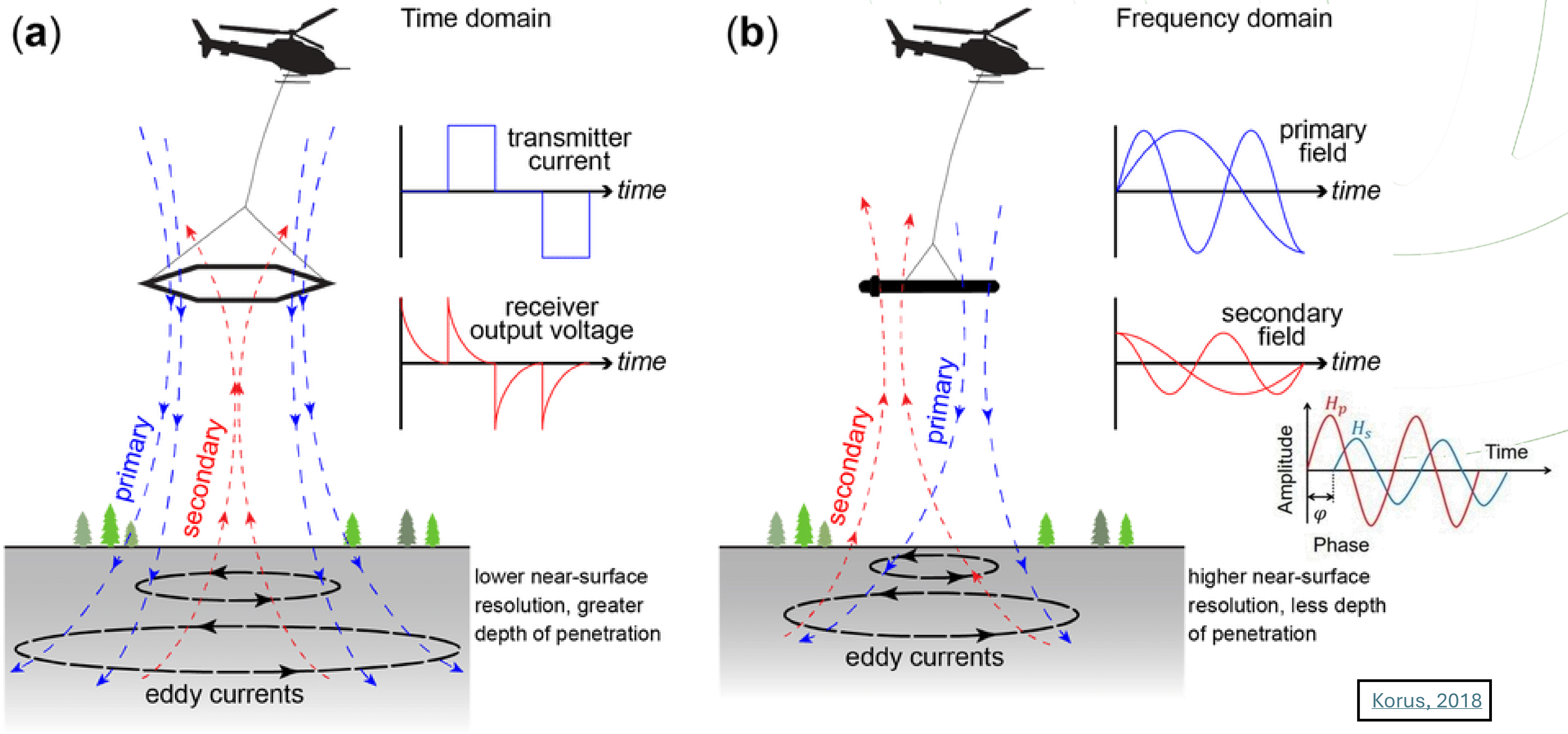
The receiver detects a combined response of the primary and secondary EM fields



Wilson et al., 2022

Frequency and time-domain electromagnetics

The two main methods for performing electromagnetic measurements



Korus, 2018

Electromagnetic measurements

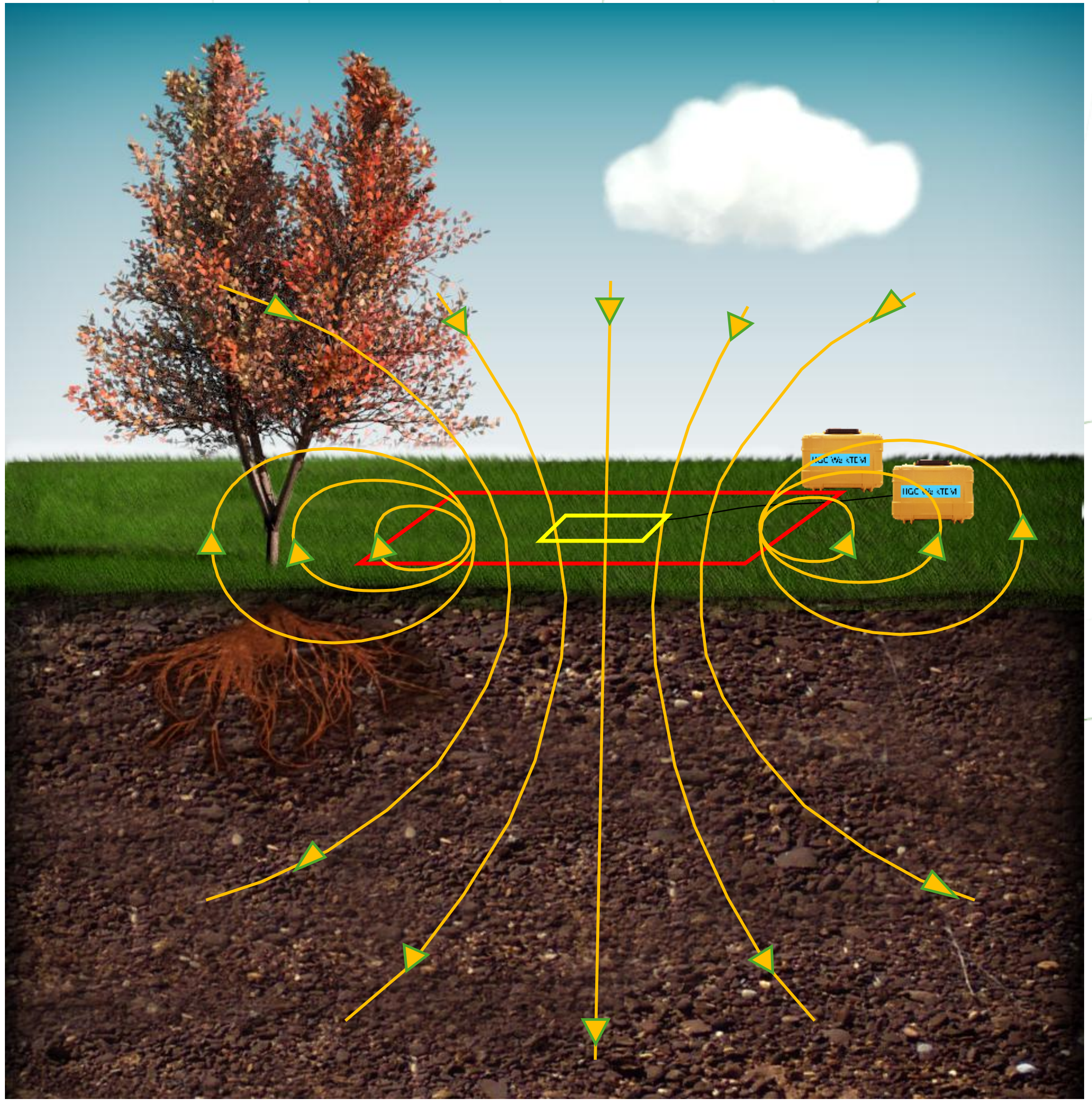
Propagation of EM fields – Time-domain

- Transmitter (Tx) and receiver (Rx)

Electromagnetic measurements

Propagation of EM fields – Time-domain

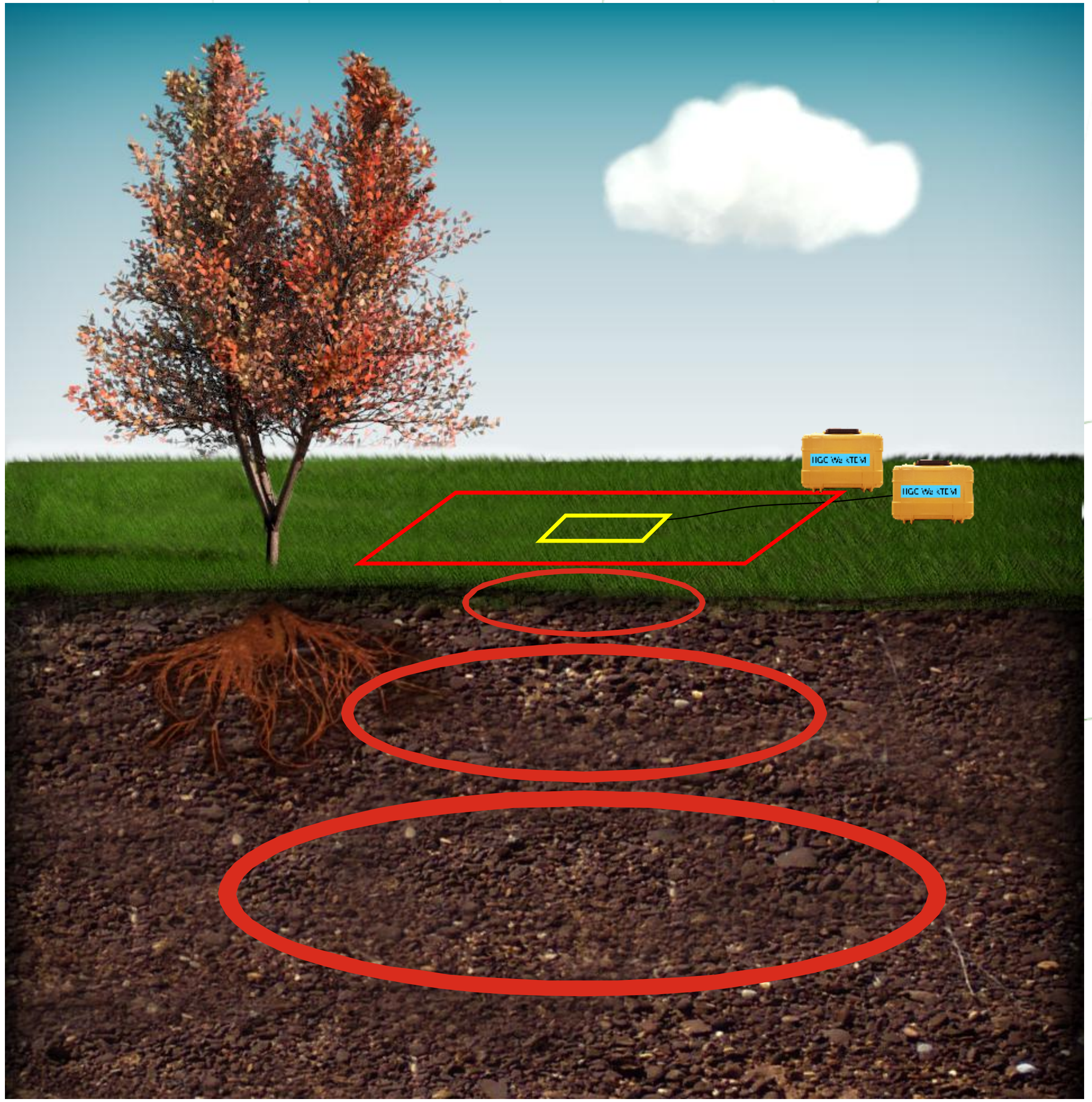
- Transmitter (Tx) and receiver (Rx)
- Phase 1 : Transmit
  - Steady current is transmitted in Tx-loop → primary magnetic field



Electromagnetic measurements

Propagation of EM fields – Time-domain

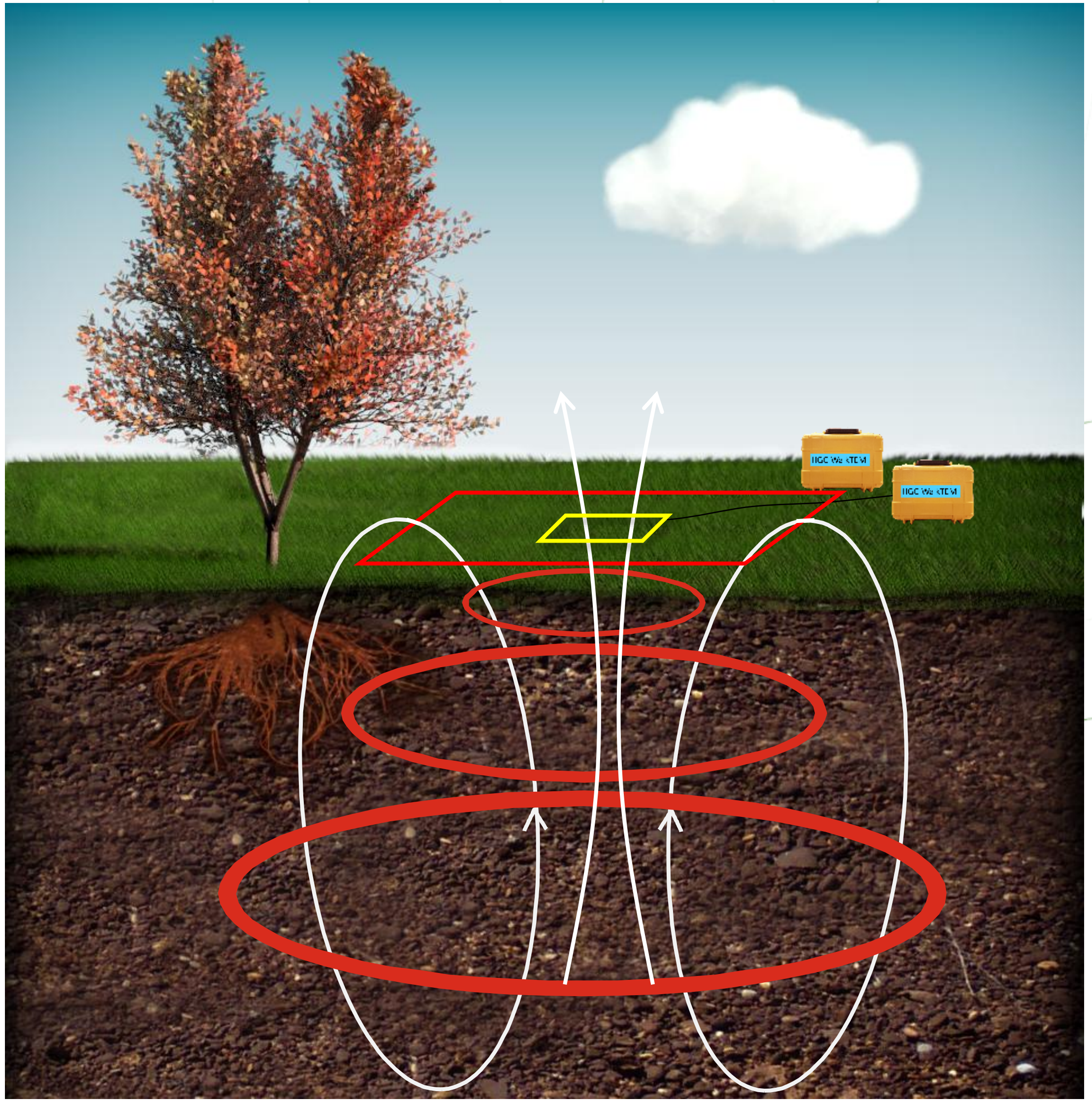
- Transmitter (Tx) and receiver (Rx)
- Phase 1 : Transmit
  - Steady current is transmitted in Tx-loop → primary magnetic field
- Phase 2 : Transmitter shut-off
  - Current is shut-off → induce inductive eddy currents in the subsurface



Electromagnetic measurements

Propagation of EM fields – Time-domain

- Transmitter (Tx) and receiver (Rx)
- Phase 1 : Transmit
  - Steady current is transmitted in Tx-loop → primary magnetic field
- Phase 2 : Transmitter shut-off
  - Current is shut-off → induce inductive eddy currents in the subsurface
- Phase 3 : Receive
  - Secondary magnetic field → induced in the receiver coil



