

Introduction to geophysical methods for soil prospecting, with a focus on electrical resistivity tomography (ERT) for characterizing periglacial terrain

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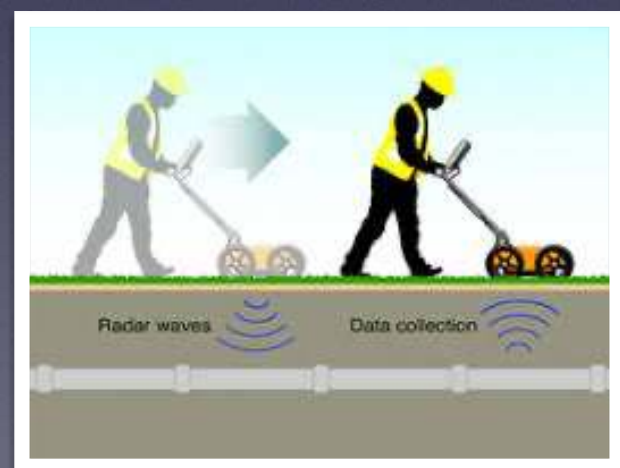
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University of Padova, Italy*

What is Applied Geophysics?

STUDY THE SUBSOIL with non invasive methods

Intro to geophysical prospecting
non-invasive techniques

Study the subsoil in a indirect way:
Getting information without
entering the domain !

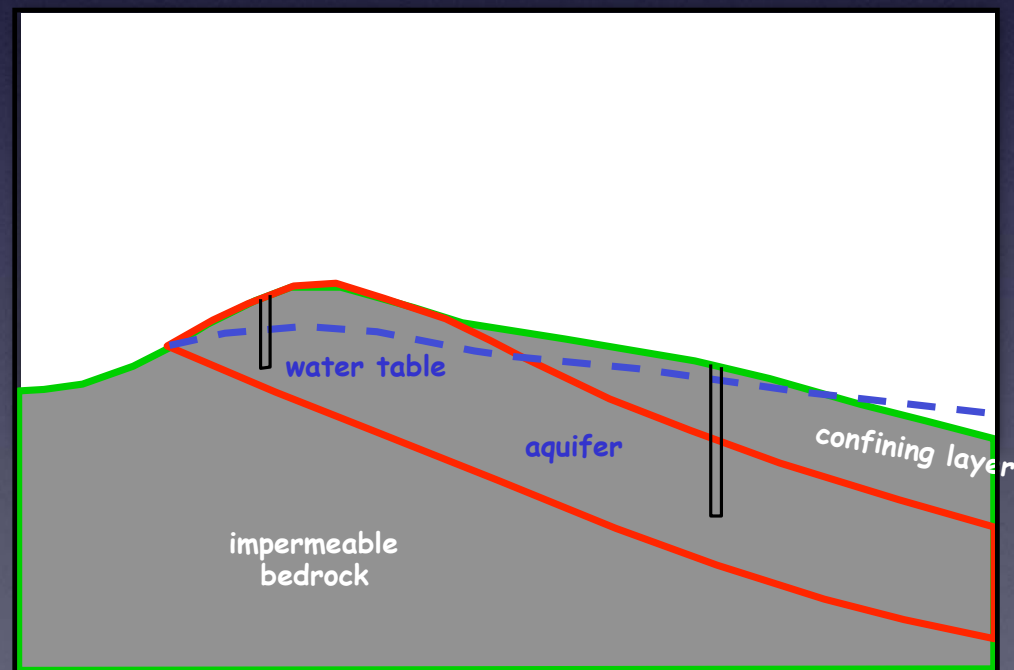


Geophysical methods for the subsoil exploration

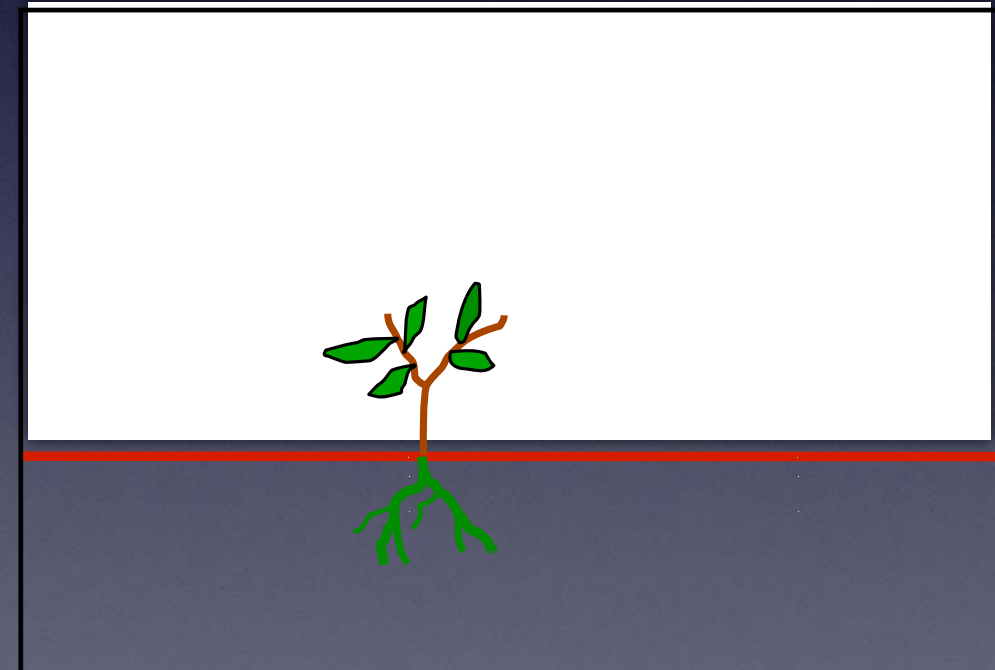
Method	Structure	Dynamic
Seismic	++	
Electro-Magnetic	+	++
ERT - DC resistivity methods	++	++
Ground Penetration Radar	++	+
Distributed Temp. Sensing		++
Magnetics	+	
Gravimetry	+	+
(Spectral) Induced	+	
Self Potential		+
Borehole logs	++	+

What geophysical methods can help define

- structure / texture (Seismic methods, EM methods, Electrical methods, Gravity methods, Radar etc)



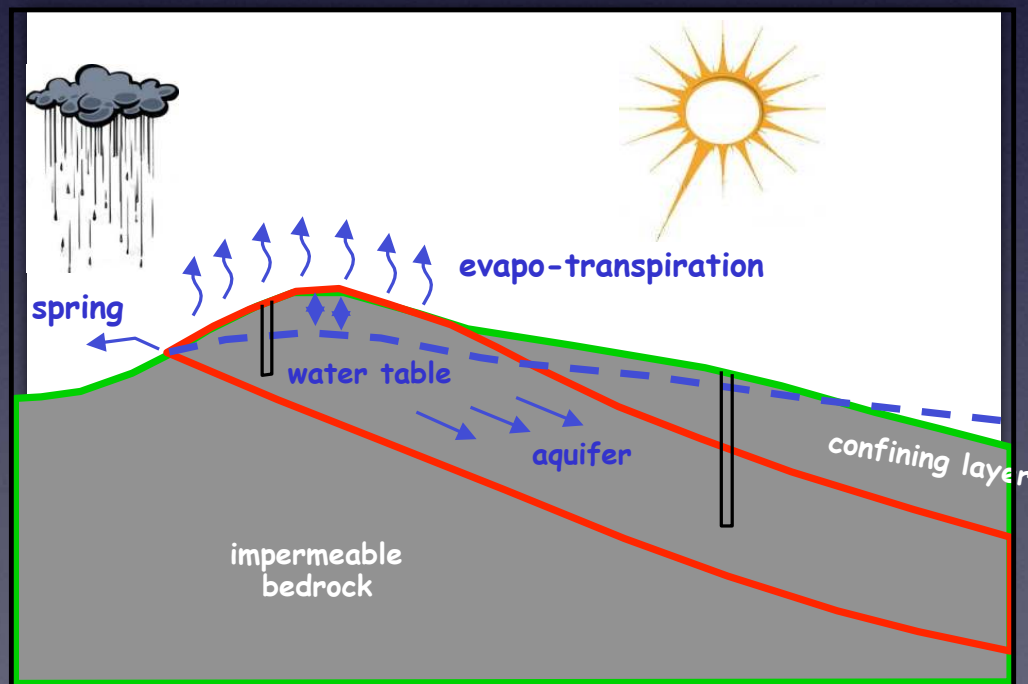
Large scale



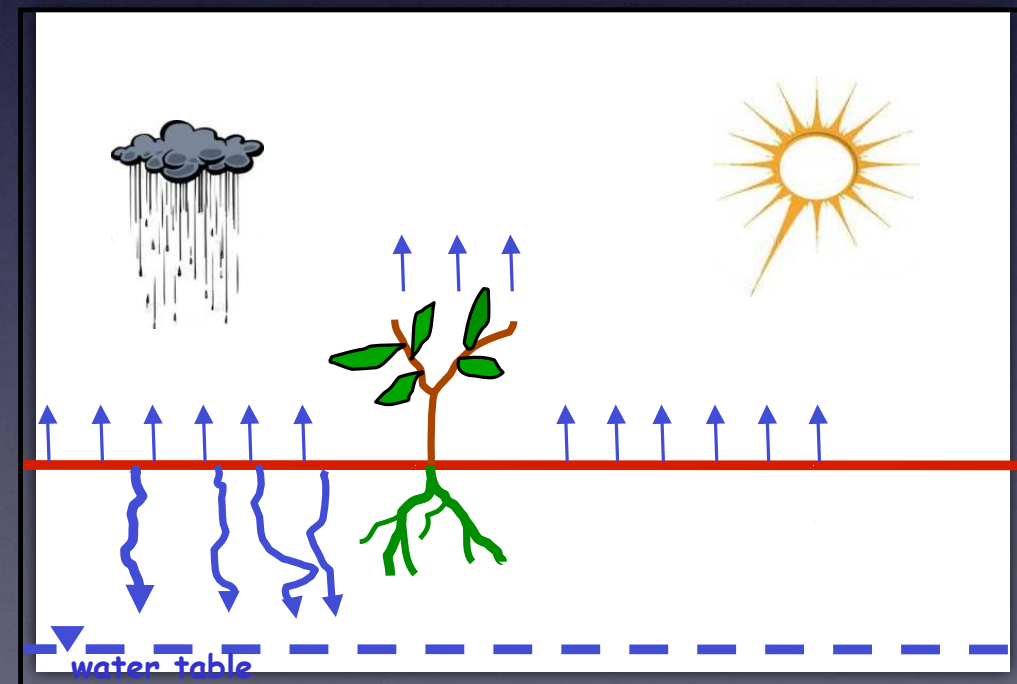
Small scale

What geophysical methods can help define

- structure / texture (Seismic methods, EM methods, Electrical methods, Gravity methods, Radar etc)
- fluid-dynamics: e.g. time-lapse evolution of moisture content (DC resistivity methods, EM methods, GPR etc)



Large scale



Small scale

The geophysical measurement

An indirect measurement

Instrument



D = geophysical quantity measured (DATA)

P = geophysical parameter who rule D

Investigated domain

$$D = D(P, F = \text{forcing conditions})$$

PHYSICAL PROPERTIES (P)

- ❑ **Seismic** : elastic moduli and density
- ❑ **Gravimetry** : density
- ❑ **Magnetic Methods** : magnetic susceptibility
- ❑ **GeoElectrics** : electric conductivity
- ❑ **Electro-Magnetic methods** : electric conductivity
- ❑ **Induced polarisation** : electric complex conductivity
- ❑ **Spontaneous potential** : electric conductivity sources
- ❑ **Ground penetrating radar** : dielectric constant

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$D = D(P, F = \text{forcing conditions})$

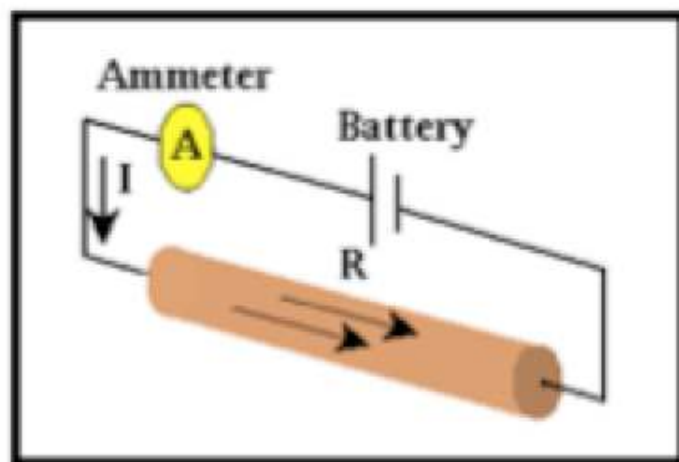
ELECTRIC RESISTIVITY TOMOGRAPHY

ERT

electrical-resistivity-tomography

OHM LAW

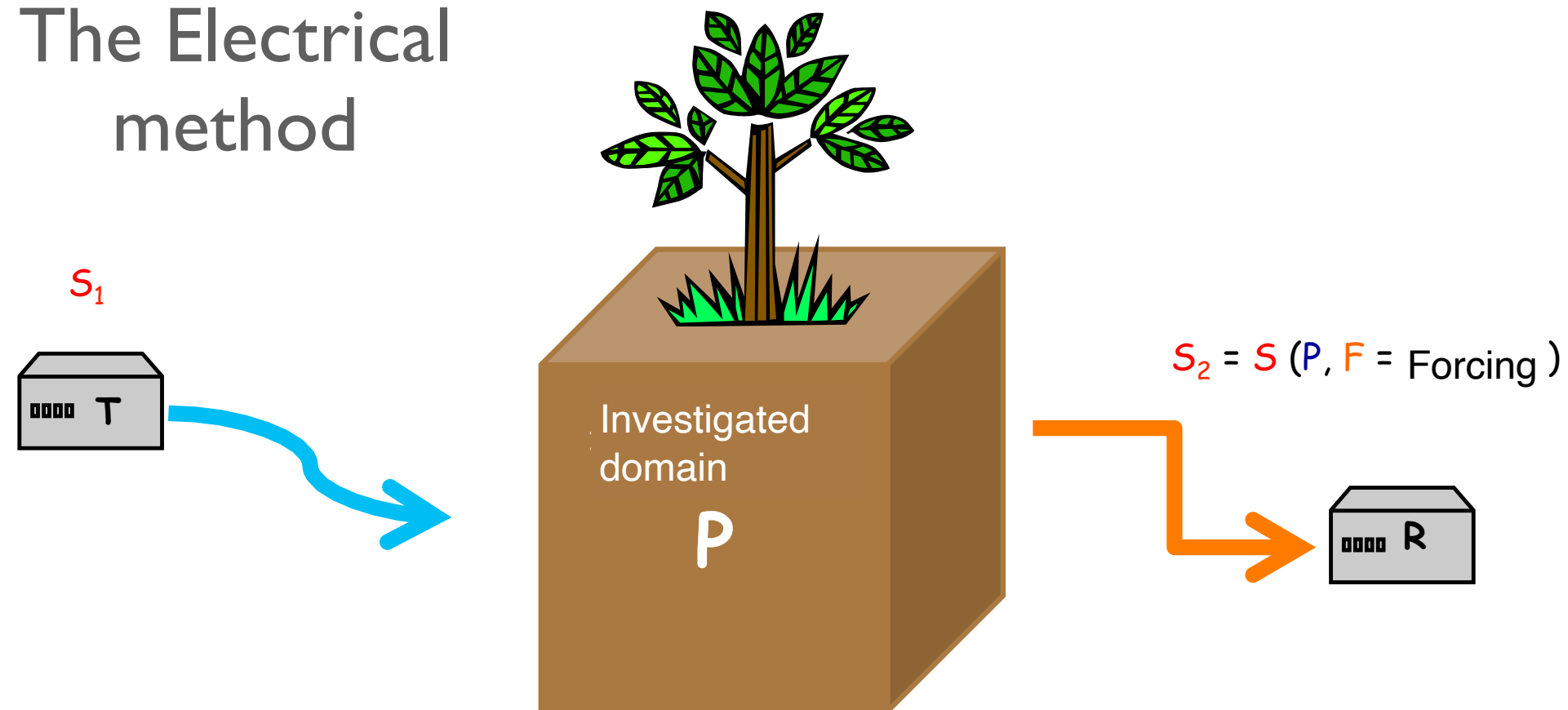
$$\Delta V = I \cdot R$$



Electric conductivity: $\sigma = \frac{1}{\rho}$

Electrical Resistivity $\uparrow$

The Electrical method



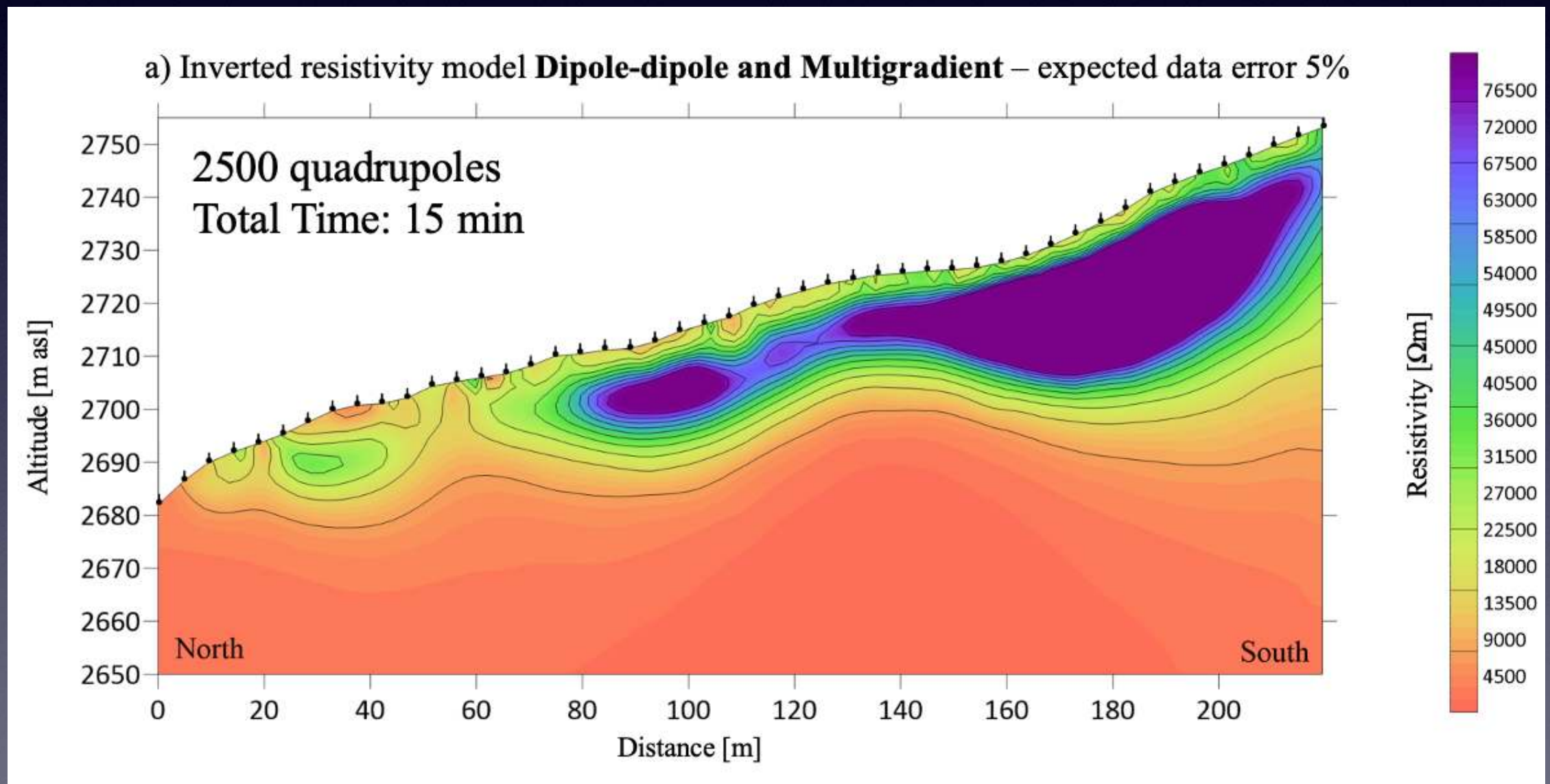
S_1 = Signal = Injected current

S_2 = Signal = Potential voltage measured

P = Physical parameter = Resistivity

ERT on Rock Glacier

- Good Resolution / penetration compromise

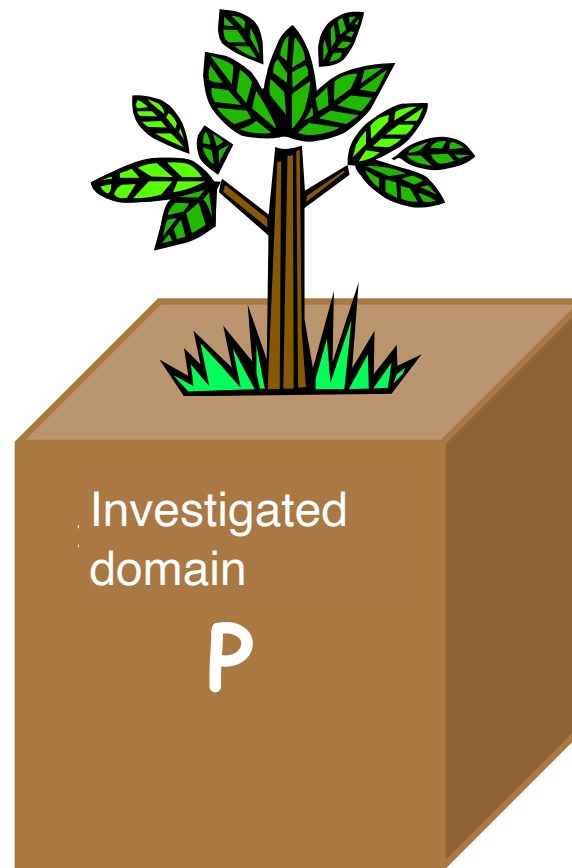
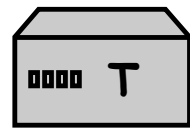


Pavoni et al 2026

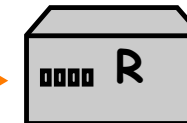
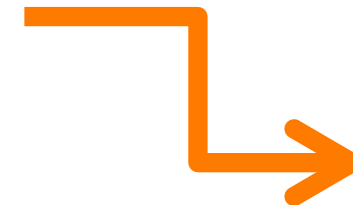
J. Boaga - introduction to geophysical methods -ERT, Trafoi 03-09-2026

The Electro- magnetic method

S1



S2 = S1 (P, F=forcing)



S1 = Signal =

EM field

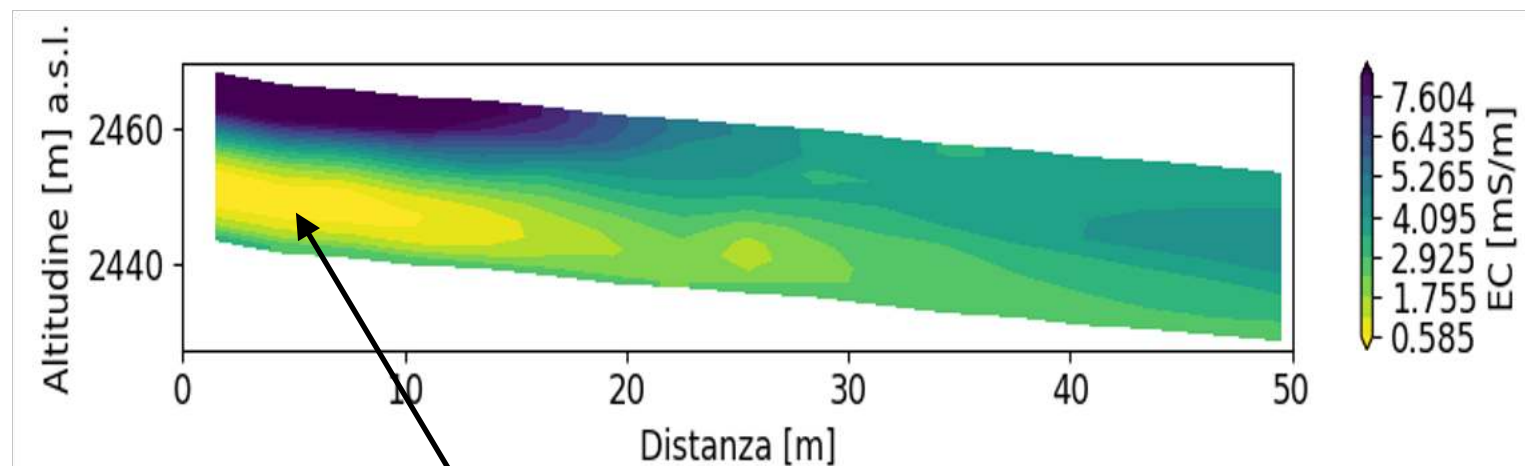
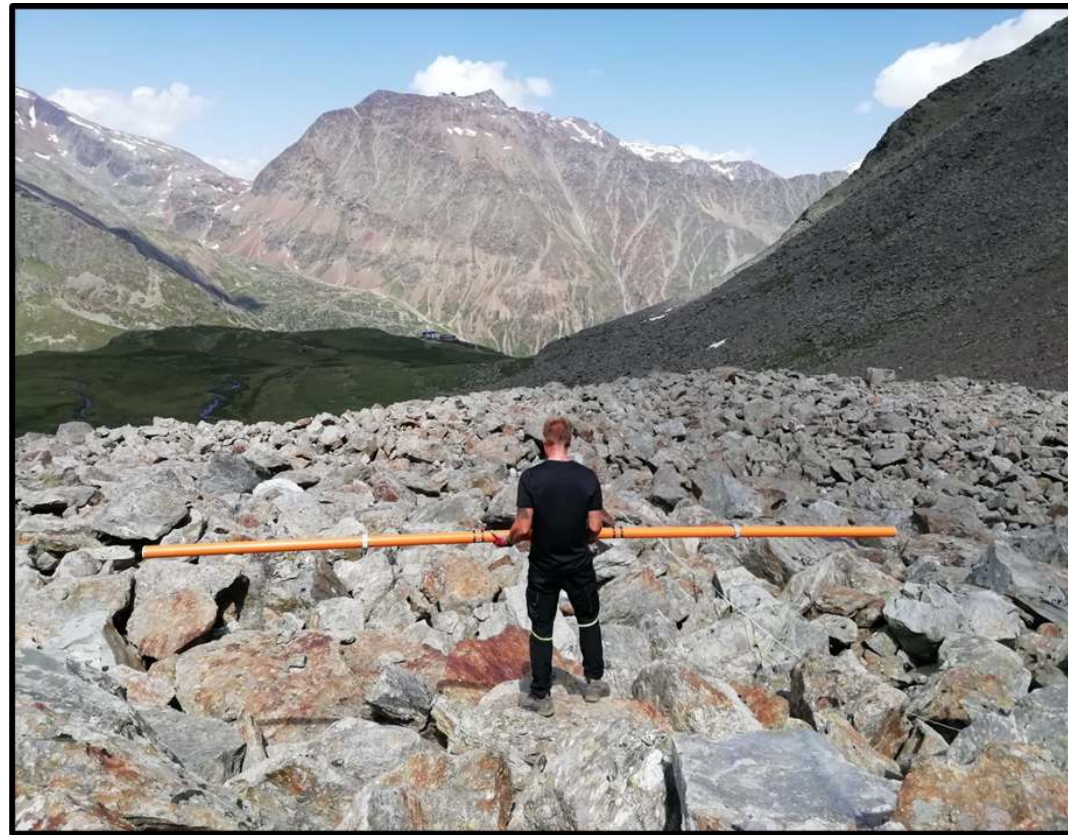
S2 = Signal

Induced EM field

P = Physical parameter

Electrical conductivity

Fdem in a Rock Glacier



FDEM conductivity

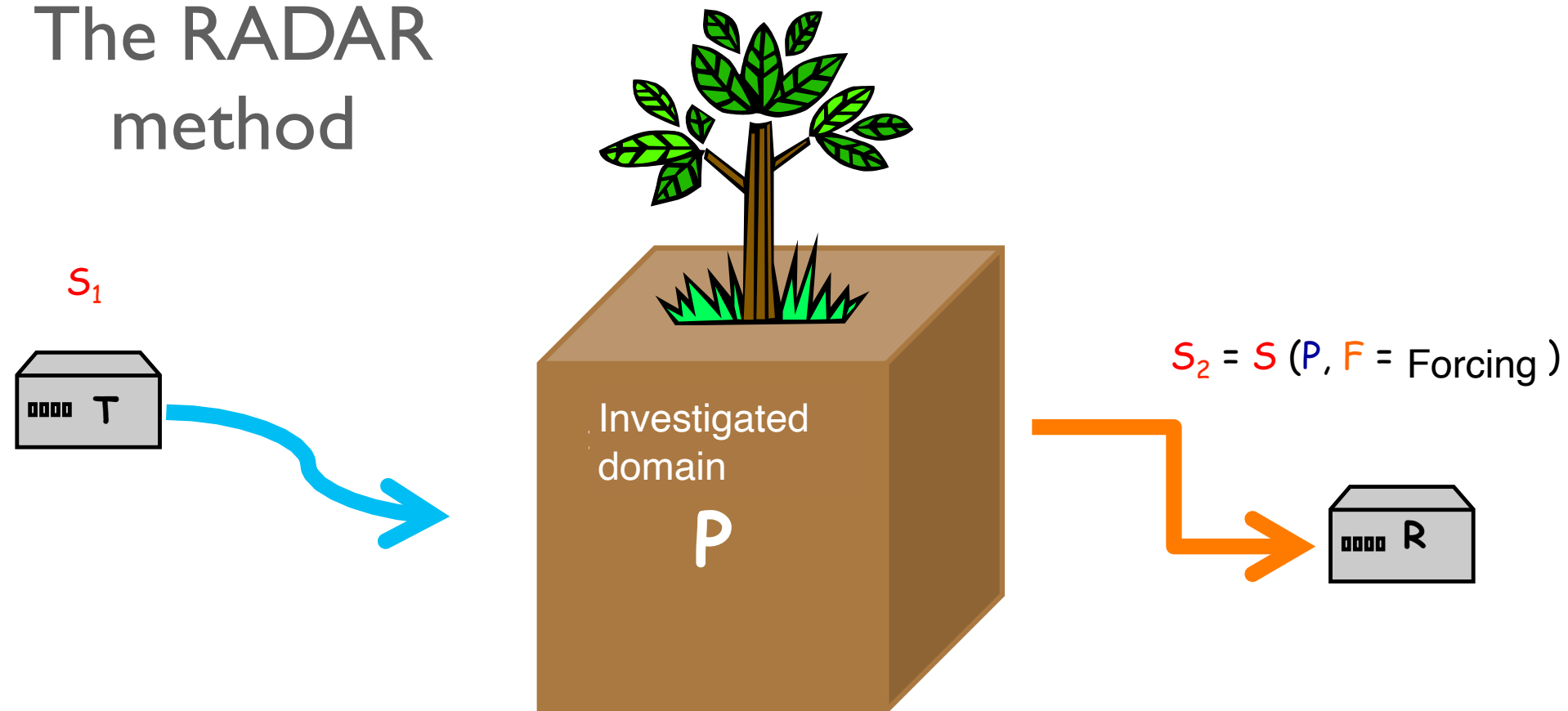
Low Cond. Frozen ground area

2) Electro-Magnetic Methods



PermaCOST

The RADAR method



S_1 = Signal = High frequency electro-magnetic waves

S_2 = Signal = Reflected electro-magnetic waves

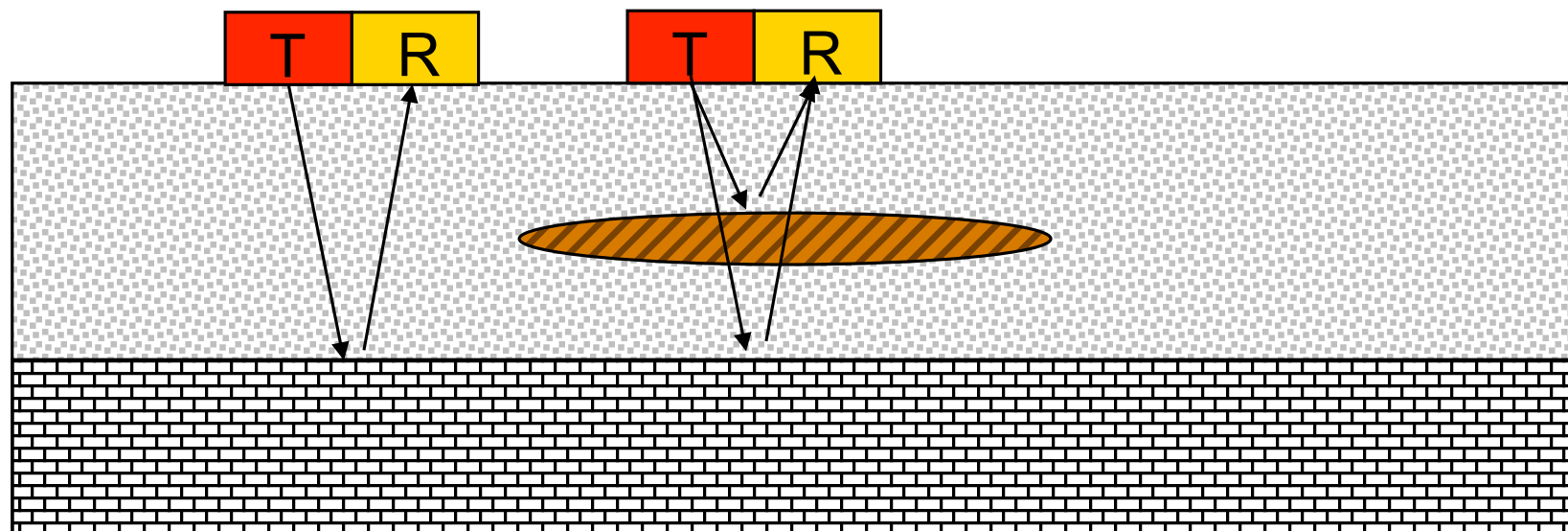
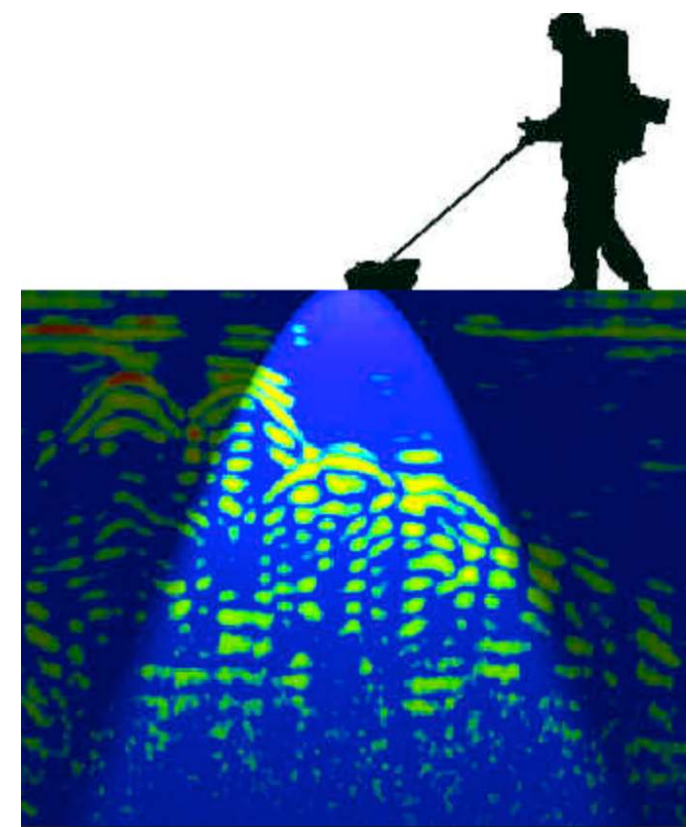
P = Physical parameter Dielectric contrast

Georadar

G P R

Ground Probing Radar (or Ground Penetrating Radar) is a high frequency EM technique (in the band 10-2500 MHz) based on the response of the subsoil to a short EM pulse.

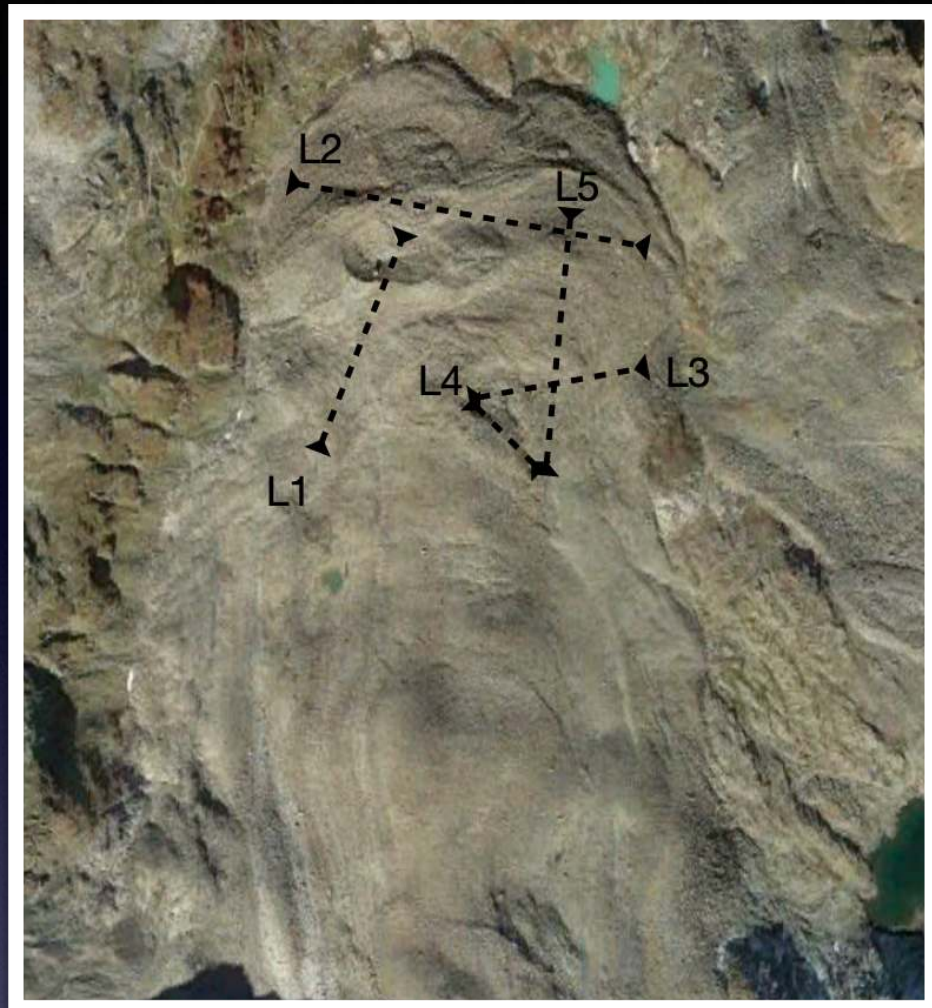
A signal of short wavelength is radiated into the ground, is reflected, refracted, diffracted and hence detects the anomalous variations in the dielectric properties.



Anomalies can be soil horizons, the groundwater surface, soil/rock interface, man made objects (pipes, foundations, cables...)