Difference between ERT and EM methods

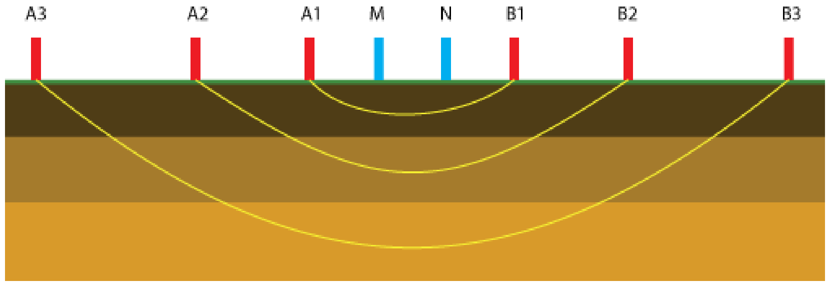
Practical consideration

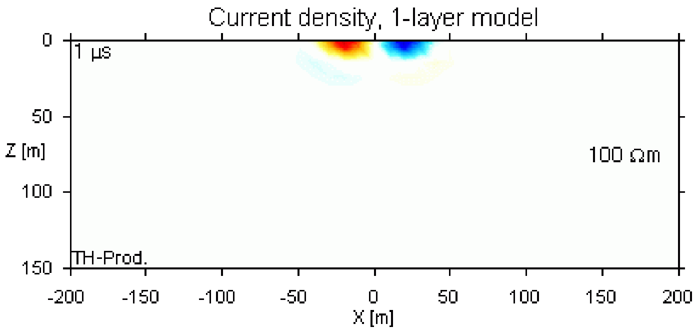
- No direct current injection into the ground (i.e., inductive versus galvanic)
- Measure voltages in receive coil, not voltage difference between two electrodes
- Practical: Use loops/coils of wire instead of long cables/electrodes

Galvanic coupling

Inductive coupling

- 1 TEM (sometimes also FDEM) measurement gives full depth profile using a single coil layout
- VES requires many electrode separations to encode depth information





Time-domain electromagnetics

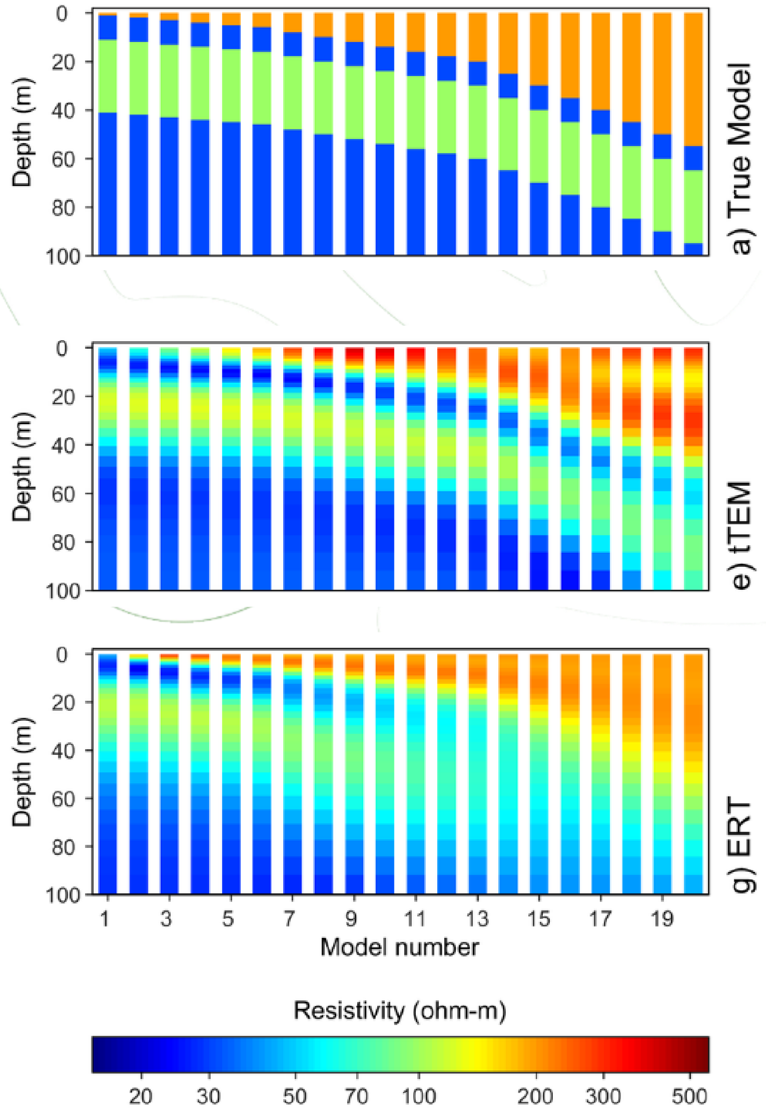
Sensitivity to resistors and conductors

- EM methods (TEM & FDEM) are sensitive to conductors (due to eddy currents creating secondary field)
- ERT directly measures the resistivity of the ground -> higher sensitivity to resistors

EM methods are more effective for:

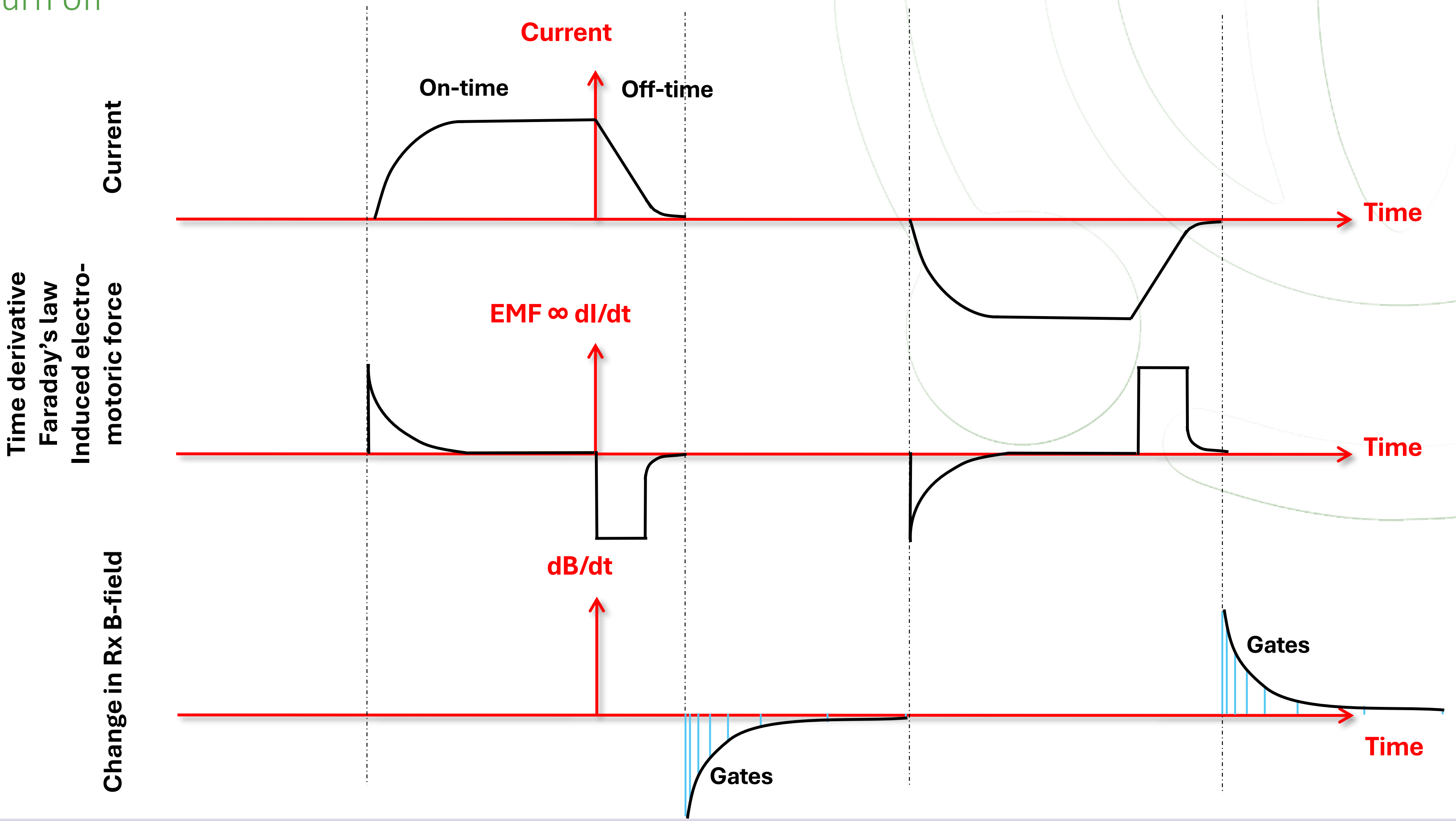
- Mapping groundwater
- Detection of metallic objects
- Investigating areas with high salinity

However, long-term monitoring using EM methods still challenging (sensitivity to coil orientation, height above the ground, system calibration, etc.)



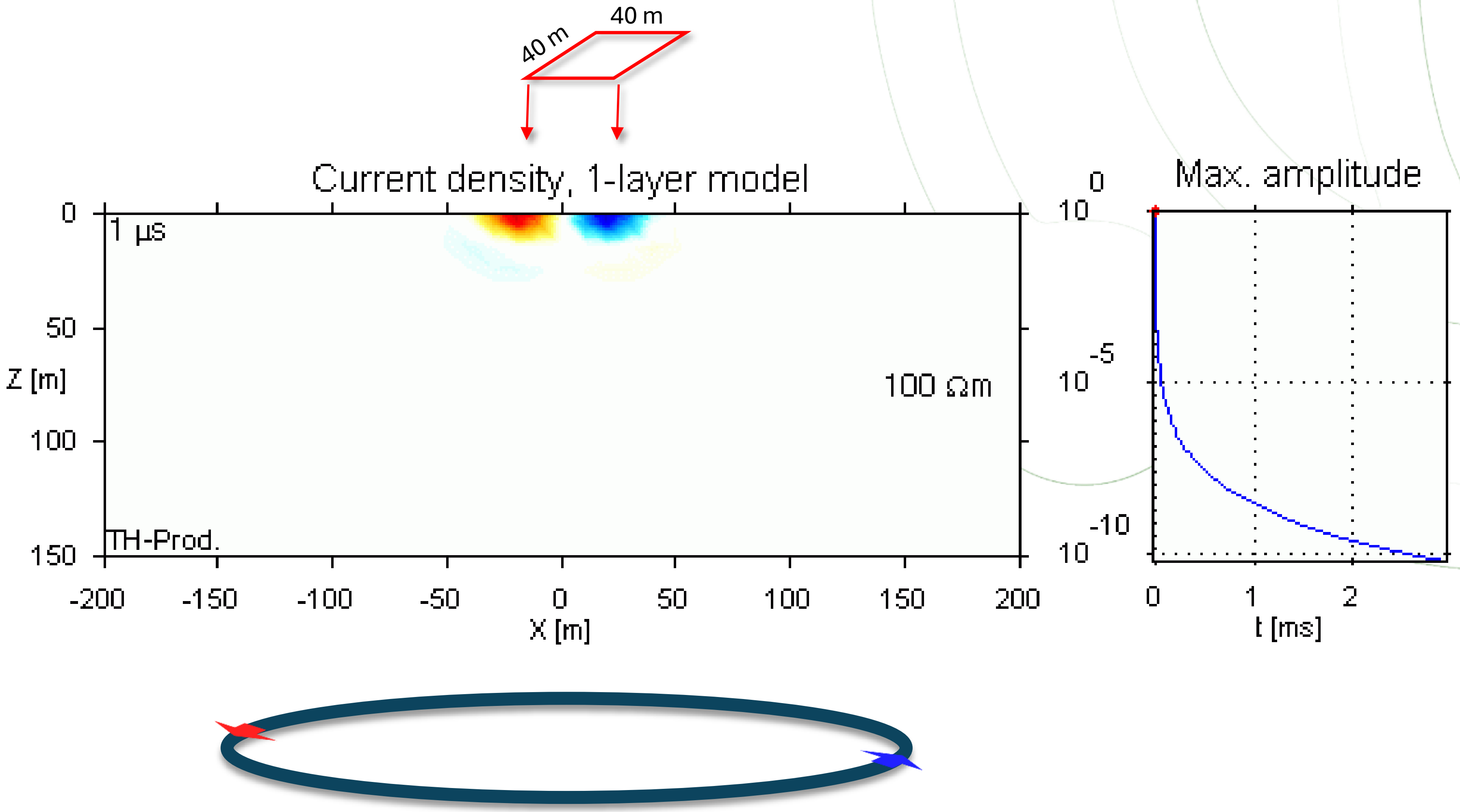
Electromagnetic surveys

Turn on and turn off



Current diffusion in the ground

100 Ωm halfspace

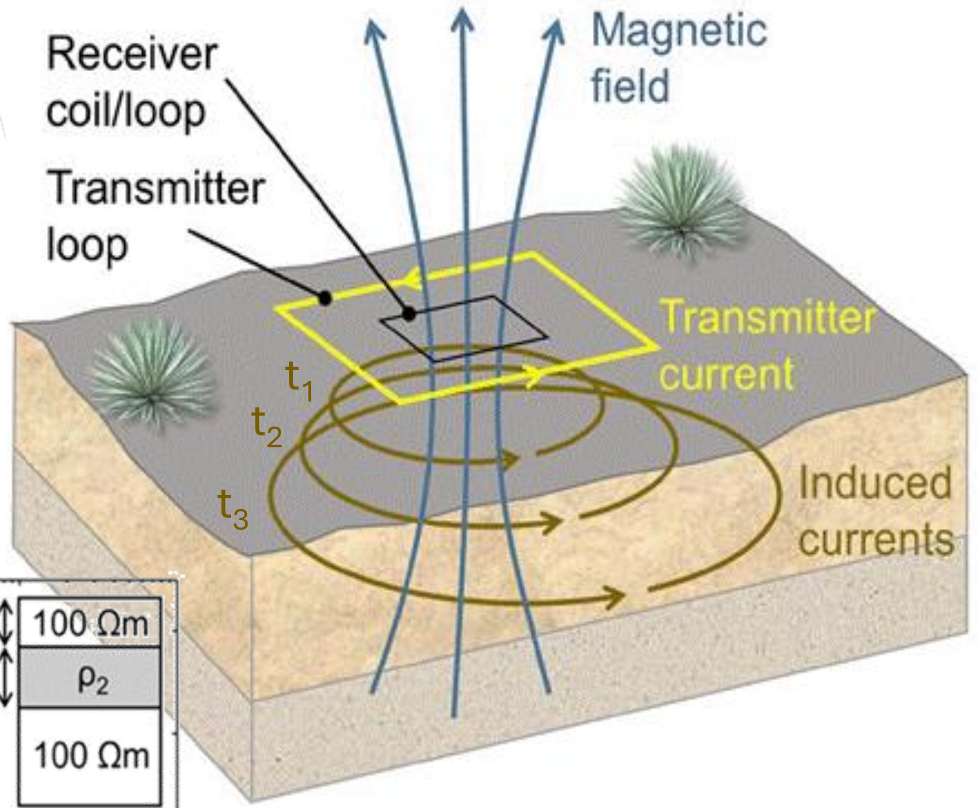


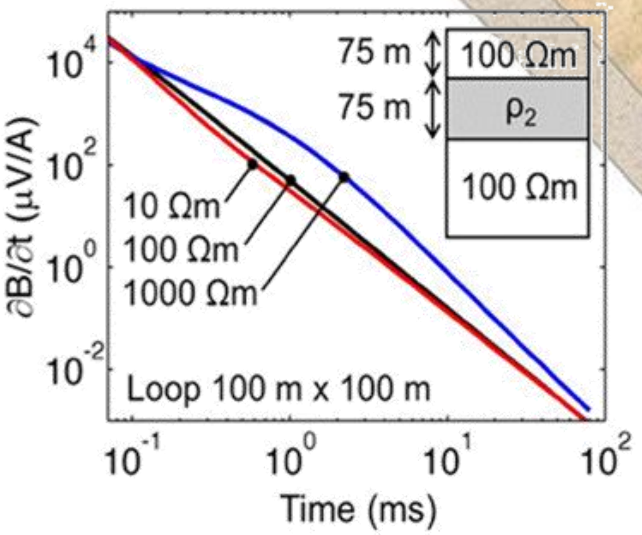
Circulating current

Current diffusion in the ground

General observations

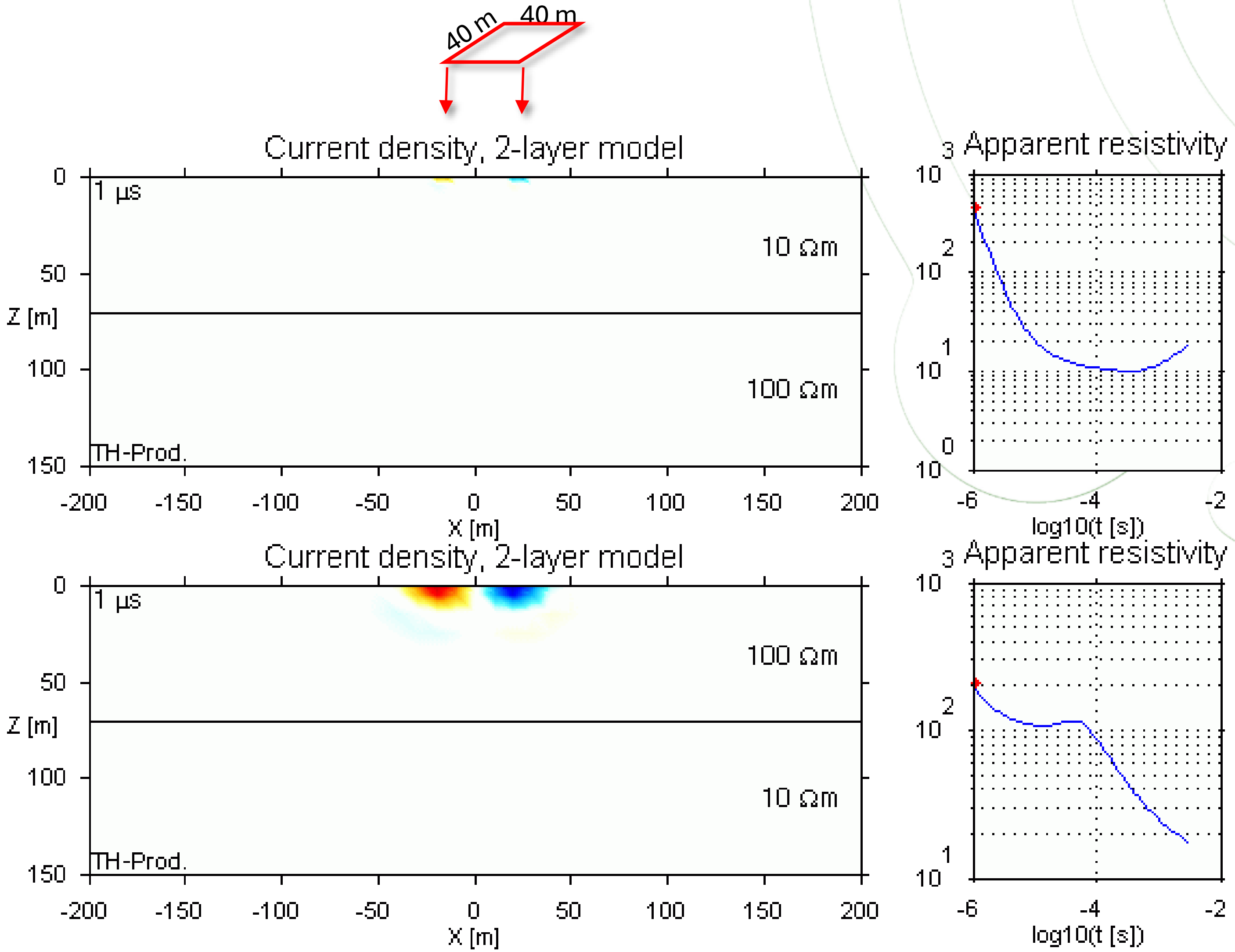
- Currents migrate downwards and outwards from the transmitter loop after turnoff
- Currents are initially concentrated at shallow depths
- Currents migrate to greater depths at larger times
- Voltages measured at different times after turn-off give information about different depths





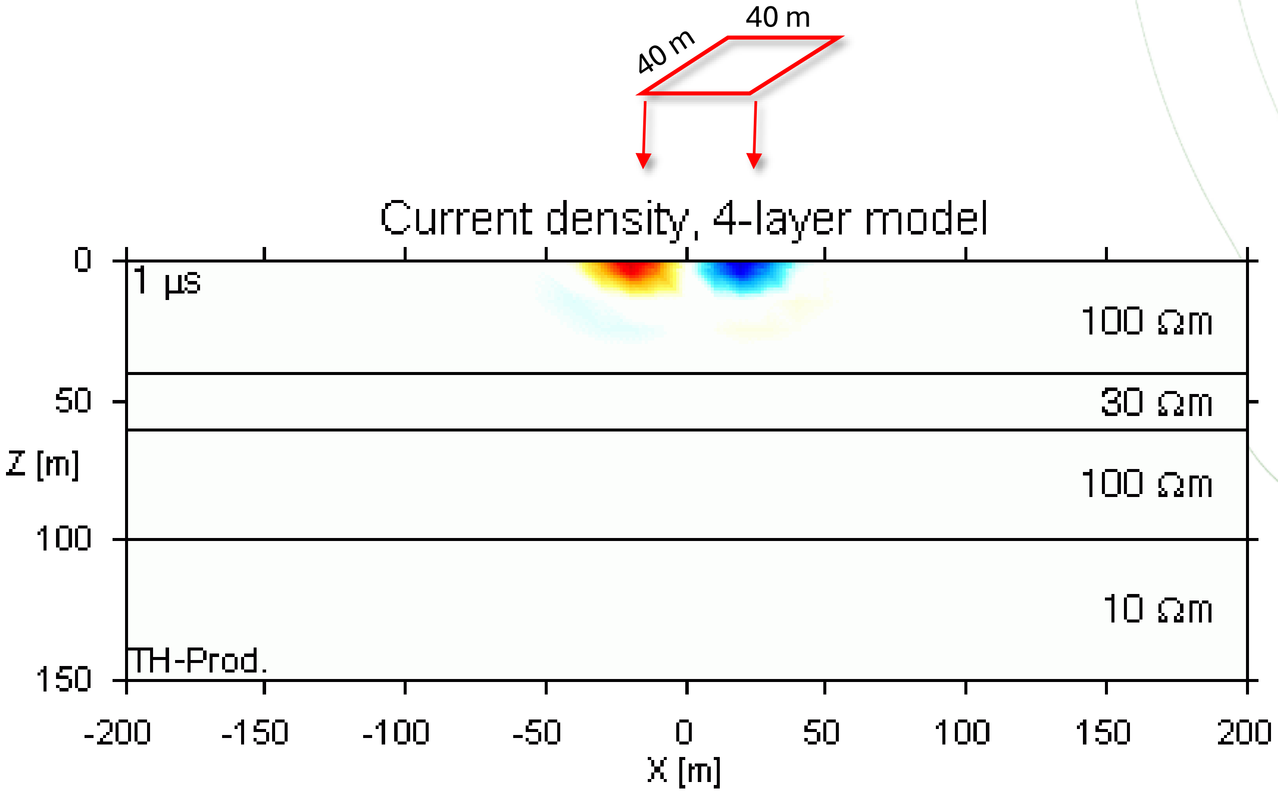
Characteristics of the decay curve

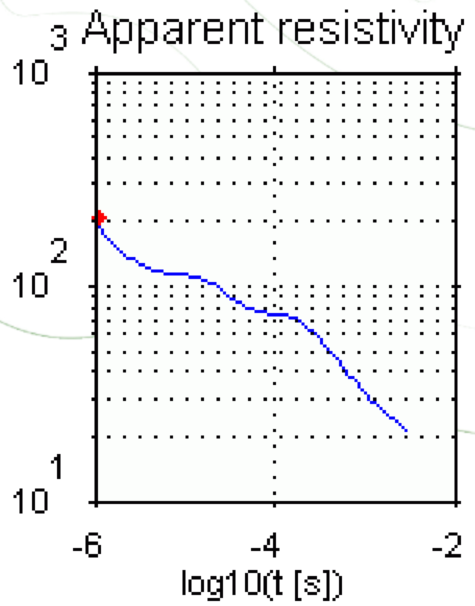
Current diffusion over 10 - 100 Ωm and 100 - 10 Ωm layered halfspace



Characteristics of the decay curve

Current diffusion over 100 – 30 – 100 – 10 Ωm layered halfspace

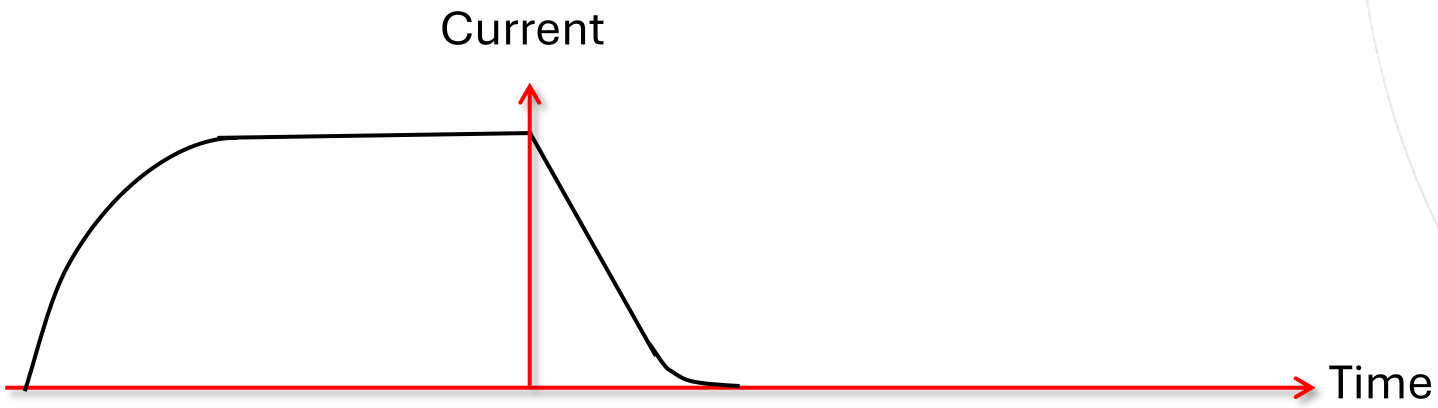


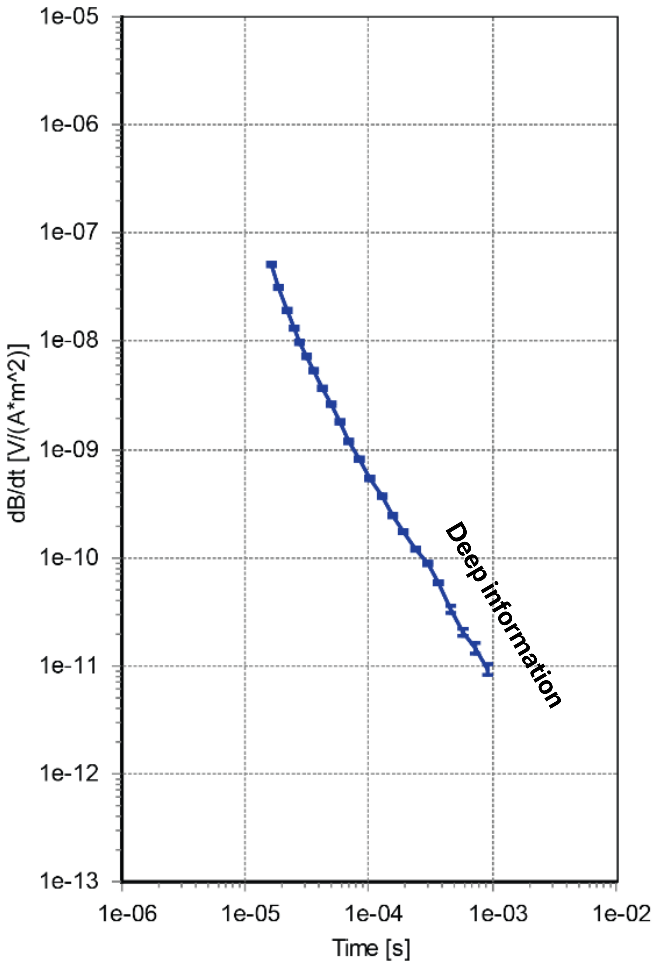


TEM is sensitive to conductive layers

TEM Response

Dual moment measurements

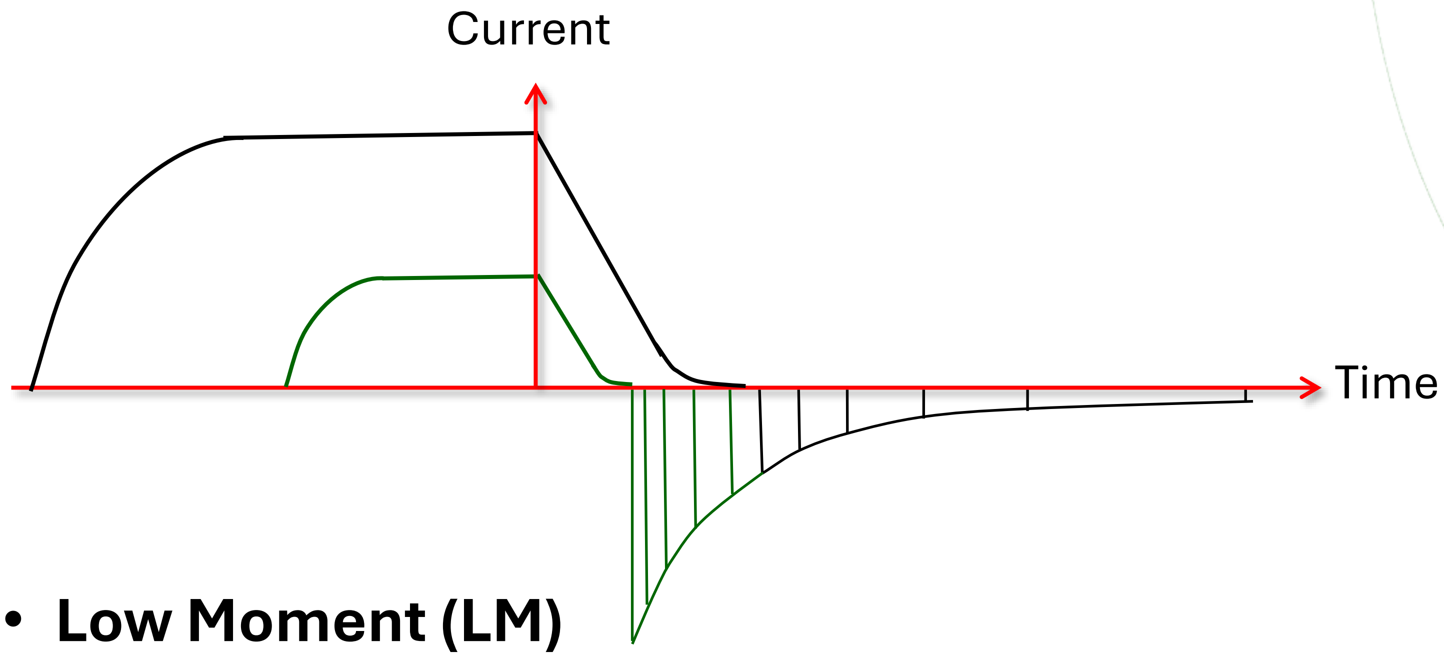




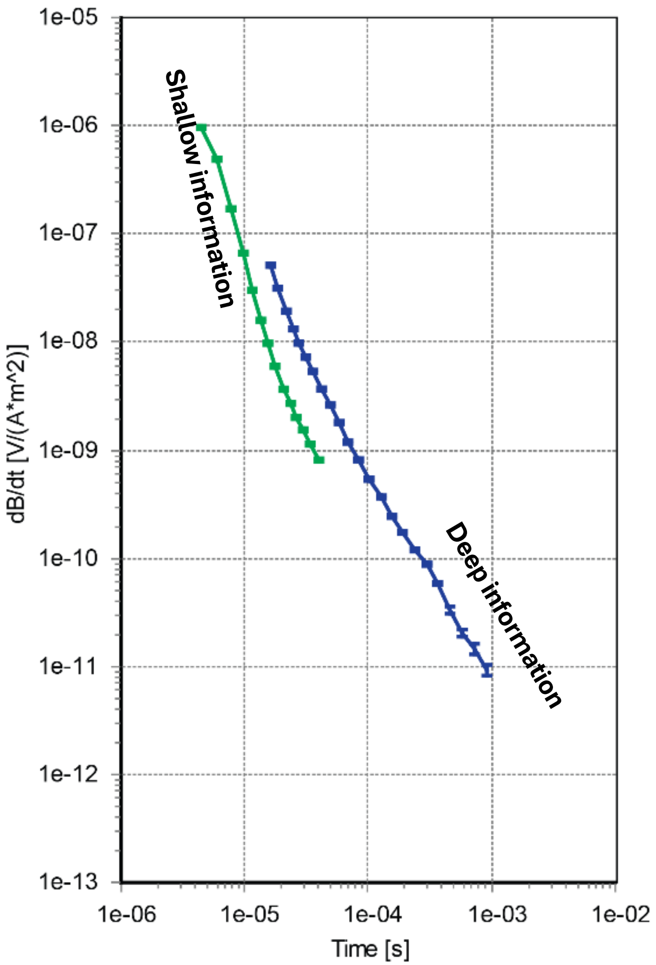
- **High Moment (HM)**
  - High Current
  - Slow turn-off
  - Deep information