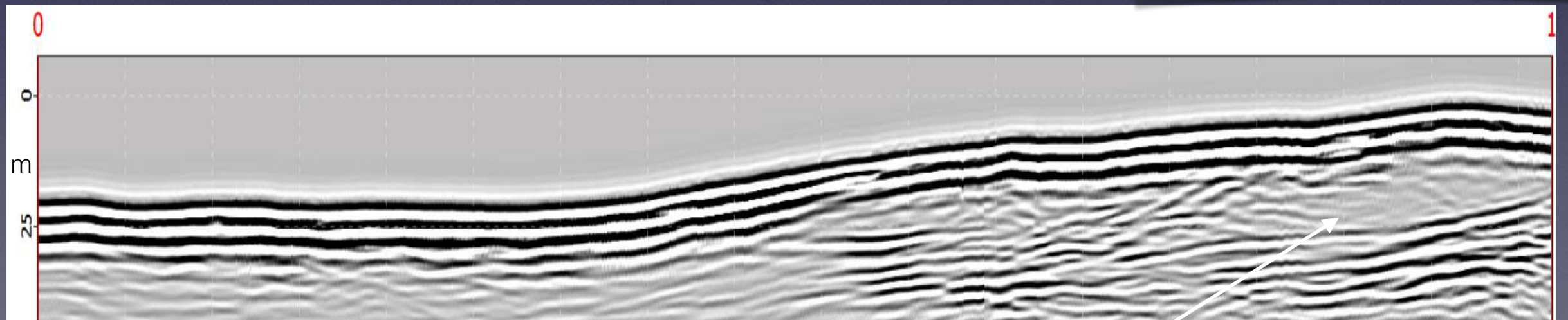
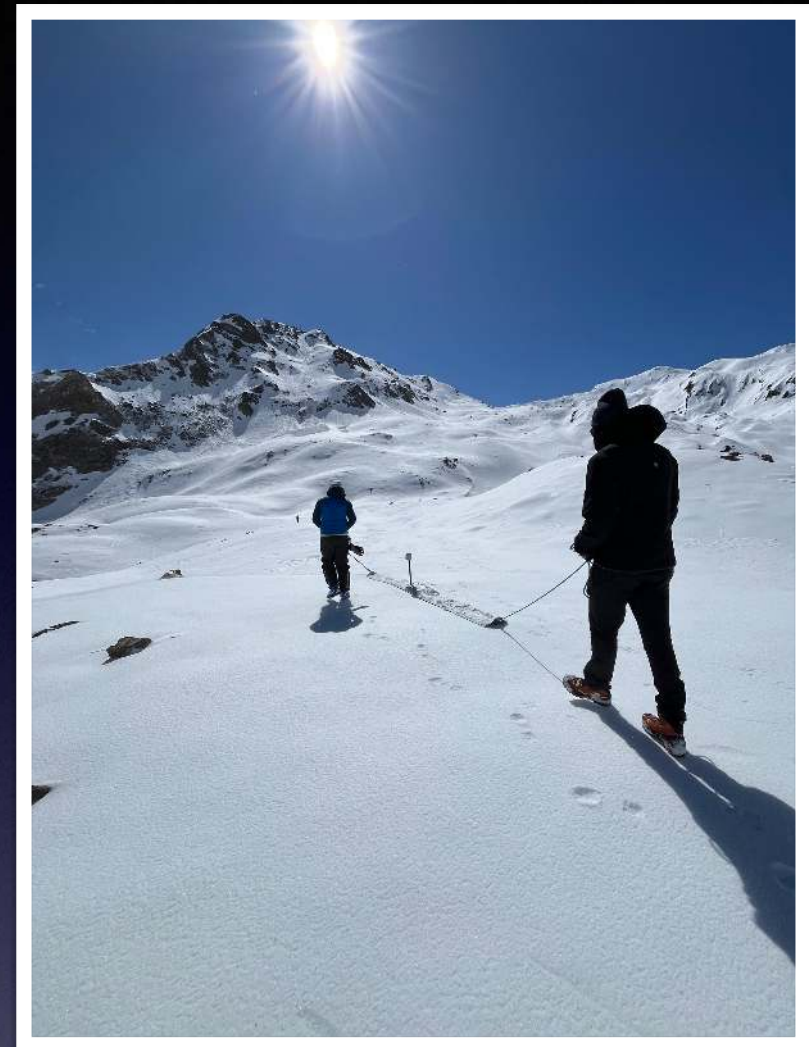
HIGH RESOLUTION, LOW PENETRATION DEPTH

Georadar on a Rock Glacier



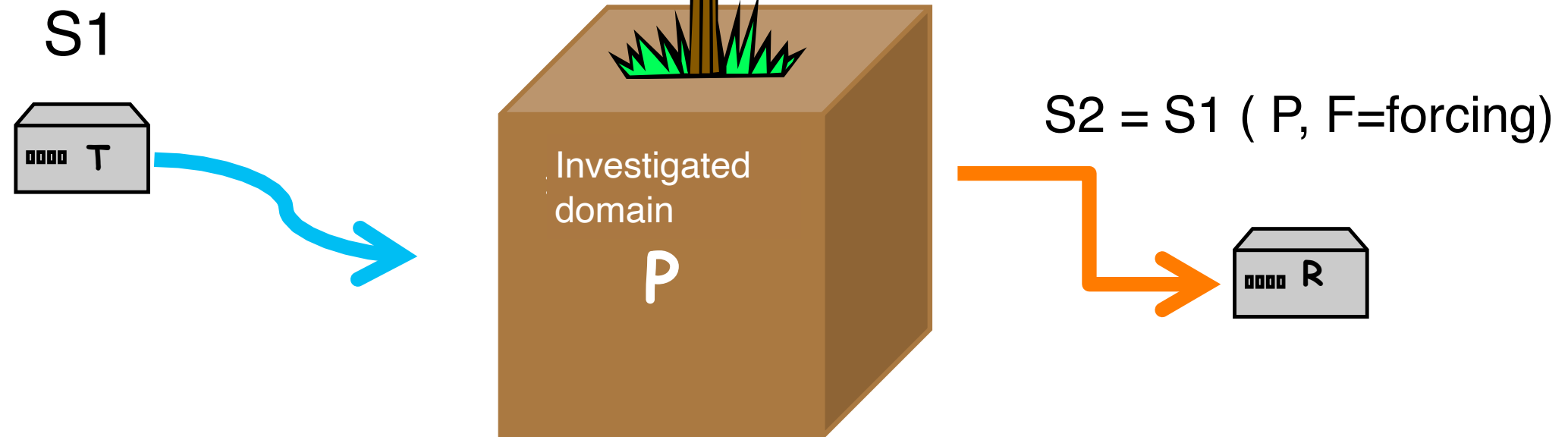
25MHz probe

Petrarca RG (Bz)



Frozen Ground

The seismic method

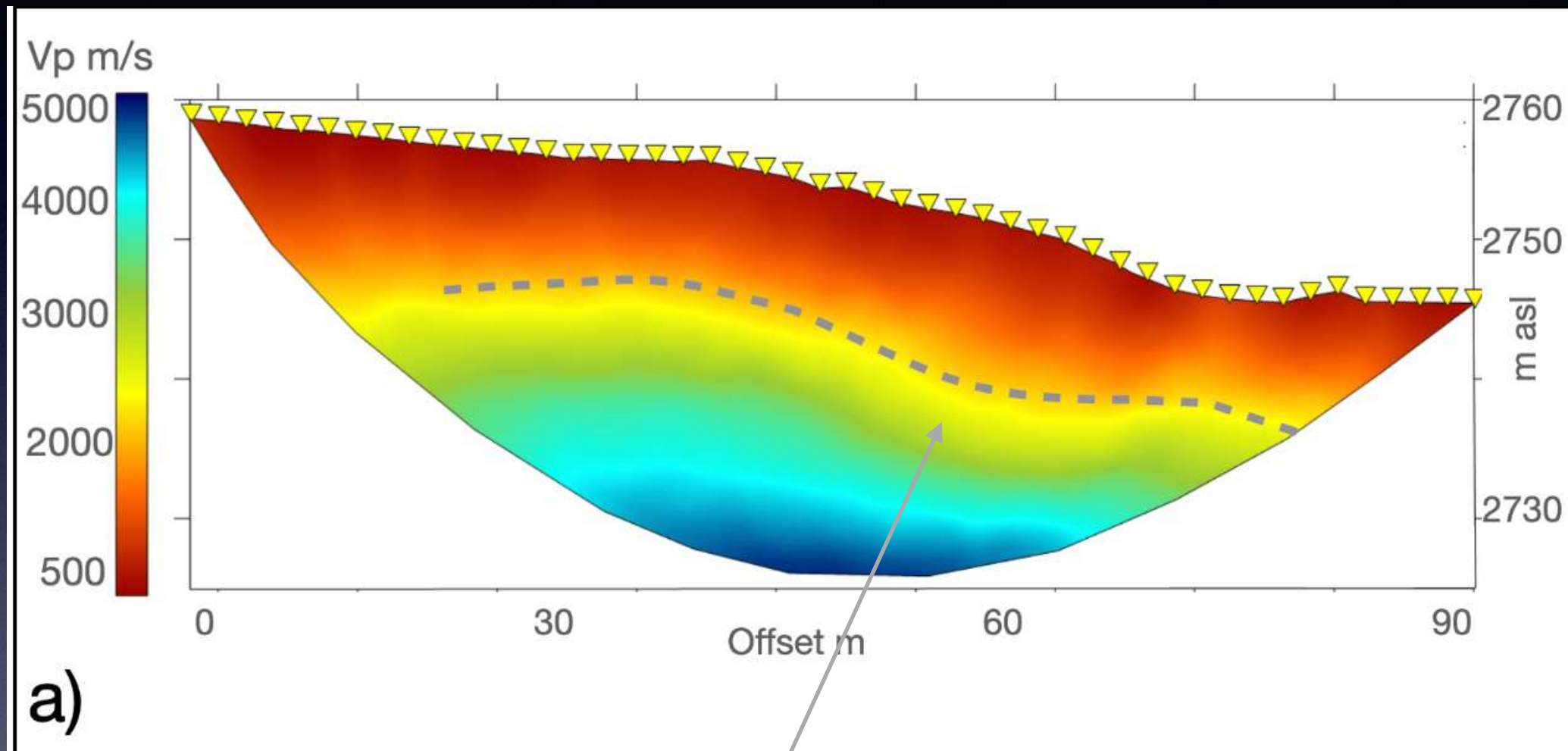


S1 = Signal = Elastic wave source

S2 = Signal = Induced vibration

P = Physical parameter Elastic moduli/ density

Refraction Seismic in Rock Glacier



Boaga et al 2025

Frozen Ground level

Take home messages



	S 1	P	S 2
Seismic methods	Elastic waves	Elastic moduli/ density	Induced vibrations
Electrical methods	Current injection	Resistivity	Voltage potential
Electro-magnetic methods	Electro-magnetic Field	Conductibility	EM secondary fields
Radar (EM)	Electro-magnetic waves	Dielectric contrast	Reflected EM waves

Geophysical
methods



Applications

The choice of the methods must follow the criteria:

- ☐ The target must be suitable with the **Physical Parameter**
INVERSION
- ☐ The method must have enough spatial (or temporal)
RESOLUTION and enough depth **PENETRATION**
RESOLUTION
- ☐ The cost
- ☐ Logistical issues
- ☐ Environmental impact

THE INVERSION

The geophysical measurement

An indirect measurement

Instrument



D= geophysical quantity measured (DATA)

P= geophysical parameter who rule D

Investigated domain

$D = D(P, F = \text{forcing conditions})$

THE INVERSION

The geophysical measurement

An indirect measurement

Instrument



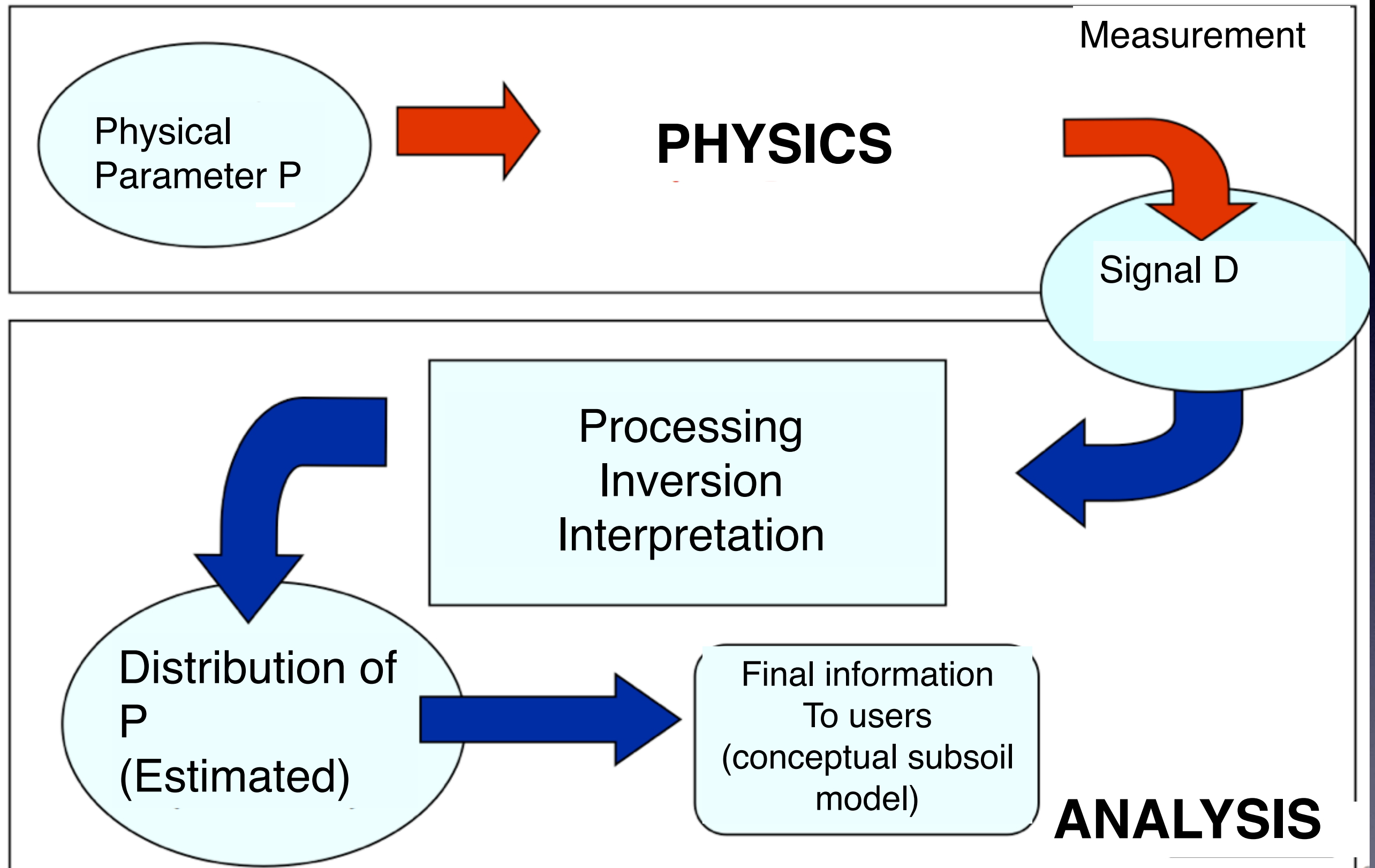
D= geophysical quantity measured (DATA)

P= geophysical parameter who rule D

Investigated domain

$$P = \textit{operator} (D)$$

Measurements and Analysis in Applied Geophysics



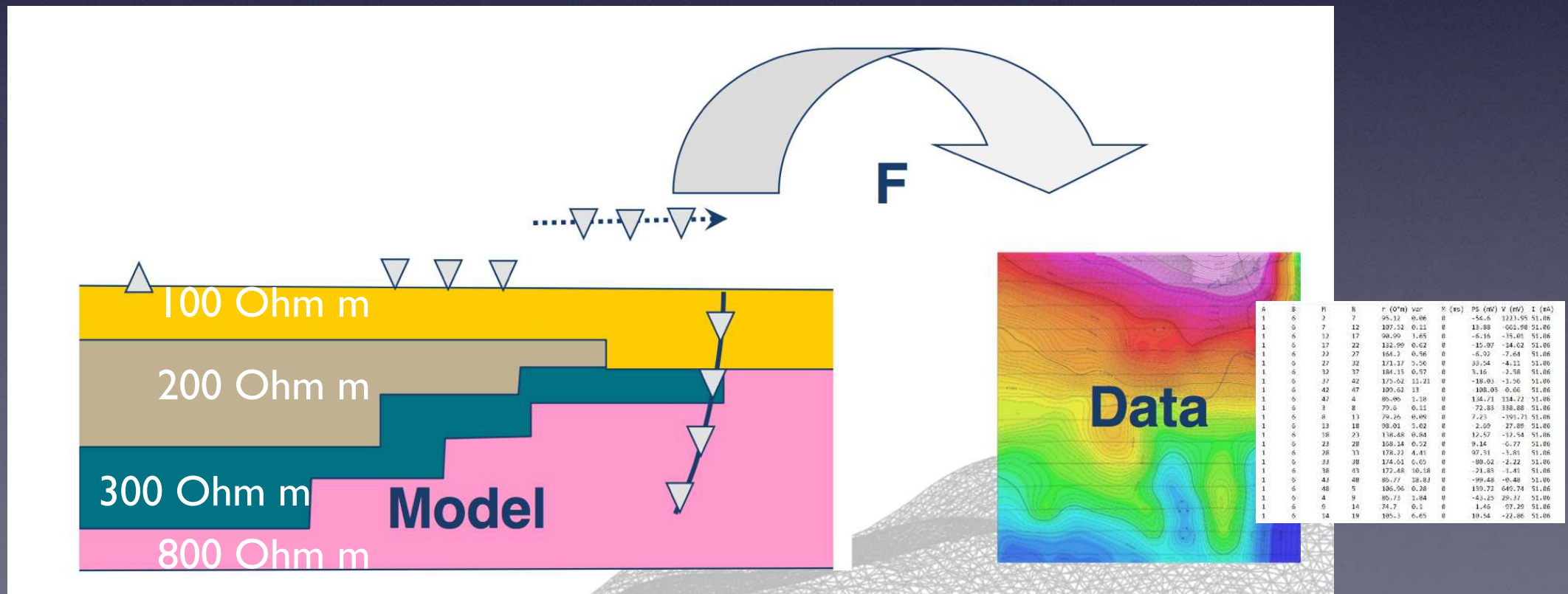
Forward and Inverse MODELS

FORWARD MODEL

From a model **M**, I get a data distribution **d**

$$\text{output } \mathbf{d} = \mathbf{F}(\mathbf{M}) \text{ input}$$

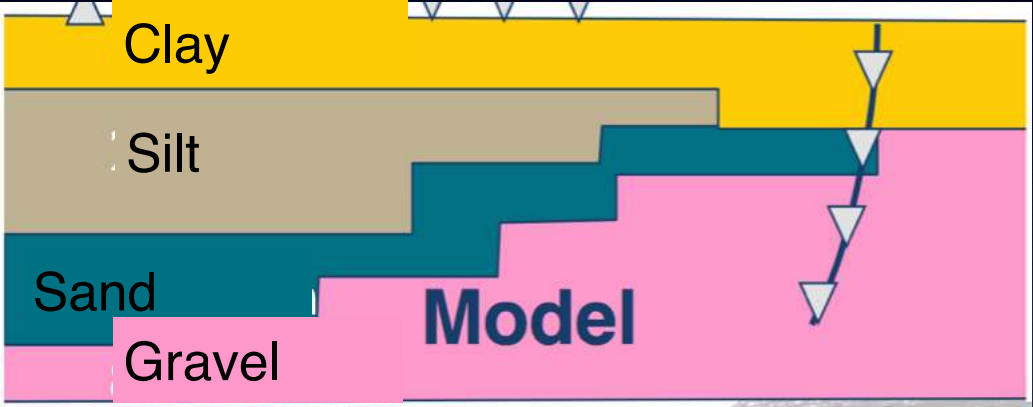
Where **F** is an operator which rules the relations between models and data



FORWARD MODEL

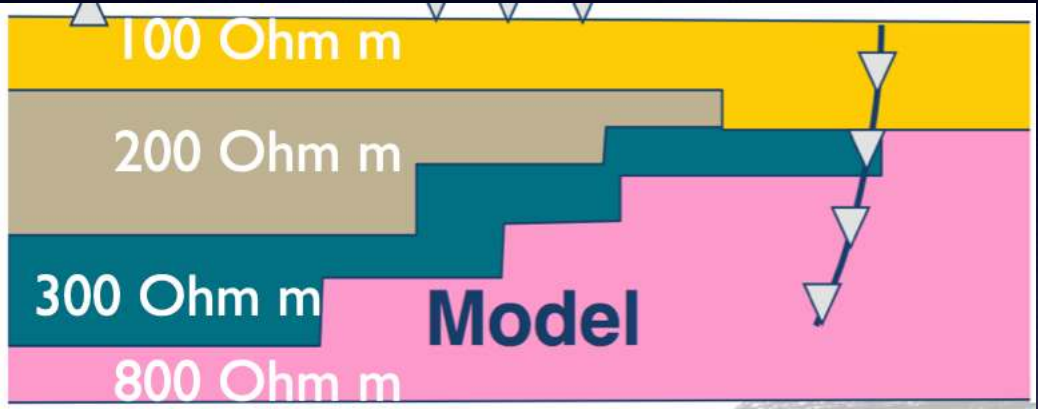
Example

1)



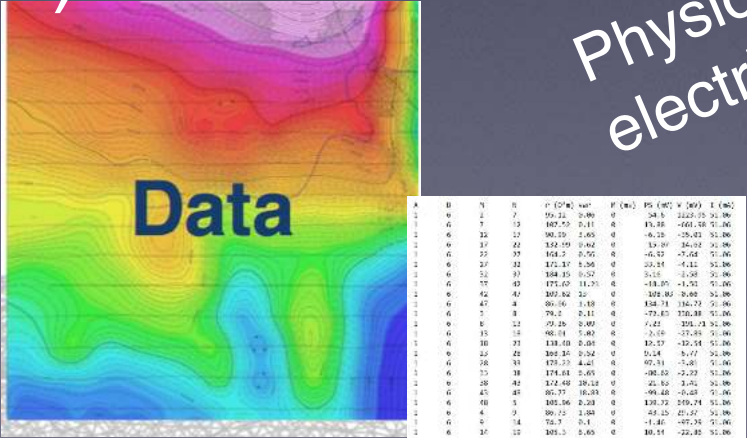
Model
of the subsoil

2)



Synthetical Electrical model
of the subsoil

3)



Physics laws who rules
electrical distribution

Knowing the physics,
I can **simulate** which DATA
I would collect in that subsoil

Forward and Inverse Models

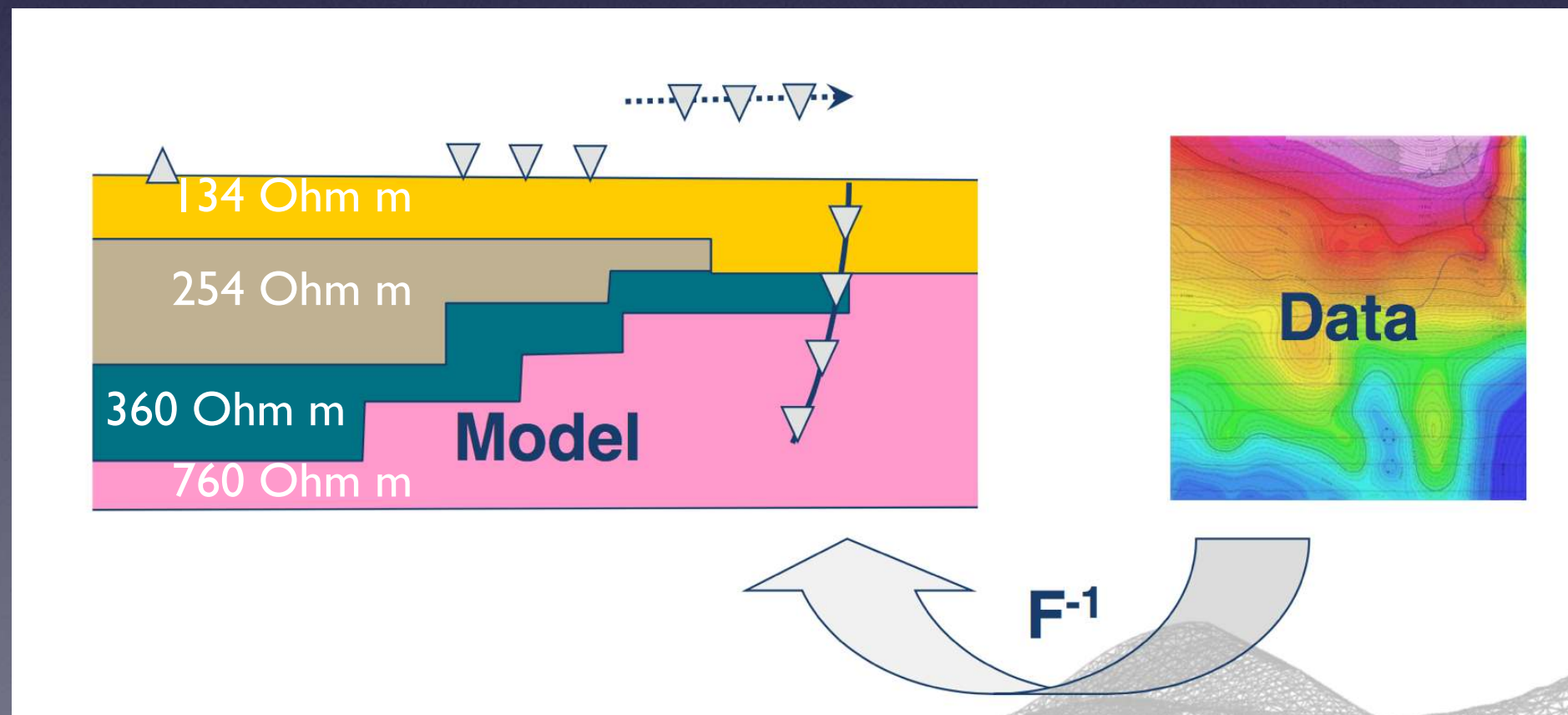
INVERSE MODEL

THE INVERSION in Geophysics are the mathematical and statistical techniques to determine the distribution of the Parameter P (e.g. *resistivity, density etc.*) starting from the observed DATA d

From the data collected d , I retrieve a subsoil model M

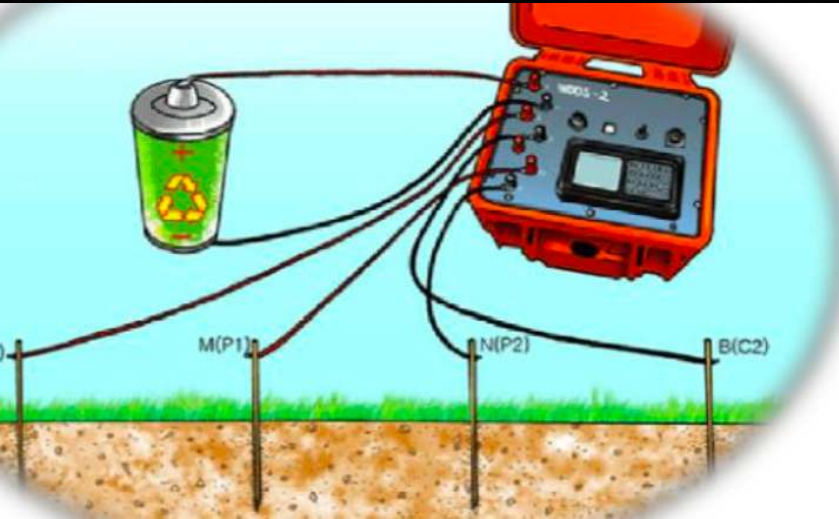
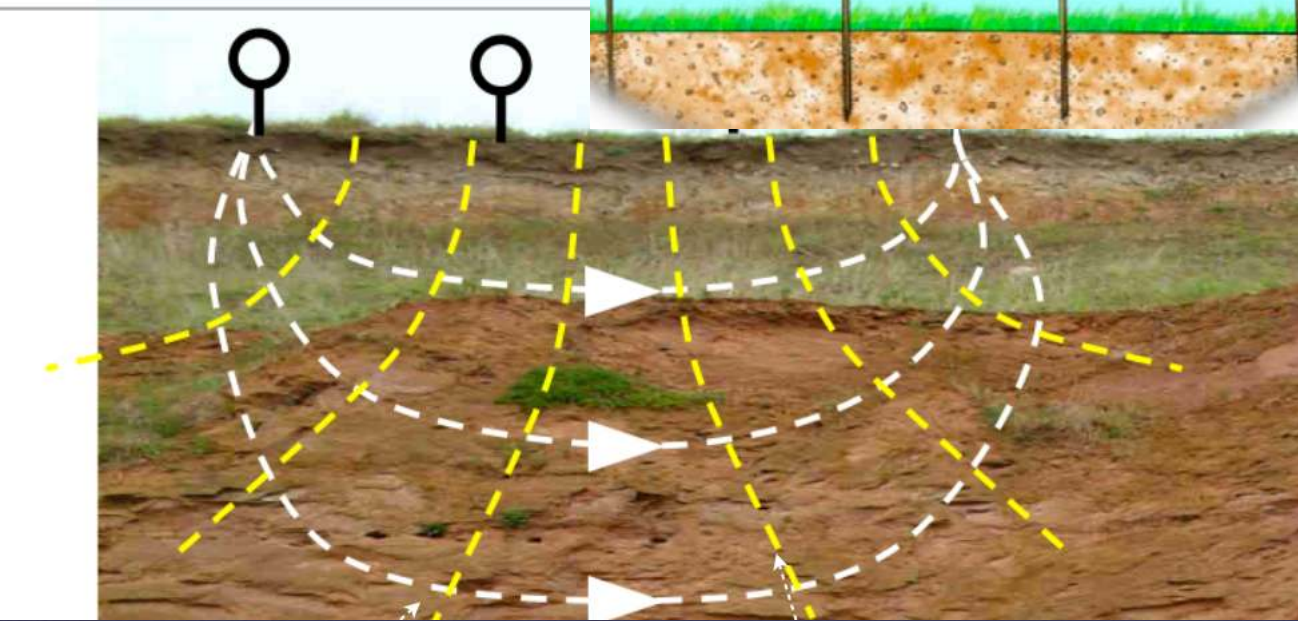
$$M = F^{-1}(d)$$

output $\nearrow$ $\nwarrow$ input



INVERSE MODEL

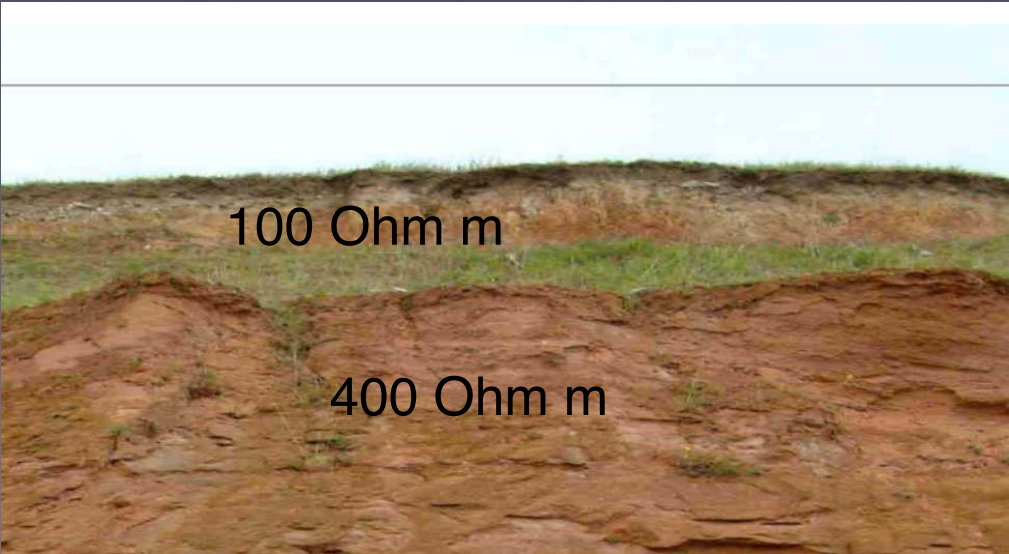
Field Measurements



Collected Data

A	B	M	N	r (O*m)	var	M (ms)	PS (mV)	V (mV)	I (mA)
1	6	2	7	95.12	0.06	0	-54.6	1223.95	51.06
1	6	7	12	107.52	0.11	0	13.88	-661.98	51.06
1	6	12	17	90.99	3.65	0	-6.16	-35.01	51.06
1	6	17	22	132.99	0.62	0	-15.07	-14.62	51.06
1	6	22	27	164.2	0.56	0	-6.92	-7.64	51.06
1	6	27	32	171.17	5.56	0	33.54	-4.11	51.06
1	6	32	37	184.15	0.57	0	3.16	-2.58	51.06
1	6	37	42	175.62	11.21	0	-18.03	-1.56	51.06
1	6	42	47	109.62	13	0	-108.03	-0.66	51.06
1	6	47	4	86.06	1.18	0	134.71	114.72	51.06
1	6	3	8	79.6	0.11	0	-72.83	338.88	51.06
1	6	8	13	79.26	0.09	0	7.23	-191.71	51.06
1	6	13	18	98.01	5.02	0	-2.69	-27.89	51.06
1	6	18	23	138.48	0.84	0	12.57	-12.54	51.06
1	6	23	28	168.14	0.52	0	9.14	-6.77	51.06
1	6	28	33	178.22	4.41	0	97.31	-3.81	51.06
1	6	33	38	174.61	6.65	0	-80.62	-2.22	51.06
1	6	38	43	172.48	10.18	0	-21.83	-1.41	51.06
1	6	43	48	86.77	18.83	0	-99.48	-0.48	51.06
1	6	48	5	106.96	0.28	0	139.72	649.74	51.06
1	6	4	9	86.73	1.84	0	-43.25	29.37	51.06
1	6	9	14	74.7	0.1	0	-1.46	-97.29	51.06
1	6	14	19	105.3	6.65	0	10.54	-22.86	51.06

Model



INVERSION

From the collected DATA
I retrieve a model of the subsoil

Forward and Inverse Models

DIRECT

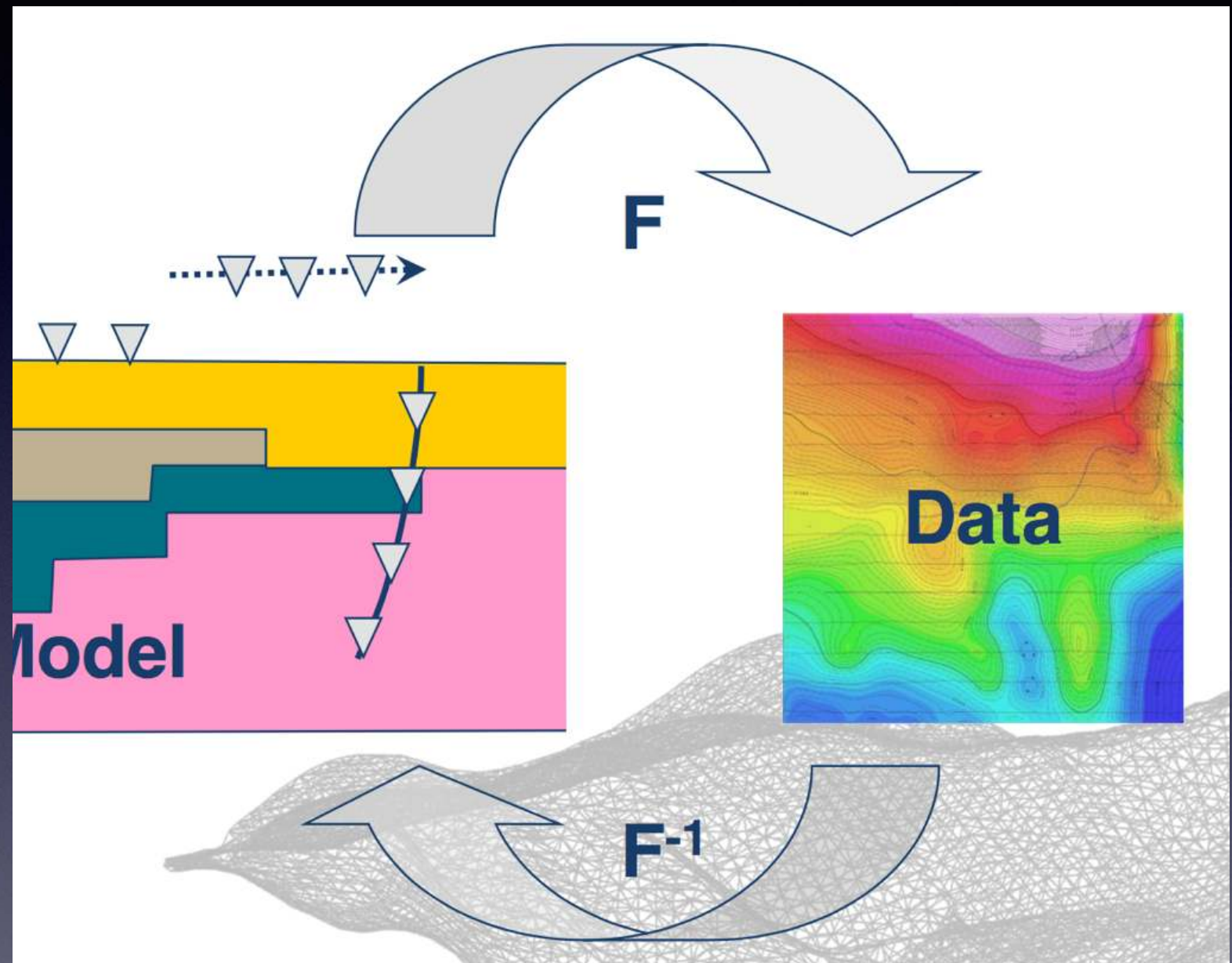
$$\mathbf{d} = \mathbf{F}(\mathbf{M})$$

output $\nearrow$ $\nwarrow$ input

INVERSE

$$\mathbf{M} = \mathbf{F}^{-1}(\mathbf{d})$$

output $\nearrow$ $\nwarrow$ input



- inversion: an ill posed problem

Hadamard 1923

Math problem is well posed if:

- 1) for all the admissible data a solution exists (existence)
- 2) for all the admissible data the solution is unique (unicity)
- 3) solution depends in a continuous way from the data (stability)

Solution must exist, be unique and stable

Es algebraic sum ($2+2=4$, $2+3=5$)

Otherwise it is ILL POSED !