TEM Response

Dual moment measurements

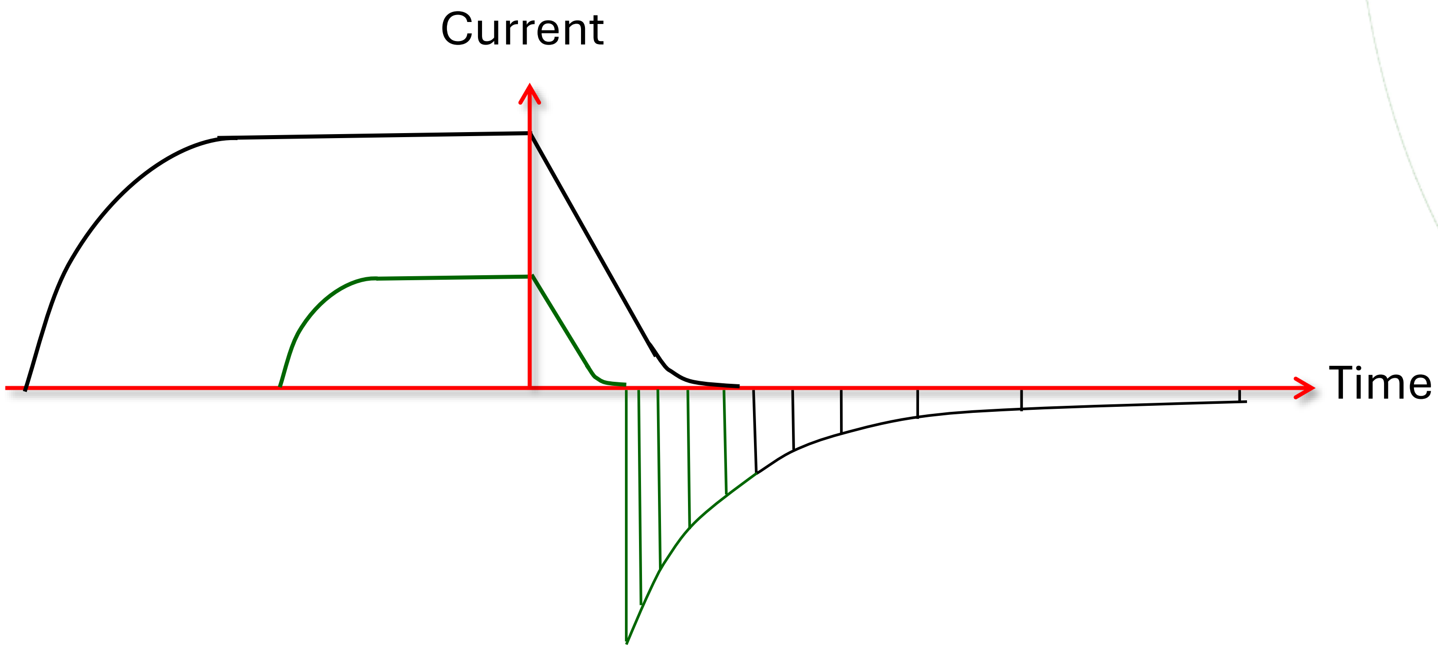


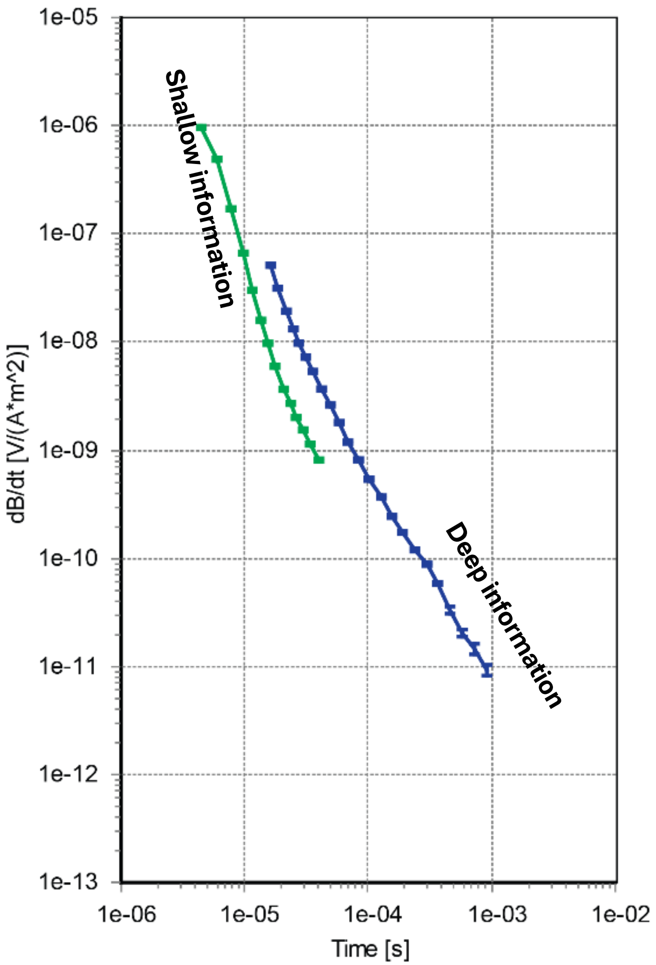
- **Low Moment (LM)**
  - Low Current
  - Fast turn-off
  - Shallow information



TEM Response

Interpretation

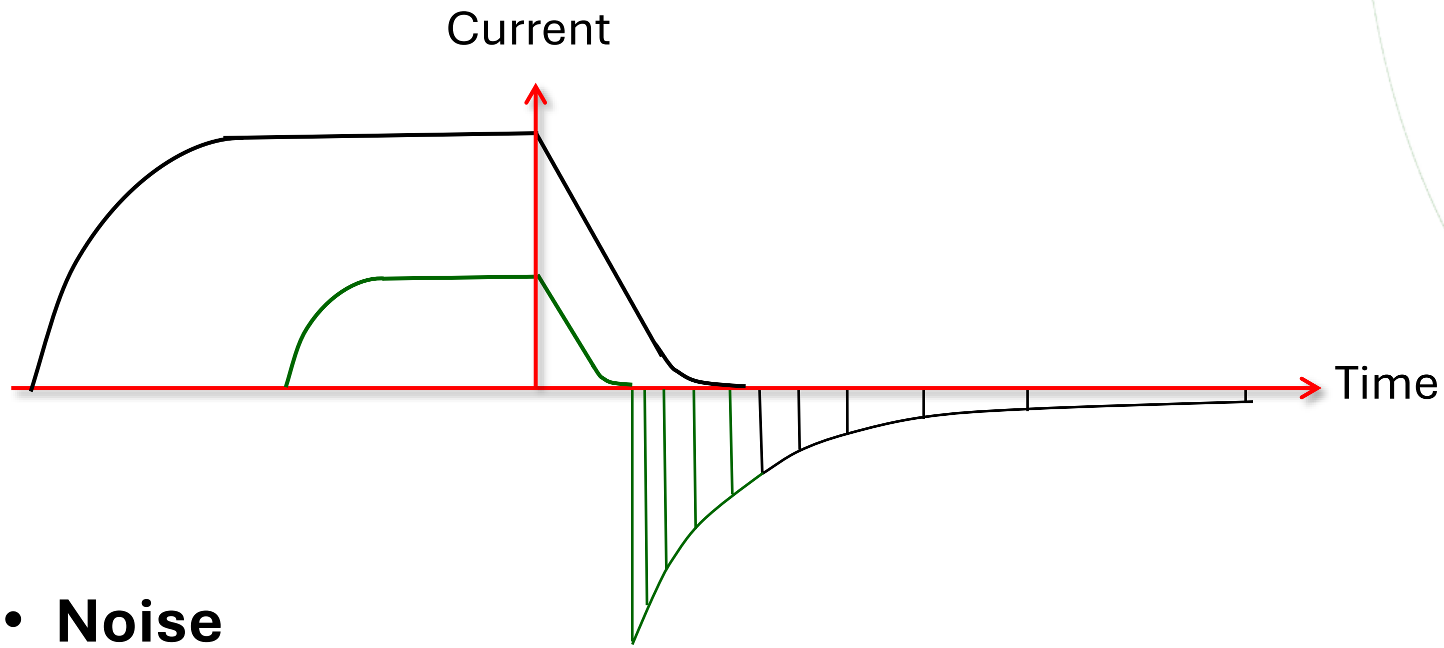


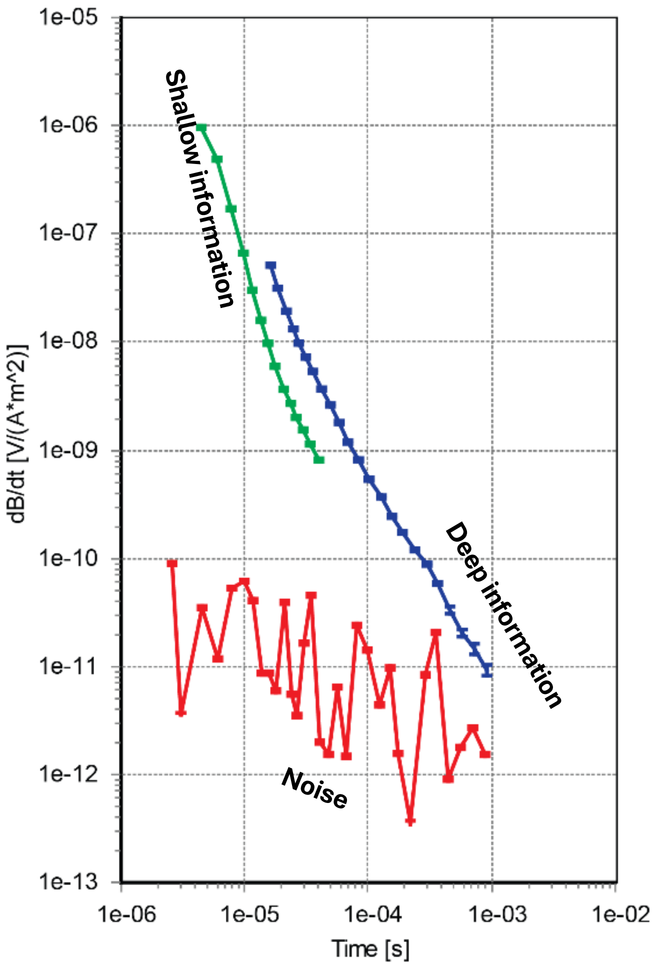


- **Dual Moment Acquisition**
  - Low moment for shallow resolution
  - High moment for deep penetration
  - Together they deliver better resolution over full depth column

TEM Response

Noise



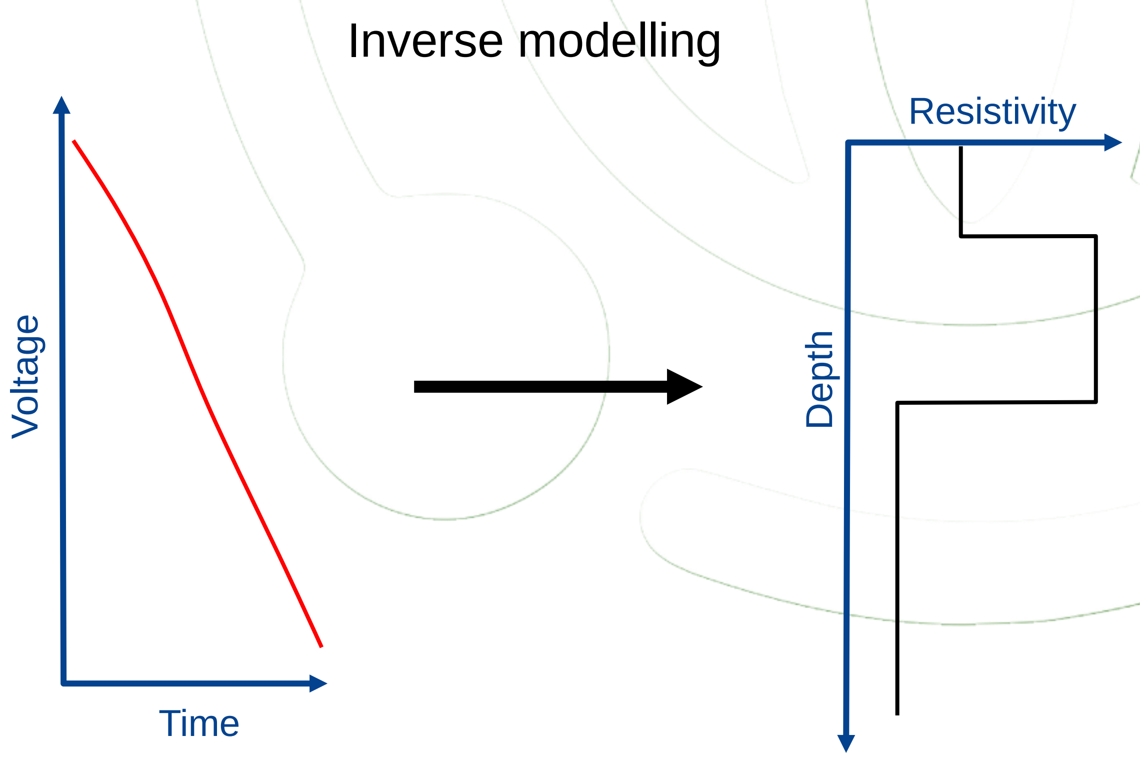


- **Noise**
  - Limiting depth of investigation (DOI)
  - Many sources of noise (anything producing a voltage on the receive coil)

Earth models

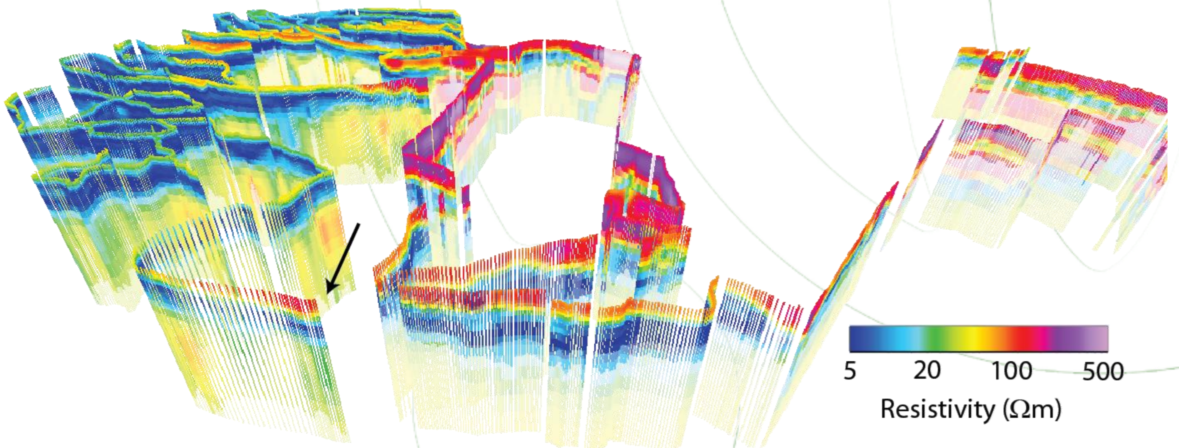
1D Assumption

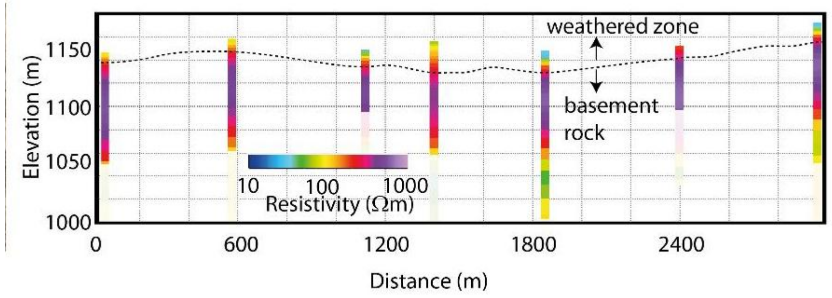
- **The Earth is described by a 1D set of layers of varying resistivity** (1D model or resistivity depth profile)
- This 1D model can change at different locations – but we assume for each individual measurement it is a 1D earth responsible for our signal
- **This is an assumption – it will breakdown in complex geologies**

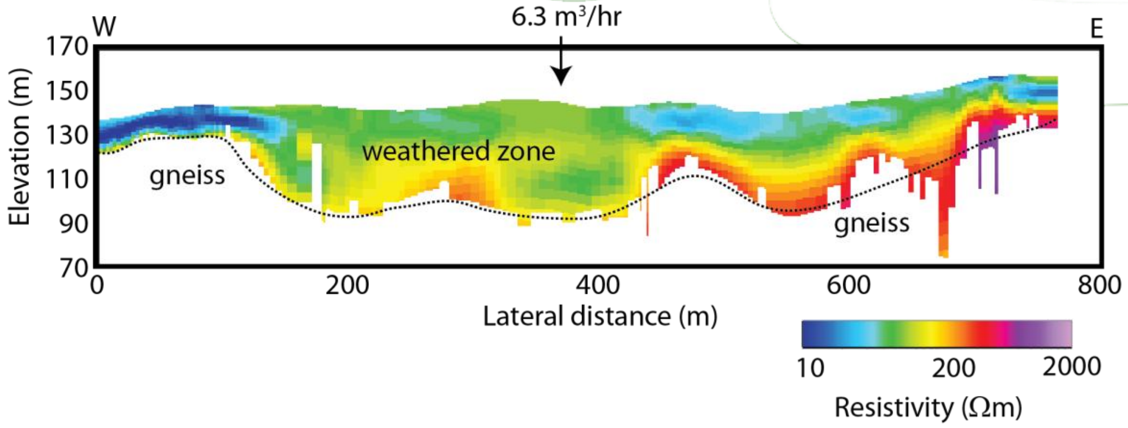


Earth models
2D/3D representation

- **Create quasi-2D/3D earth models by stitching together 1D models**
- **2D/3D models built on a 1D assumption**







Earth models

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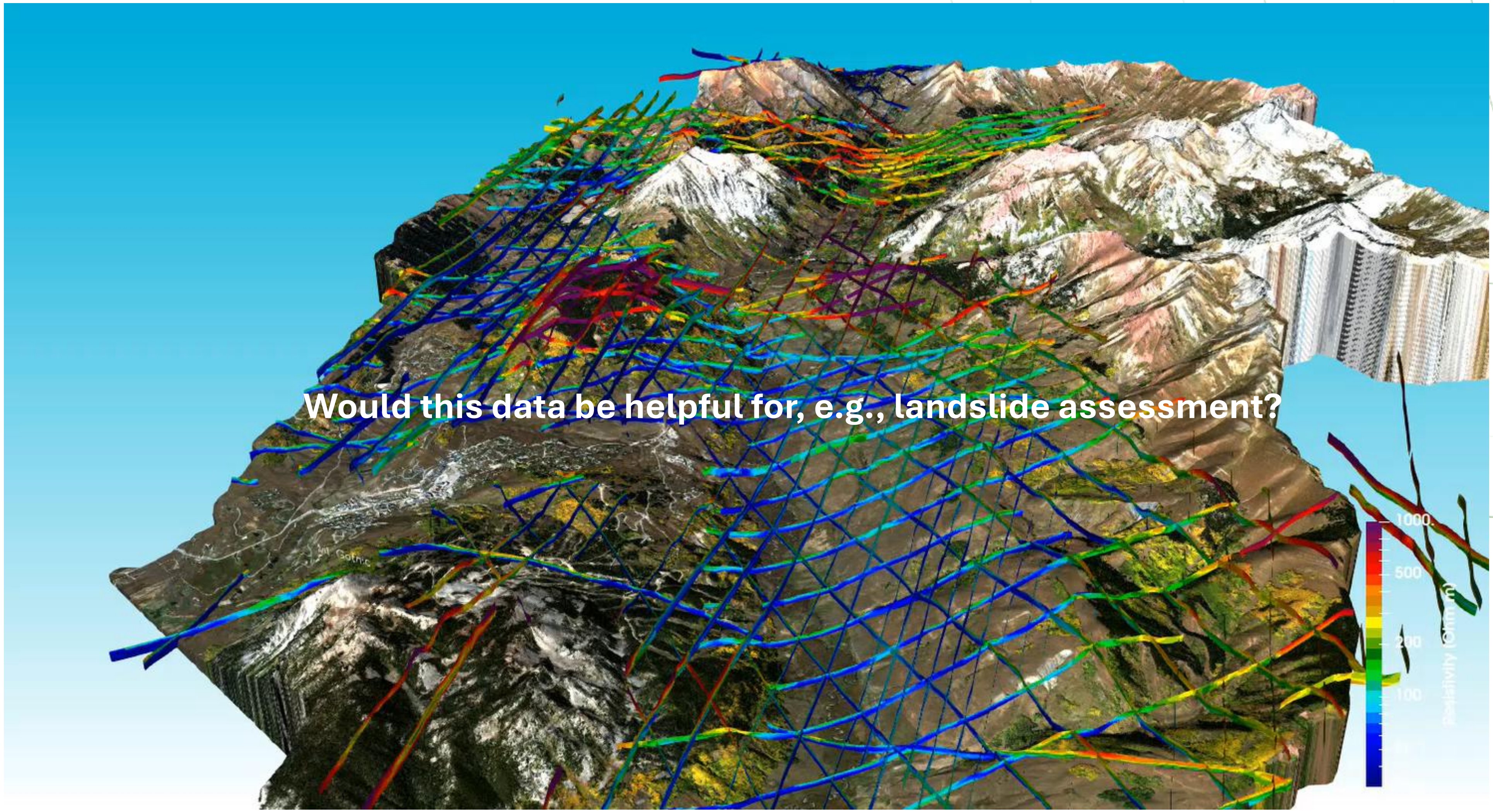
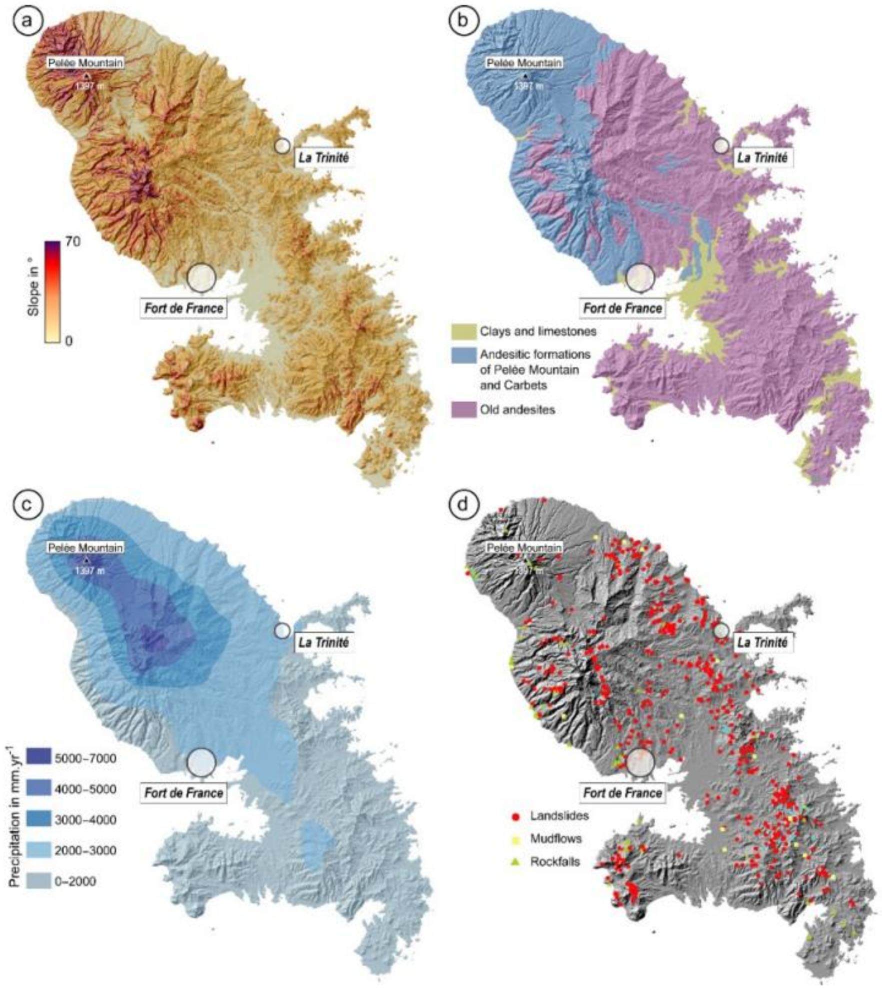
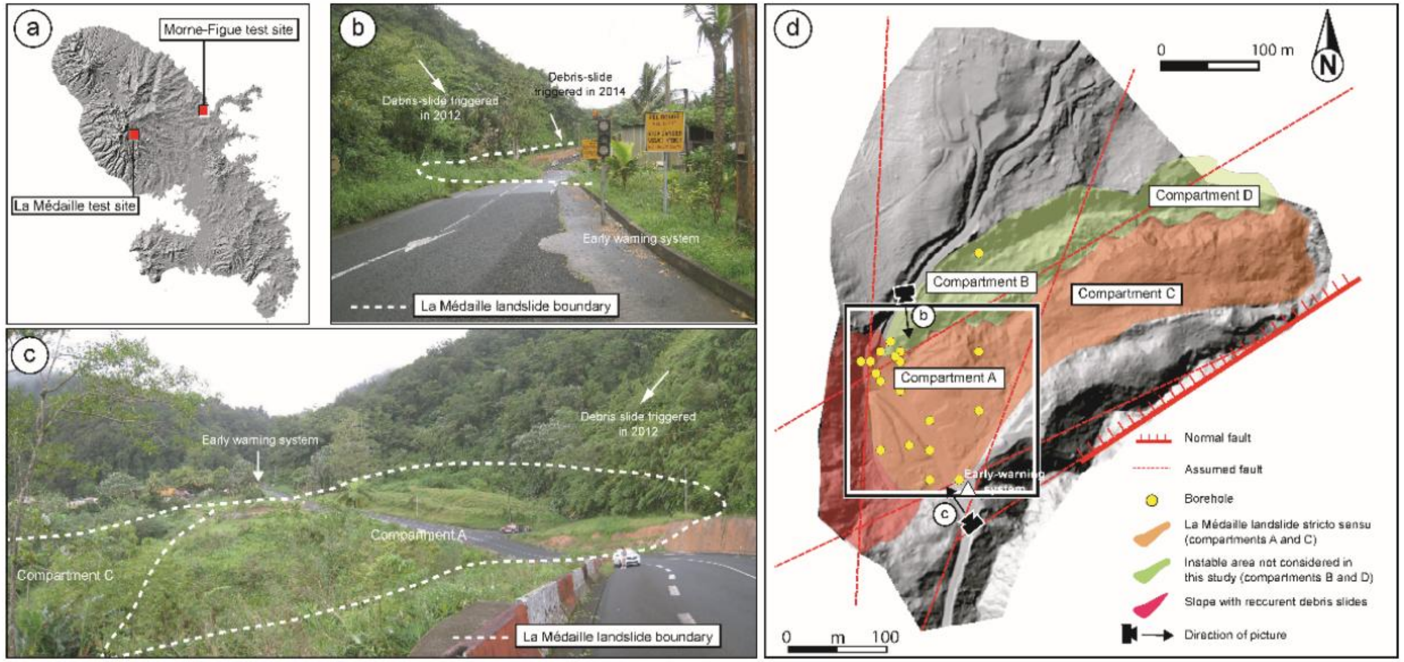


Landslide hazard assessment on La Martinique

Settings





Thiery et al., 2021

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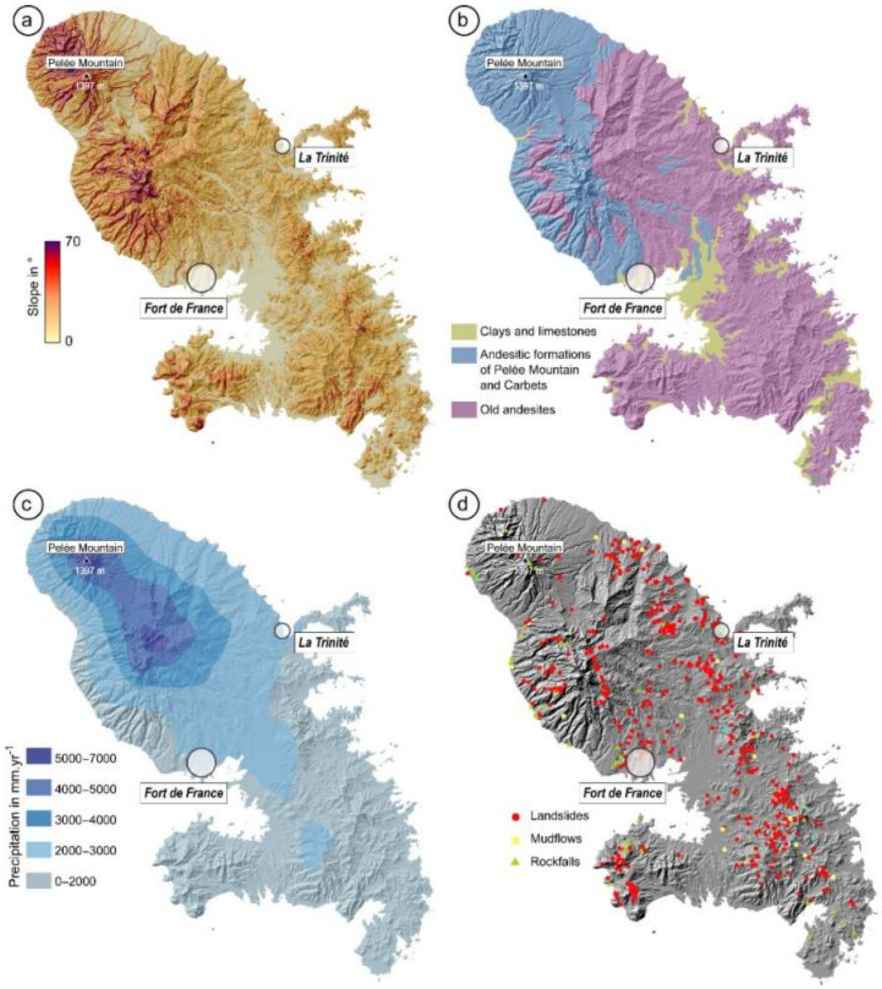
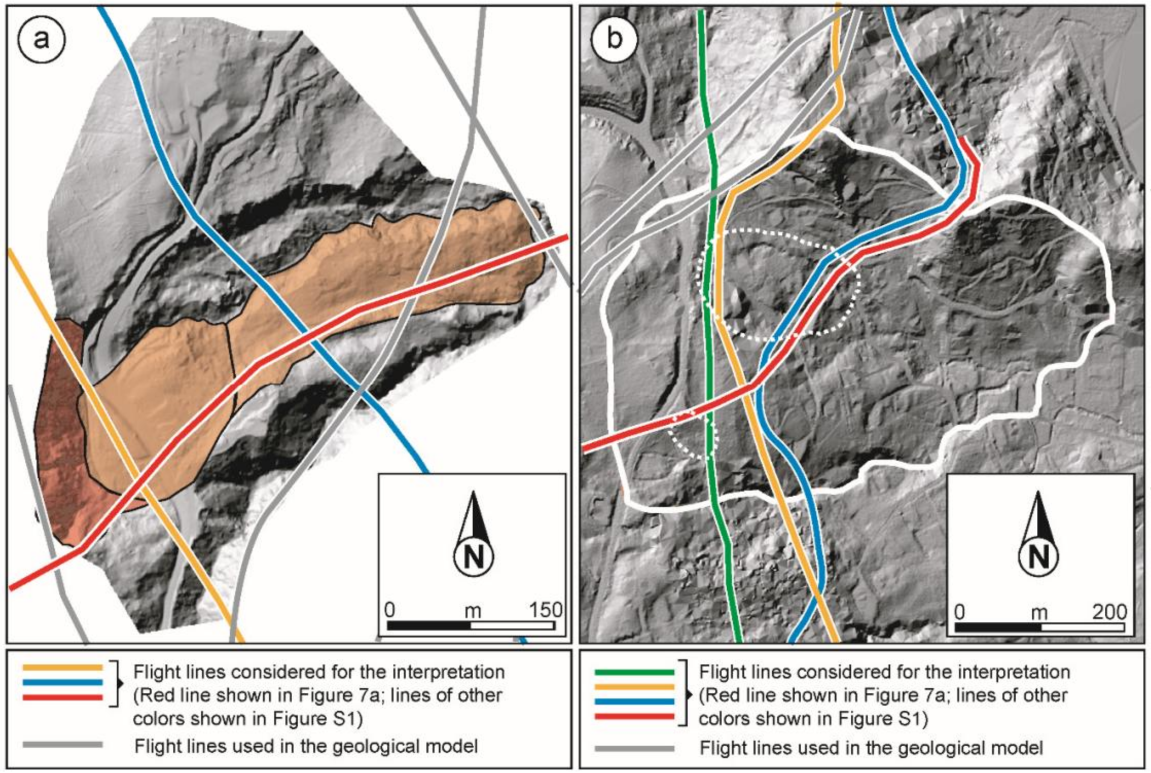
Settings