- inversion: an ill posed problem

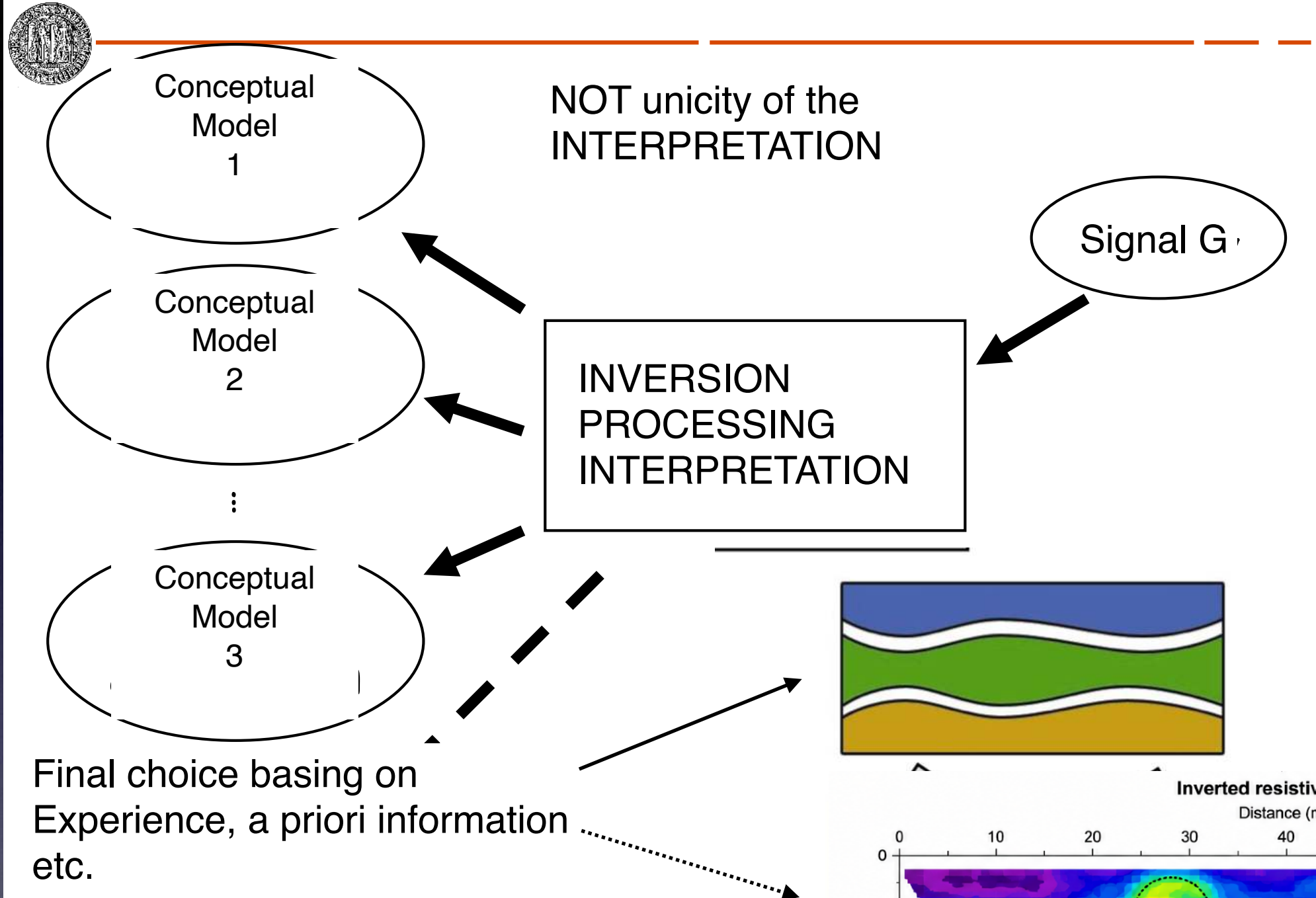
Hadamard 1923,

Math problem is well posed if:

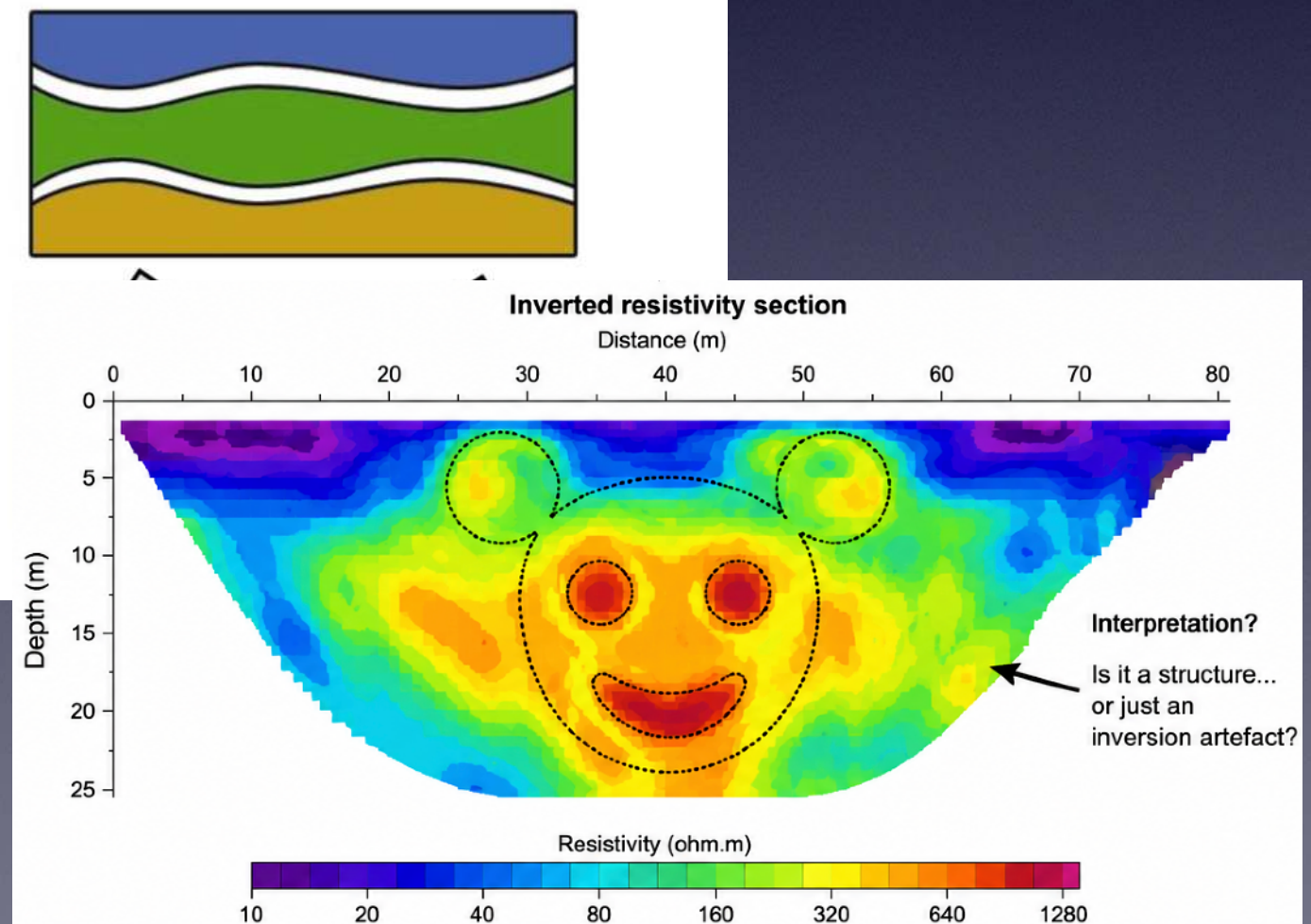
- 1) for all the admissible data a solution exists (existence)
- 2) for all the admissible data the solution is unique (unicity)
- 3) solution depends in a continuous way from the data (stability)

Inverse problem is ILL POSED !

Direct and Inverse models

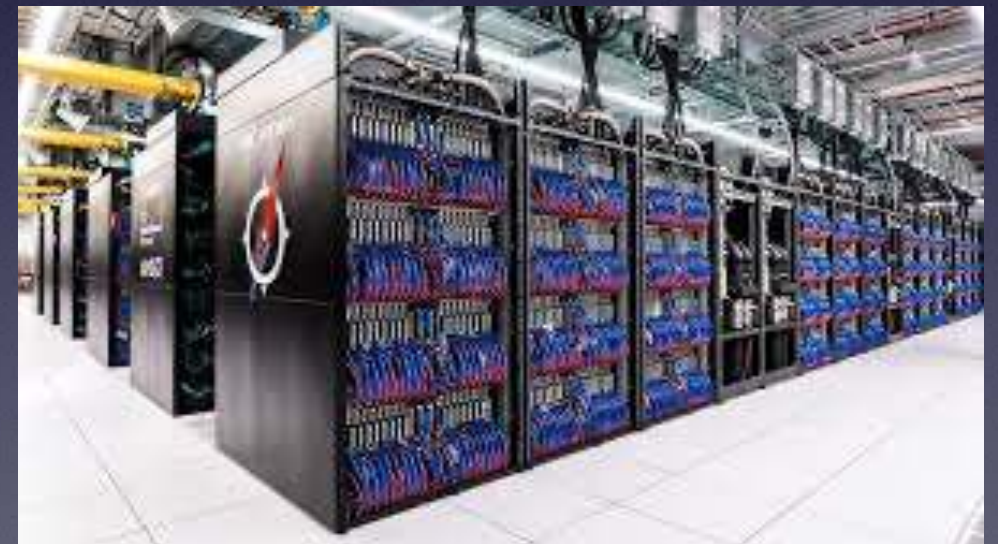


Correct Interpretation Can be Hard



- *Bad cases*

Bad data input to excellent inversion algorithm



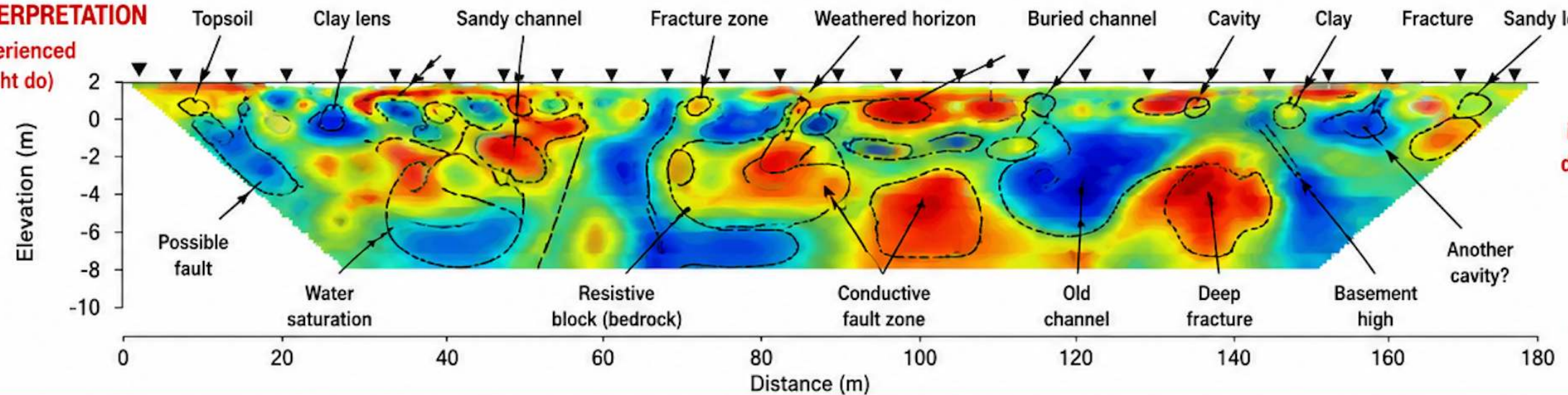
BAD OUTPUT

Garbage in, garbage out!

Please do not over-interpret ERT!

(b) OVER-INTERPRETATION

(what an inexperienced interpreter might do)



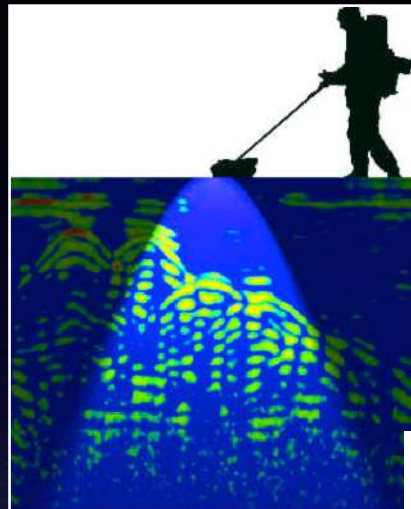
Every color variation is interpreted as a different feature!

Result: confusing and geologically unrealistic interpretation.

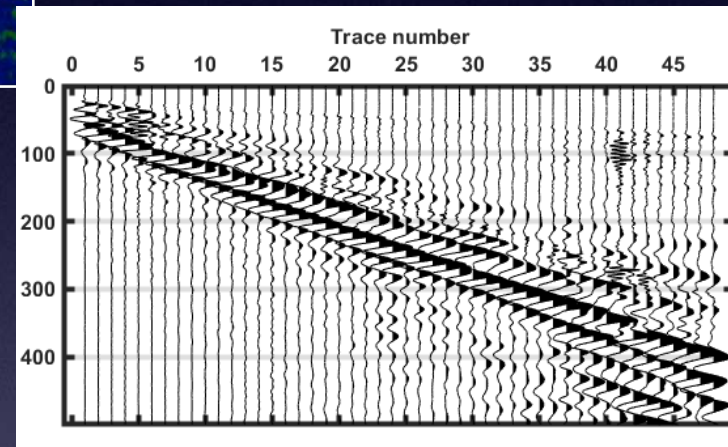
AI generated or real figure of a paper?

Geophysics in Periglacial Environments

- GPR Georadar

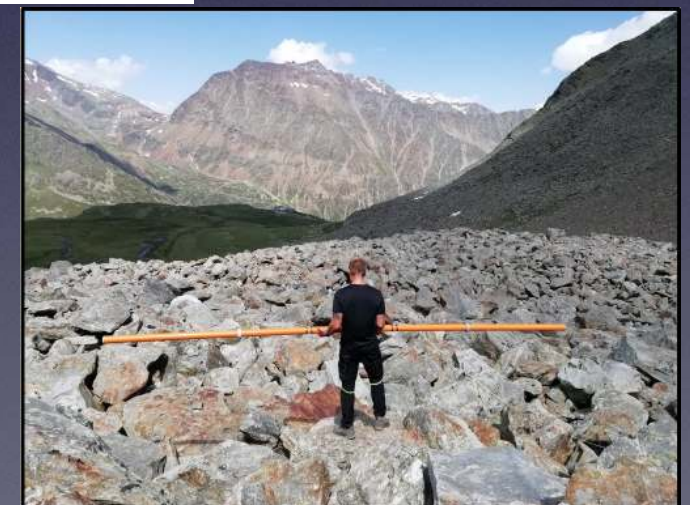


- Seismic methods



- FDEM Electromagnetic method

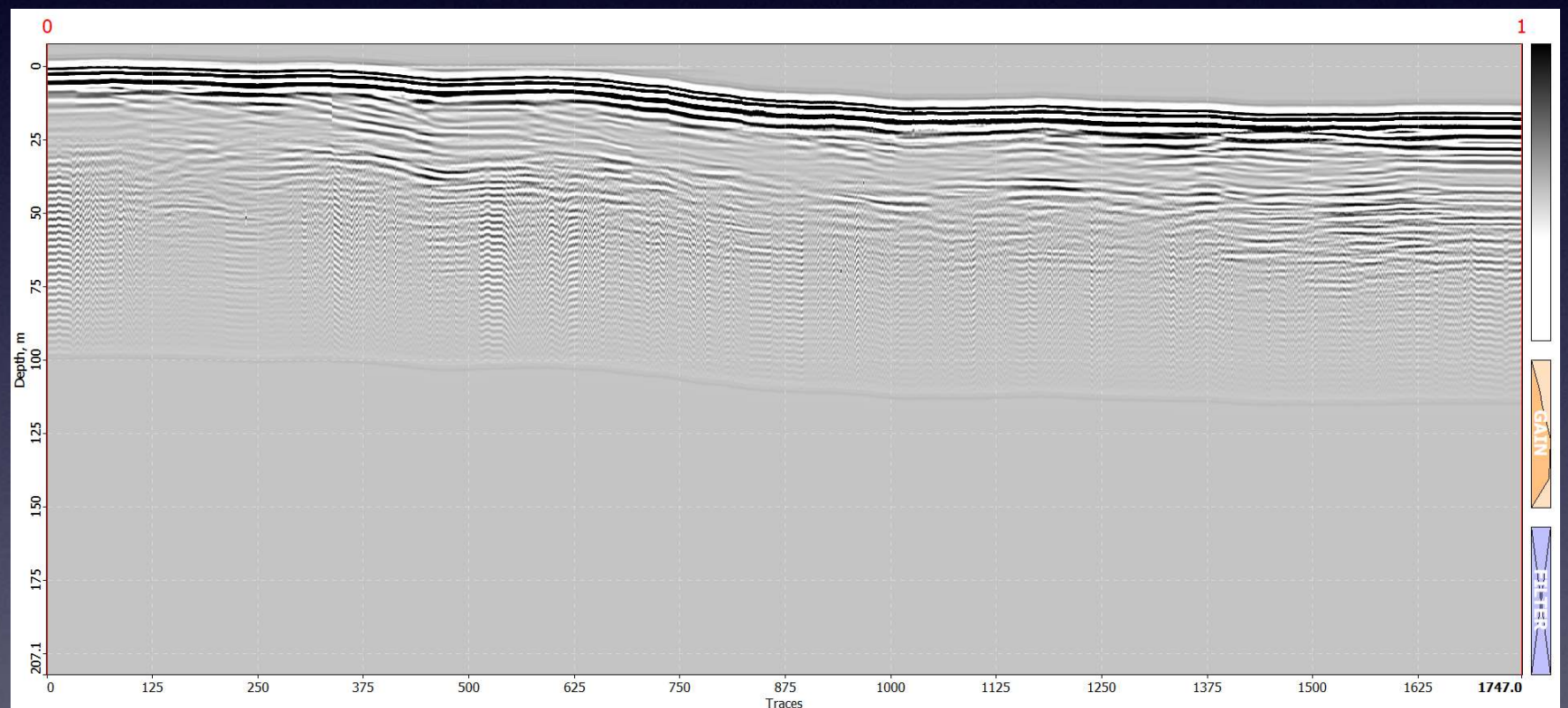
- ERT



Geophysics in Periglacial Environments

- GPR Georadar

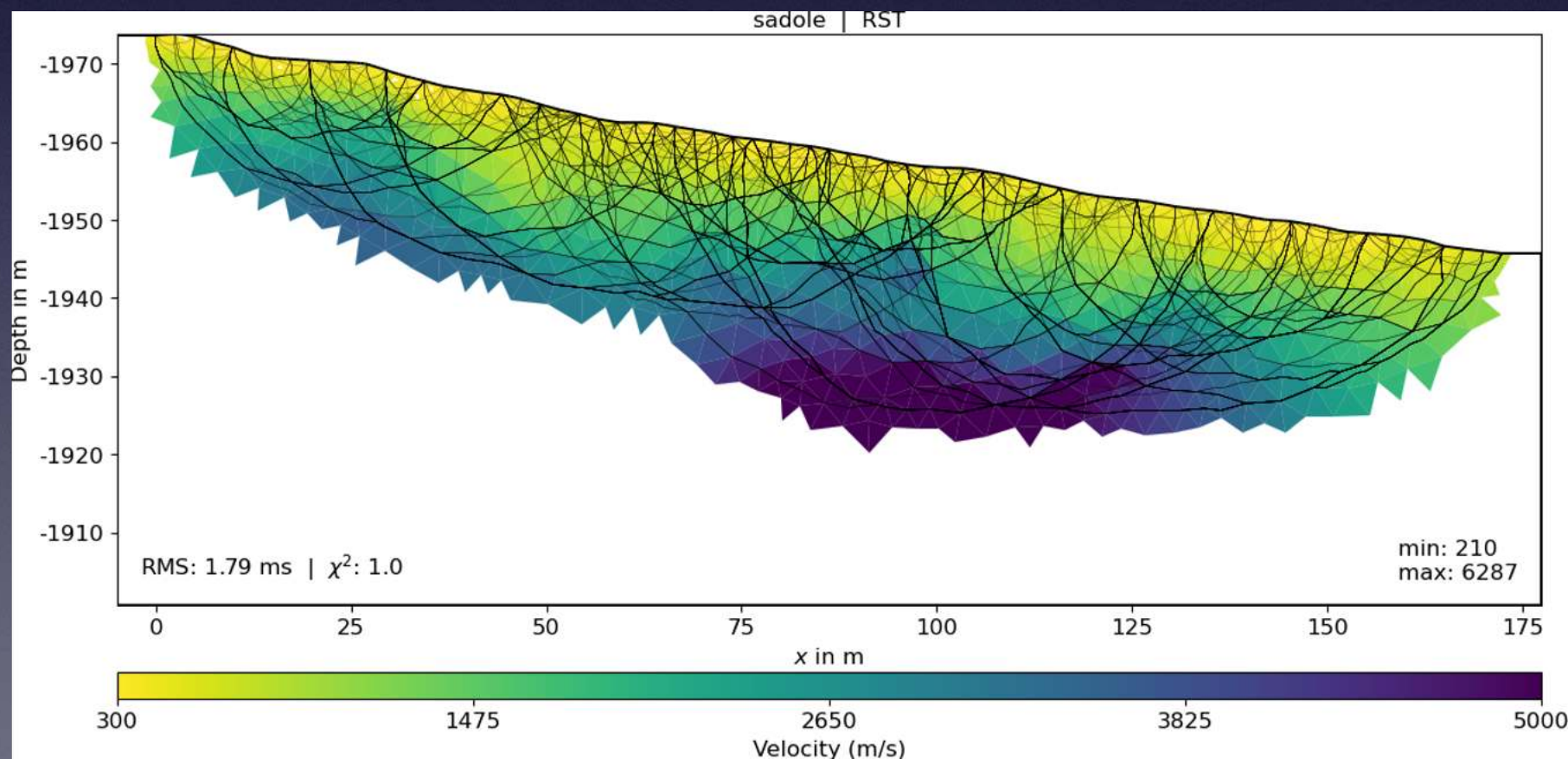
GPR has high penetration in resistive media (ice), but it is strongly scattered/attenuated from blocky coarse sediments



- Much more suitable for **GLACIAL** env.

Geophysics in Periglacial Environments

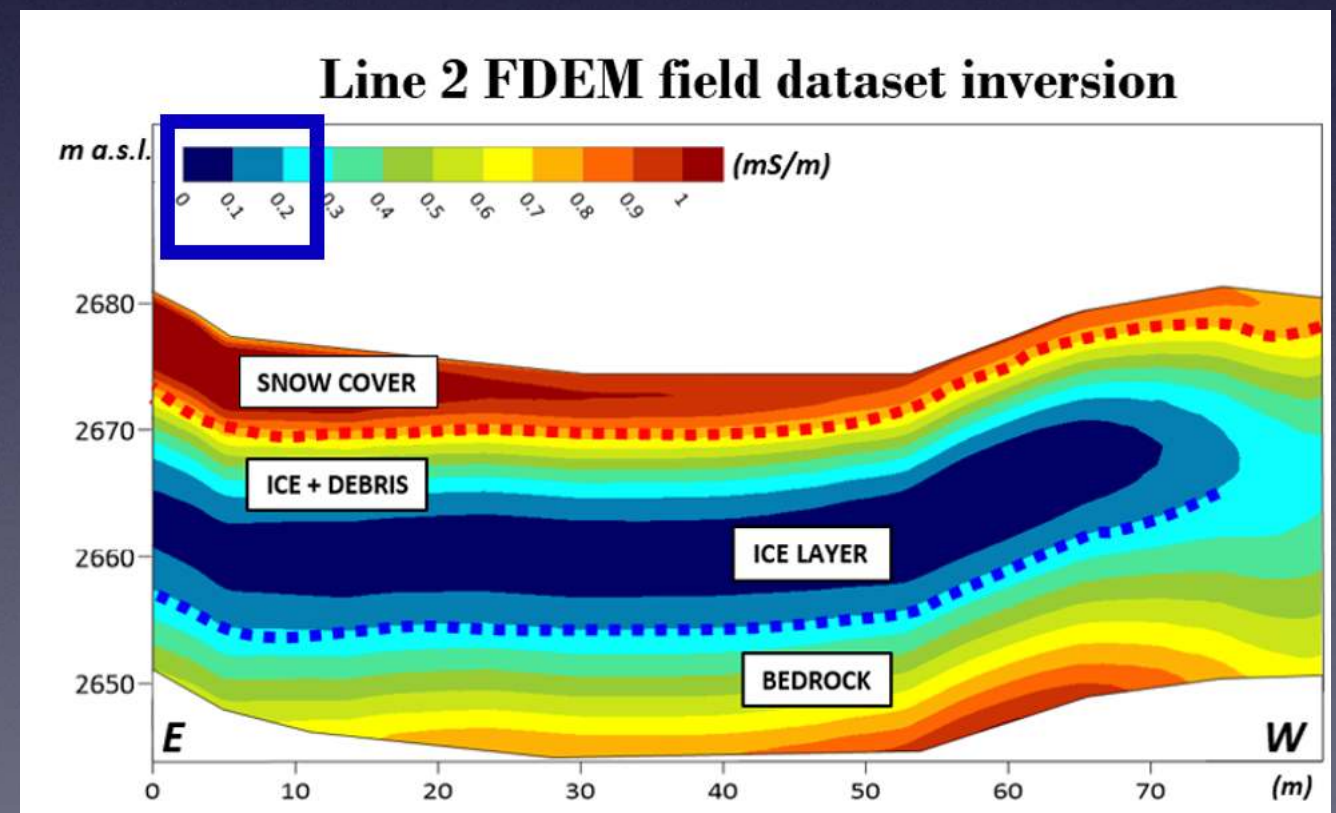
- **Seismic methods**
- Frozen ground has higher velocity than coarse sediments
- Seismic refraction can solve only faster layers below slower ones...



Geophysics in Periglacial Environments

- FDEM Electromagnetic methods

Measuring electrical conductivity are suitable for frozen ground, but have poor resolution



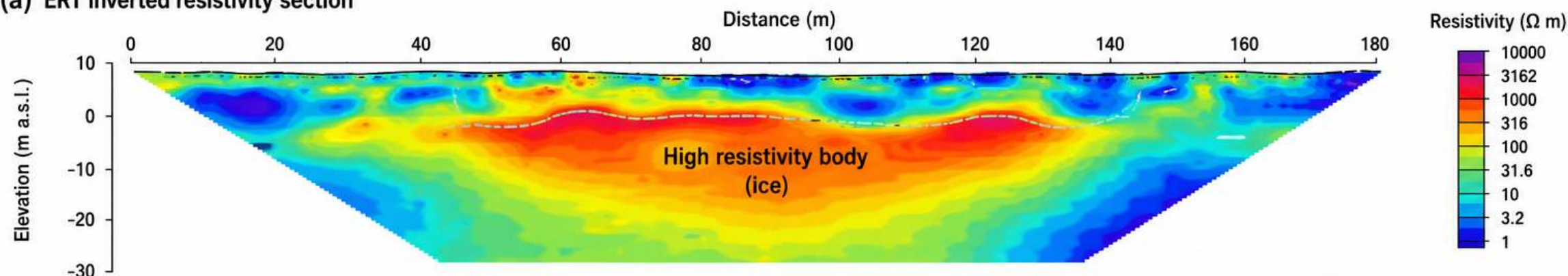
Geophysics in Periglacial Environments

Why ERT in Permafrost ?

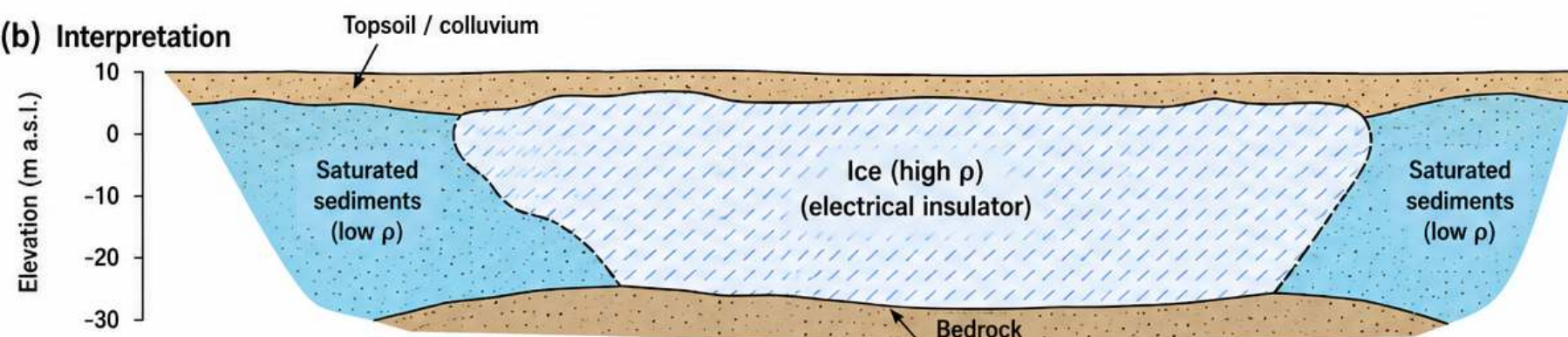
ICE AS AN ELECTRICAL INSULATOR – EXAMPLE FROM ERT

Higher resistivity (warm ice) compared to surrounding sediments/groundwater

(a) ERT inverted resistivity section



(b) Interpretation

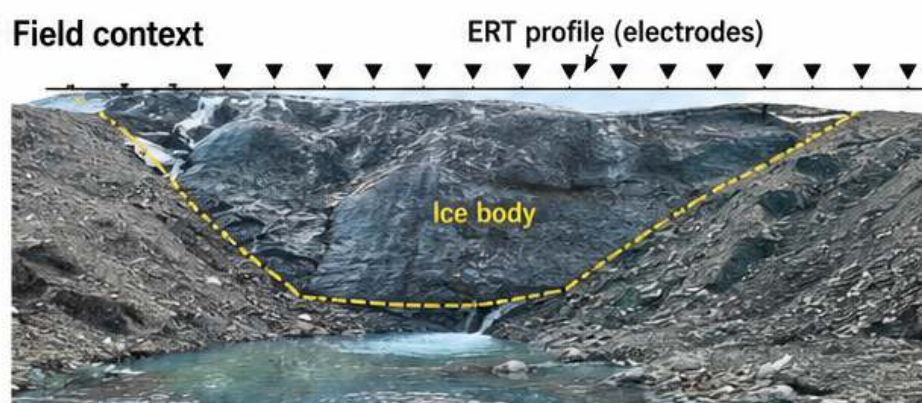


Why ice is an insulator

At DC to low frequency (typical for ERT), electrical current in soils and rocks is carried mainly by ions in pore water.

Ice contains almost no free water or ion mobility, therefore it has very high resistivity.

(c) Field context



(d) Typical resistivity values

Material	Resistivity (Ω m)
Warm ice (0 °C)	$10^3 - 10^5$
Frozen sediment (ice-cemented)	$10^2 - 10^4$
Dry rocks / boulders	$10^2 - 10^5$
Saturated sediments (with groundwater)	$1 - 10^2$
Clay / conductive sediments	0.1 – 10
Fresh water	0.1 – 10
Seawater	0.2

Higher resistivity
(more insulating)

Lower resistivity
(more conductive)

→ High resistivity anomalies in ERT sections in cold regions are commonly interpreted as ice (glacial ice, buried ice, permafrost ice) because ice is an electrical insulator compared to water-saturated sediments.

Introduction to Electrical Resistivity Tomography ERT

Physical Properties (P)

- ❑ **Seismic** Elastic moduli and density
- ❑ **Gravimetry** : Density
- ❑ **Magnetic meth.** Magnetic susceptibility
- ❑ **ERT meth.** Electrical resistivity
- ❑ **Electro-magnetic meth.** Electrical conductivity
- ❑ **Induced Polarisation** Chargeability /Electrical complex conductivity
- ❑ **Spontaneous Potentials** Electrical conductivity
- ❑ **Ground penetrating Radar** Dielectric constant

ERT

Electrical-Resistivity-Tomography

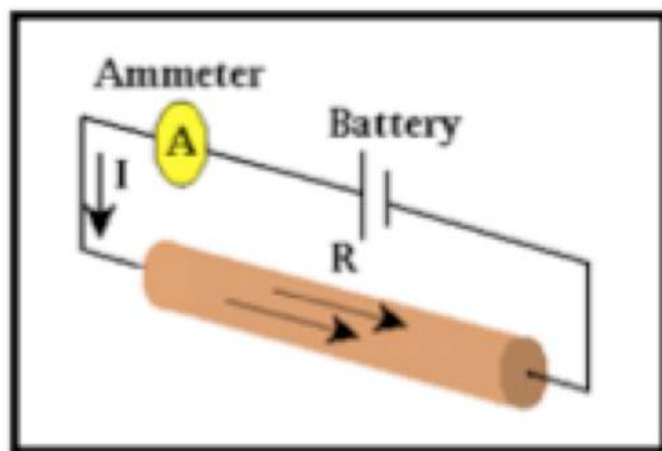
- Physical principles
- Acquisition methods
- Processing

ERT

Electrical-Resistivity-Tomography

Ohm's law

$$\Delta V = I \cdot R$$



$$\sigma = I / R$$

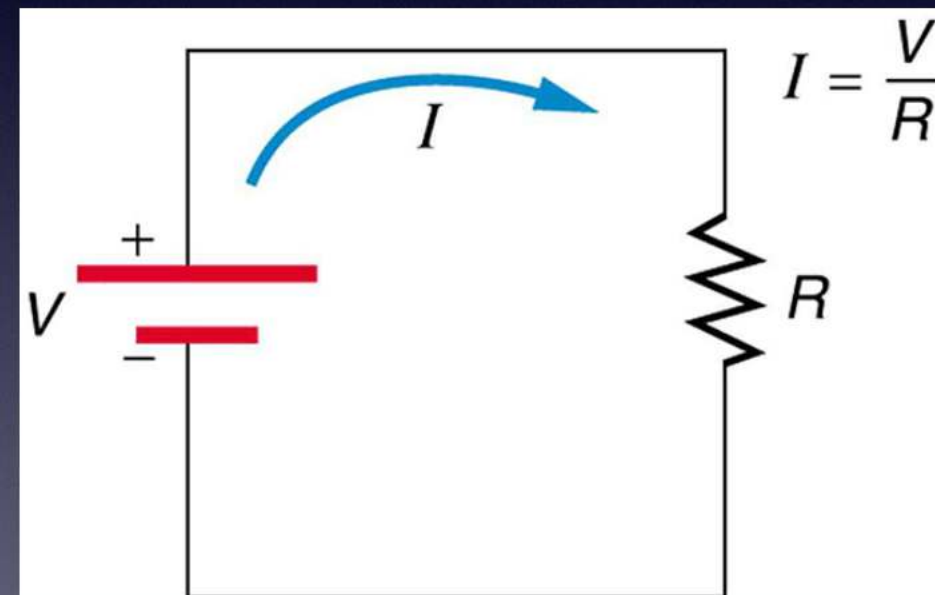
$$I = \Delta V \sigma$$

ΔV = POTENTIALS Difference in Volts

I = Intensity Current in Amperes

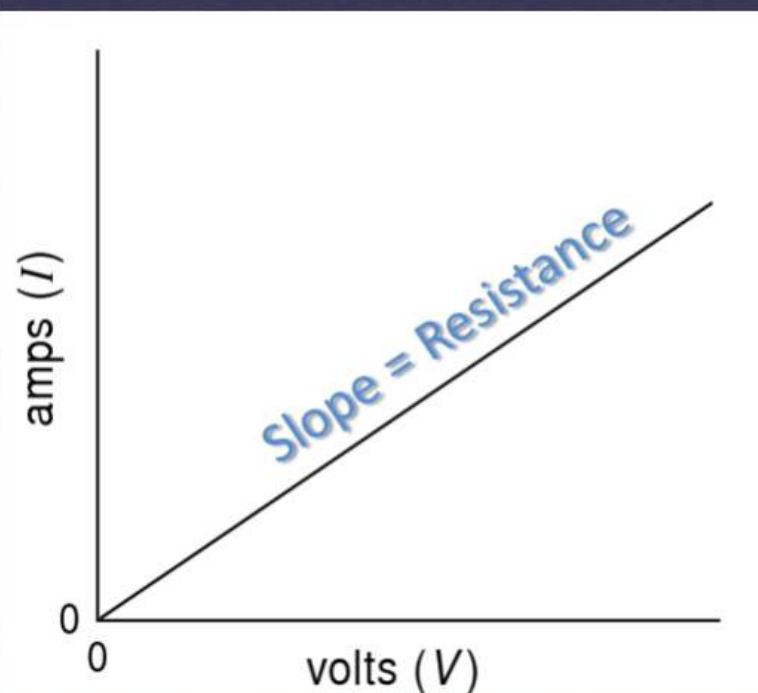
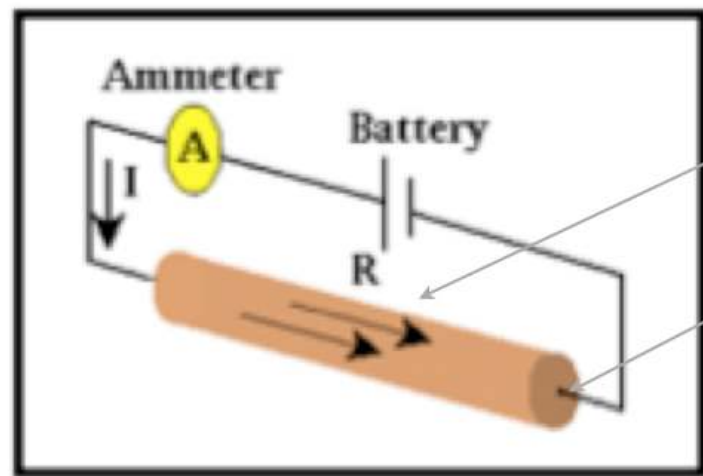
R = resistance in Ohm

σ = Conductibility in Siemens



The OHM LAW

$$\Delta V = I \cdot R$$



Electrical Resistivity:

$$\rho = \frac{R A}{L}$$

Resistance (Ω)

Area (m^2)

Length (m)

Unit of measurement is $\Omega \text{ m}$
Ohm meter

Electrical Methods

In 3d media we have to consider geometry

Electrical Resistivity	$\rho = \frac{1}{\sigma}$	SI unit $\Omega \text{ m}$ ohm meter
Electrical conductivity	$\sigma = \frac{1}{\rho}$	S/m Siemens / meter

Diffusion Equations for currents fluxes

$$\vec{J} = \sigma \vec{E}$$

Ohm's Law
(vectorial)

Conductivity

Charges density

Electrical Field
(forcing conditions)

$$E = J/\sigma$$

$$\sigma = 1/\rho$$

$$E = J \rho$$

$$\sigma = \text{conductivity}$$

$$\rho = \text{resistivity}$$

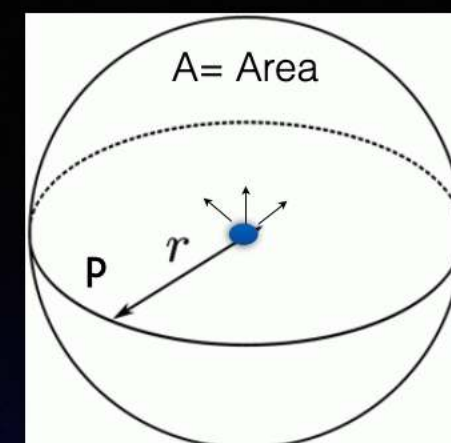
$$J = \text{charges density}$$

In stationary flux equation

The **voltage** is the work done from the electric field E to move a charge from ∞ to P

$$J_p = I/A = \frac{I \hat{r}^{\text{Versor}}}{4 \pi r^2}$$

$$E = J \rho$$



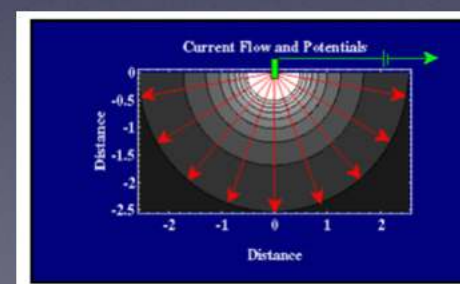
A = Area

I = Injection

$$V = \int_r^{\infty} E dr = \int_r^{\infty} \frac{I \rho}{4 \pi r^2} dr$$

Sphere

$$V = \frac{I \rho}{4 \pi r}$$



Semi-sphere

$$V = \frac{I \rho}{2 \pi r}$$

$$\rho_a = \frac{V}{I} K$$

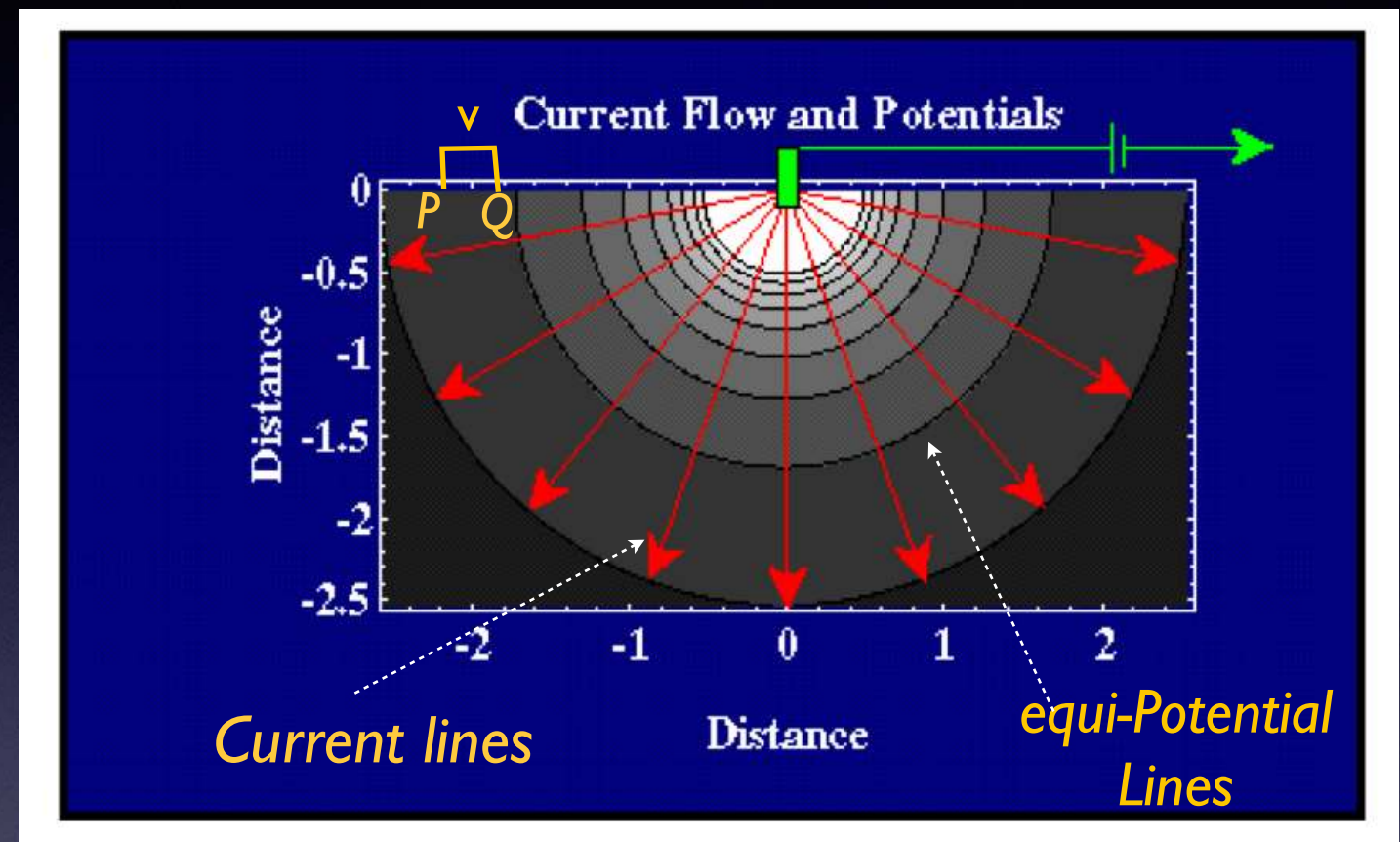
Geometrical Factor

Apparent resistivity

Current immersion in a point (electrode) on a homogenous half-space (the subsoil):

$$V = \frac{I \rho}{2 \pi r}$$

Current fluxes in a semi-sphere of ray r and area $2 \pi r$



Current density becomes:

$$J = \frac{I \hat{r}}{2 \pi r^2}$$

$$V_{PQ} = V_P - V_Q = \frac{I \rho}{2 \pi} \left[\frac{1}{r_P} - \frac{1}{r_Q} \right]$$