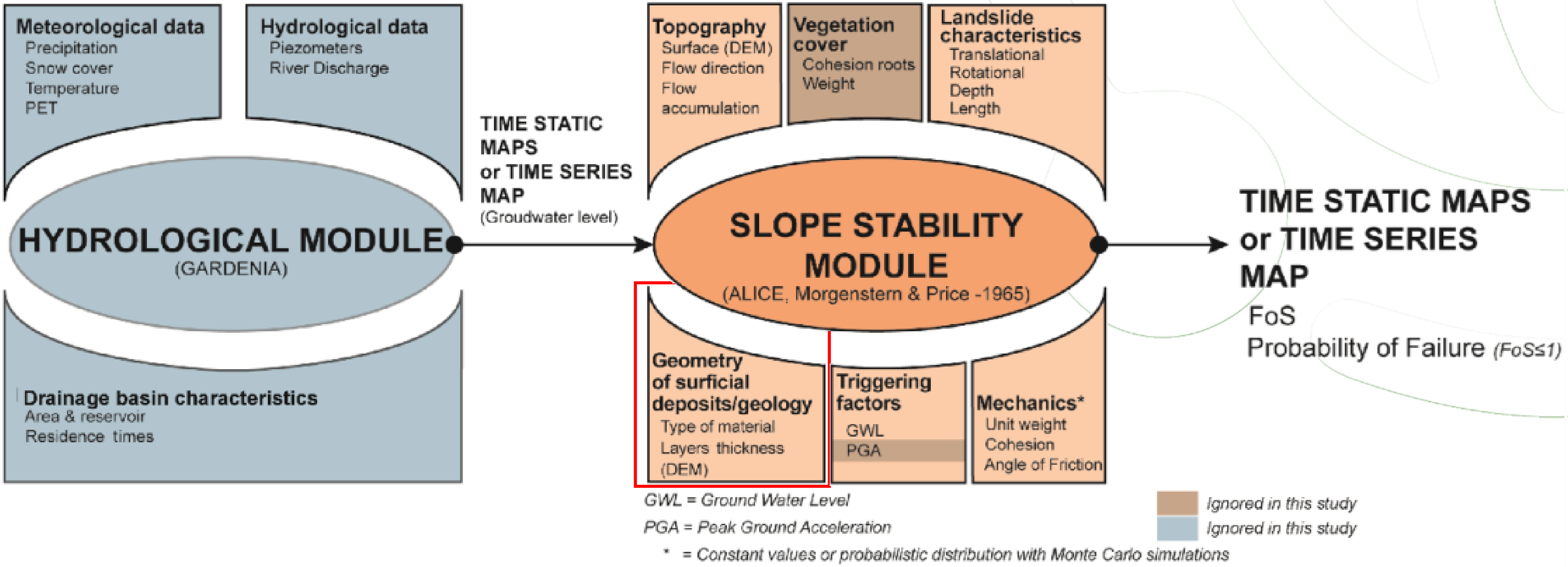




Thiery et al., 2021

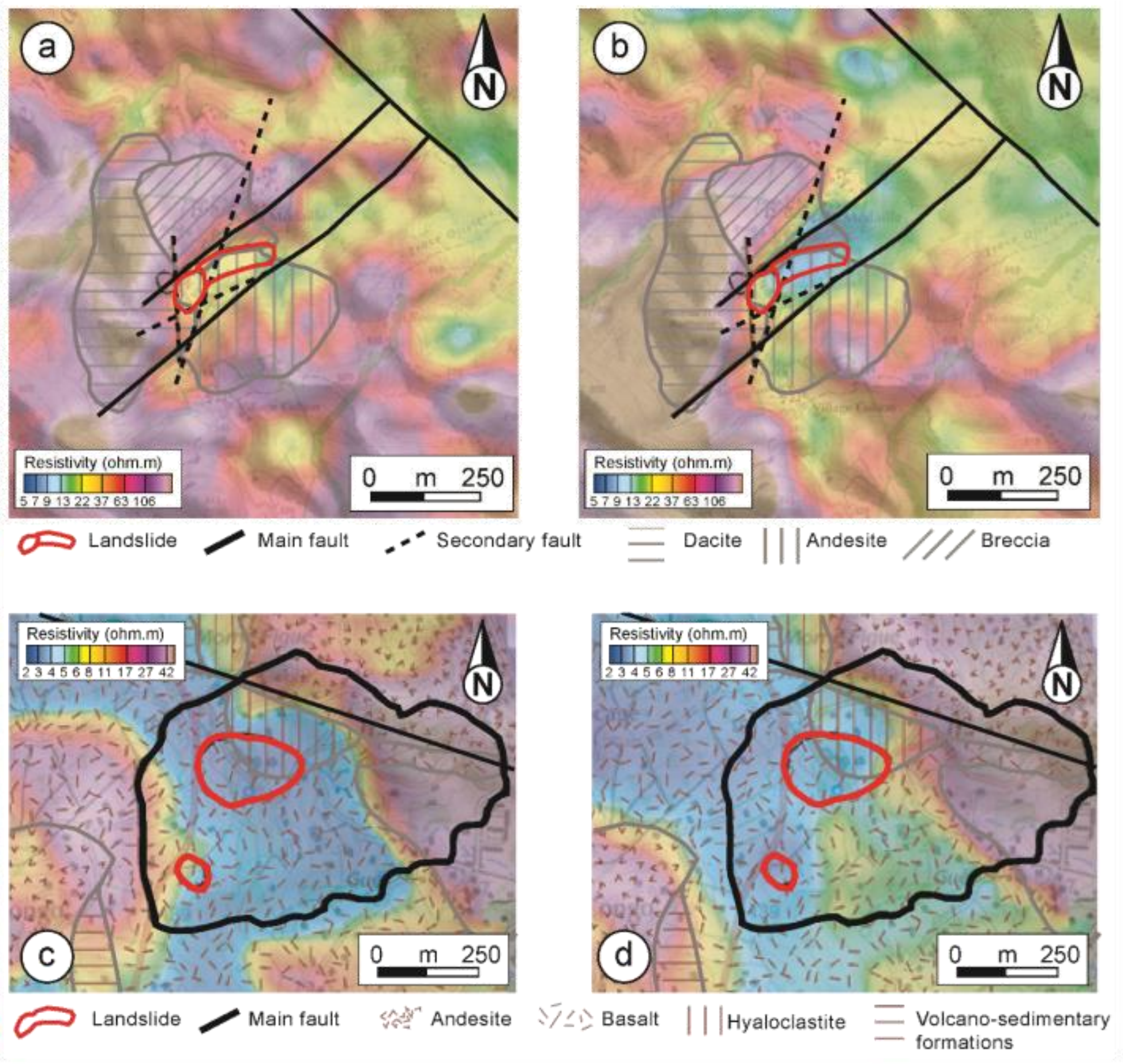
Landslide hazard assessment on La Martinique