But the subsoil is NOT homogenous and isotropic

From the potential and current injection measurements we retrieve an
APPARENT RESISTIVITY ρ_a (function of geometry of acquisition)

$$\rho_a = \frac{V_{PQ}}{I} \left[\frac{1}{r_P} - \frac{1}{r_Q} \right]$$

$$\rho_a = \frac{V_{PQ}}{I} \left[\frac{1}{r_P} - \frac{1}{r_Q} \right] \leftarrow \text{Geometric factor } K$$

$$\rho_a = \frac{V_{PQ} K}{I}$$

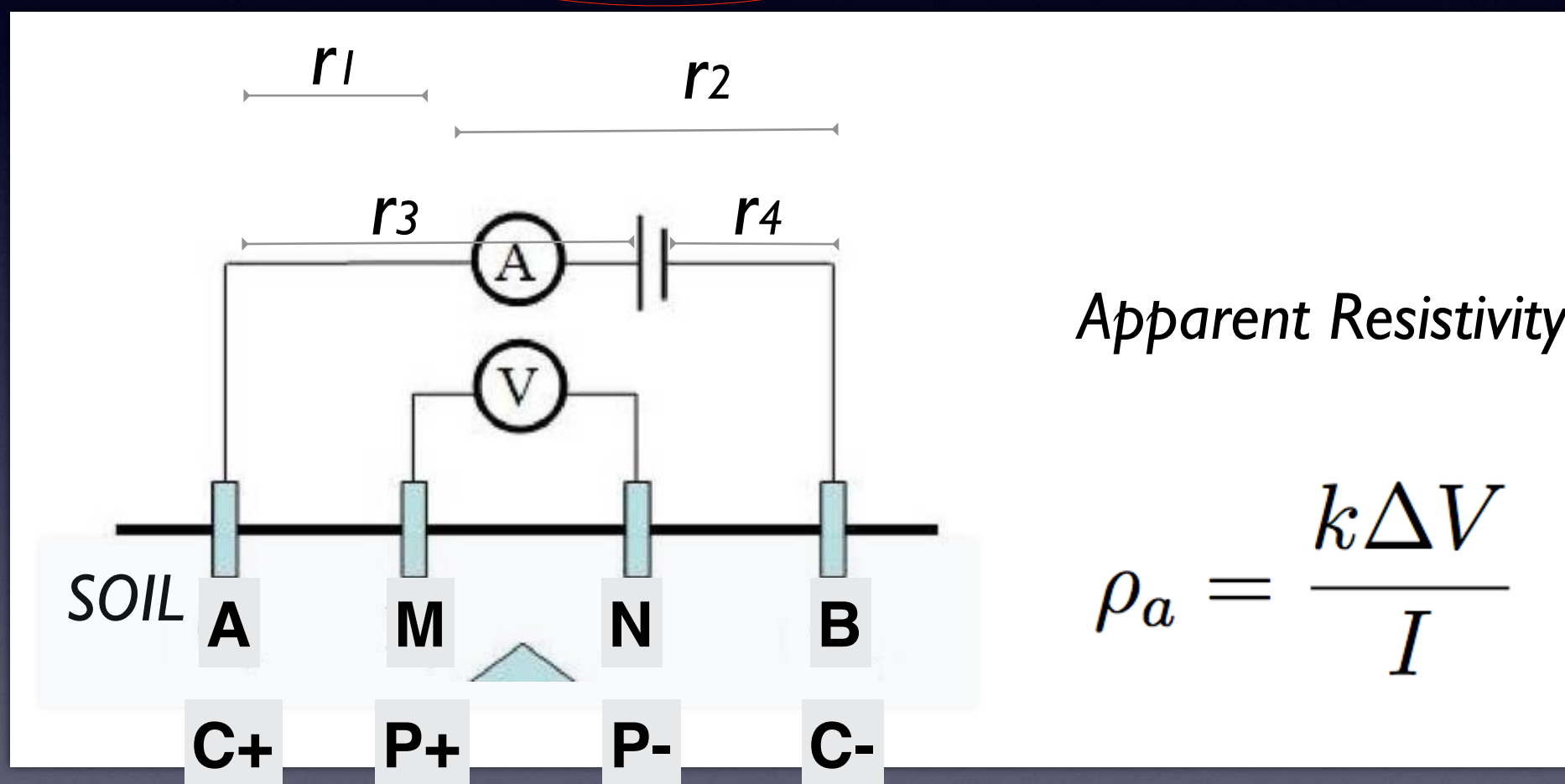
ELECTRIC QUADRIPOLE

I)

$$\Delta V = \frac{I\rho}{2\pi} \left[\left(\frac{1}{r_1} - \frac{1}{r_3} \right) - \left(\frac{1}{r_2} - \frac{1}{r_4} \right) \right]$$

K

Geometric Factor

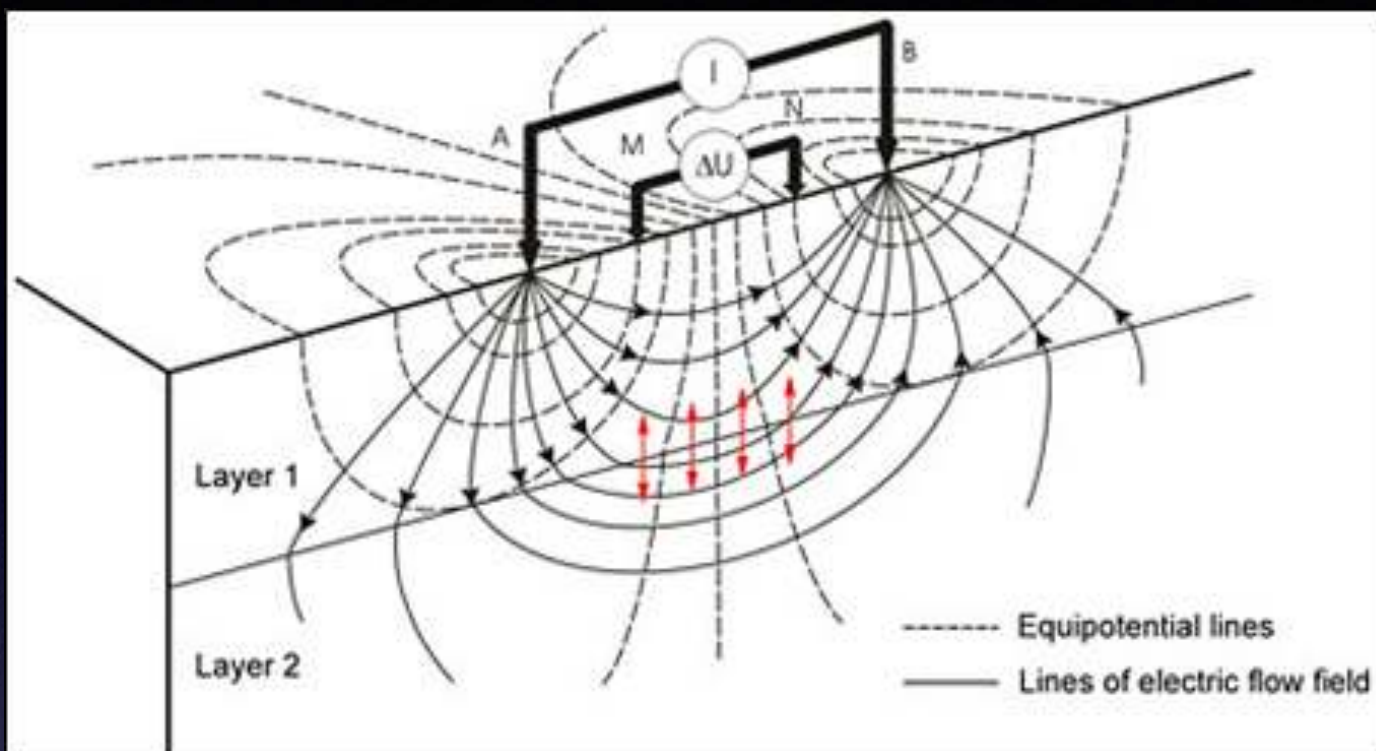


$$\rho = \frac{I}{\sigma}$$

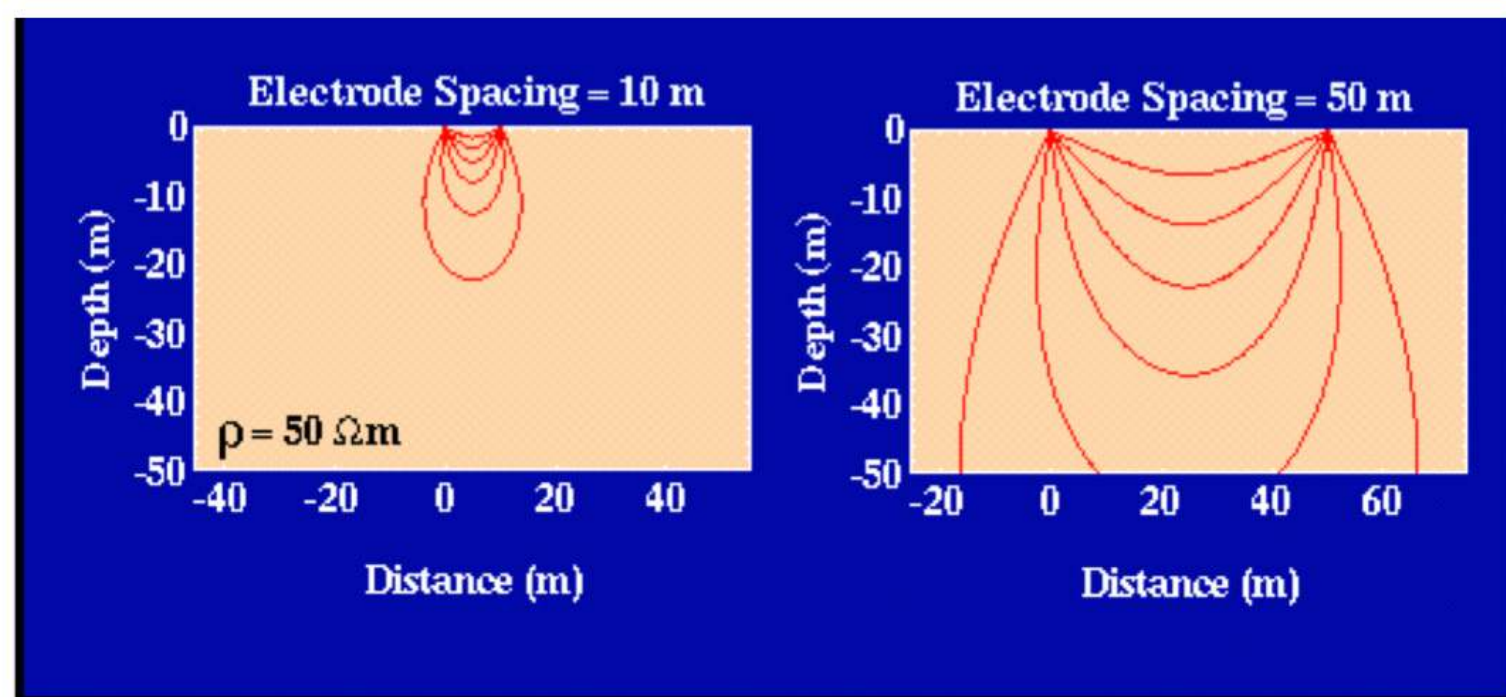
Resistivity *Conductivity*

Different media,
different current lines
distribution

Different current lines
distribution, different
voltage fields
measurements



I can explore different
depth varying
geometry of
acquisition



ARRAY CONFIGURATIONS

AB = current electrodes
MN = voltage electrodes

a) Wenner array

$$AM = MN = NB$$

A & B = Injection
electrodes

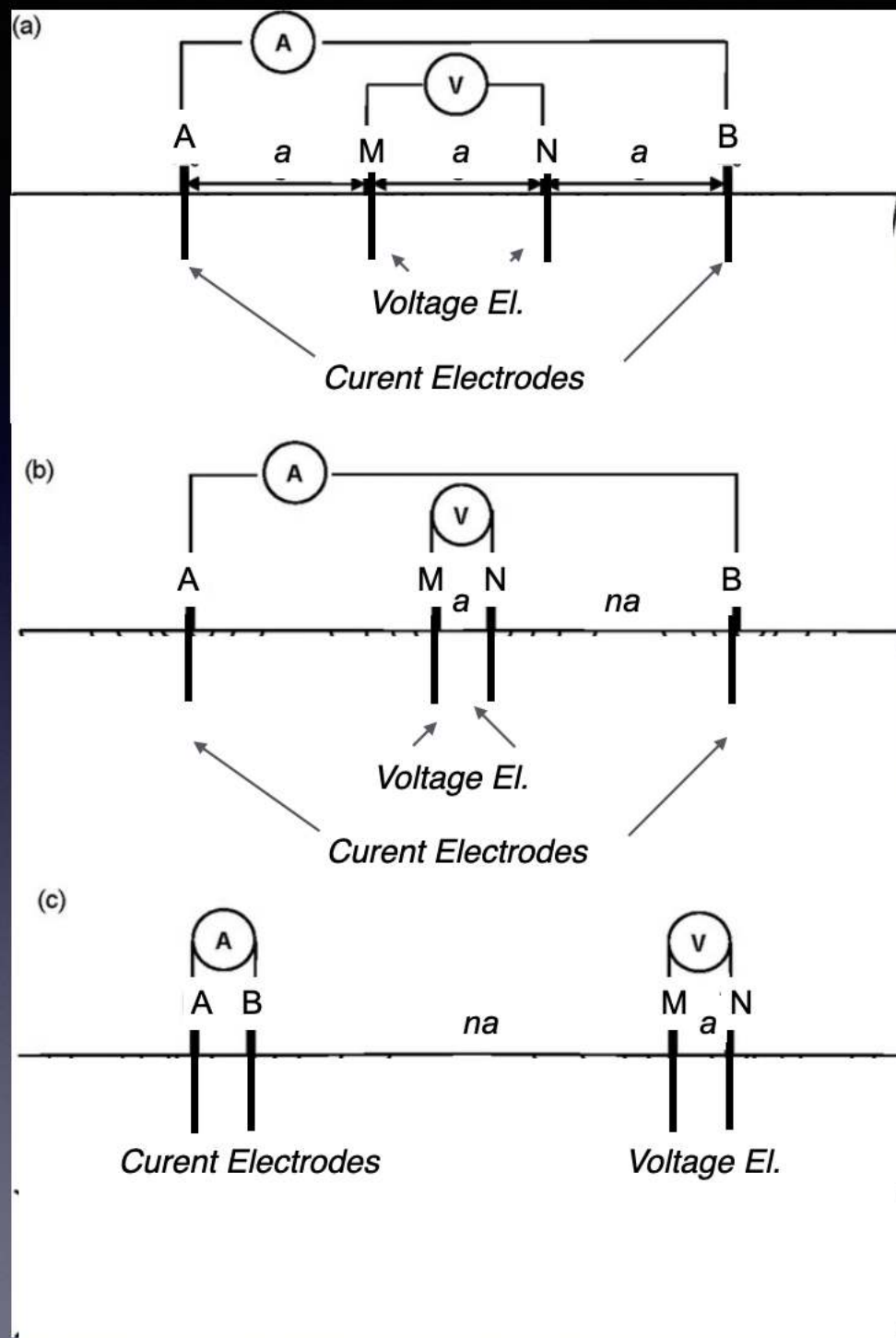
M & N = Potential
electrodes

b) Schlumberger array

$$AM = n \cdot MN$$

c) Dipole-dipole array

$$AB = MN$$



ARRAY CONFIGURATIONS

AB = current electrodes

MN = voltage electrodes

Multi Gradient Array

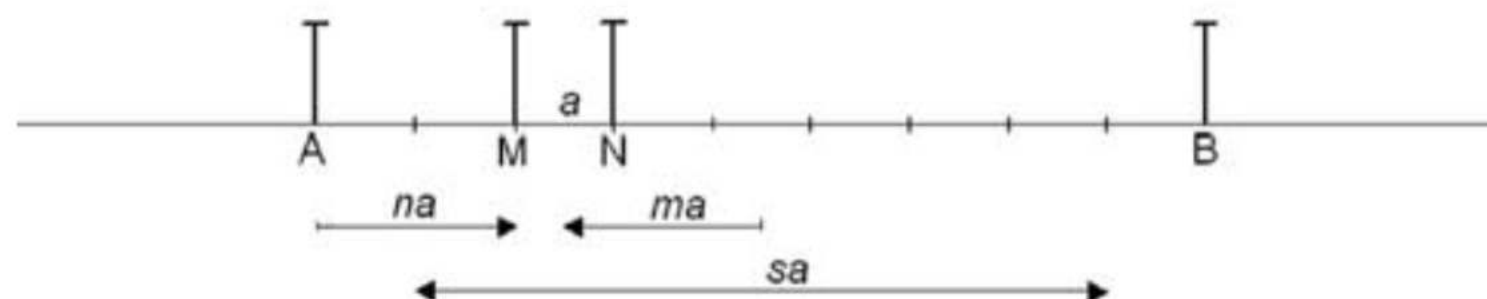
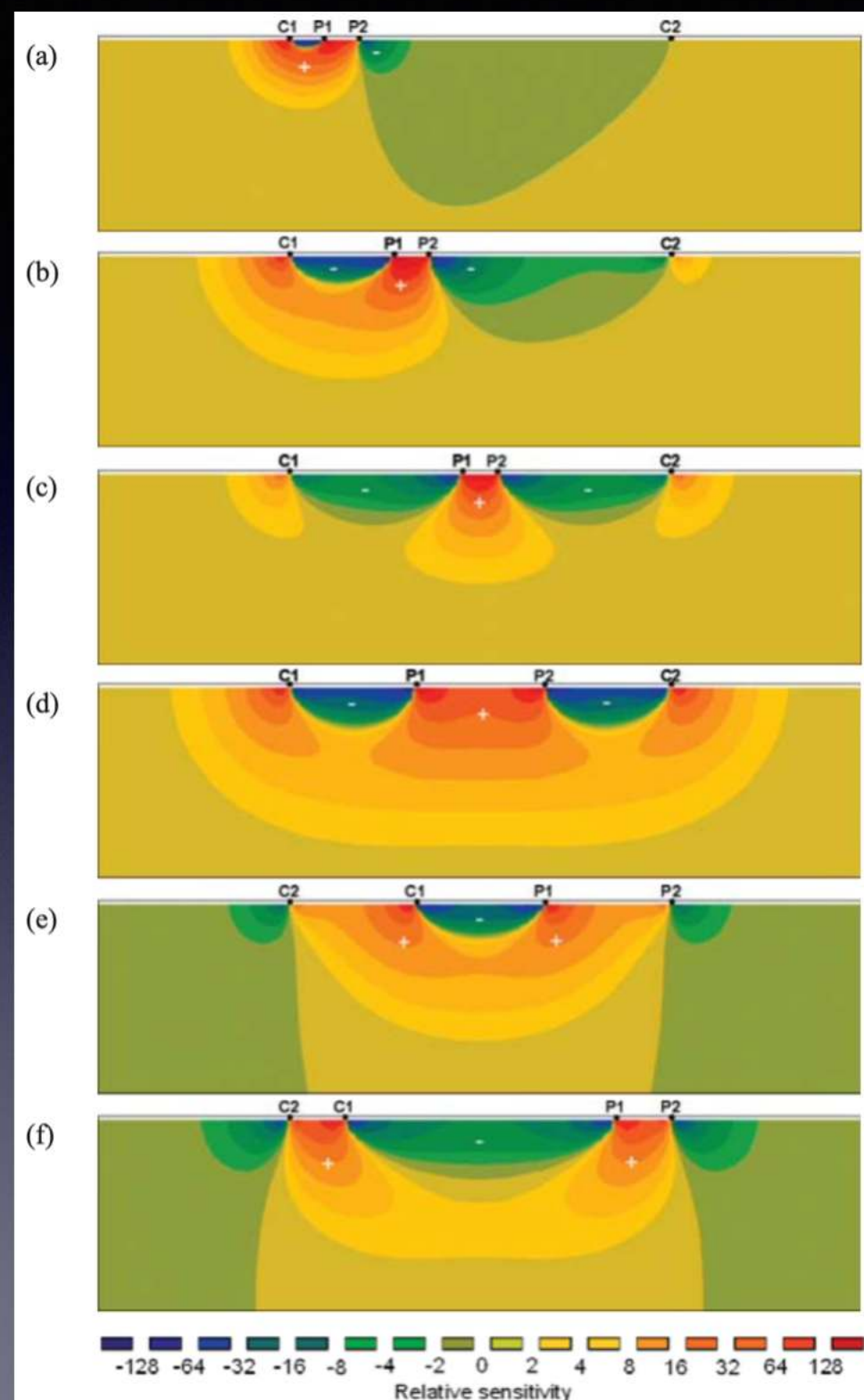


FIGURE 1

Sketch of gradient array showing the position of the electrodes for a measurement with a current-electrode separation of $(s+2)a$, where the separation factor $s = 7$, the n -factor = 2 and the midpoint factor $m = -2$. Here, the n -factor is defined as the smallest relative spacing between a current electrode and a potential electrode.



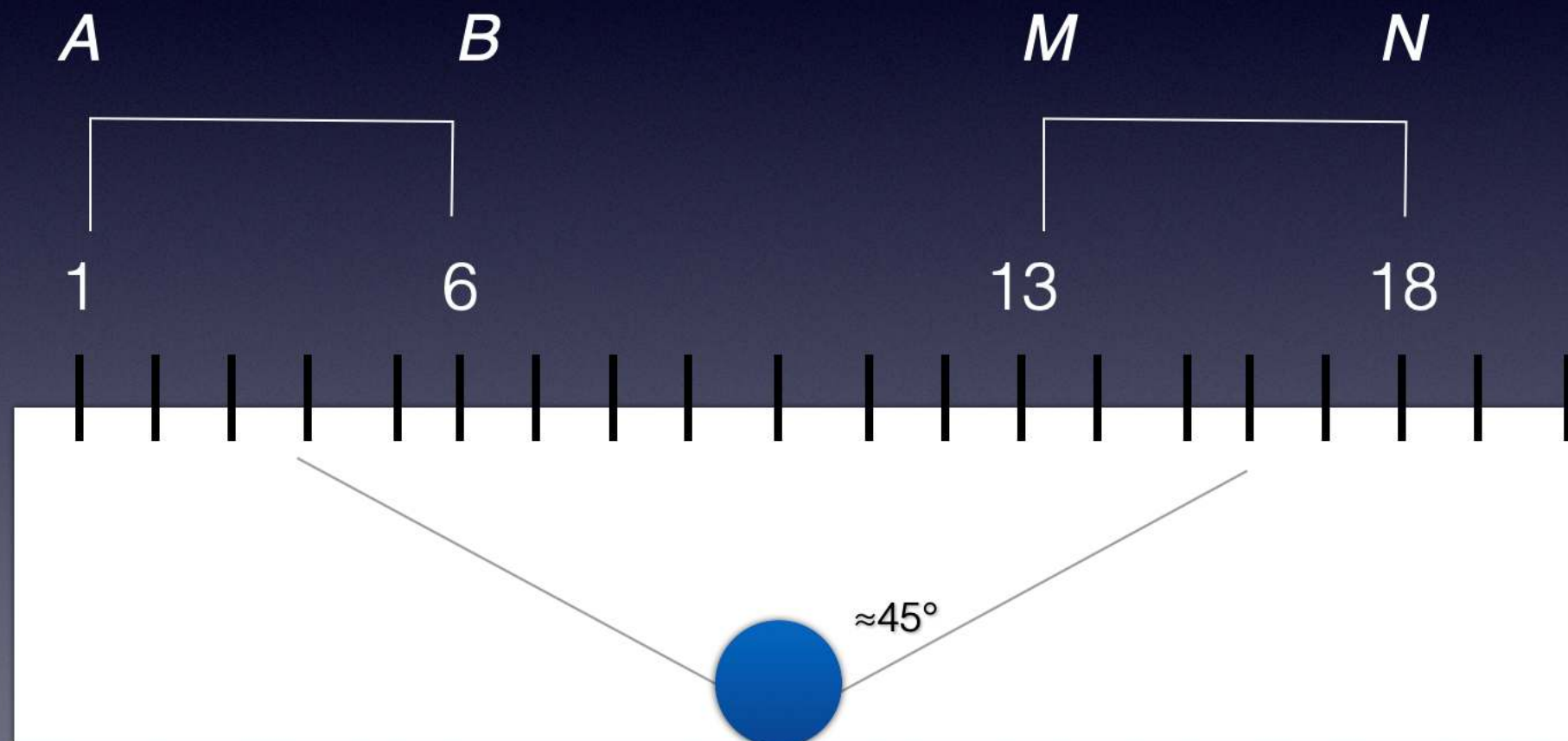
ARRAY CONFIGURATIONS

AB = current electrodes

MN = voltage electrodes

Or multi skip dipole dipole

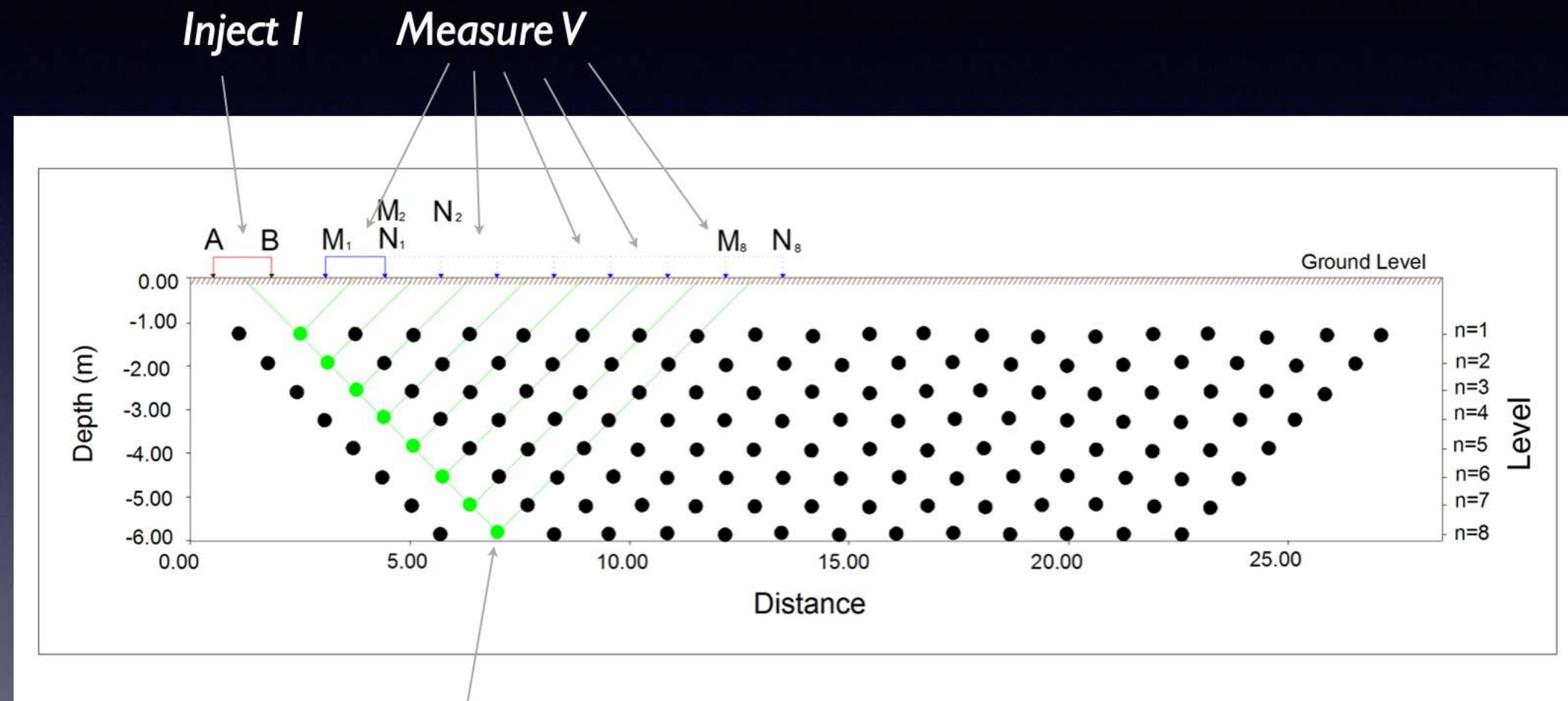
e.g. skip 4 dipole



Multi-channels autonomous systems open large perspectives

Geo-electrical methods

Moving quadripoles we can retrieve 2D section on 3D volume

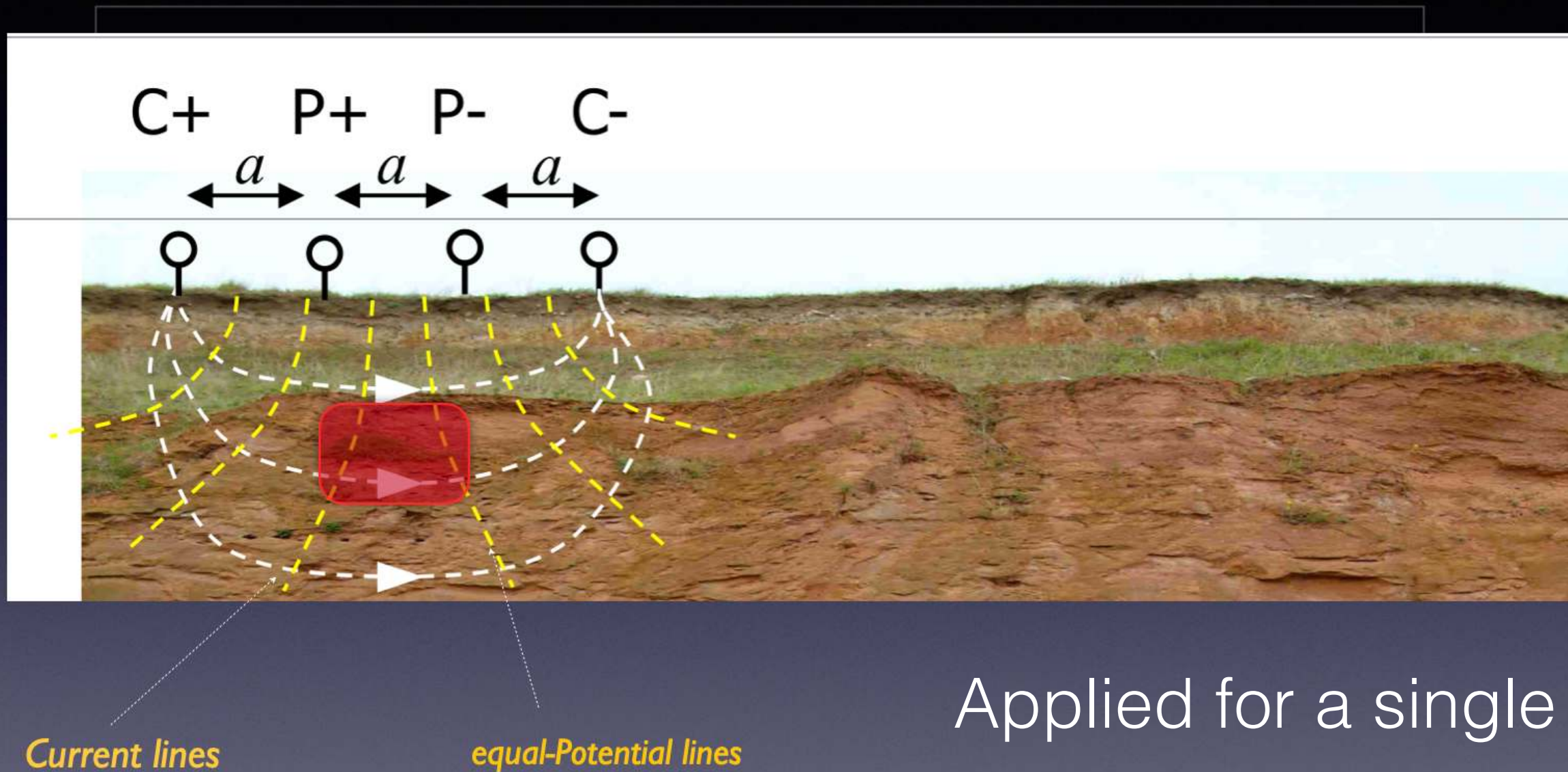


● Point where I measure ρ_a

We can do it automatically with a multi-electrodes system

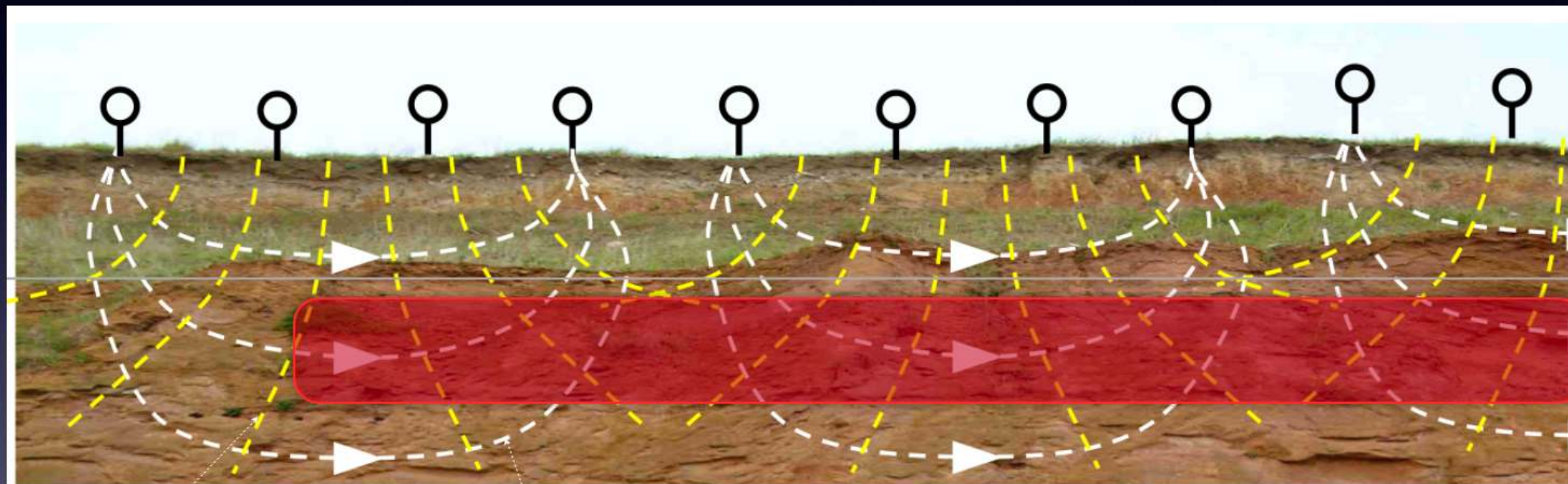
Geo-electrical methods

Area of interest in depth ?



Applied for a single
Quadrupole

Geo-electrical methods



Current lines

equal-Potential lines

Applied for a number of
Quadrupoles

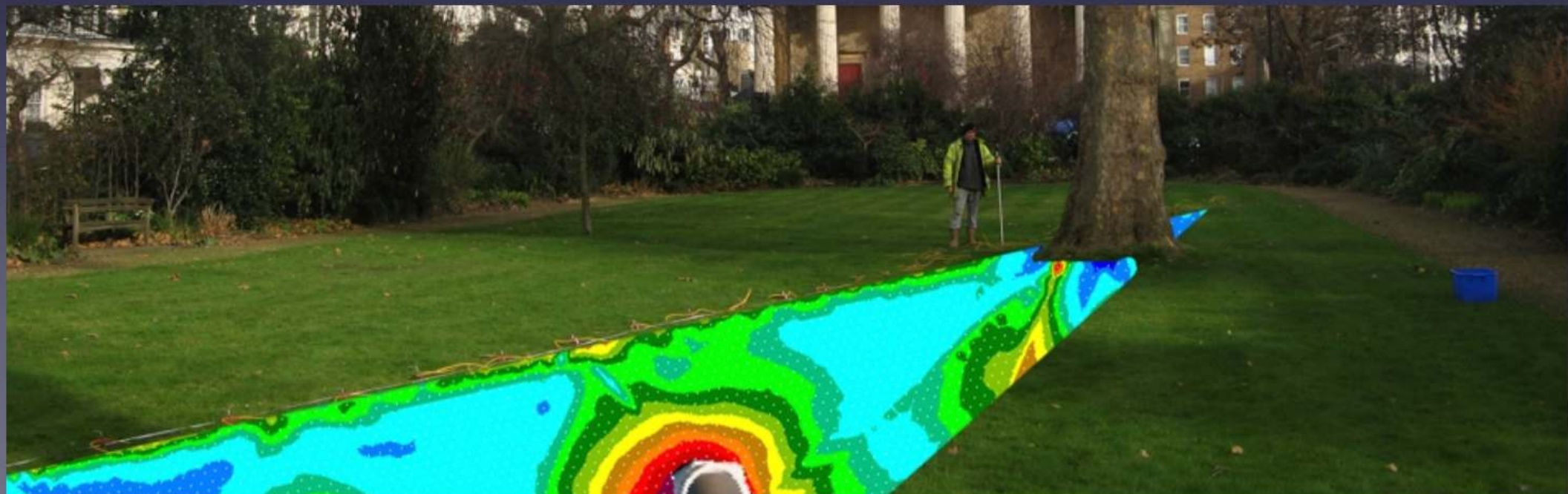
Geo-electrical methods

MULTI-ELECTRODES

ERT

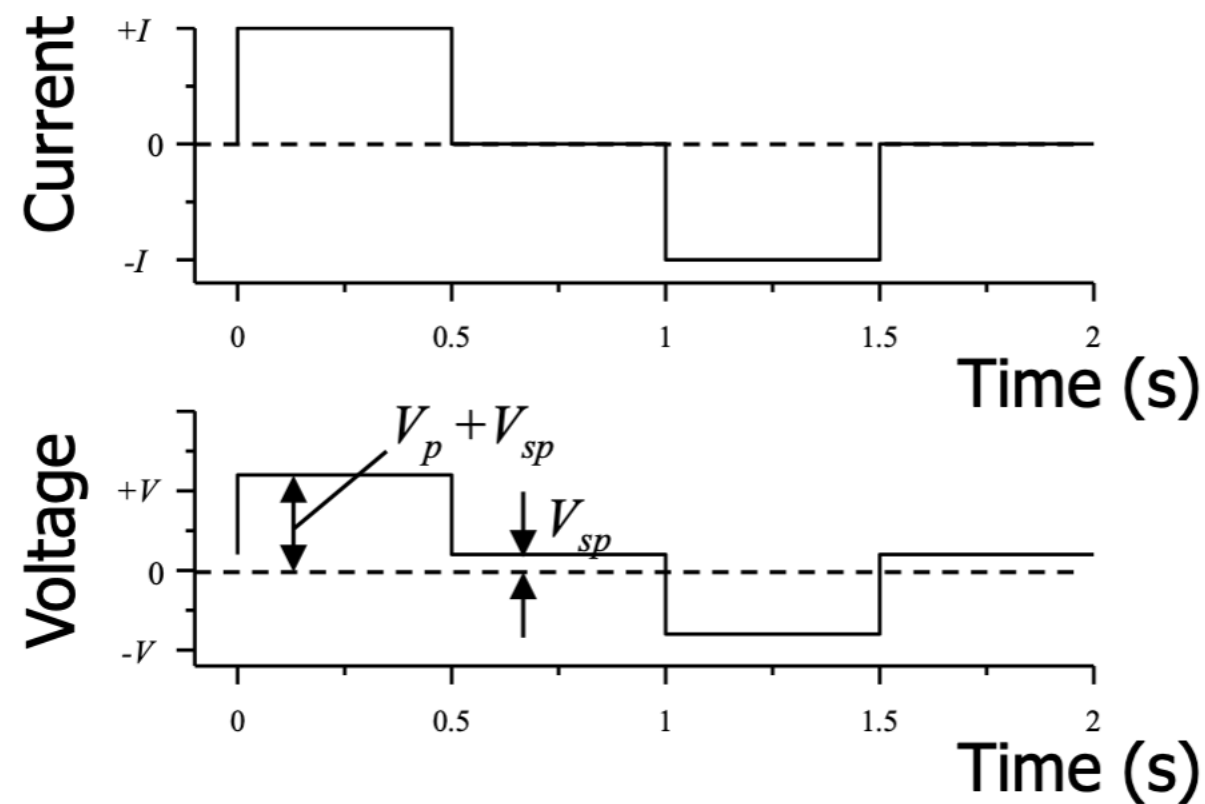
ELECTRICAL RESISTIVITY TOMOGRAPHY

An image of the subsoil.....