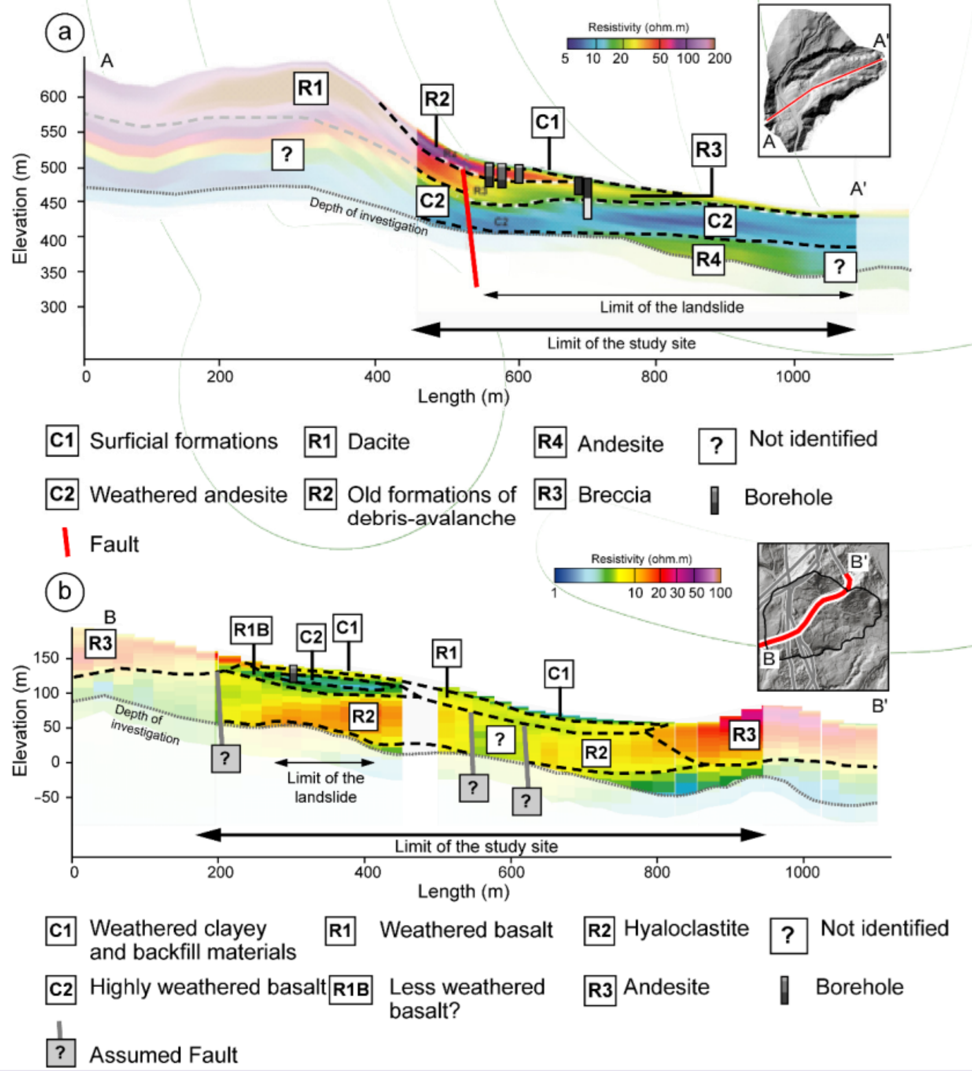
Integrated modelling



Landslide hazard assessment on La Martinique

Airborne EM results

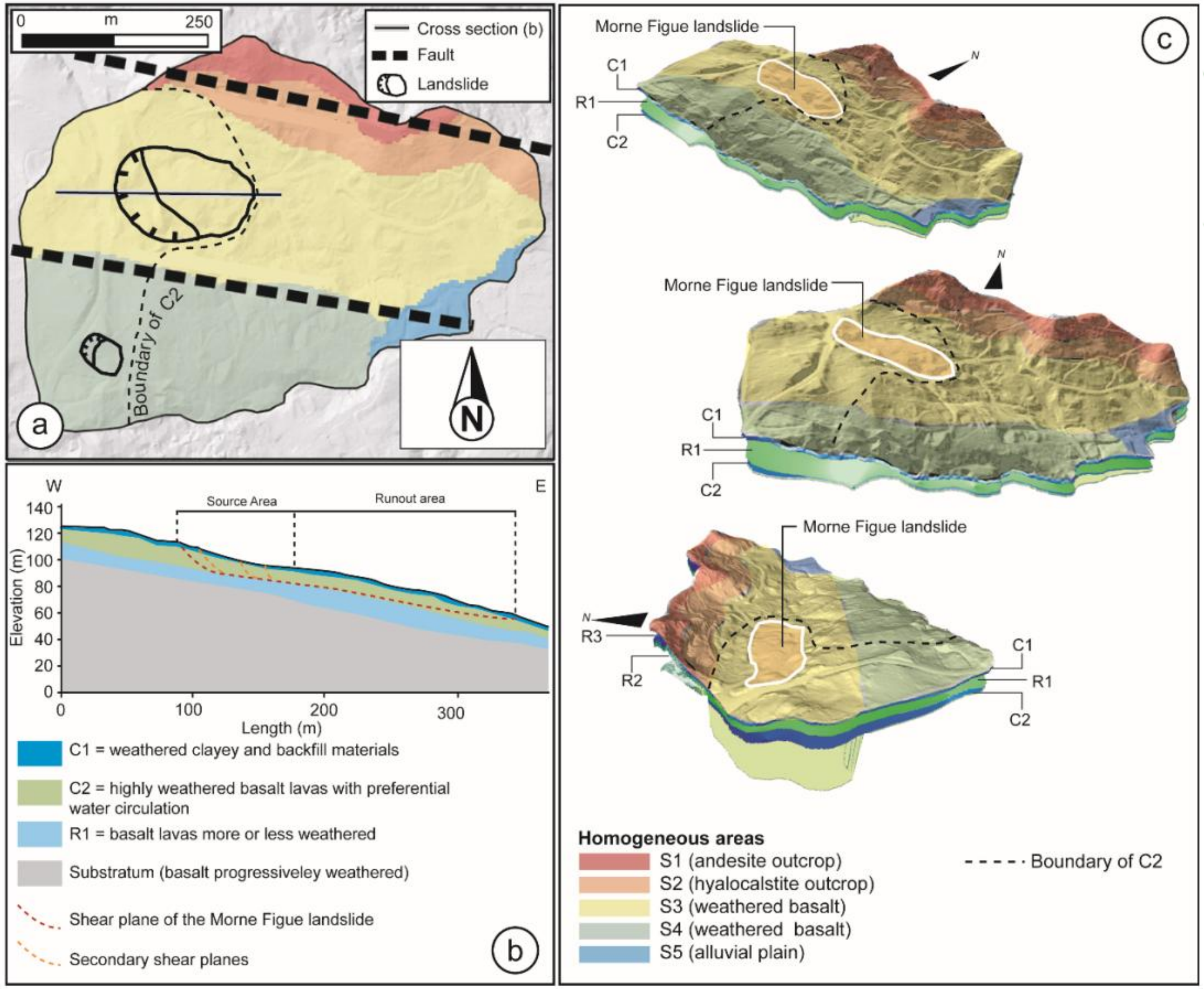




Thiery et al., 2021

Landslide hazard assessment on La Martinique

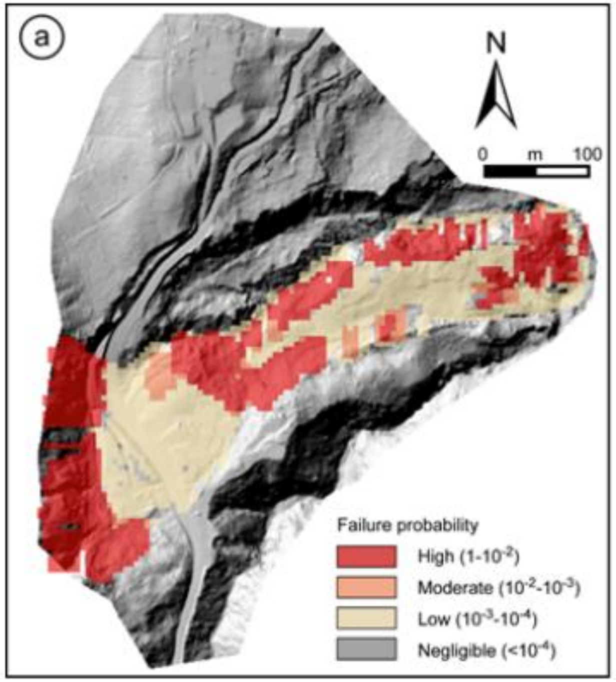
Geological model from AEM data

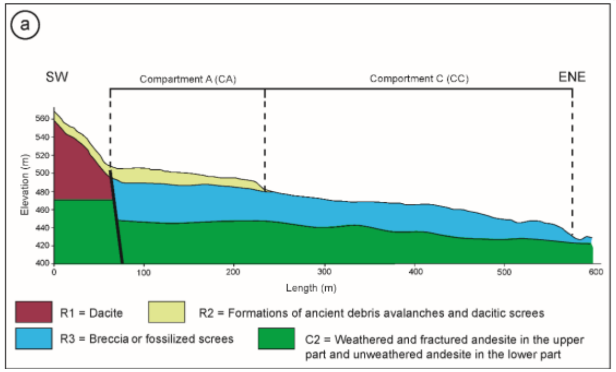


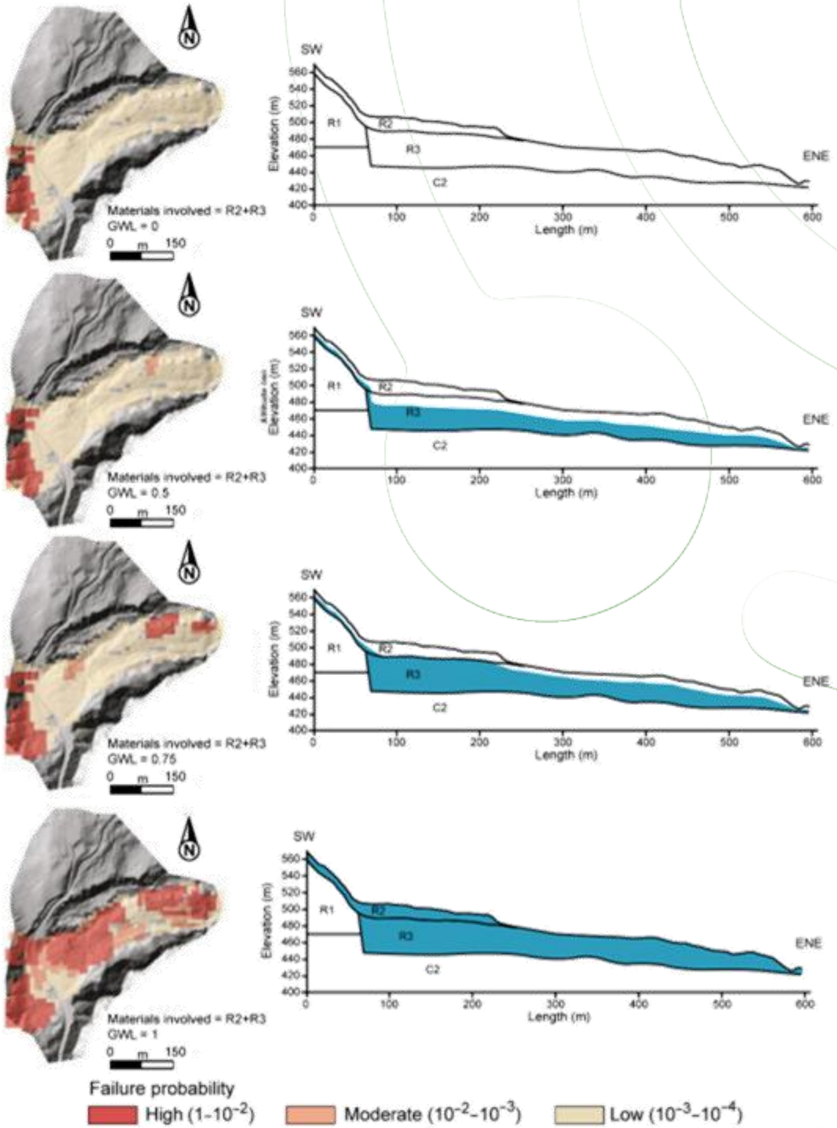
Thiery et al., 2021

Landslide hazard assessment on La Martinique

Hazard assessment



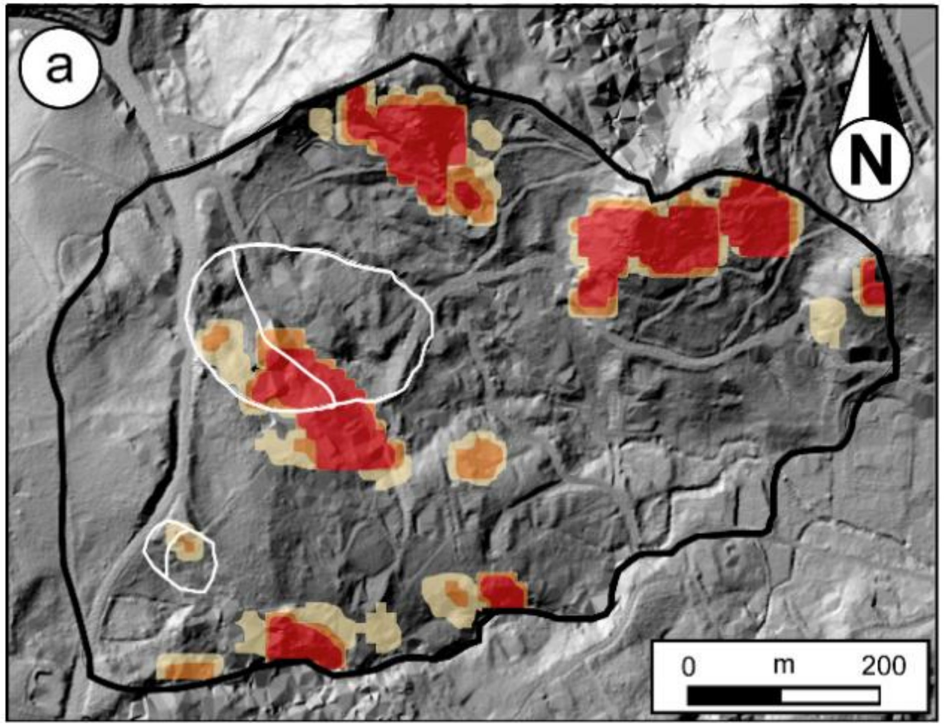




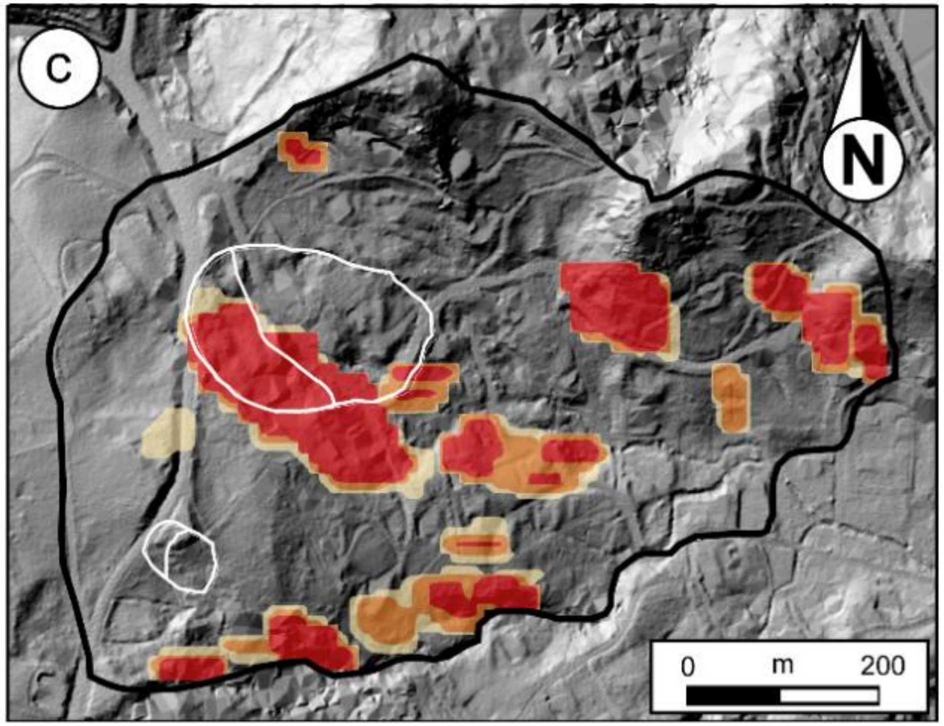
Landslide hazard assessment on La Martinique

Settings

Shallow, translational landslides



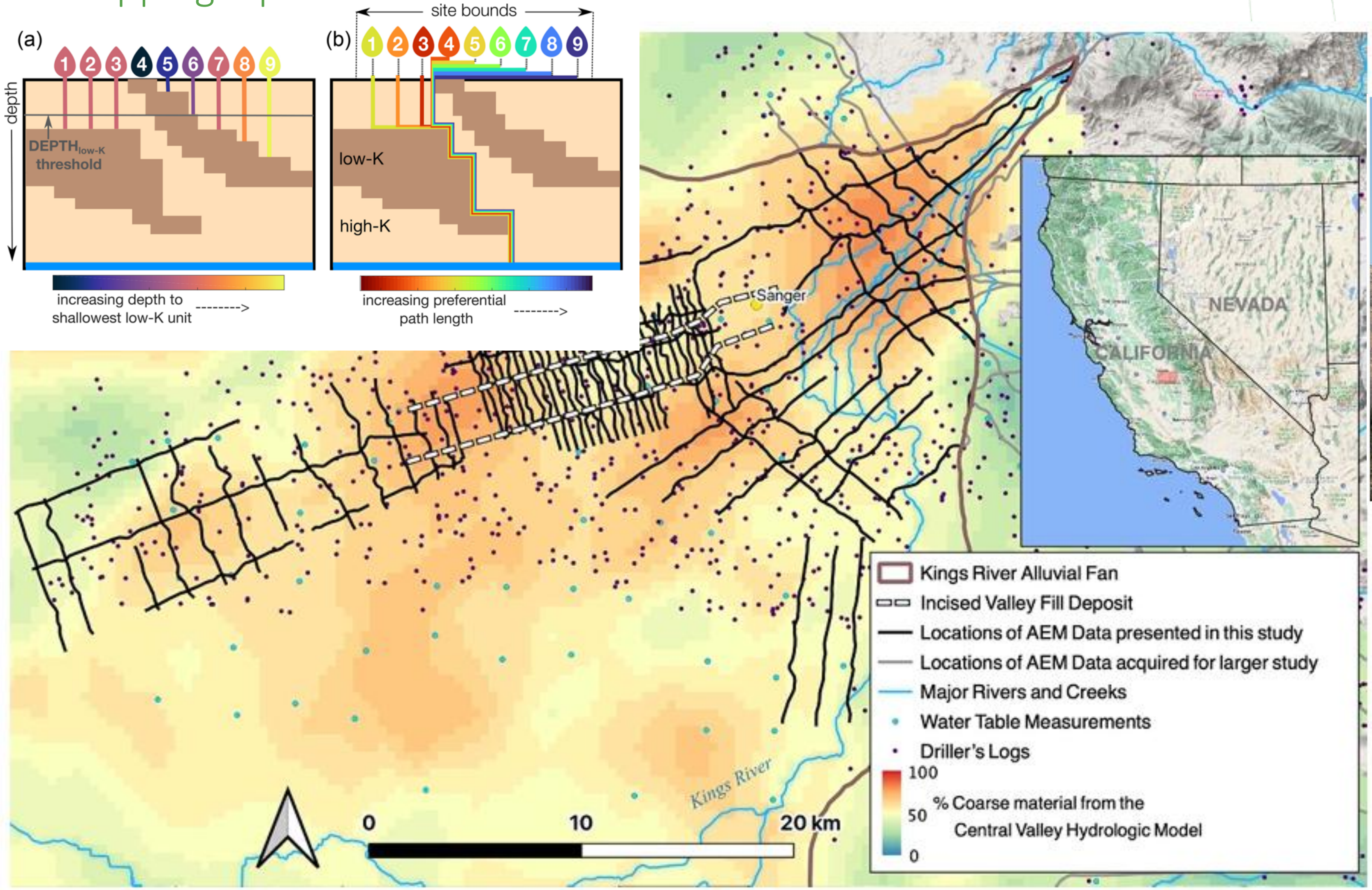
Moderately deep, rotational landslides



Thiery et al., 2021

Time-Domain EM survey example

Mapping aquifers in California



Knight et al., 2022

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California is prone to drought!

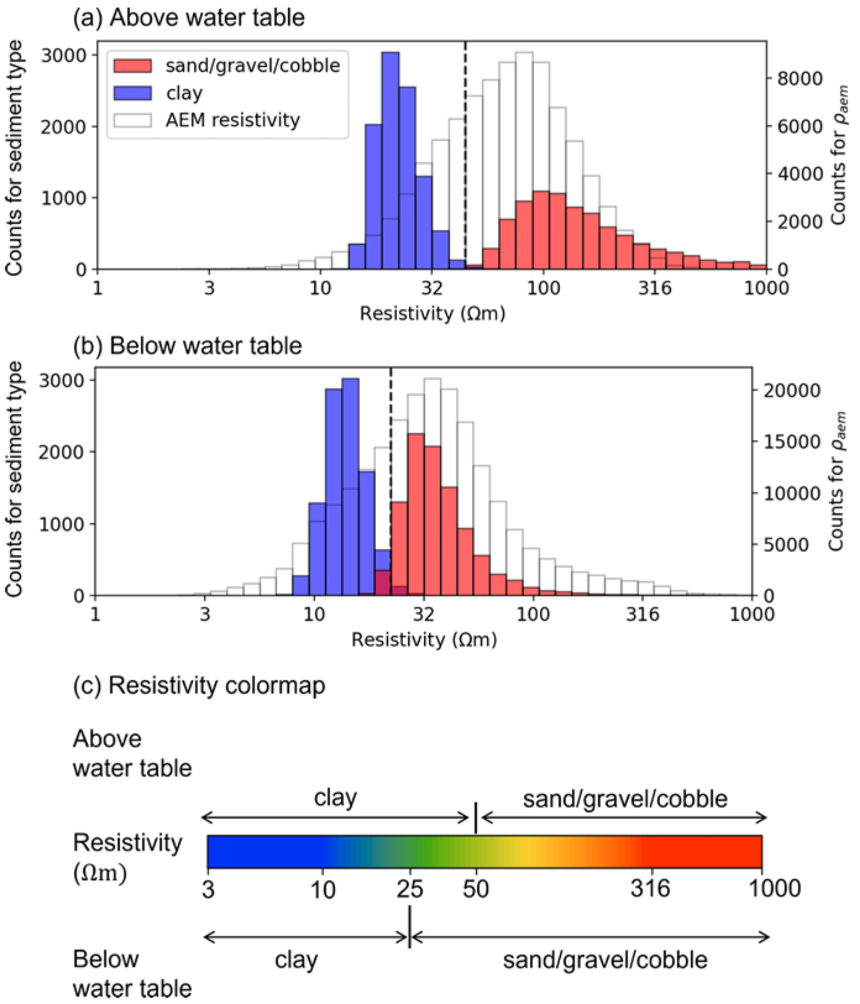
- The state invests heavily to mitigate groundwater stress
- Managed aquifer recharge a key mitigation technology

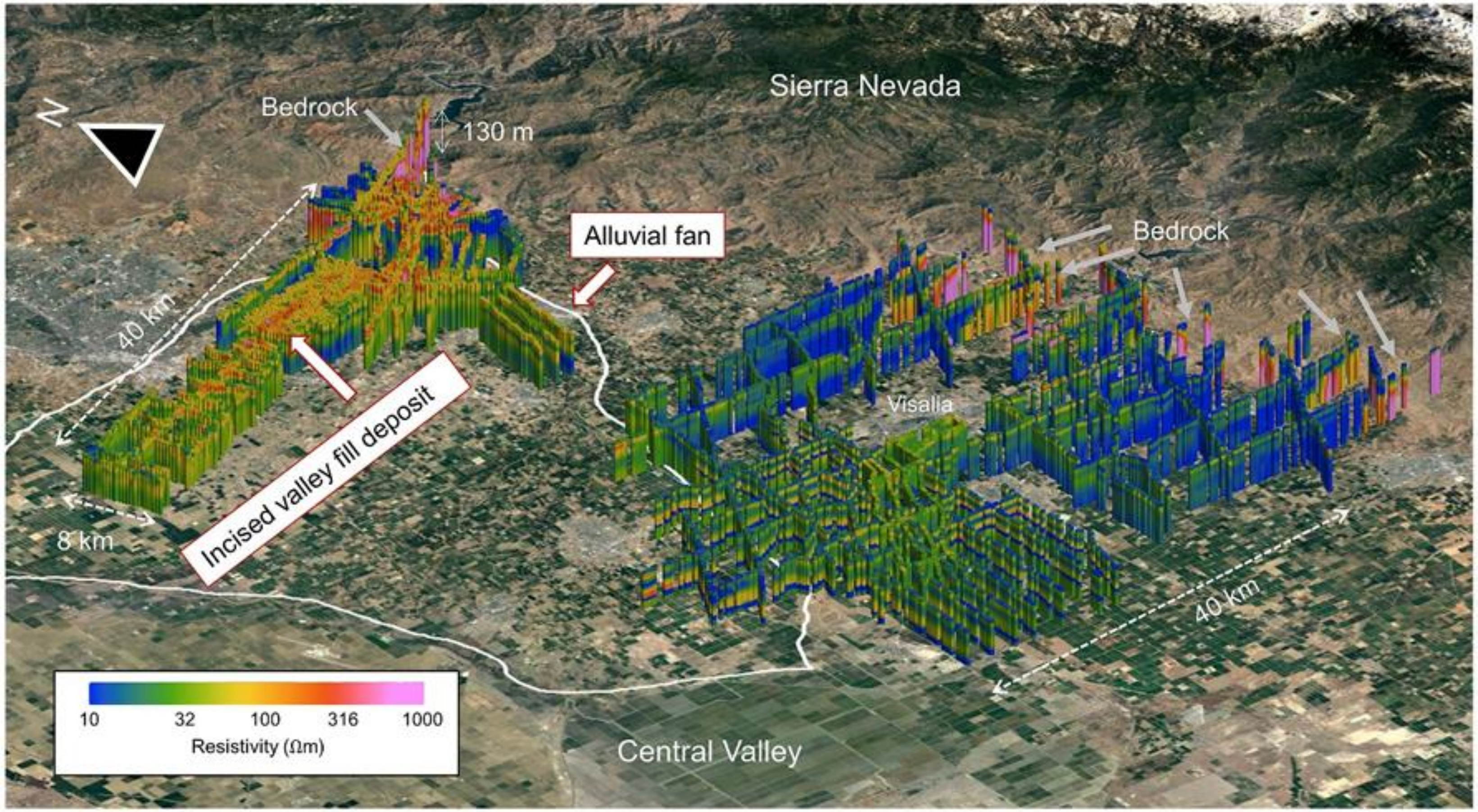
Question? Where are the right conditions for effective recharge?

To answer this on a relevant scale, airborne EM studies are conducted

Time-Domain EM survey example

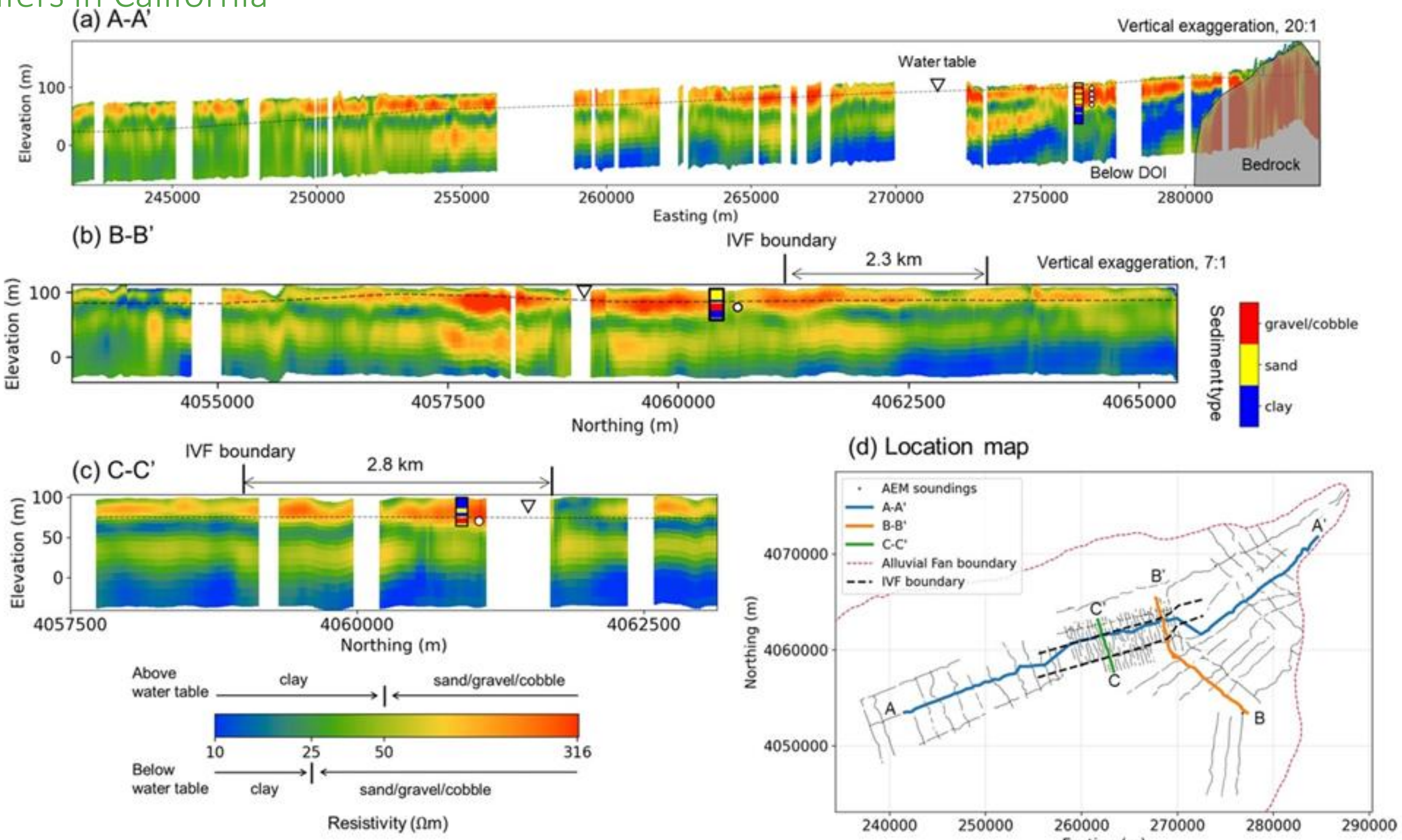
Mapping aquifers in California





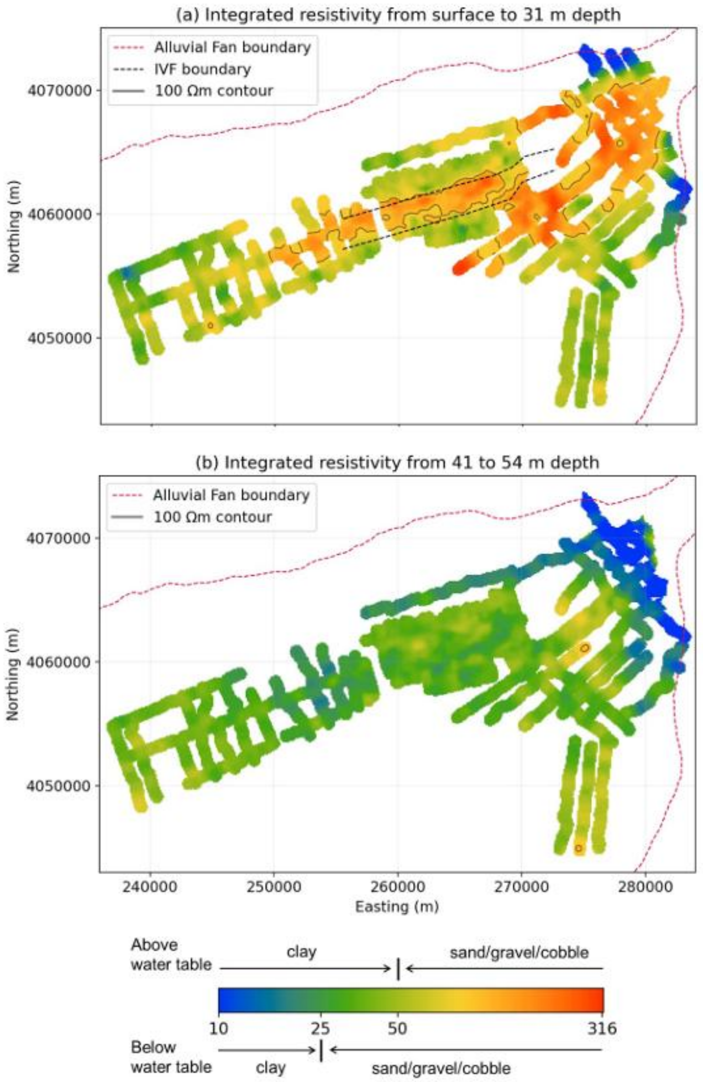
Time-Domain EM survey example

Mapping aquifers in California



Time-Domain EM survey example

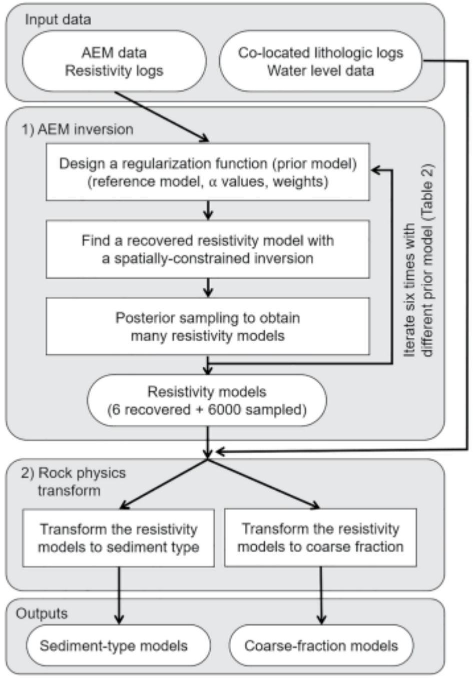
Mapping aquifers in California

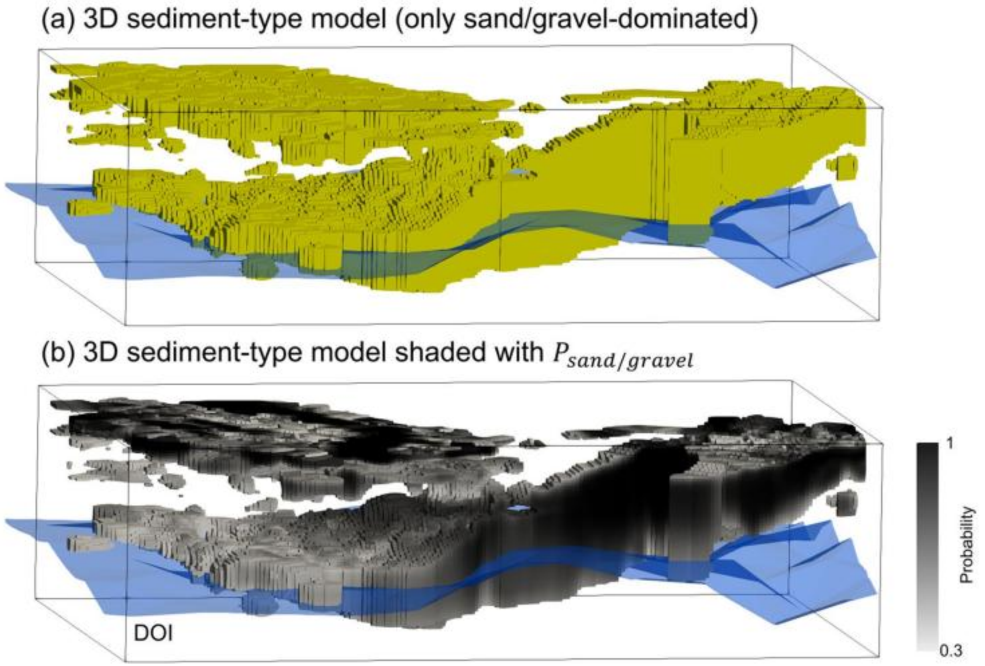


AEM measurements map resistivity distribution from the surface (with limitation) to depths of 100s m

Resistivity data provides insights into the hydrostratigraphy, delineating bedrock, sandy aquifer units, and clay rich areas

Resistivity transfer functions can be used to quantify the aquifer properties (in terms of fine-coarse material content)





Summary EM measurements

Rapid, shallow to deep resistivity measurements

EM uses a set of coils (Transmitter and Receiver coil) to measure the subsurface conductivity

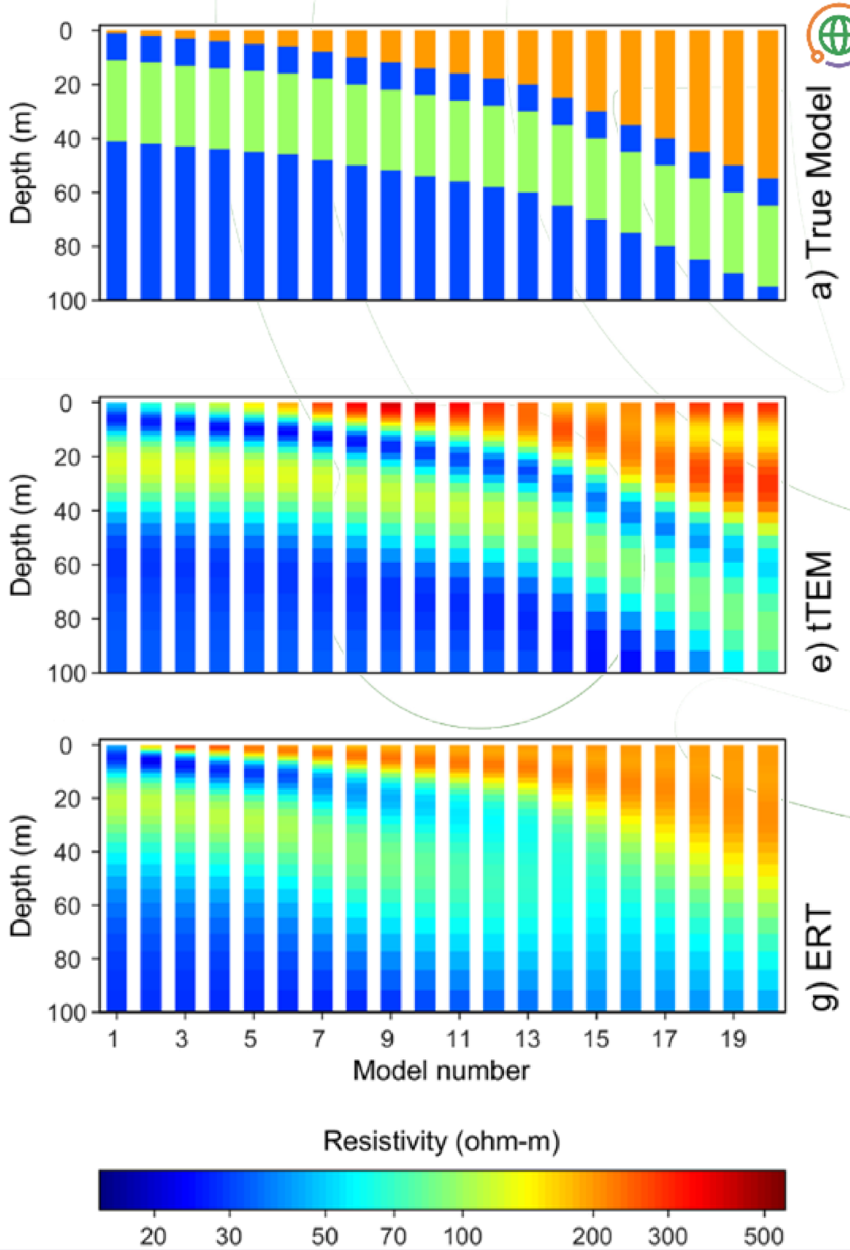
Source: TEM = Impulse source (= rapid turn-off of current in Tx coil)
FDEM = continuous, sinusoidal waveform

Depth of investigation: Depends mostly on (TEM) magnetic moment of Tx and Rx coils, (FDEM) Tx-Rx coil spacing/orientation & Tx frequency and subsurface conductivity distribution

Requires no galvanic coupling (i.e., no electrodes stuck into the ground)

Instruments coils can be laid out manually, or be mounted on frames to be towed or airborne

Very sensitive to conductors!



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THANKS!

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