Current is normally injected as a switched square wave

Why is this ?



Polarization of media...

Geo-electrical methods HYDRO GEOPHYSICS

Electrical conductivity $\sigma = (1 / \rho)$
Resistivity

Archie's law

$$\sigma = a \sigma_w S_w^n \phi^m$$

Archie's constants

Cond-ucibility (S/m)

Pore Water conductivity

Water Saturation

Porosity

Formation
factor
(for $S_w = 1$)

$$F = \frac{a}{\phi^m} = \frac{\sigma_w}{\sigma}$$

Formation	Electrical resistivity range
Sea water	0.1 0.3 Ωm
Salted water	0.3 0.9 Ωm
Brackish water	0.9 5 Ωm
Leachate	0.9 5 Ωm
Fresh water	5 80 Ωm
Clay	5 30 Ωm
Wet sand	20 150 Ωm
Sandstone	30 300 Ωm
Limestone	100 800 Ωm
Dry sand	250 4000 Ωm
Granite	1000 20,000 Ωm

Archie's constants (empirical)

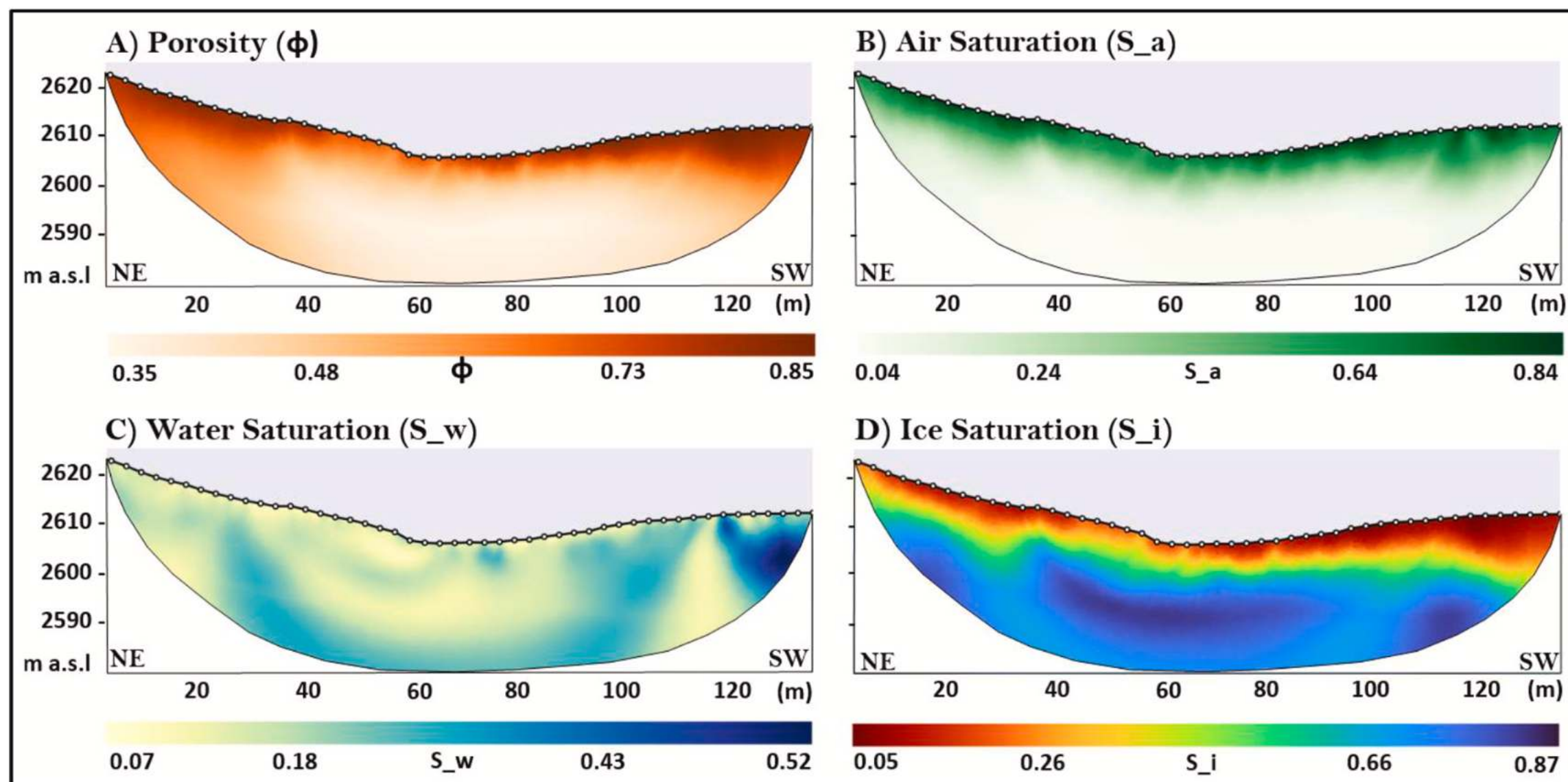
$a \approx 0.5-1.5$ f (tortuosity, grain size, clay content, etc.)

$n \approx 2$ exp factor

$m \approx 1.2-2.3$ Cementation factor

Porosity $\phi = V_v / V_t$ Pore Volume / Total Volume

Petrophysical relations + geophysics =



Petrophysical Joint Inversion ERT- Seismic *from Pavoni et al 2024*

Geo-electric survey

Steps

What

1. Design the acquisition	<i>A priori info, electrodes number, array length, configuration, location, logistic, cost</i>
2. Put on the ground the array	<i>Logistic limitations, Installation of electrodes with good galvanic contact, transport/deploy cables</i>
3. Set the instrument and acquire the data	<i>Instrumental Setting and data storage</i>
4. Data Processing and interpretation	<i>Quality check, INVERSION, interpretation, Results presentation</i>

Step 1: Design the acquisition

I. Design the acquisition

Cost:

Based on:

- Access to the site*
- Persons / hours count*

*E.g. 72 channels, 3 m spacing need:
2 person and 1/2 day workin on flat
grass site;*

*7-8 persons and entire daywork in
mountain steep slope*

Geo-electrical methods

Geo-electric survey

Which georesistivimeter
I need ?

I. Acquisition design

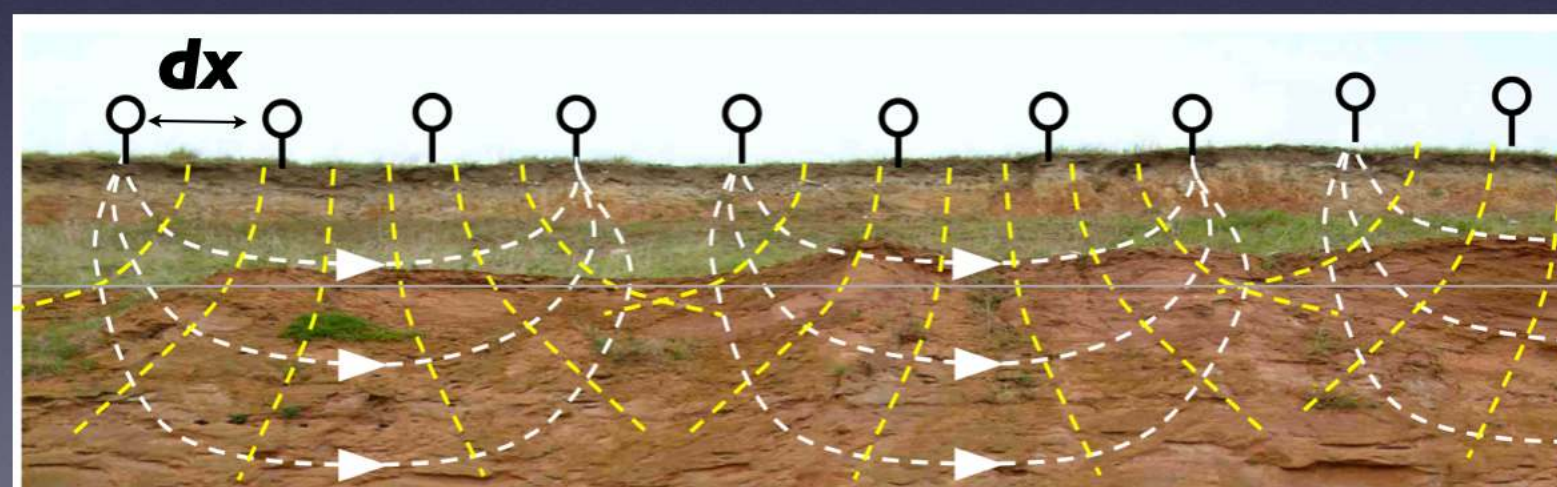
Number of electrodes **N** available

*

=

Total length **L**
of the electrical array

Electrodes spacing **dx**



es:

$$N = 10$$

$$dx = 2$$

$$L = 18 \text{ m}$$

$$L = (N-1) * dx$$

Geo-electrical methods

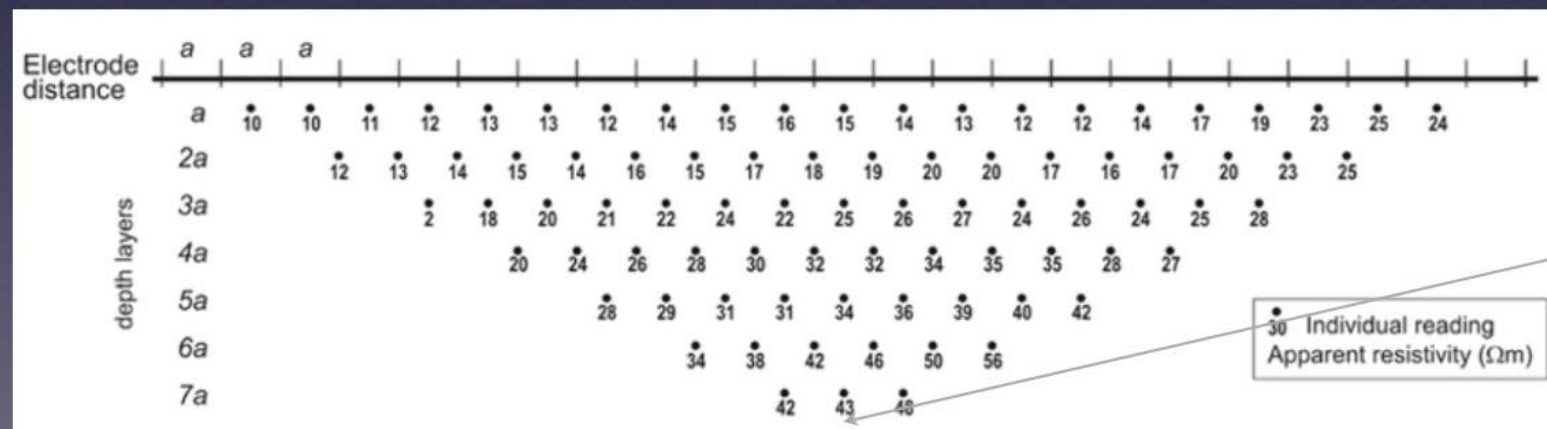
Geo-electric survey

I.Acquisition design

PENETRATION

Rule of thumb

Penetration depth $\approx 1/5$ Array total length L



Note:
Maximum penetration is in the middle of array L !

es: $N=48$, $dx=2m$, $L=94\text{ m}$

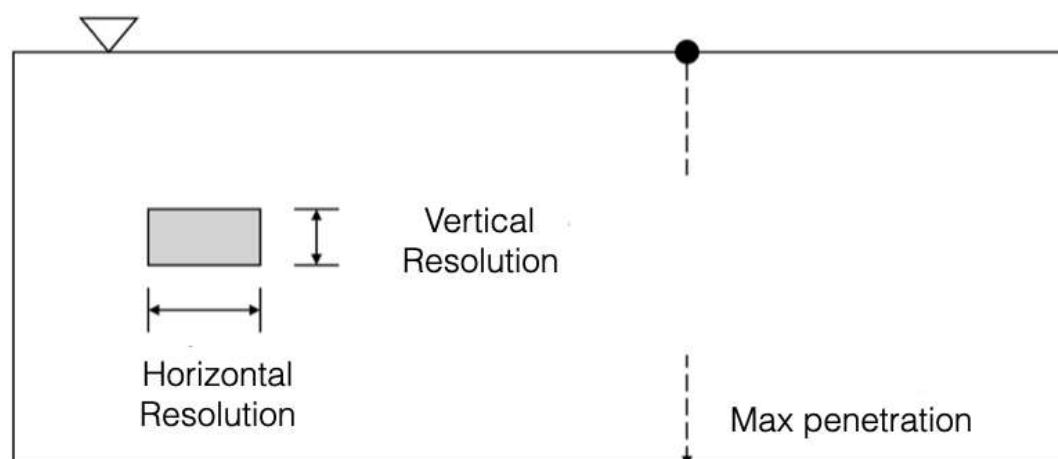
Penetration max (middle) ≈ 19 m

Geo-electric survey

I. Acquisition design

RESOLUTION

Resolution and penetration

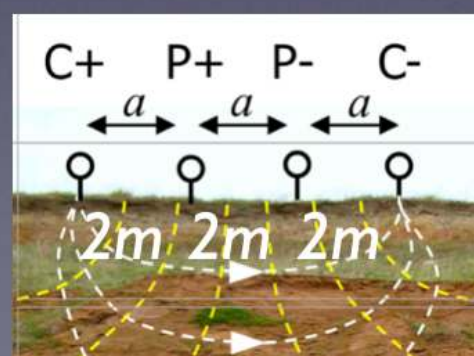


*In geo-electric
Is a function of
Electrodes spacing*

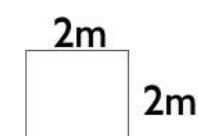
*Resolution capacity
Rule of thumb*

$\approx$
*Distance between electrodes
(spacing)*

eg. Electrodes spacing= 2m



Resolution cell $\approx$

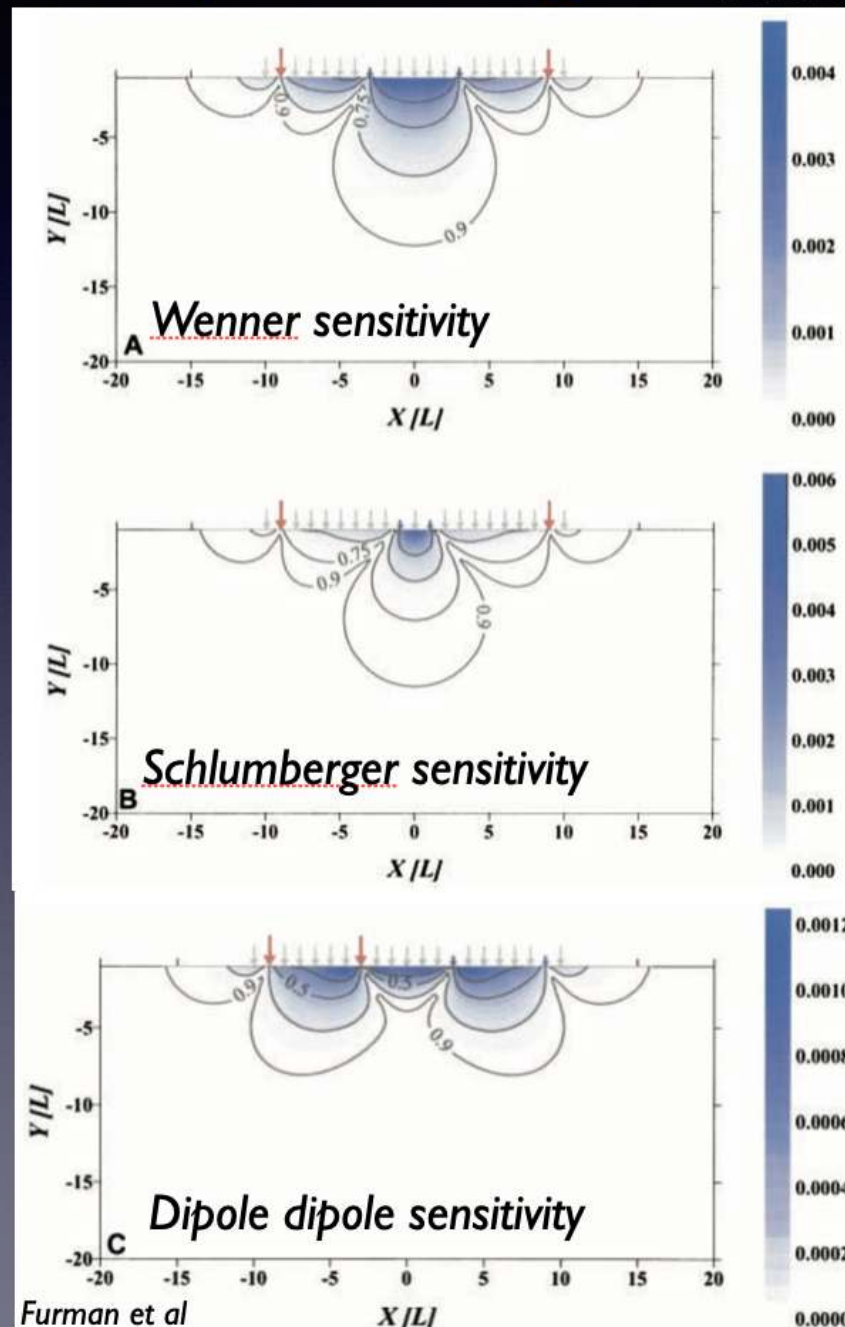


(Cell 2X2)

Geo-electric survey

I. Acquisition design

ARRAY CONFIGURATION CHOOSE



Current lines distribution change, than
the measurement **SENSITIVITY**

$$S = |\Delta V|$$

← Magnitude of the Potential
voltage measurable

sensitivity

es.
Wenner-Schlumberger
Better in depth image

Dipole-Dipole
Better in lateral resolution

Nowadays thanks to modern multi-channel georesistivimeters we can reach good sensitivity depth keeping lateral resolution



UNIVERSITÀ
DEGLI STUDI
DI PADOVA



DIPARTIMENTO
DI GEOSCIENZE

Multigradient- multi-skip hybrid approach

Electrode configuration to combine the good signal strength of Wenner-type arrays with the high spatial coverage and acquisition speed of dipole-dipole arrays.

Dip-Dip skip 0

A B M N

1 2 3 4

Dip-Dip skip 4

A . . . B M . . . N

1 2 3 4 5 6 7 8 9 10 11 12 13

Dip-Dip skip-n

A B M N

A ----- B

M N

M N

M N

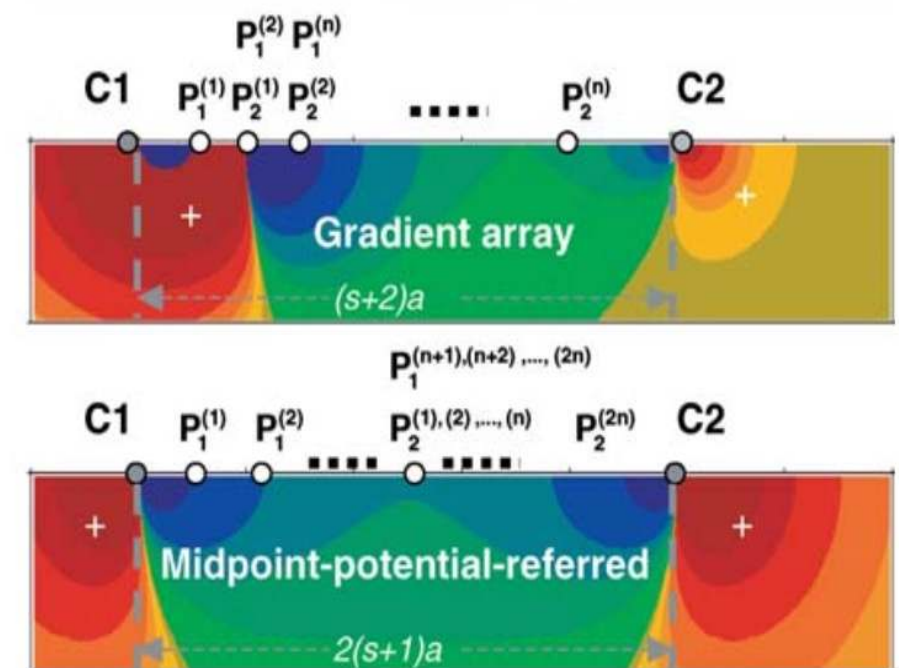
M N

Multi-grad

+

+

+



Dahlin & Zhou 2005

Contact author: jacopo.boaga@unipd.it

Step 1: Design the acquisition

Nowadays modern multi-channel system allows every kind of multi-gradient configuration, remote pole, remote dipole....

We can have resolution and (sufficient) depth of penetration....

Standard old configuration (e.g. wenner) are very limited!

Step 2: Array on ground In PERIGLACIAL environments!

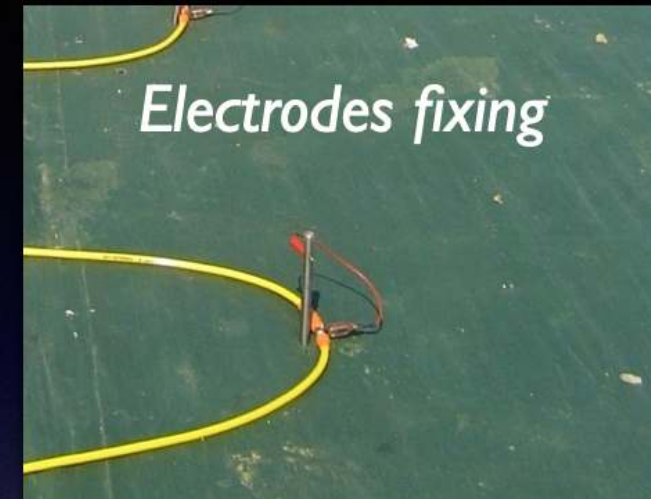
2. Putting on the ground The array

Geo-electric survey



Electrodes (st, steel)

Electrodes fixing



Galvanic contacts: the MAIN PROBLEM

Good contact: 1-50 K Ohm
Poor contact: 50 - 300 K Ohm
Bad contact: > 300 K Ohm

999 K Ohm means electrodes unplugged !

Battery supply

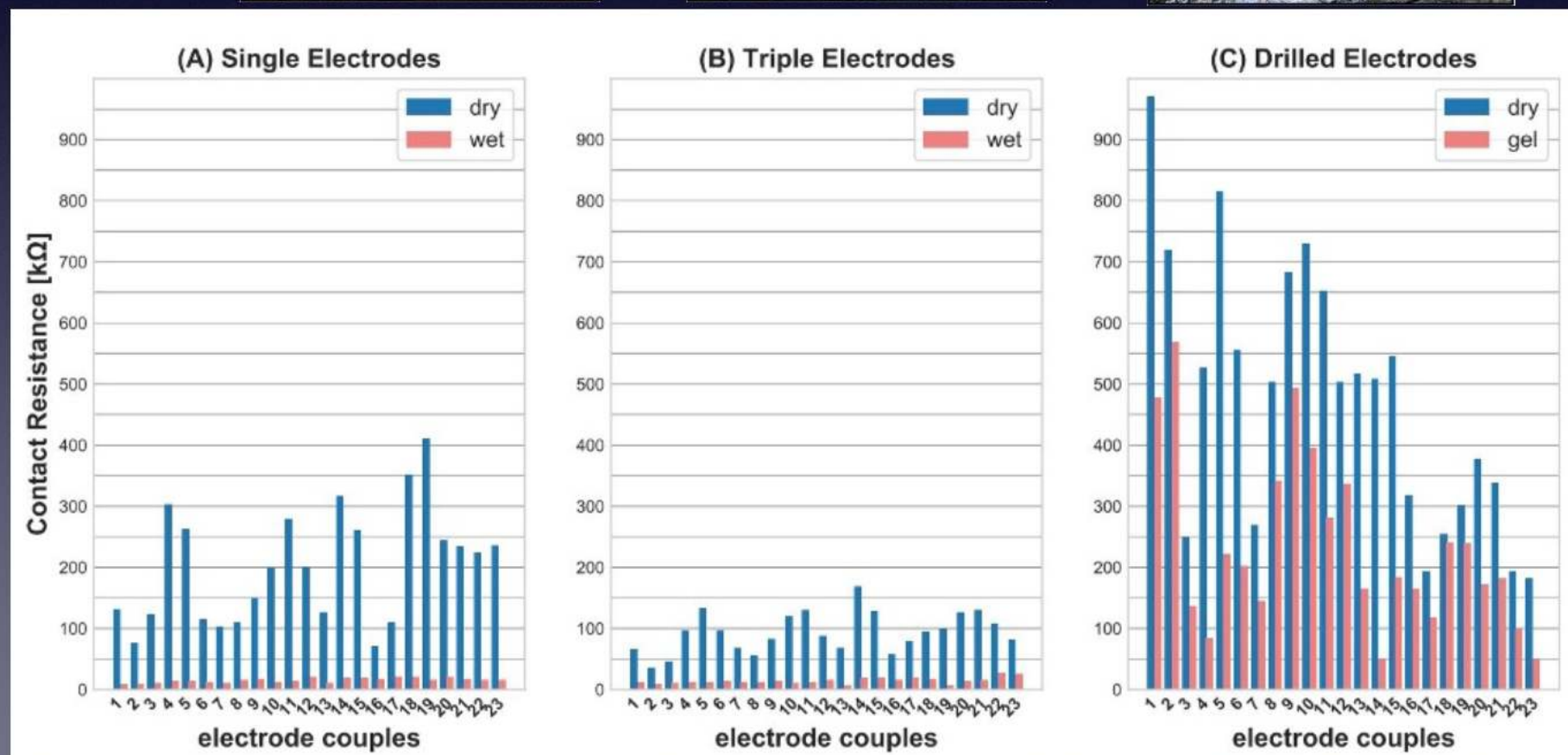
Common 150m array: 20Ah 12 V battery (e.g. internal one)
More than single array: 60 Ah 12 V battery
Several array: 2x60Ah batteries or 120Ah big battery need

2. Putting on the ground The array

Galvanic contacts: the MAIN PROBLEM



Geo-electrical methods



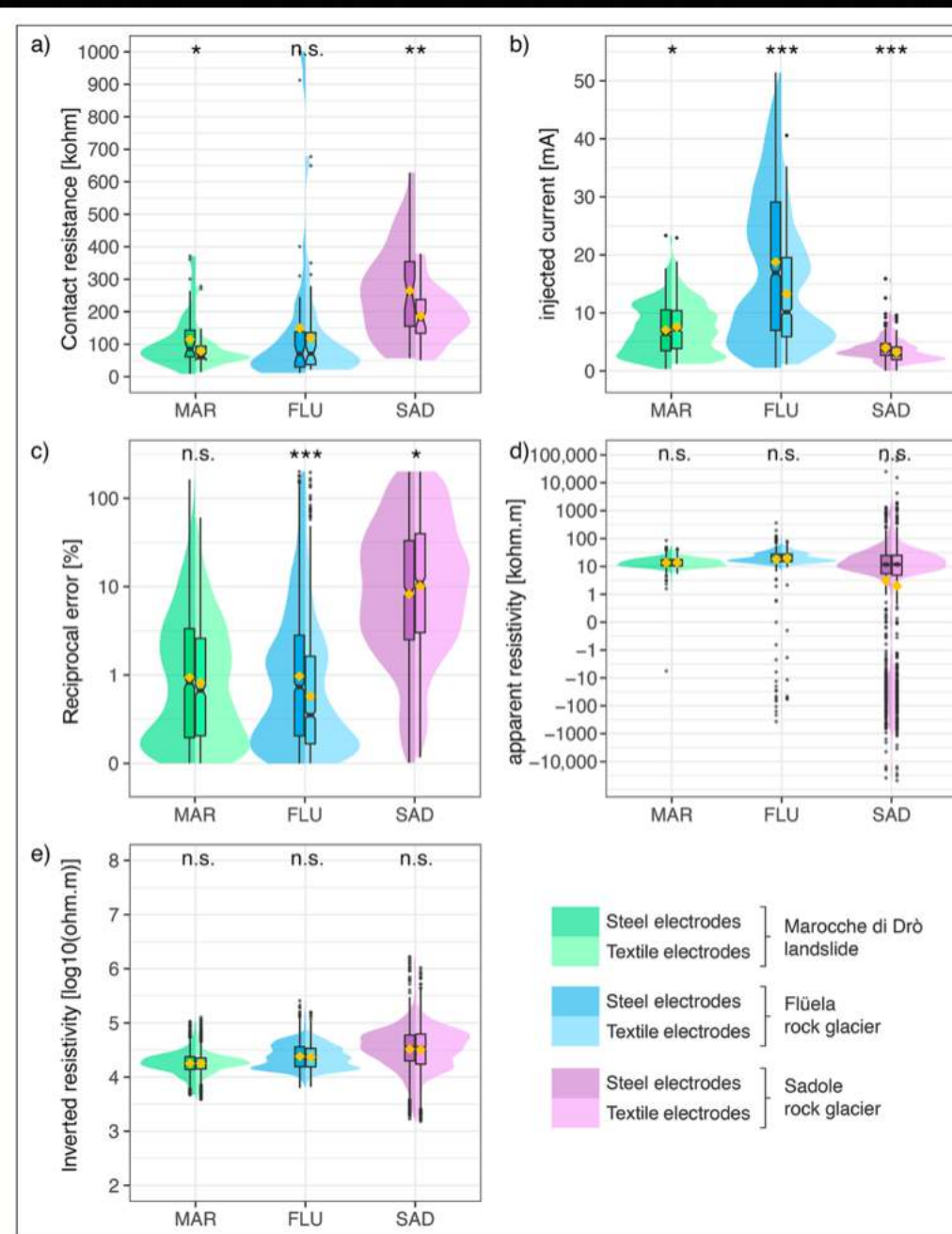
Pavoni et al 2023

2. Putting on the ground The array

Galvanic contacts: the MAIN PROBLEM



Geo-electrical methods



YOU
NEED
WATER!!

Pavoni et al 2024

In Rock glacier and Periglacial environments main problem is the galvanic contact!

Collecting data without checking or with hundreds of KOhm resistance contacts is useless... (garbage in - garbage out)

You must help electrodes contact:

- using different electrodes types
- wetting (with salty-water)



Active rock glacier in the Stelvio Pass area (Northern Italy)

Quasi 3D ERT survey 05/08/2025

48 electrodes 5 m spacing



48 electrodes 3 m spacing



- Syscal Pro (Iris instruments)
- Steel net electrodes
- Hybrid Dipole-dipole and multigradient multi-skip
- 2500 quadrupoles
- Time window rec. : 250 ms
- Stacking 3
- Direct and reciprocal meas.

Why continue using heavy cables, electrodes, and bulky standard batteries?

**Traditional 24 ch
5m spacing cable 24 kg**



Spike electrode 0.5 kg hammer 0.5 kg



15 kg lead car battery

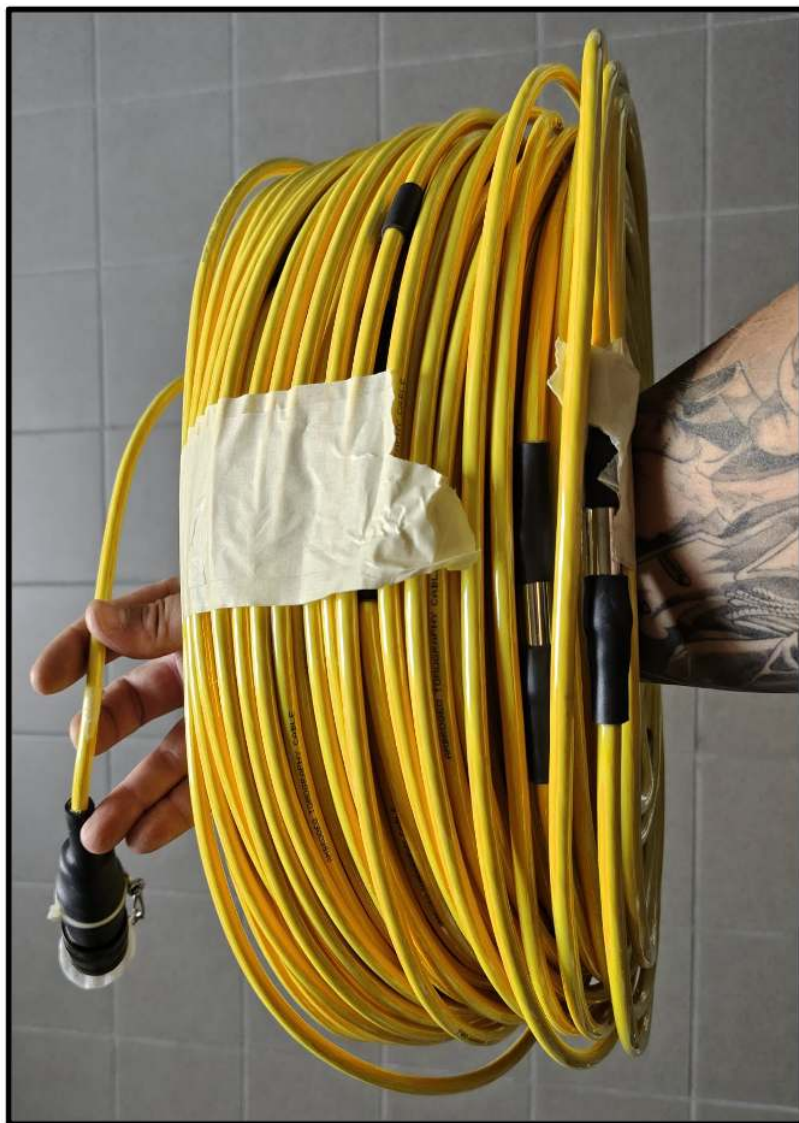


**48-electrode array
80-90 kg**

Pavoni credit

We can make our lives easier and our work more comfortable...

**Alternative 5 m spacing cable thinner
and lighter (8 kg)... and NO wheels !!!**



Steel-net electrode 50 g



2 kg lithium battery



**48-electrode array
20 kg**

Pavoni credit

Steel spike electrodes 48-96



Sponges 48-96



Hammers 2-3



15-40 kg

(Depending on the number
and size of the spikes)

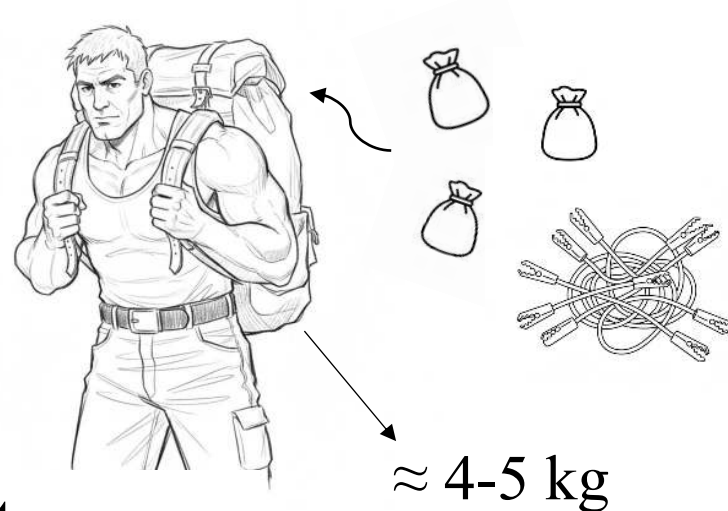
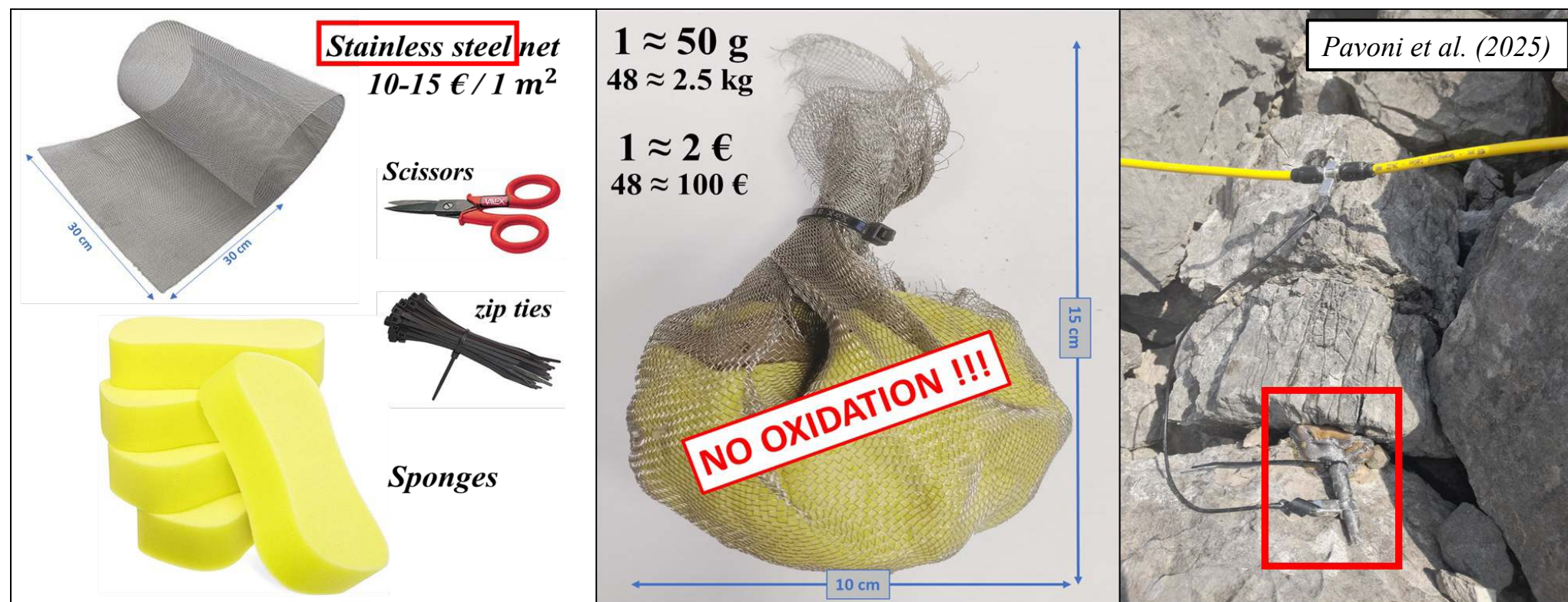


**Energy & time
consuming**

(boring & annoying !!!)



Pavoni credit



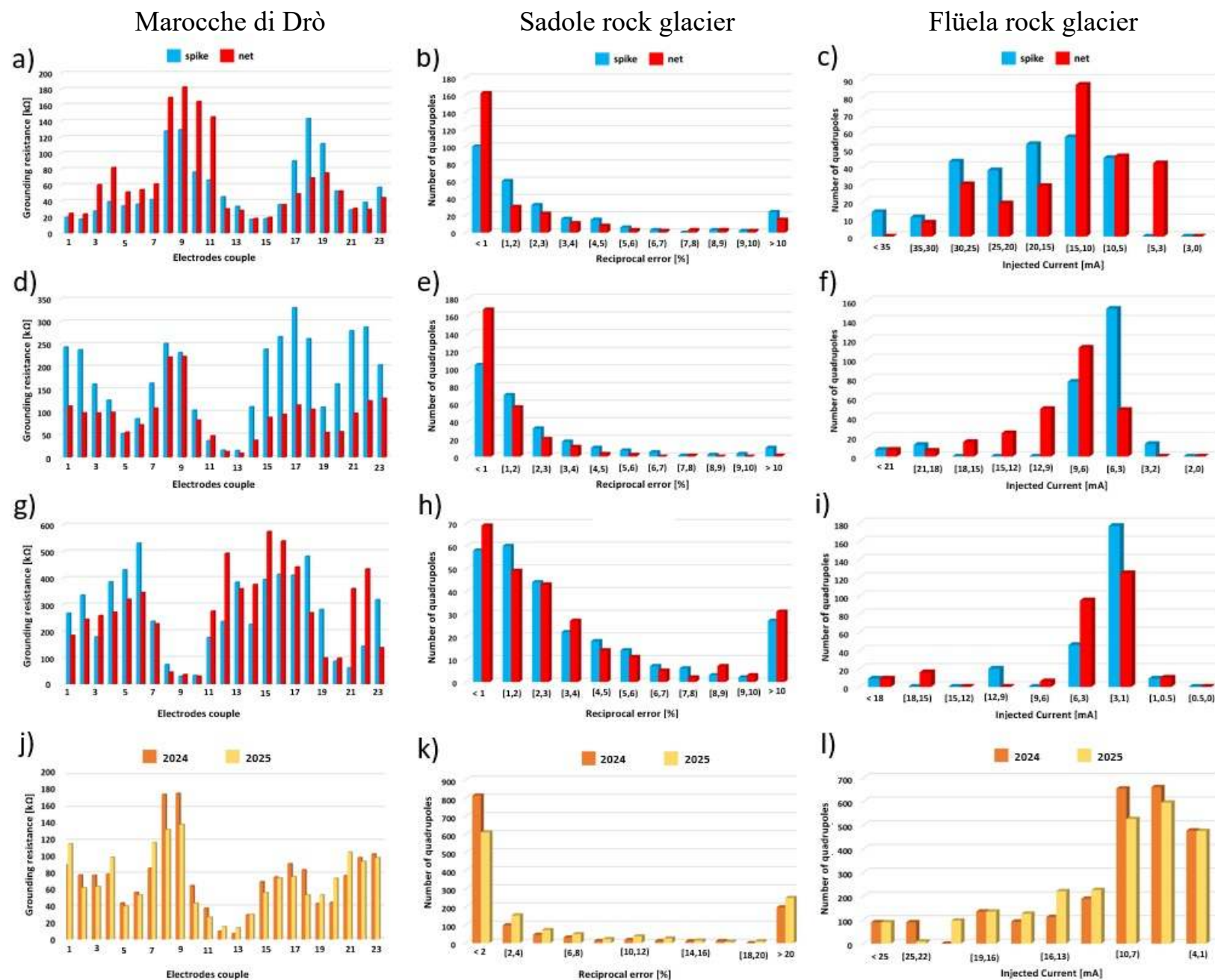
Easy & Light to carry



Easy & Fast to insert and to remove

Pavoni credit

Comparison test steel-net electrodes with traditional steel spikes:



Tests of steel-net electrodes on blocky and debris surfaces (1 landslide and 2 rock glaciers), showing the same performance as steel stakes in terms of contact resistance (a, d, g), reciprocal error (b, e, h), and current injection (c, f, i). Both electrodes were wetted with the same amount of saltwater.

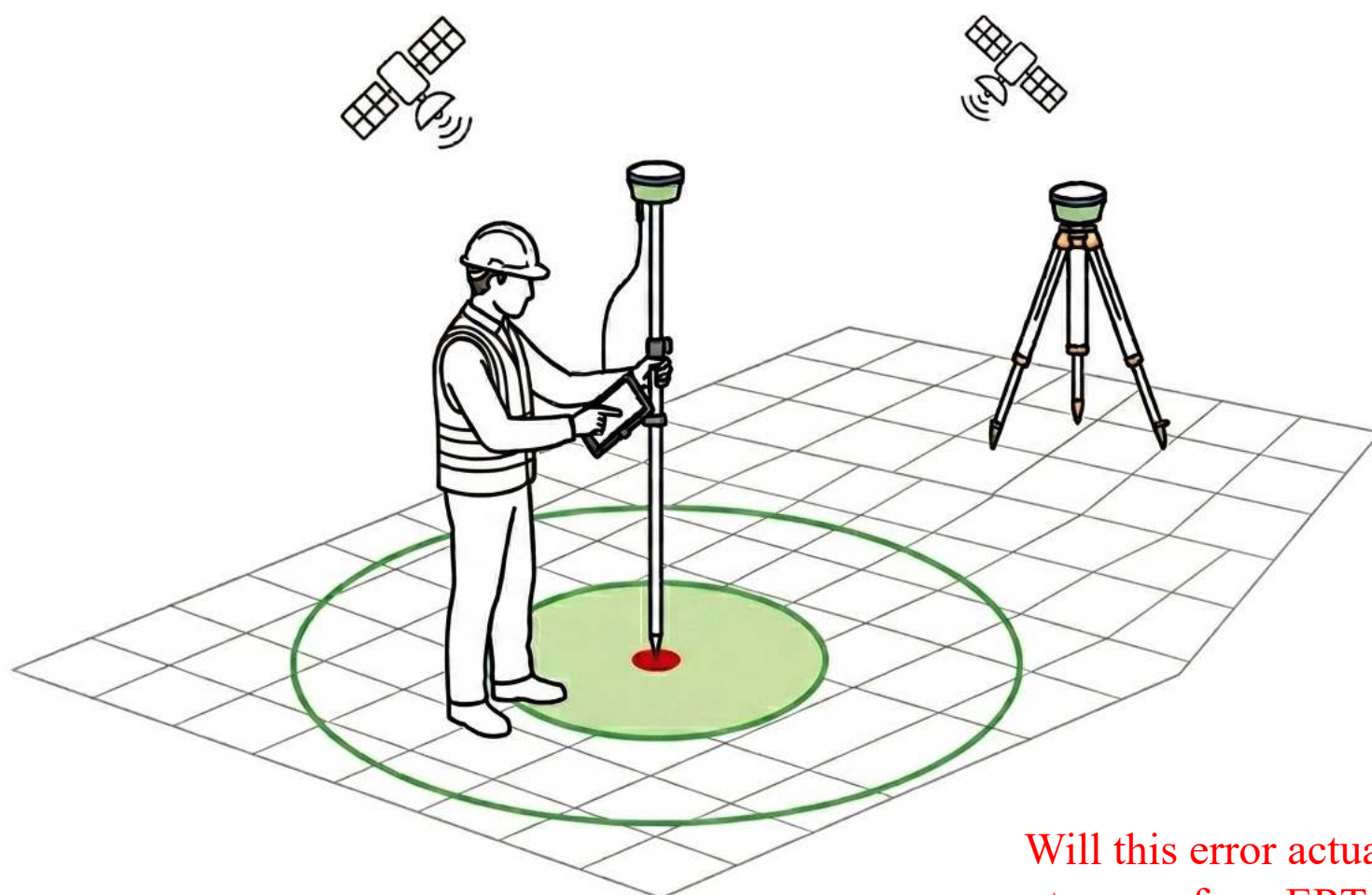
Note that, steel-net electrodes maintain equivalent performance in terms of contact resistance (j), reciprocal error (k), and current injection (l), even one year after installation in a permanent ERT line on a rock glacier.

(Pavoni et al. 2025)

In a rock glacier environment, do we really need 1–2 cm GPS precision or is 5–10 cm accuracy sufficient to speed up operations?

Is this level of error truly significant given electrode spacings of 3–5 meters?

Also accounting for frequent electrode misalignment during rock glacier ERT surveys



Will this error actually affect the outcome of my ERT investigation?

Pavoni credit

Geo-electric survey

Steps

What

**3. Set the instrument and
acquire the data**

*Instrumental Setting and data
storage*

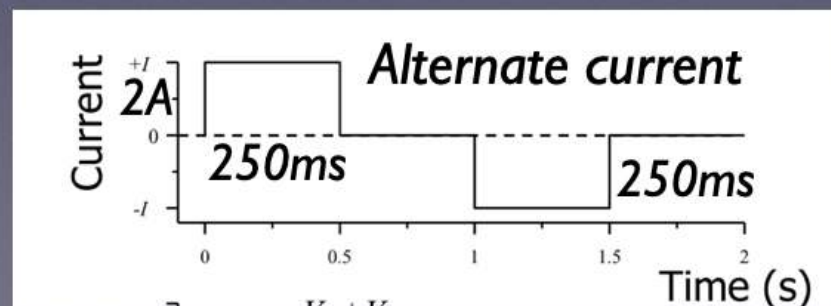
Step 3: Setting instrument In PERIGLACIAL environments! Geo-electric survey

3. Setting instrument and Acquire the data



Setting:

- Acquisition sequence (wenner, dipole, etc)
- Time of current Injection (eg 250 mS)
- minimum voltage to consider (eg 5 mV)
- maximum current to inject (eg 2.5 A)

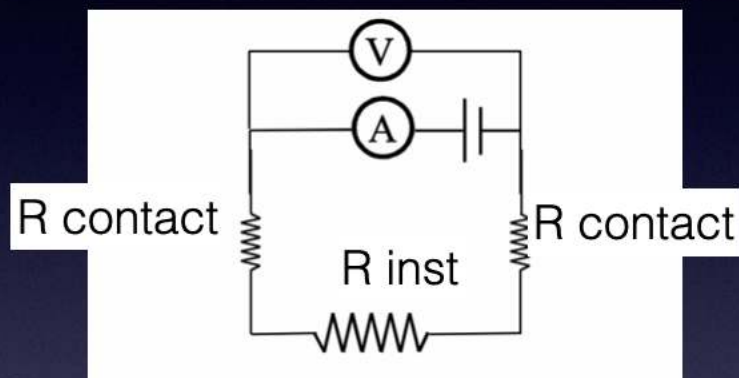


Geo-resistivimeters are not all the same!

Geo-electric survey

3. Setting instrument and Acquire the data

Iris Instrument has an **internal resistance** of 100 M Ω m



Abem terrameter 200 M Ω m

GEOTOM 1000 M Ω m !

Better for high galvanic contact terrains !!



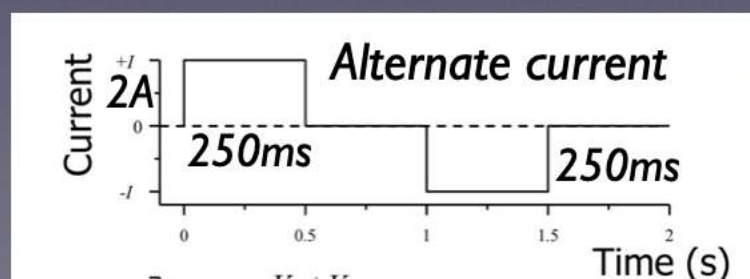
Iris
Syscal



Geotom



Abem



Geo-electric survey

3. Setting instrument and Acquire the data

Instruments choice...

- *electronic quality (mV or less !)*
- *toughness (fieldwork)*
- *NUMBER OF CHANNELS (same-time measurements to be taken)*

+

- **NUMBER OF ELECTRODES (nodes) manageable**

> RESOLUTION ($< dx$)

+ ELECTRODES =

>> \$\$\$

> PENETRATION ($> L$)

Step 3: Setting instrument In PERIGLACIAL environments!

The error issue...

To invert correctly ERT Dataset **you need** to know the
ERROR of your data

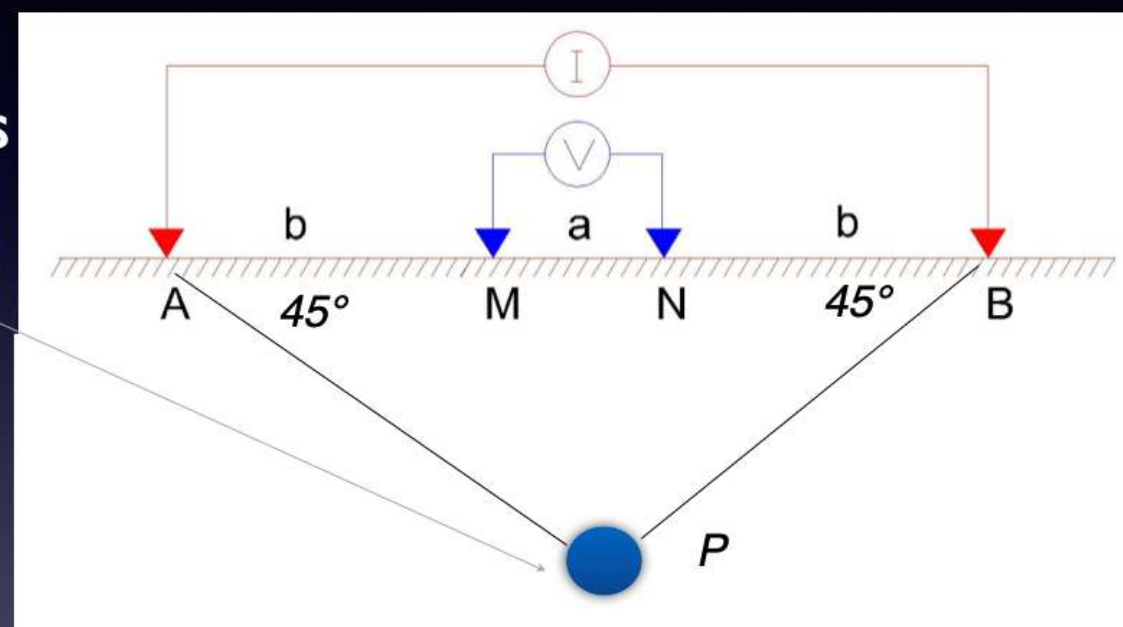




Geo-electric survey

We do not take only one measurements
 ρ in point P

We perform more than one meas.
(usually 3 - 6 times)
Taking the average of the results



Es 6 meas.:

$$\rho_a = \frac{1}{6} \sum_{i=1}^6 \rho_i$$

>> N measur. >> acquisition time!

$$\rho_a = K \frac{dV}{I}$$

ρ_a : Apparent resistivity
 K : Geometric Factor
 $\frac{dV}{I}$: Δ potential / Injected Current



Best thing is to perform
DIRECT and RECIPROCAL
Data

(if configuration admits it)

Inverting the quadruple

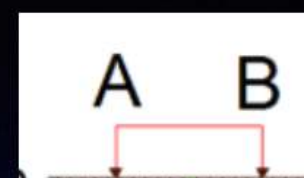
The measure of ρ_{ap}
should be **the same**

But instrumental errors
(always present)

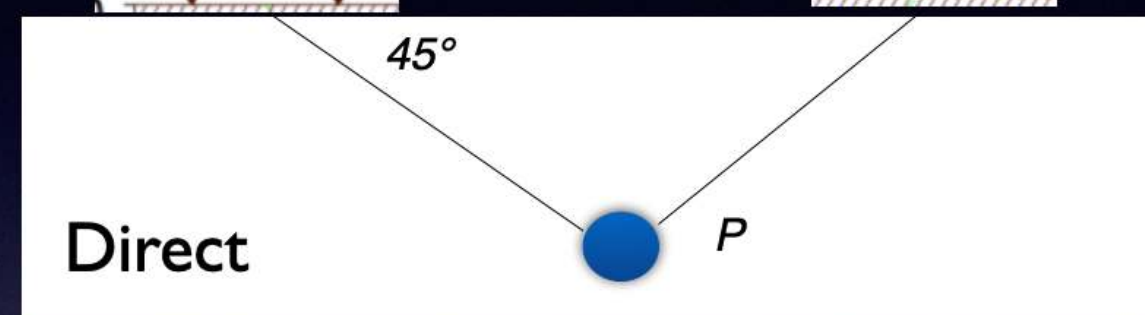
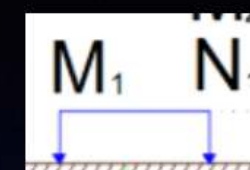
Longer acquisition time /cost

Geo-electric survey

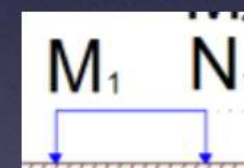
I current



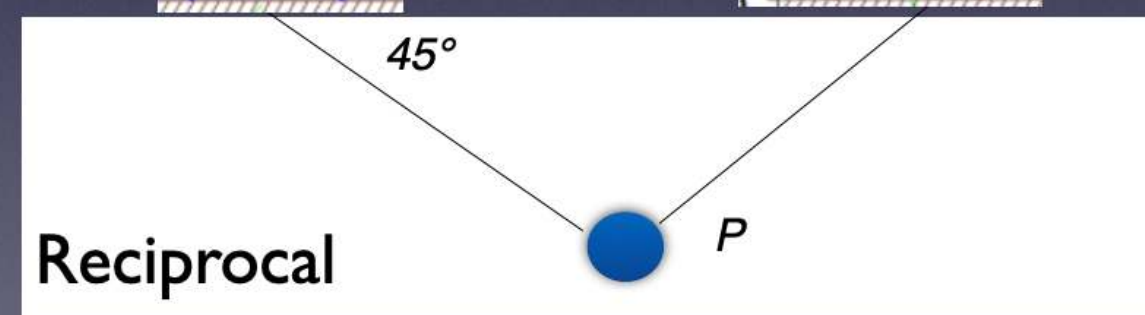
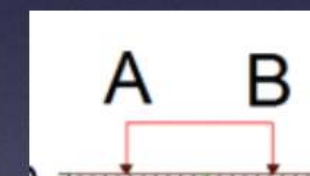
dV potential



dV potential



I current



Step 4: Data processing

Geo-electric survey

Steps

What

4. Data Processing and interpretation

*Quality check, INVERSION,
interpretation,
Results presentation*

Geo-electric survey

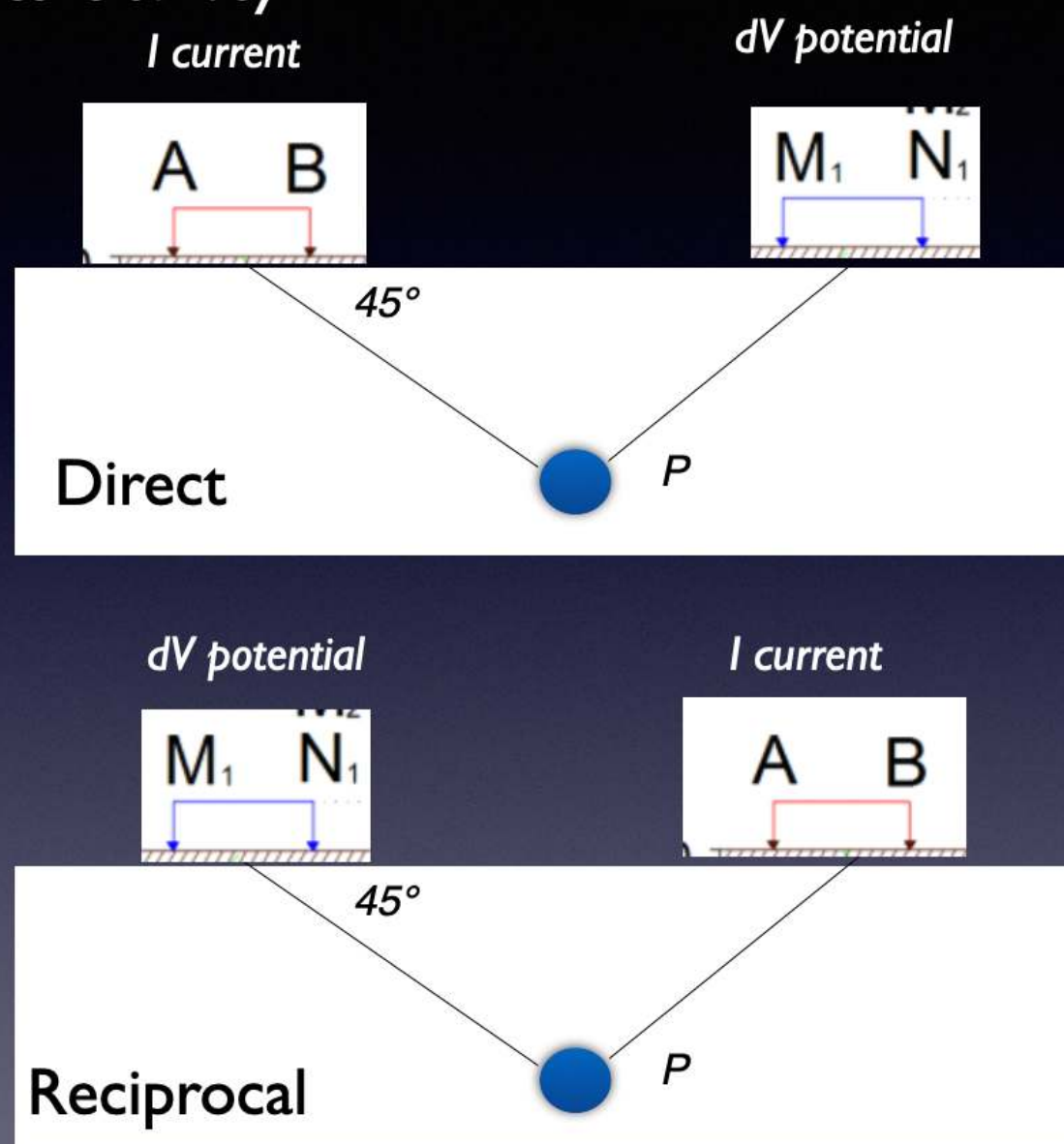
4. Data processing

1. Data Quality check

I can check
The reciprocals

And eliminate all the measur. that
exceed a certain threshold (es. 5%)

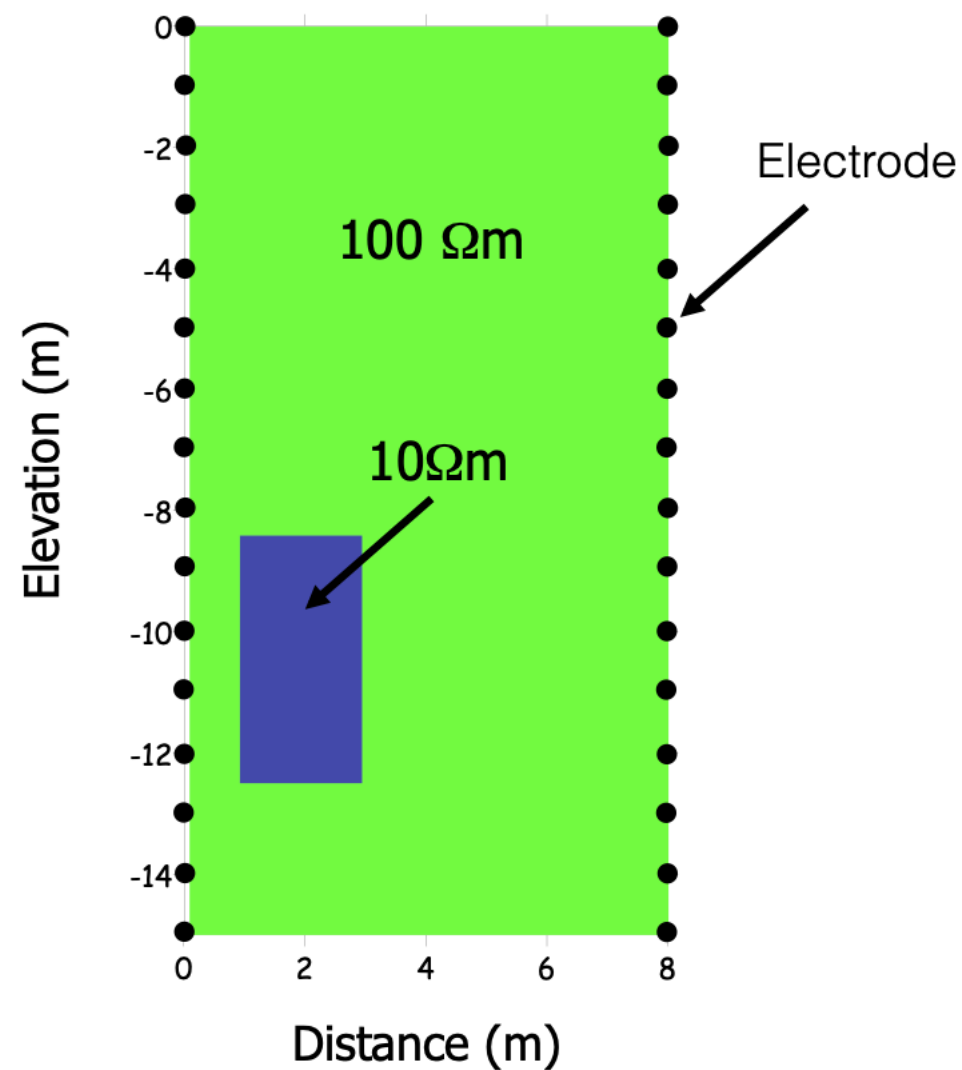
$\Delta (\rho_{ap DIRECT} \rho_{ap RECIPROCAL})$
 $< 5\%$ Accepted
 $> 5\%$ Eliminated



I CAN HAVE A REAL QUALITY ESTIMATION OF MY DATASET

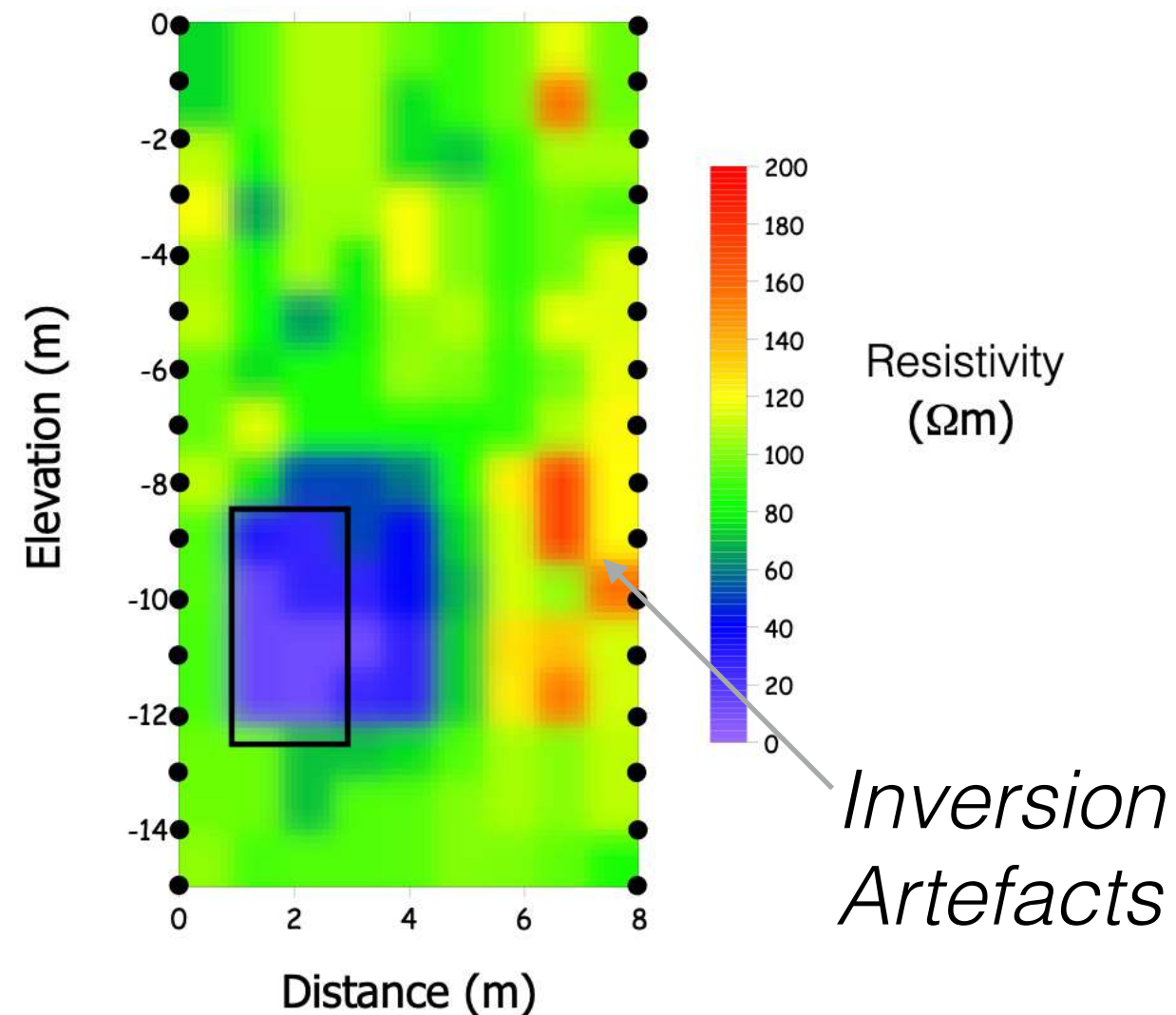
Step 4: Data processing

Synthetic boreholes dataset



Step 4: Data processing

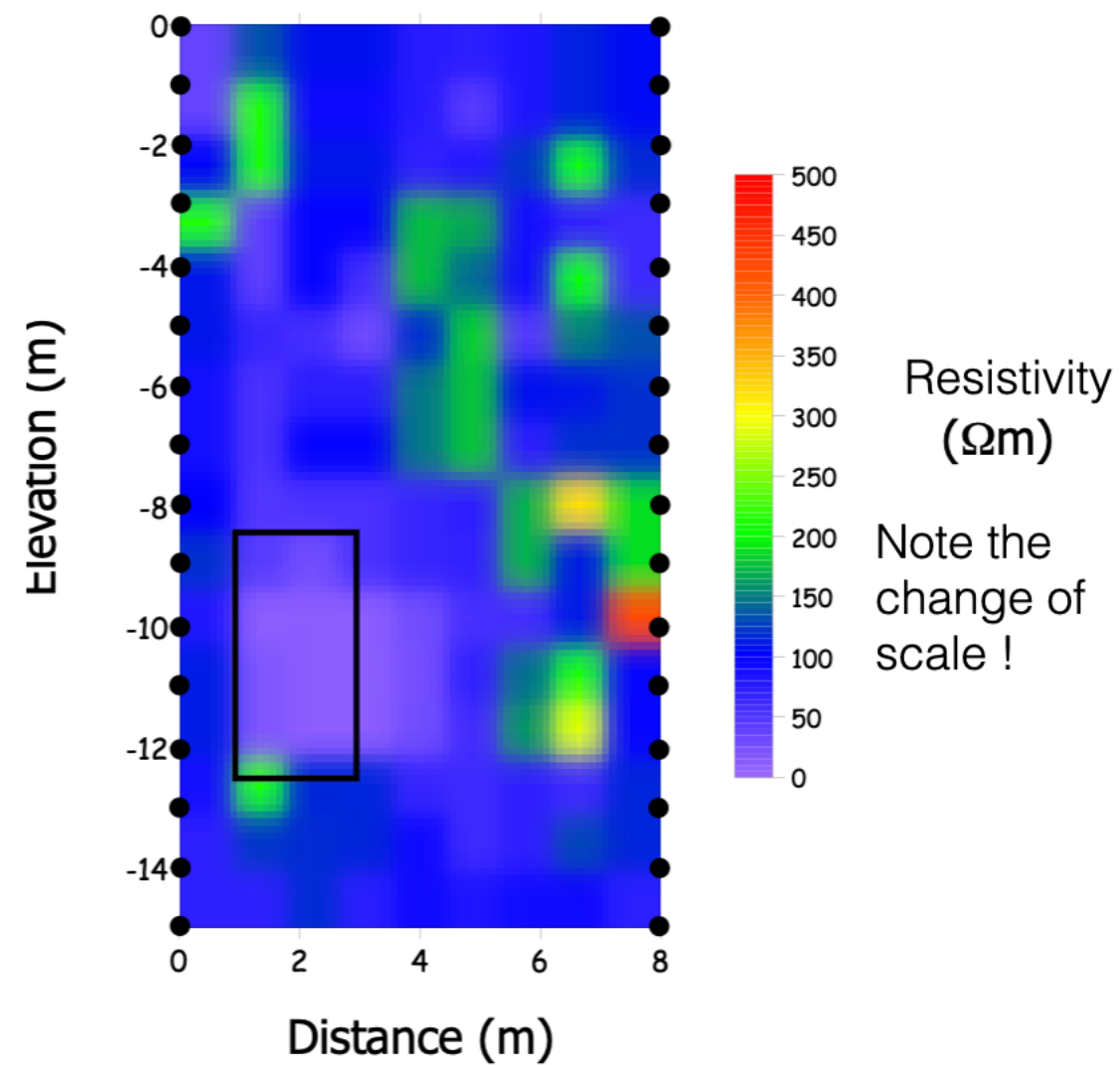
Inversion error requested **2 %**
Error in the dataset: **5%**



Step 4: Data processing

Inversion error requested **2 %**

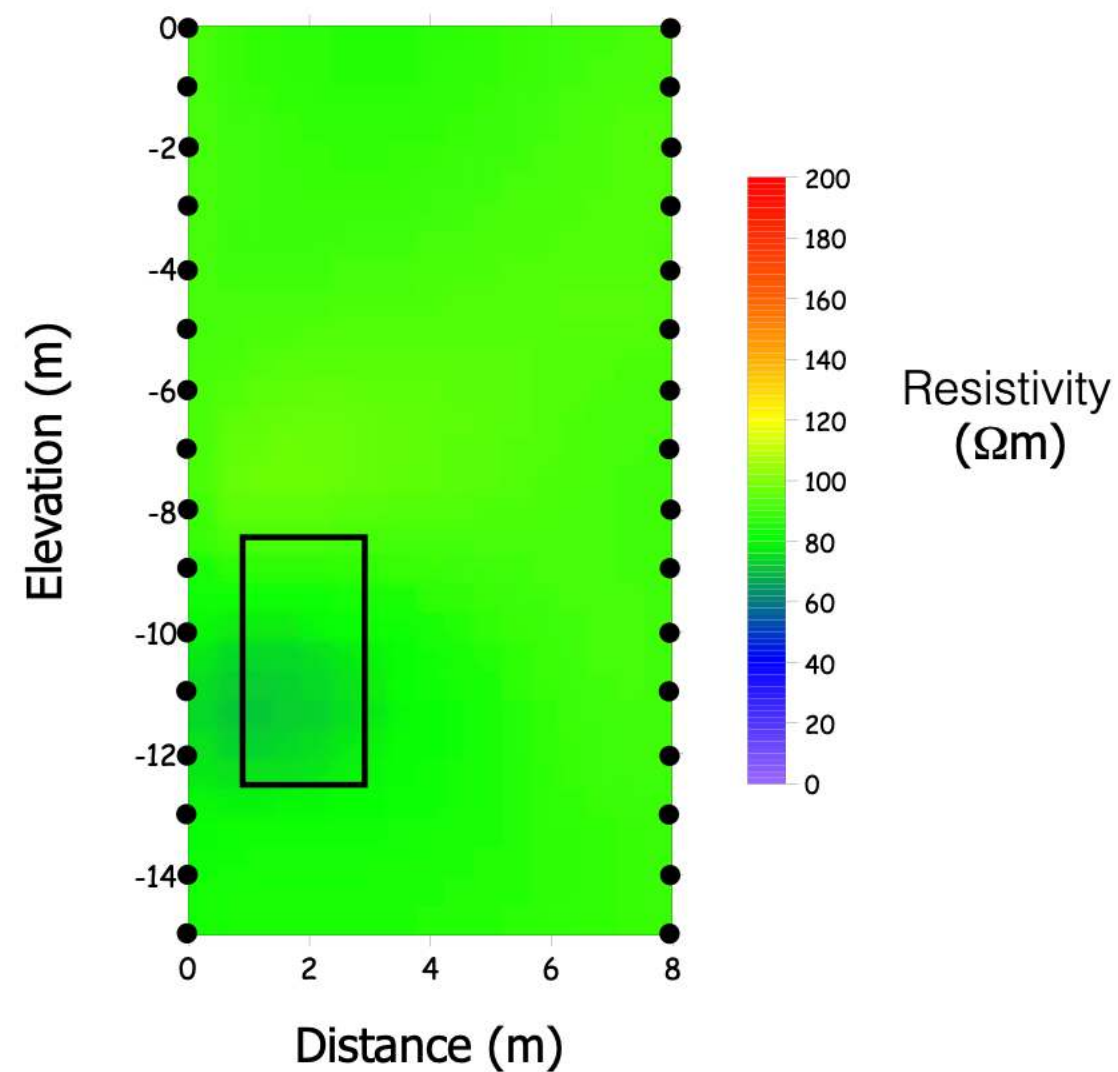
Error in the dataset: **10%**



Step 4: Data processing

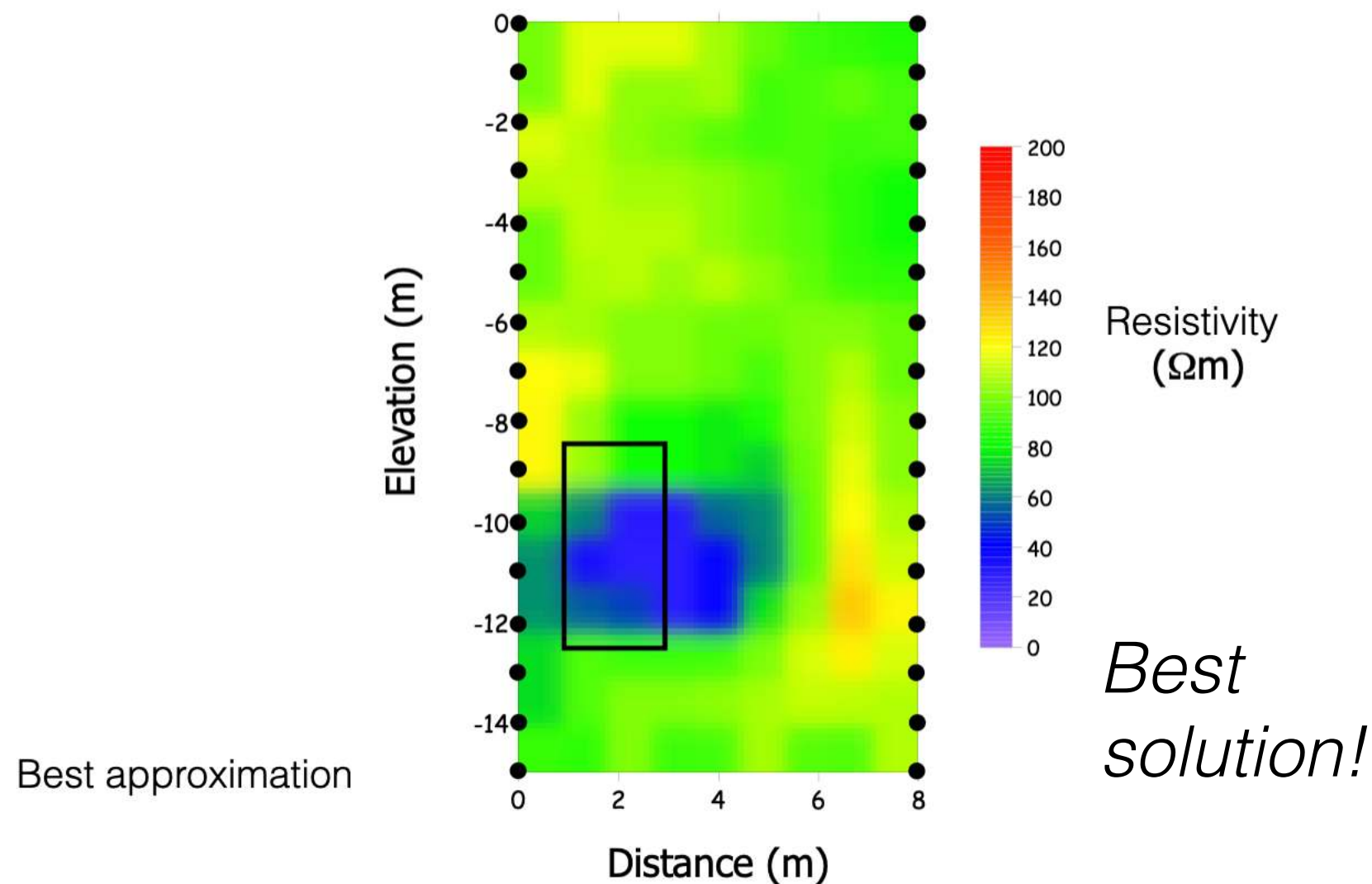
Inversion error requested **20 %**

Error in the dataset: **10%**



Step 4: Data processing

Inversion error requested **10 %**
Error in the dataset: **10%**



Geo-electric survey

4. Data processing 2. INVERSION

Form the
PSEUDO-SECTION
in ρ apparent

Inversion

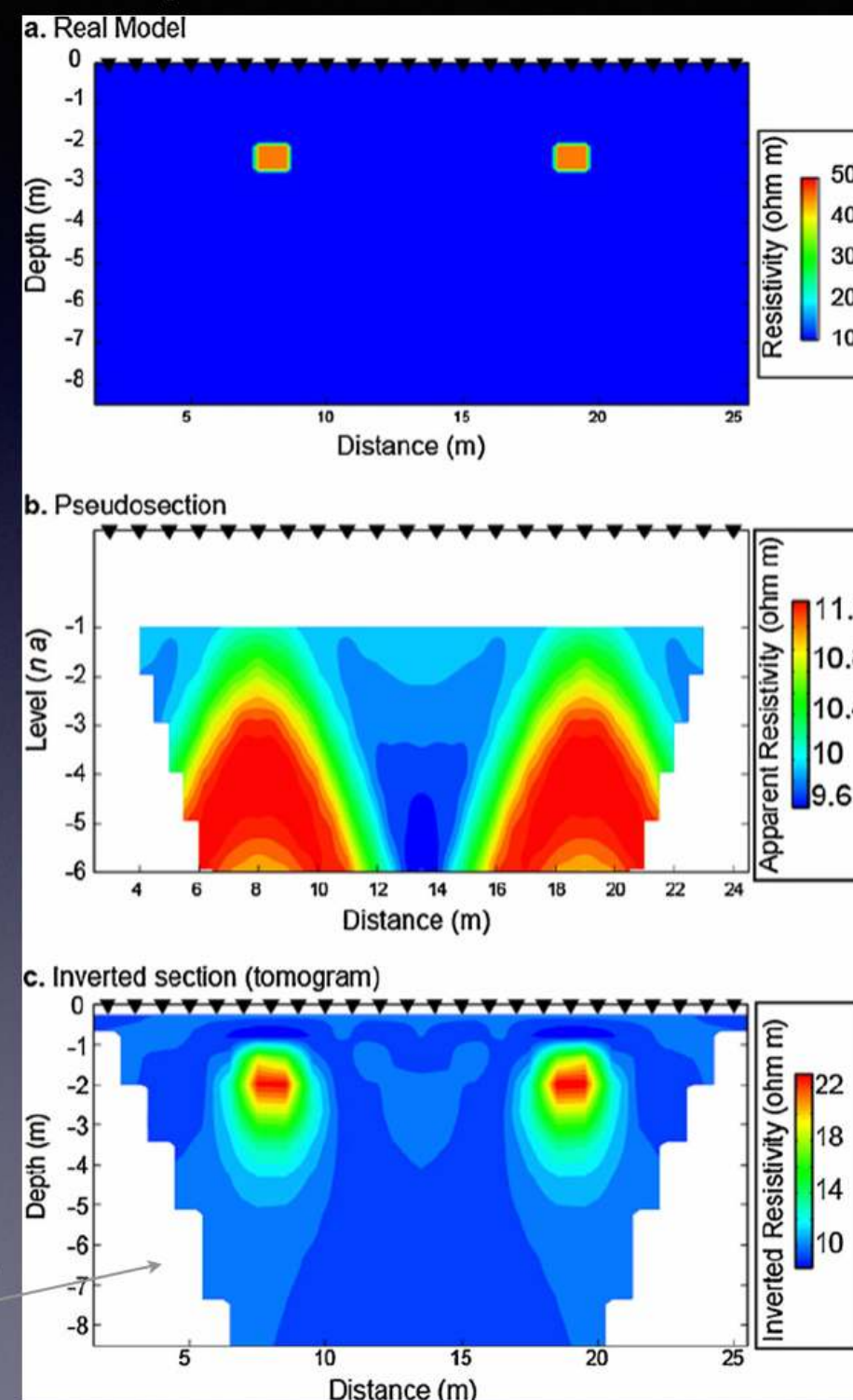
To tomographic section
in ρ real

Real
Model

Pseudo
Section

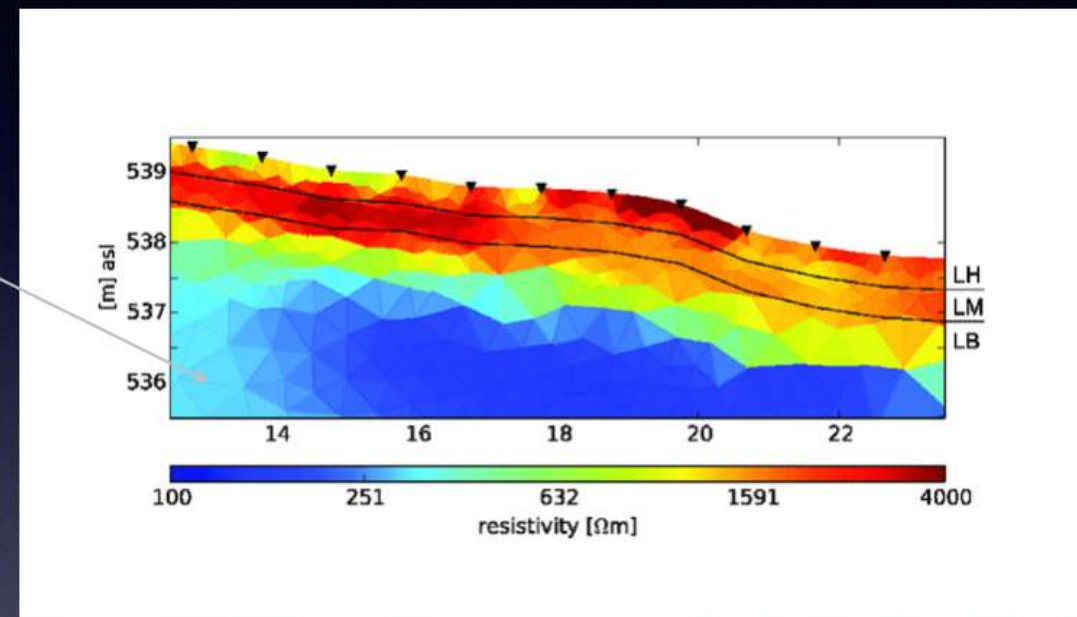
Inverted
Section

Shadow
Zones



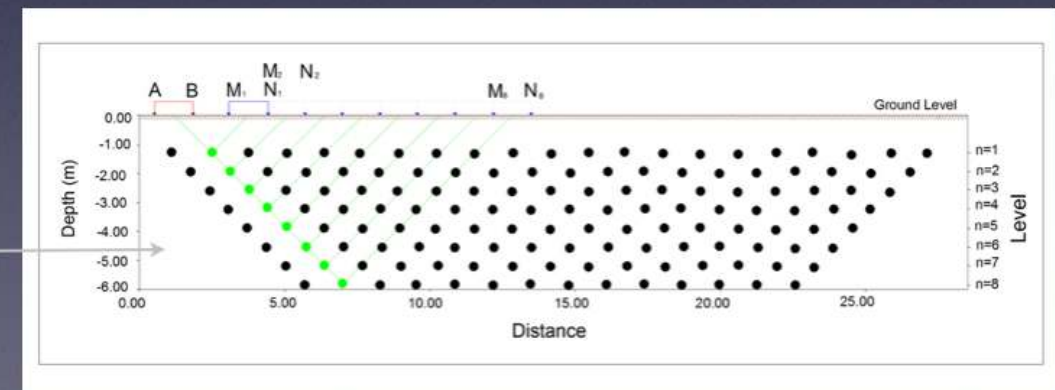
4. Data processing

Zone with less saturation
(lower resistivity) ?

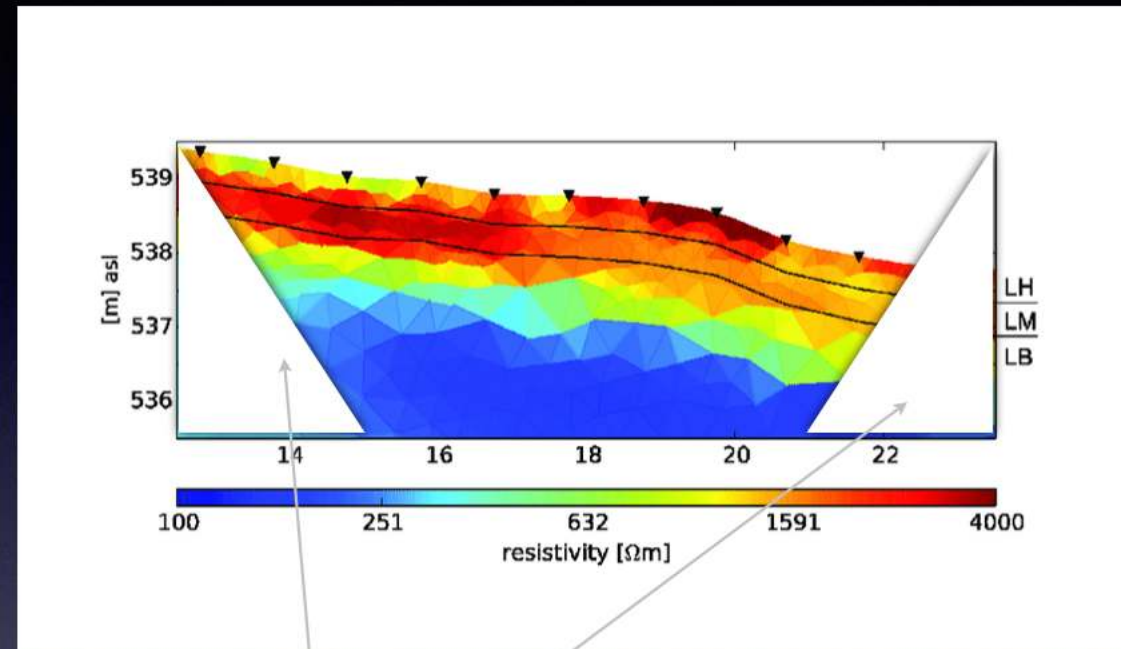


NO !

At the lower margin we in
surface ERT we have the
'shadow zones'

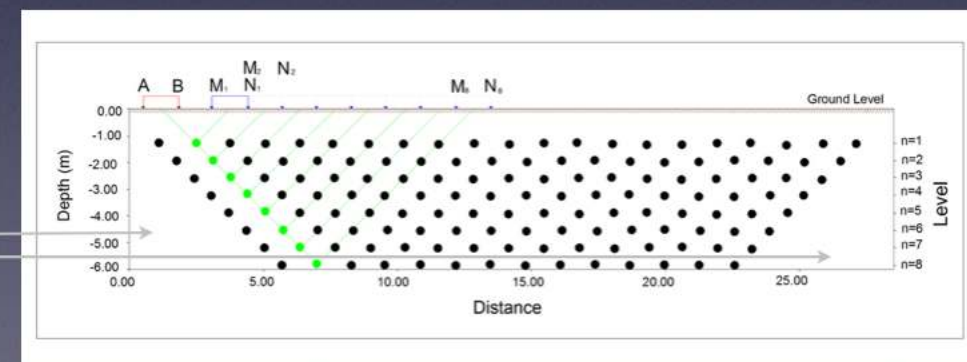


4. Data processing

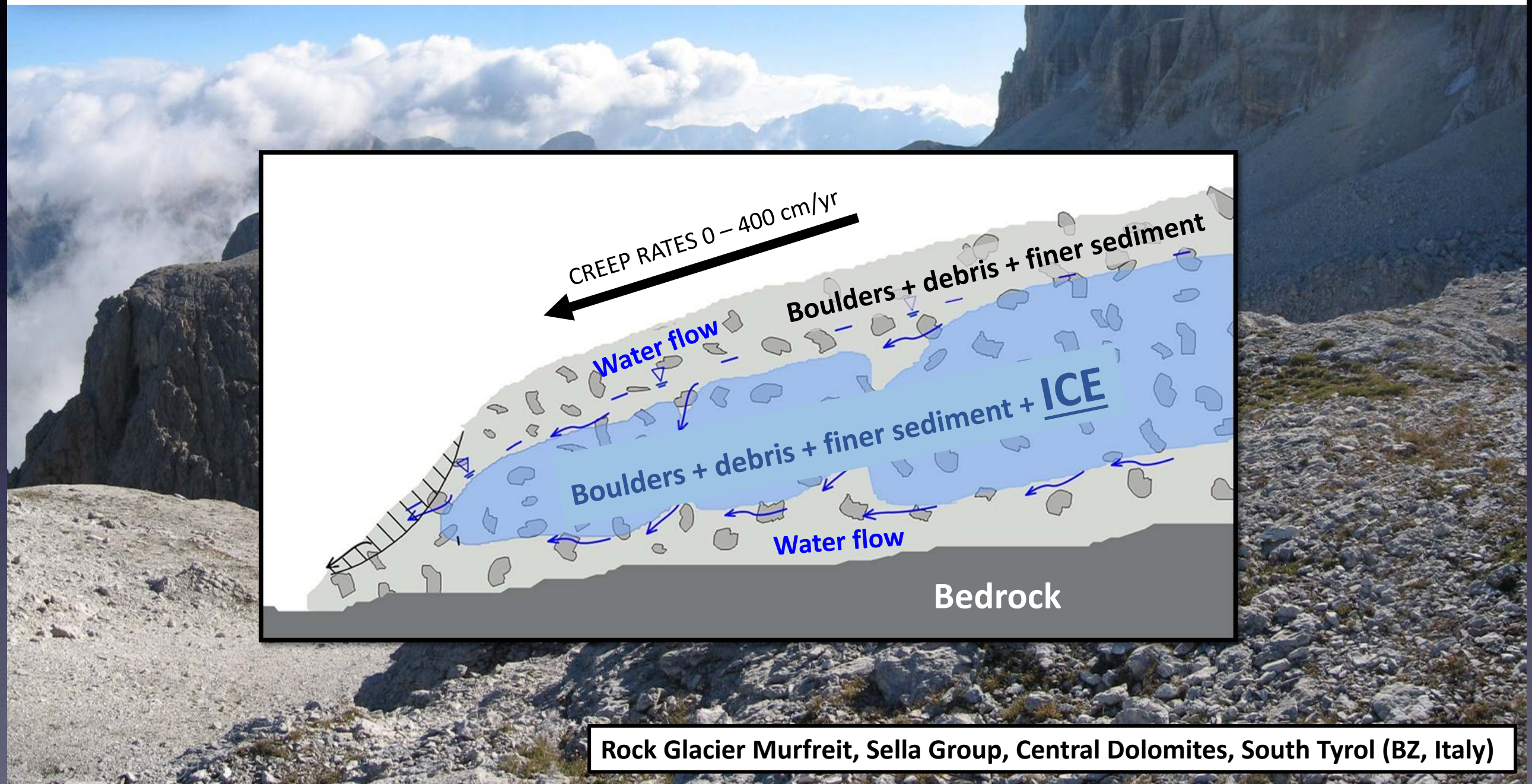


YES !

At the lower margin we in
surface ERT we have the
'shadow zones'

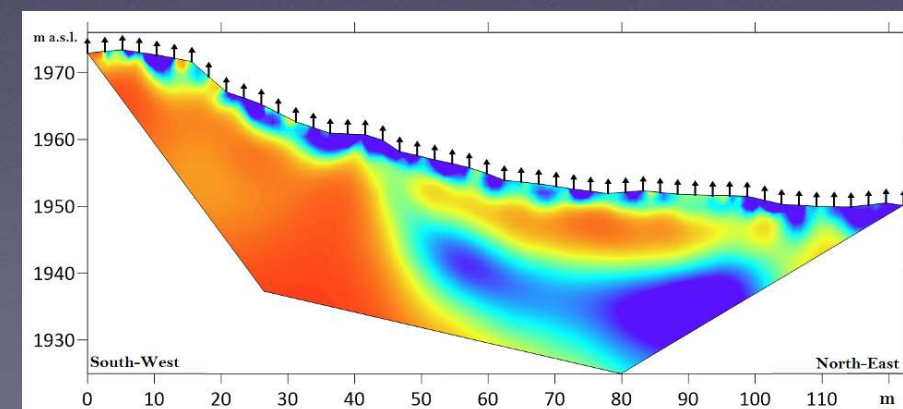
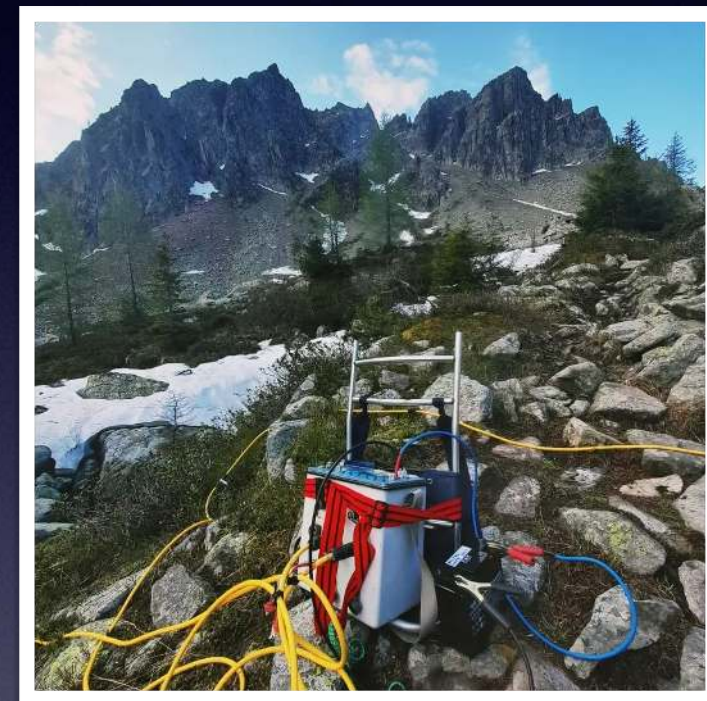


1. Mountain permafrost: Rock Glaciers



What WE DO

1. We installed textile electrodes
2. We wet with salty water
3. We used multi-grad dipole conf.
4. We do quality data check and then invert with the correct error



What to avoid:

1. We installed textile electrodes

Stainless steel electrodes...

2. We wet with salty water

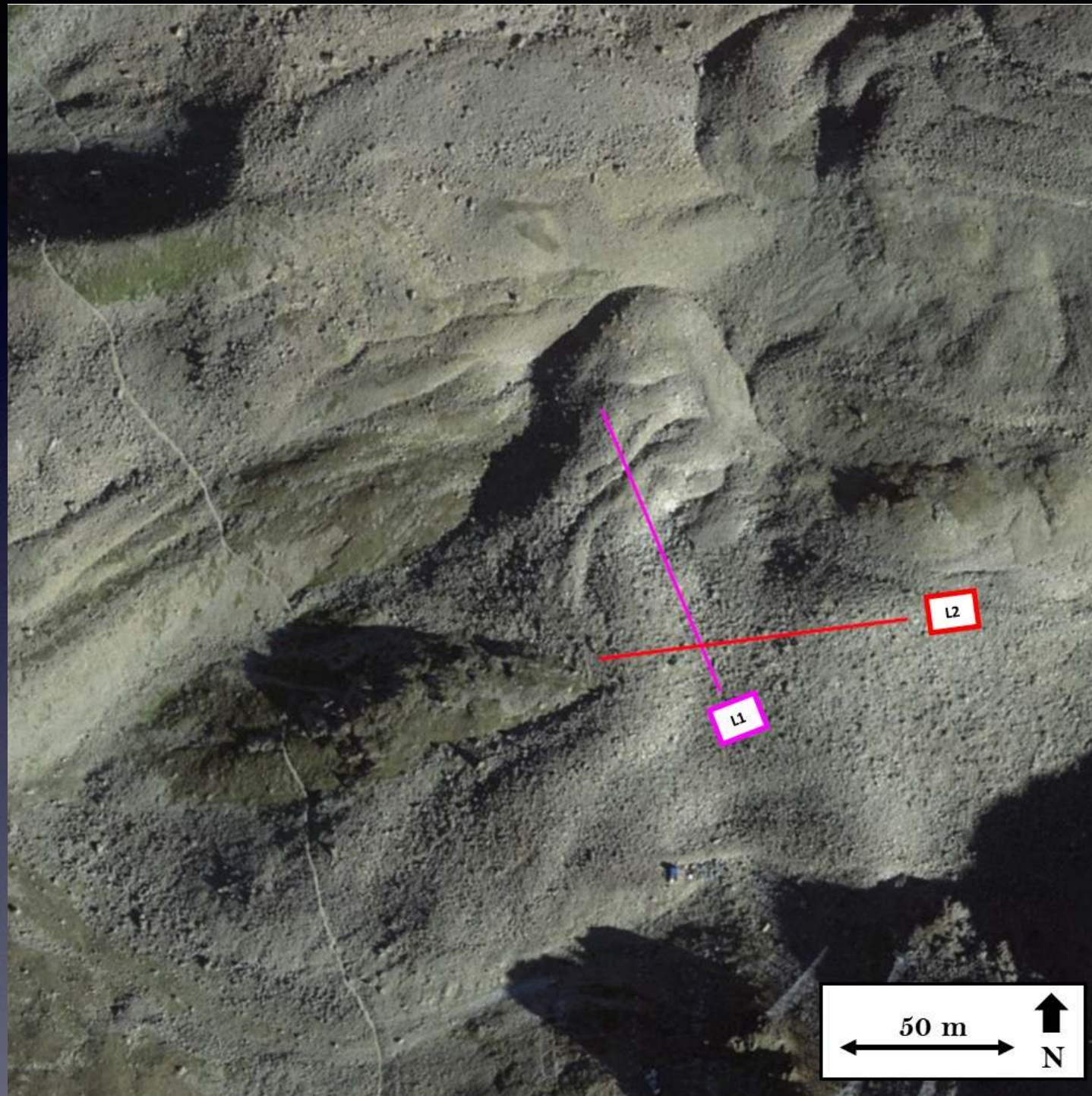
No water...high
contact resistance

3. We used multi-grad dipole conf.

Wenner - Schlumberger

4. We do quality data check and
then invert with the correct error

Invert ignoring dataset error



**Schafberg rock glacier
(Engadin, Switzerland)
August 2022**

**Traditional Wenner-alpha
360 quadrupoles
Total Time: 30 min
VS**

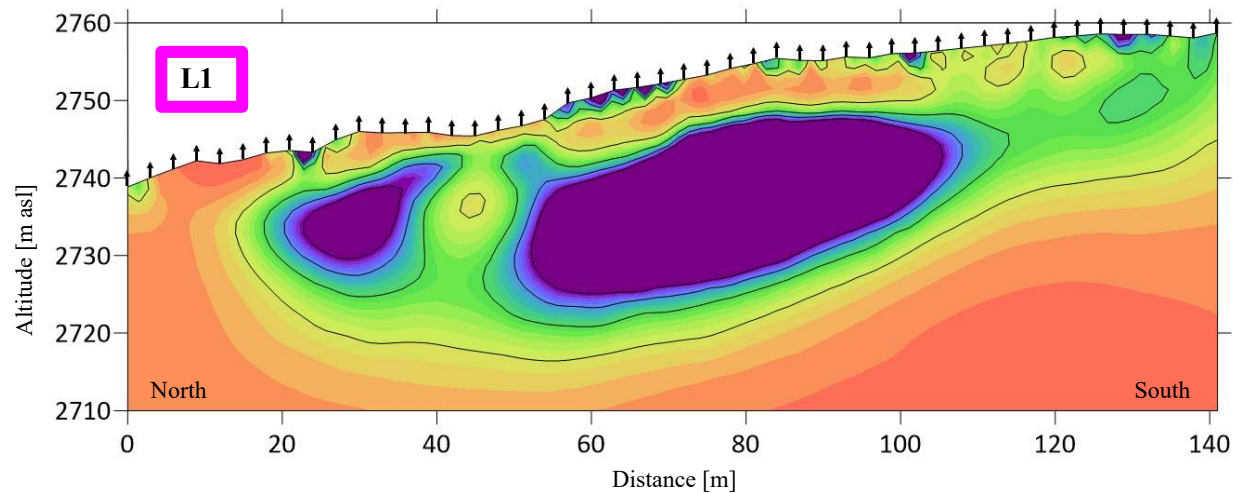
**Mixed Dipole-dipole and
Multigradient Multi-skip
2500 quadrupoles
Total Time: 15 min**

L1 48 electrodes 3m spacing

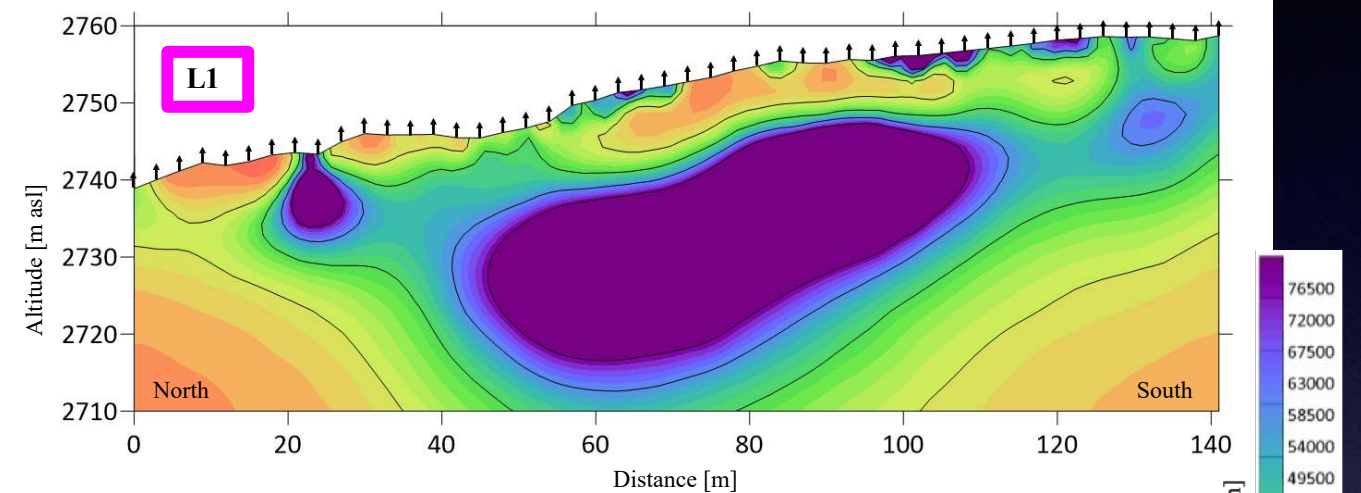
L2 48 electrodes 2m spacing

Comparison test: Wenner-alpha VS mixed Dipole-dipole Multigradient multi-skip

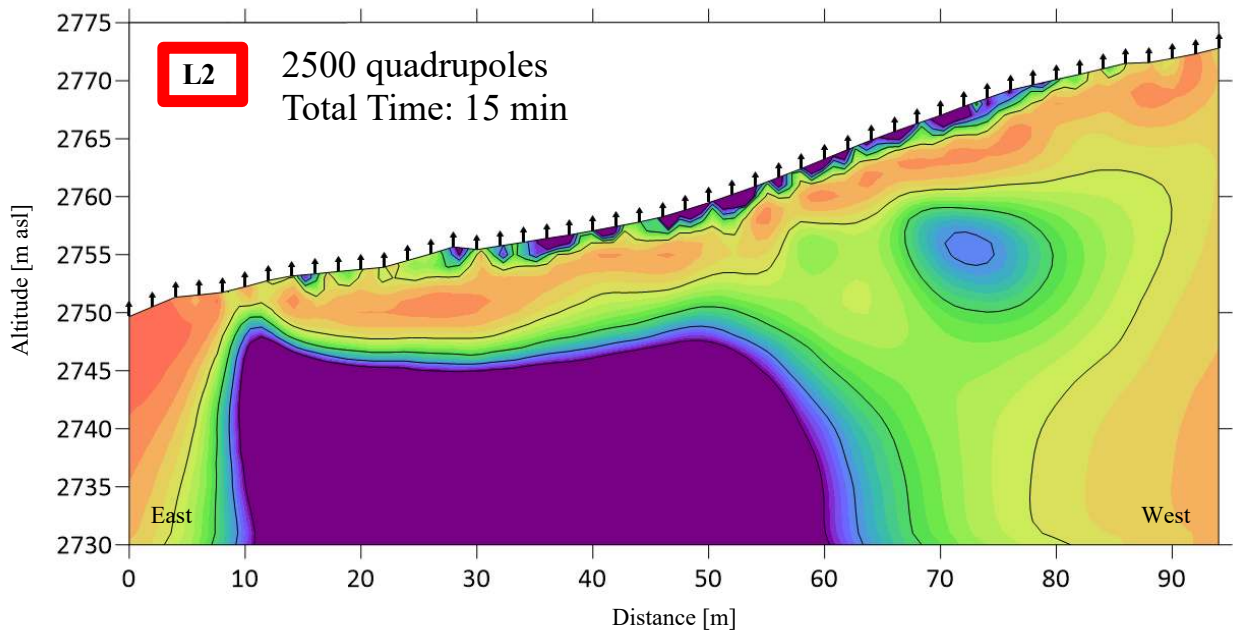
a) Inverted resistivity model **L1 Dipole-dipole and Multigradient** – expected data error 5%



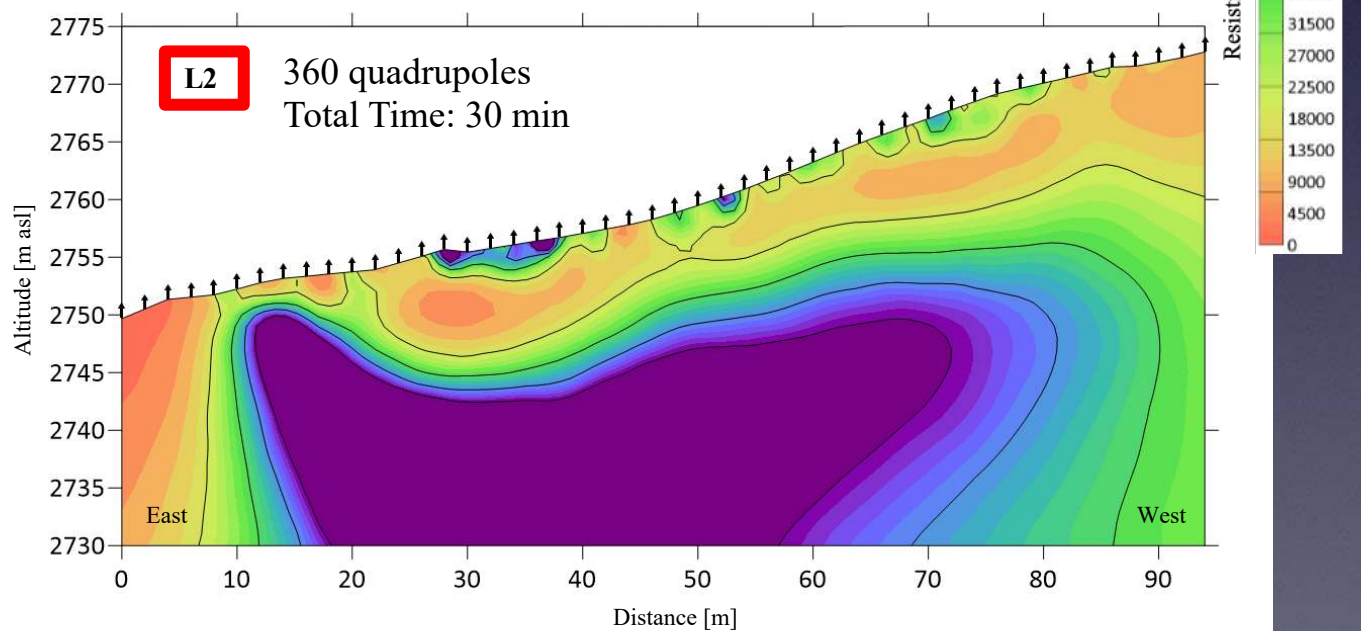
c) Inverted resistivity model **L1 Wenner-alpha** – expected data error 5%



b) Inverted resistivity model **L2 Dipole-dipole and Multigradient** – expected data error 5%

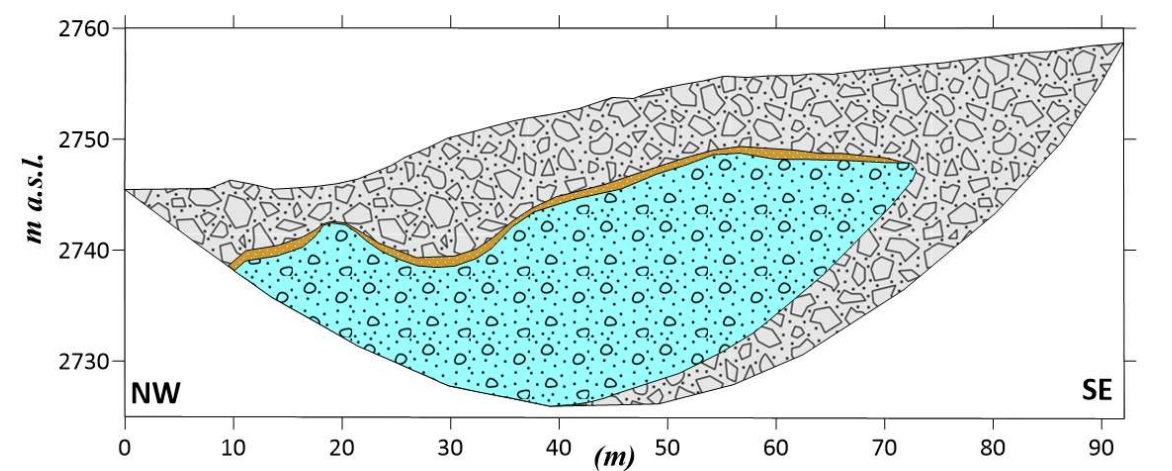
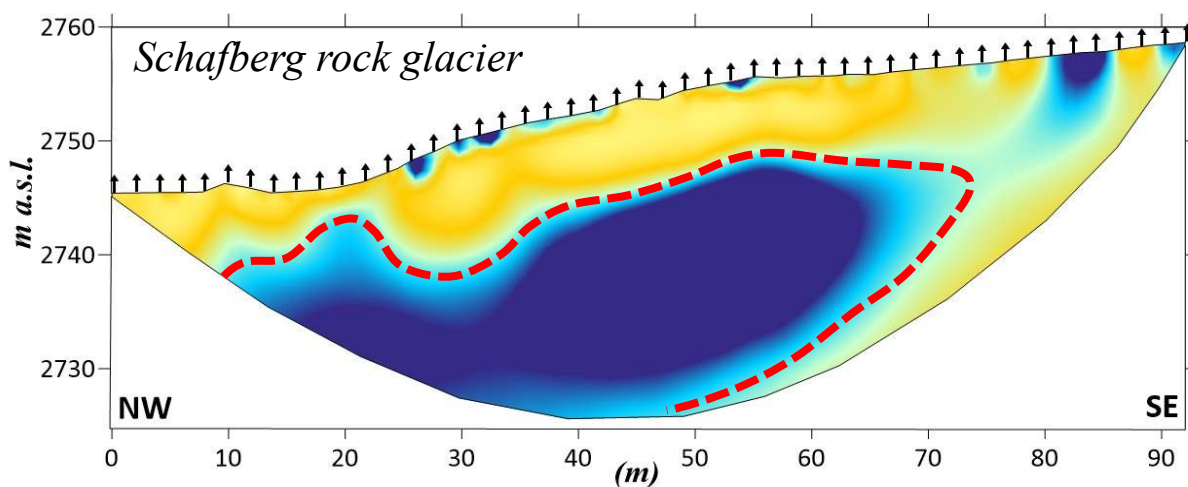
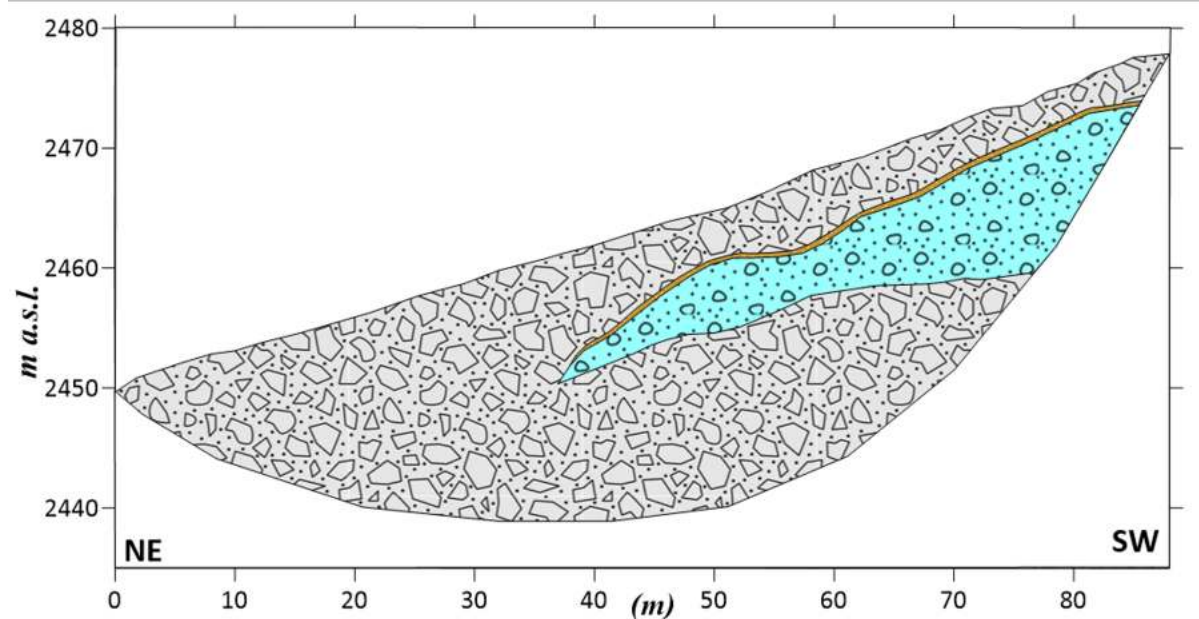
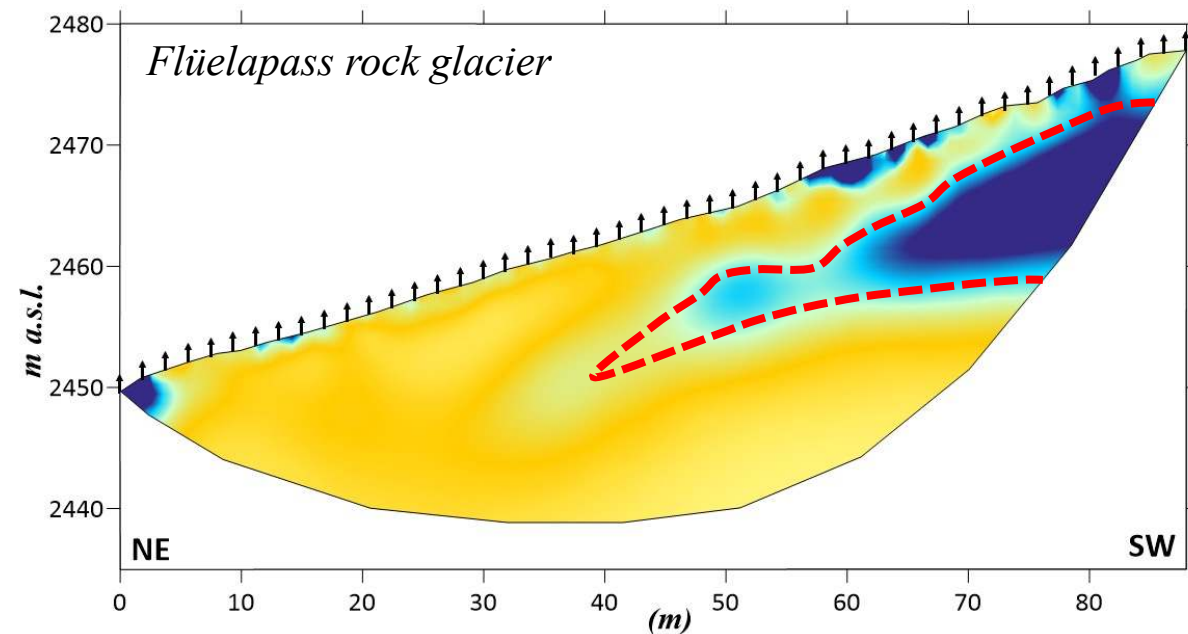


c) Inverted resistivity model **L2 Wenner-alpha** – expected data error 5%



ERT in a Rock Glaciers - Dipole dipole multi skip 48 textile electrodes

Electrical resistivity models

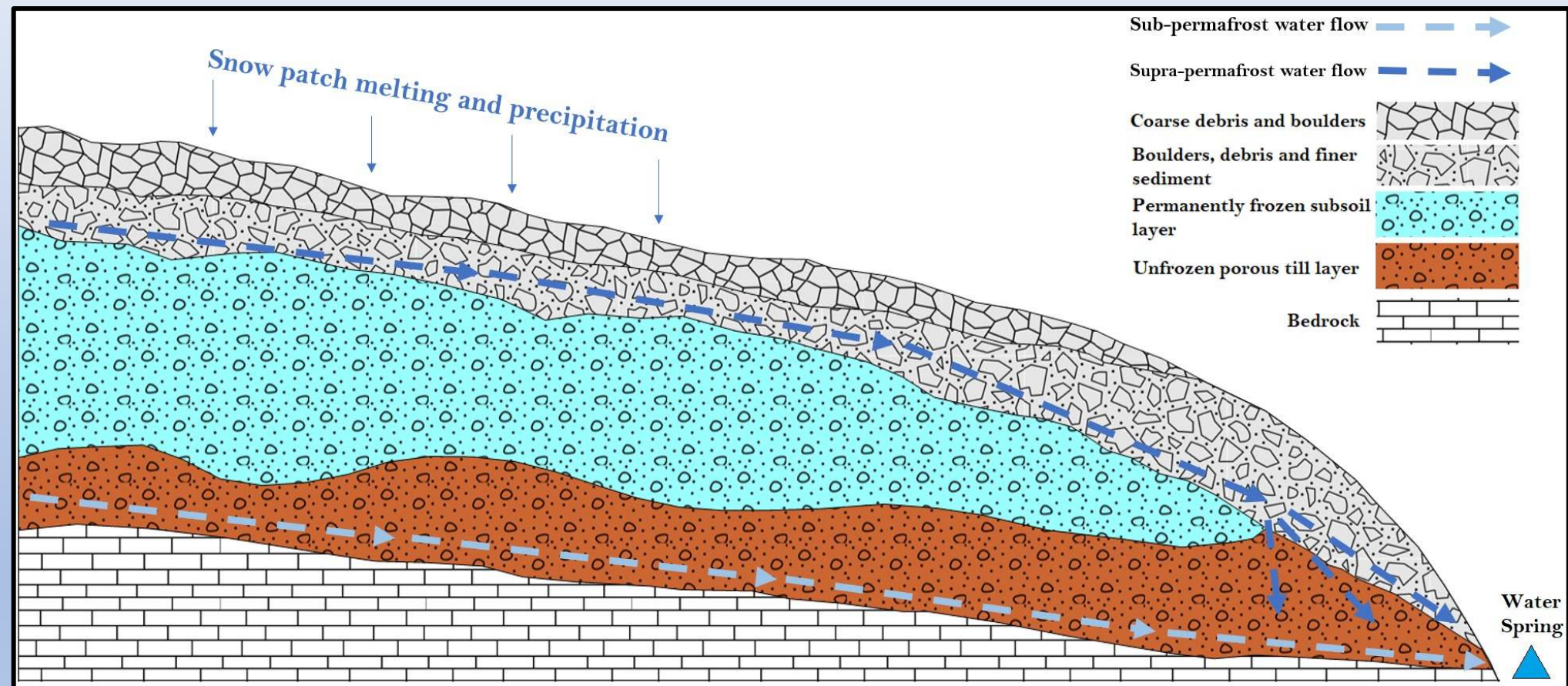


Boaga et al. (2024)

Time Lapse ERT: DYNAMIC

5. Hydraulic evaluation of the frozen layer via ERT time-lapse experiment

So far the hydraulic behavior of rock glacier subsoils has been estimated only with geochemical analysis of their spring water (e.g. stable isotopes of hydrogen and oxygen)

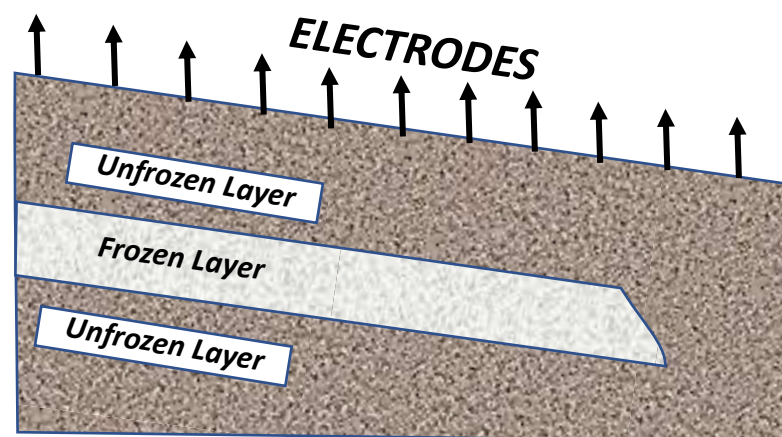


TARGET: for the 1st verify the low permeability of the frozen layer with a geophysical method by performing an infiltration experiment with ERT time-lapse measurements !!!

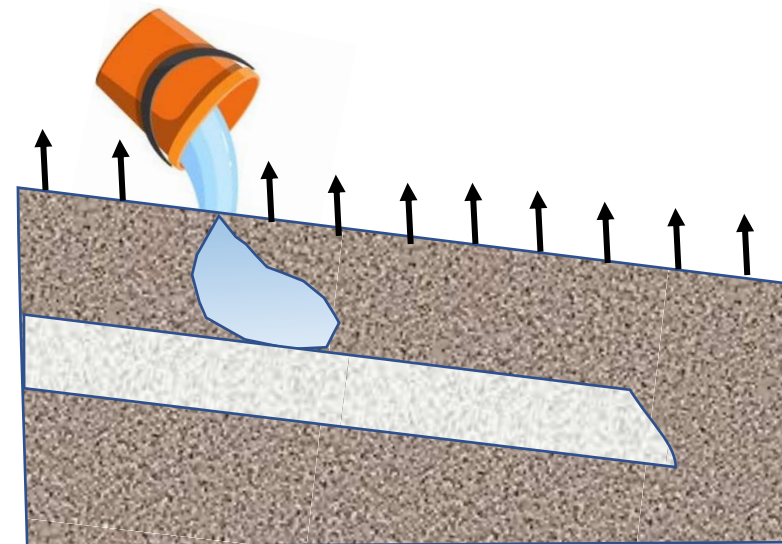
Pavoni et al 2024

5. Hydraulic evaluation of the frozen layer via ERT time-lapse experiment

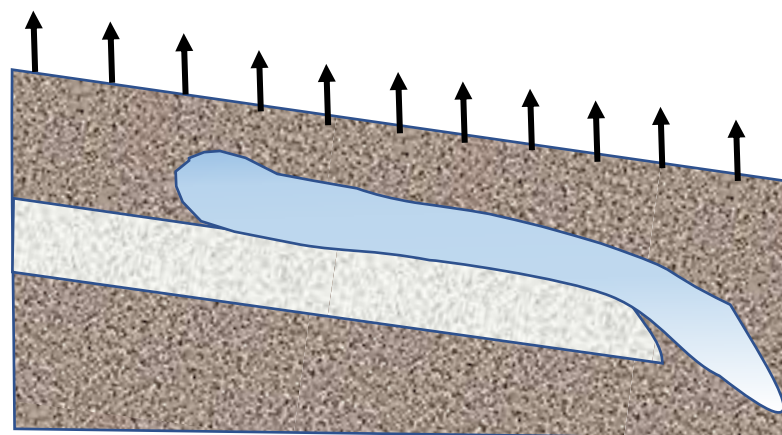
How the experiment works and what we expect to see when the water flows in a subsoil with a discontinuous frozen layer



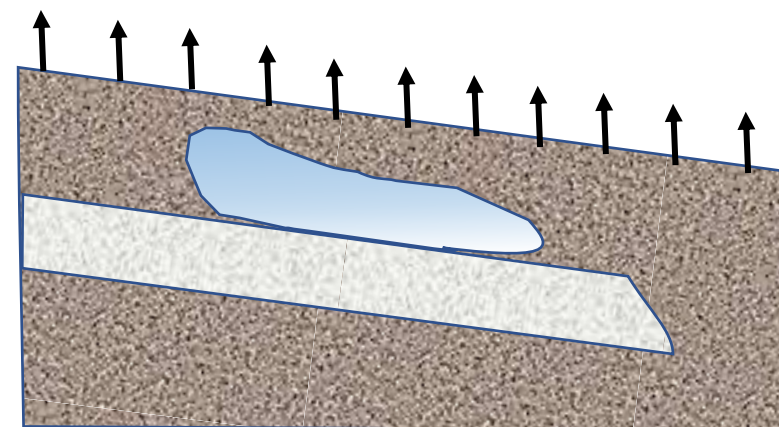
*Time zero
 t_0 ERT dataset*



*Time zero + $\frac{1}{2}$ hour
 t_1 ERT dataset*



*Time zero + n hour
 t_n ERT dataset*

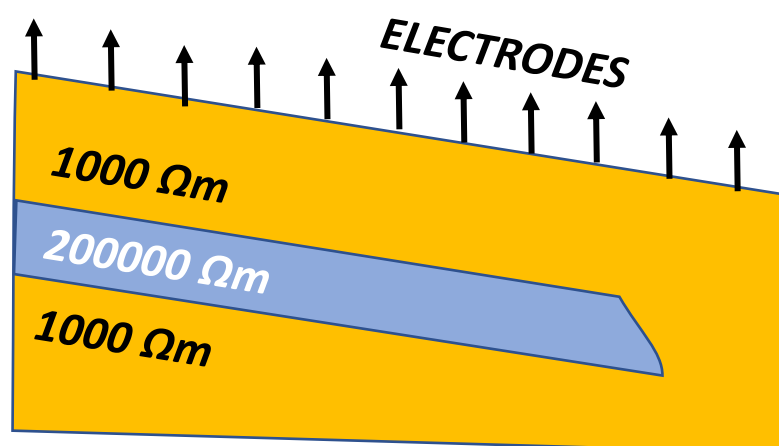


*Time zero + 2 hour
 t_2 ERT dataset*

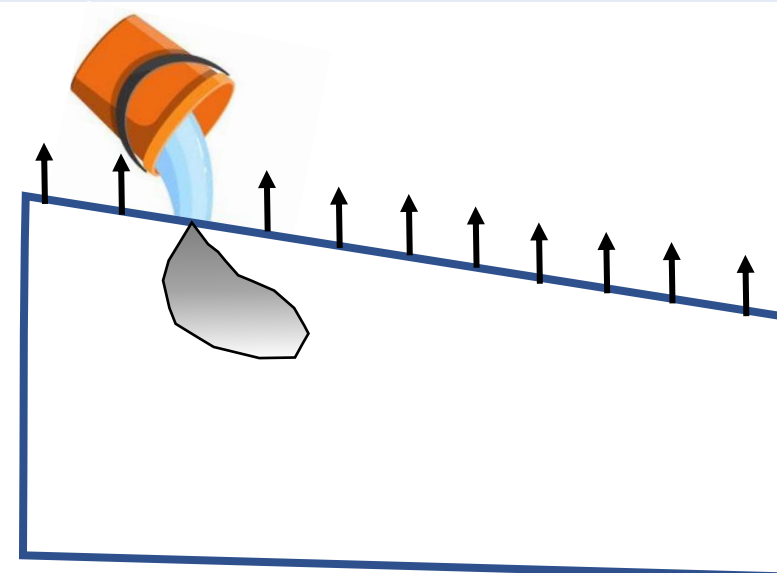
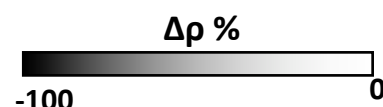
Pavoni et al 2024

5. Hydraulic evaluation of the frozen layer via ERT time-lapse experiment

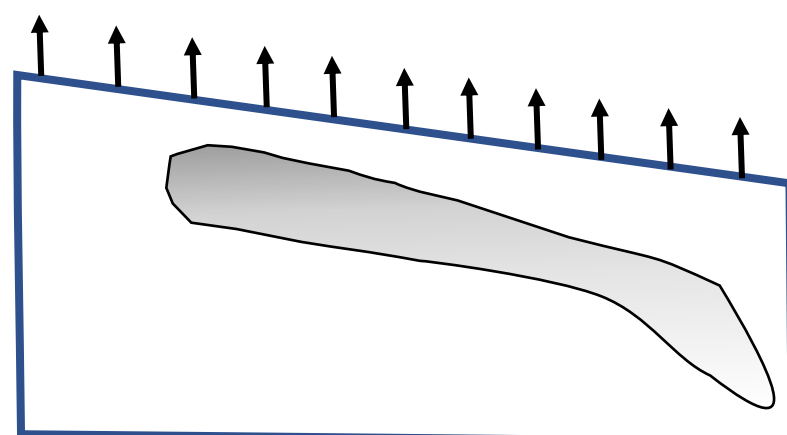
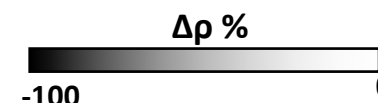
How the experiment works and what we expect to see when the water flows in a subsoil with a discontinuous frozen layer



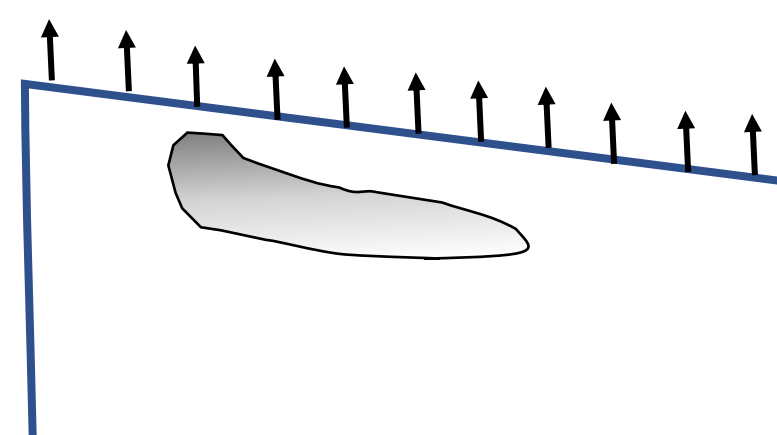
*Time zero:
Inverted
Resistivity
Model to*



*Time zero + $\frac{1}{2} h$:
 t_1 Inverted
Resistivity
Variations
compared to
 t_0 Model*



*Time zero + $n h$:
 t_n Inverted
Resistivity
Variations
compared to
 t_0 Model*

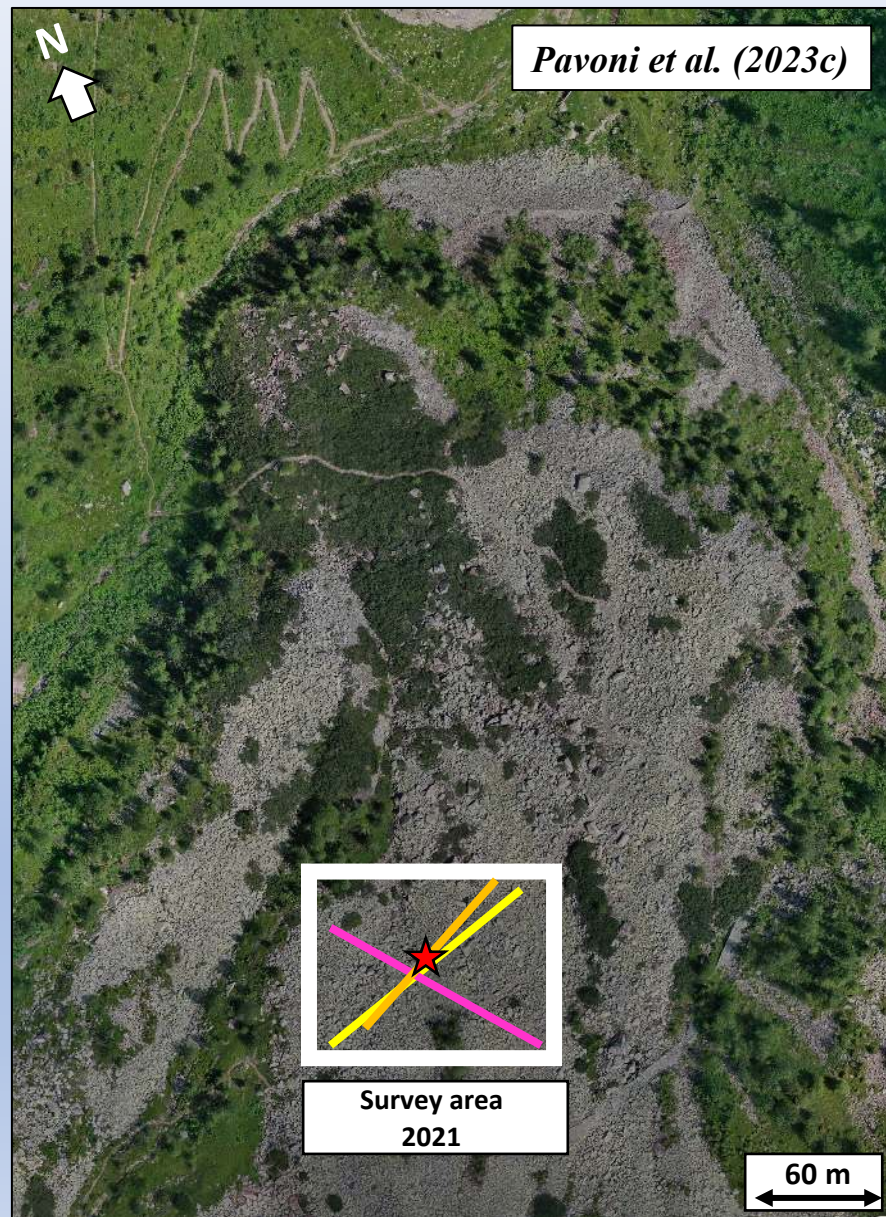


*Time zero + $2 h$:
 t_2 Inverted
Resistivity
Variations
compared to
 t_0 Model*

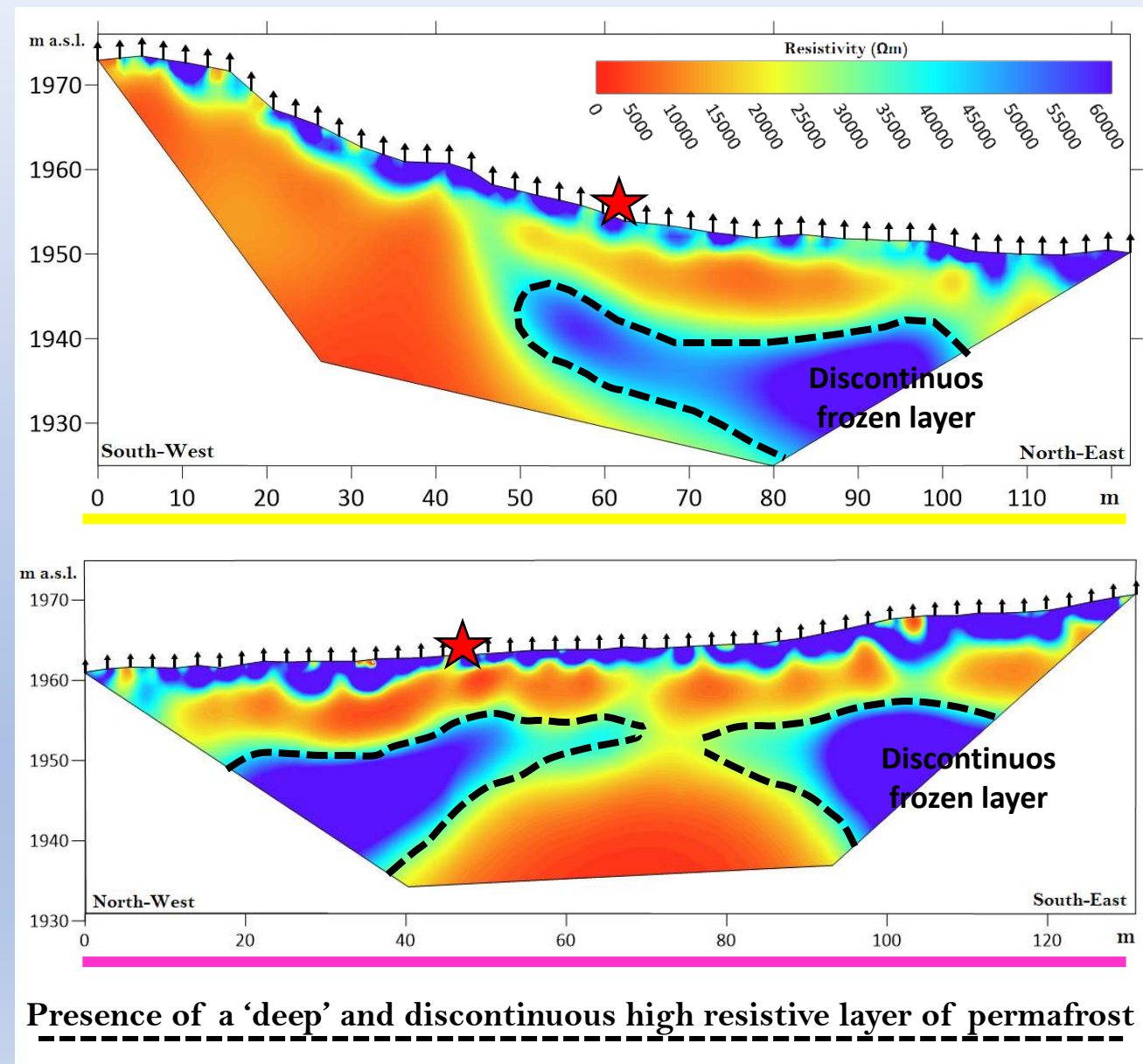
Pavoni et al 2024

5. Hydraulic evaluation of the frozen layer via ERT time-lapse experiment

Sadole rock glacier, Sadole Valley, Trento, Italy



ERT survey lines performed in summer 2021

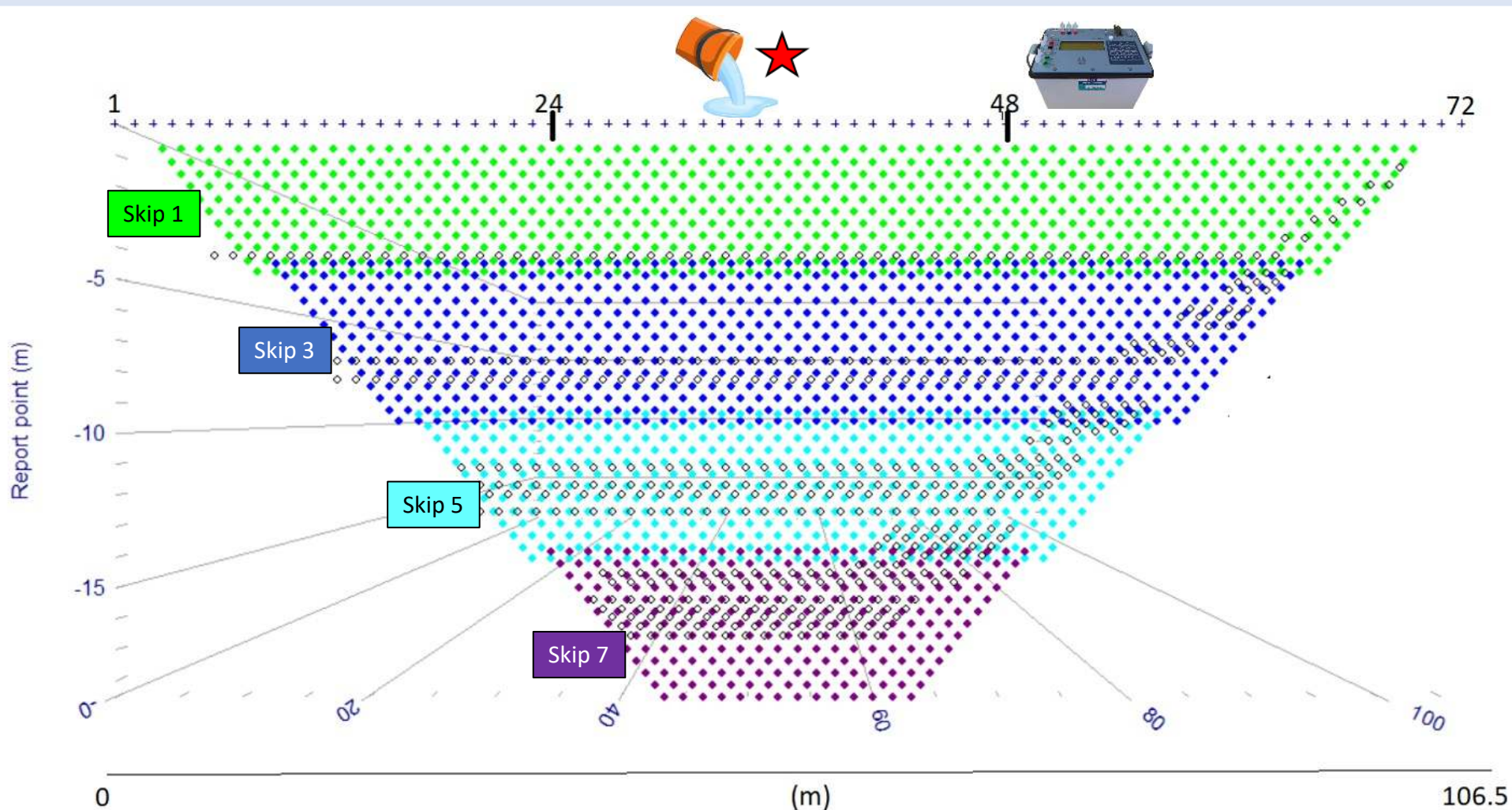


Pavoni et al 2024

5. Hydraulic evaluation of the frozen layer via ERT time-lapse experiment

Syscal Pro, 72 electrodes, 1.5m spacing, Dipole-dipole configuration, Direct and Reciprocal measurements

ERT acquisition
time steps



14/06/2022

t0	09:30
800 l water injection	10:00
t1	10:15
t2	10:30
t3	10:45
t4	11:00
t5	12:15
t6	13:15
t7	14:15
t8	15:15
t9	17:15

15/06/2022

t10	09:30
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Pavoni et al 2024

5. Hydraulic evaluation of the frozen layer via ERT time-lapse experiment

March - April 2022

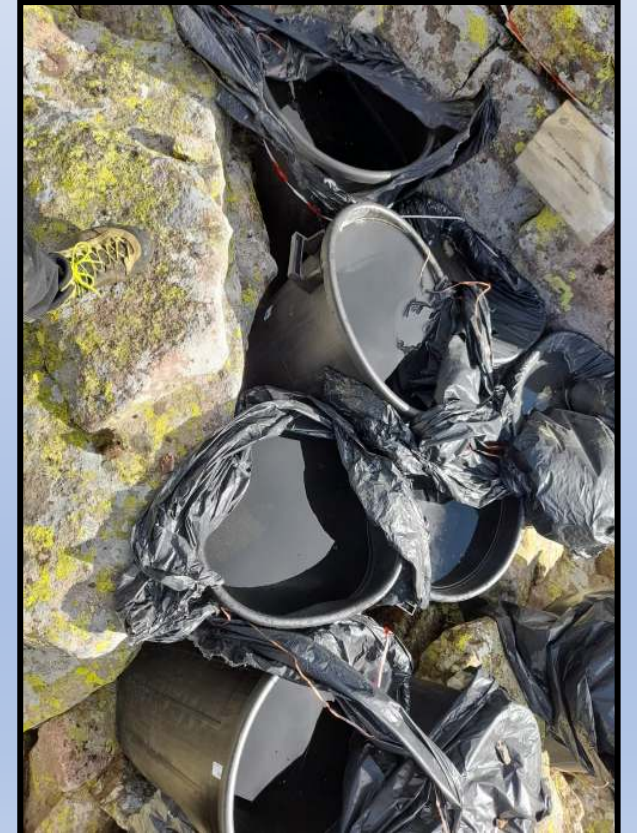


10 x 120 liters bins
to collect the water
for the experiment



Bins carried on the rock glacier, filled with snow,
coated with with nylon sheets pierced at their
center, and covered with a snow layer

Middle June 2022



1000 liters of water

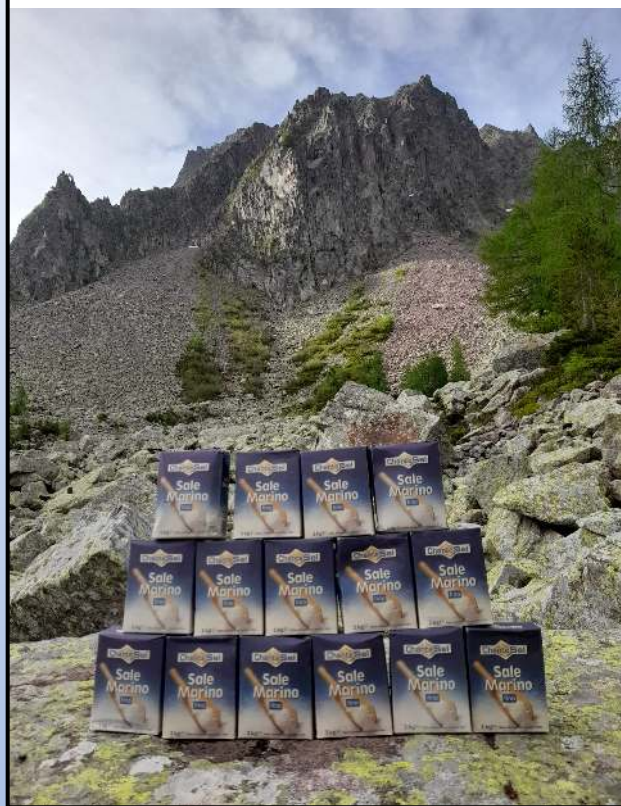
Pavoni et al. (2023c)

Pavoni et al 2024

5. Hydraulic evaluation of the frozen layer via ERT time-lapse experiment

Infiltration Experiment with ERT Time-Lapse Measurements

3 kg of NaCl in each bin



Electrodes inserted between the boulders using sponges soaked with salt-water



Before each acquisition, electrodes wet to guarantee homogeneous contact resistances

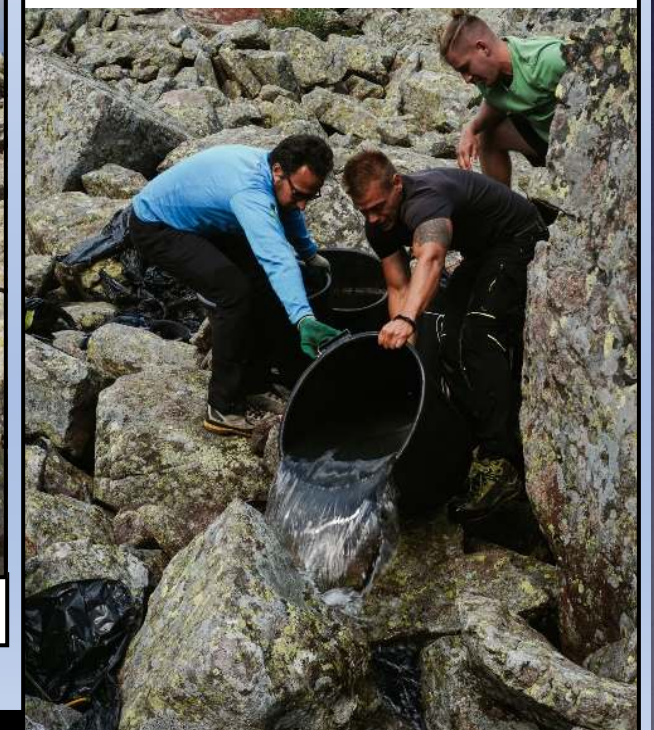
Pavoni et al. (2023c)

to dataset acquisition



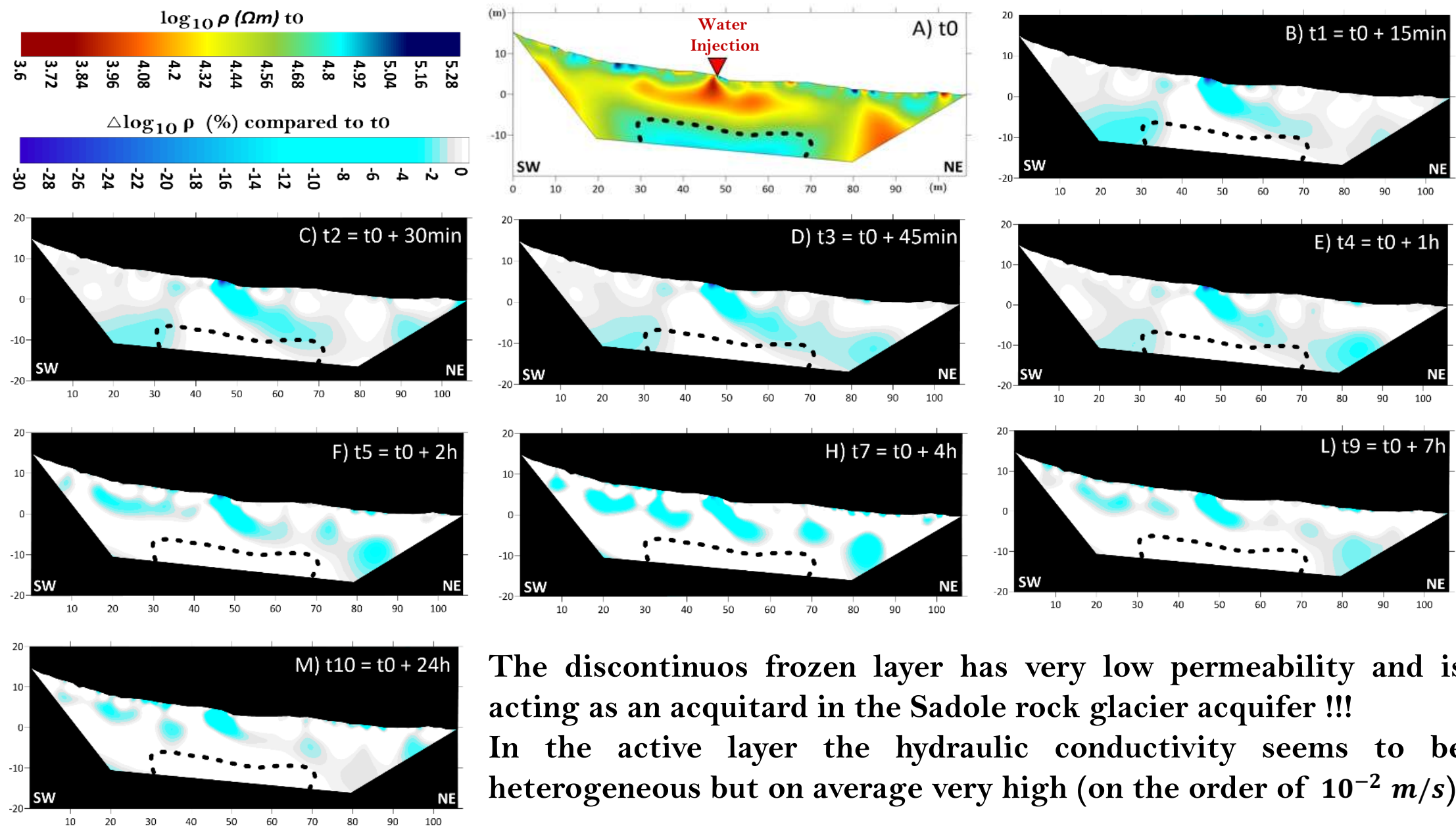
Time-lapse ERT acquisition

Injection of 800 liters of salt water !!!

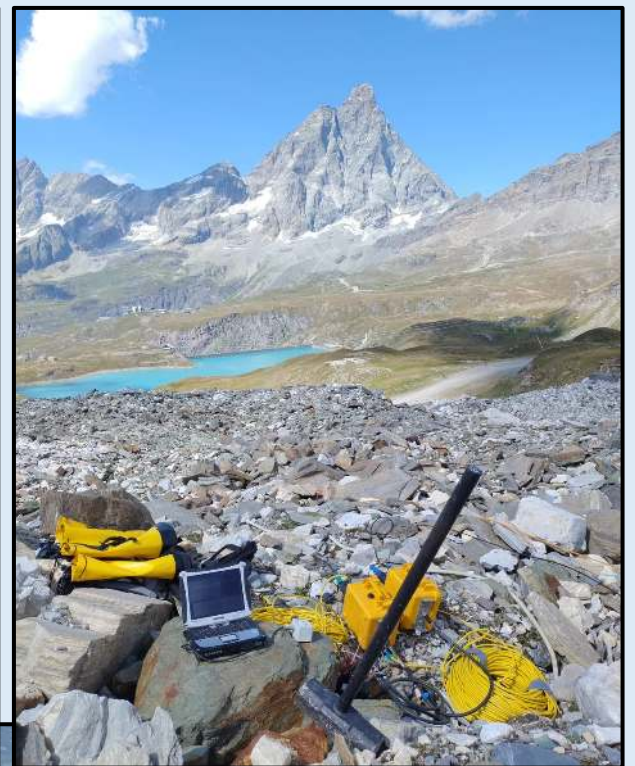
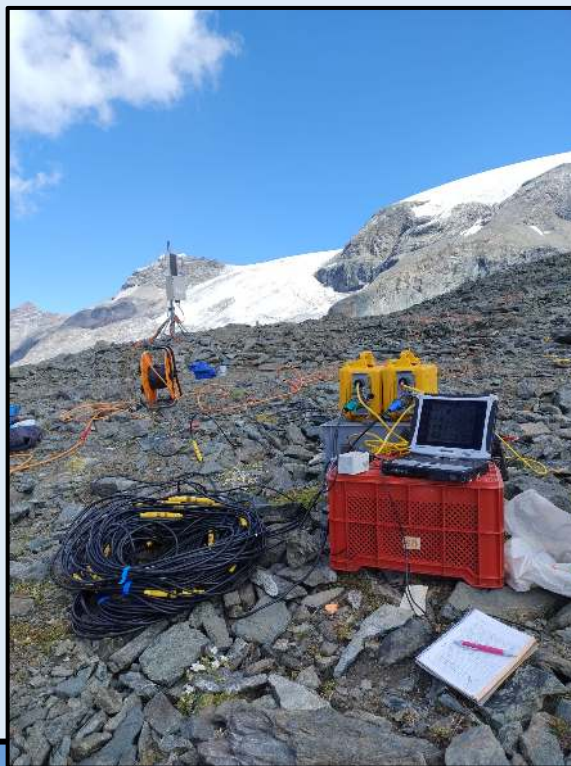


Pavoni et al 2024

5. Hydraulic evaluation of the frozen layer via ERT time-lapse experiment



Pavoni et al 2024



Thank you for the attention



THANK YOU FOR THE ATTENTION... QUESTIONS ???

