RESISTIVITY

1) Resistivity of rocks
2) General principles of resistivity surveying
3) Field procedures, interpretation and examples
4) Summary and conclusions

INDUCED POLARIZATION

1) General principles of IP and measured parameters
2) IP properties of rocks
3) Survey strategies, interpretation and examples
4) Conclusions

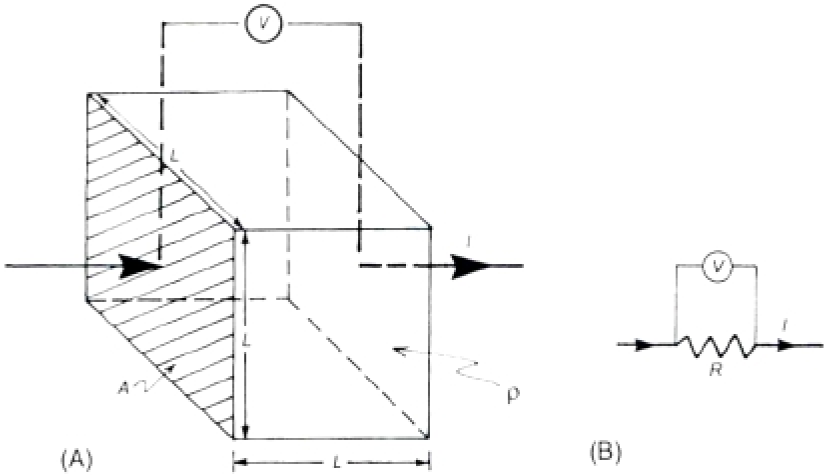
Resistivity method

The resistivity method is used in the study of horizontal and vertical discontinuities in the electrical properties (resistivity) of the subsurface

Applications

- Exploration of mineral deposit (sand, gravel)
- Exploration of groundwater
- Engineering/construction site investigation
- Waste sites and pollutant investigations
- Cavity, karst detection
- Glaciology, permafrost
- Archaeological investigations

1. Resistivity of rocks



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

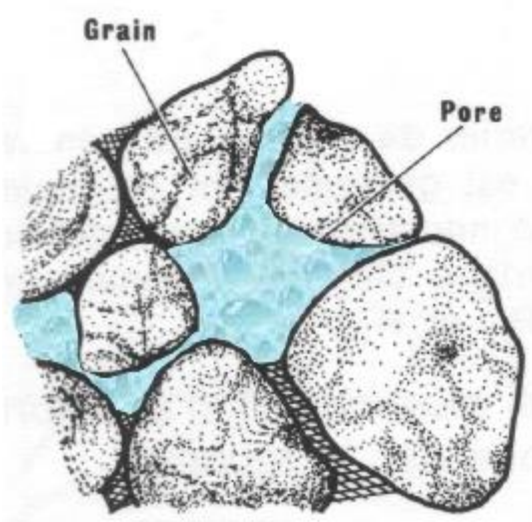
$$\rho = \delta R \frac{\delta A}{\delta L}$$

ρ	resistivity in ohm.m (Ωm)
$\sigma = 1/\rho$	conductivity in Siemens per meter (S/m)

Resistivity is the physical property which determines the aptitude of this material to be opposed to the passage of the electrical current

Electrolytic conductivity

The current is carried by ions. The electrical resistivity of rocks bearing water is controlled mainly by the water which they contain.



Electrolytic conductivity

The resistivity of a rock will depend :

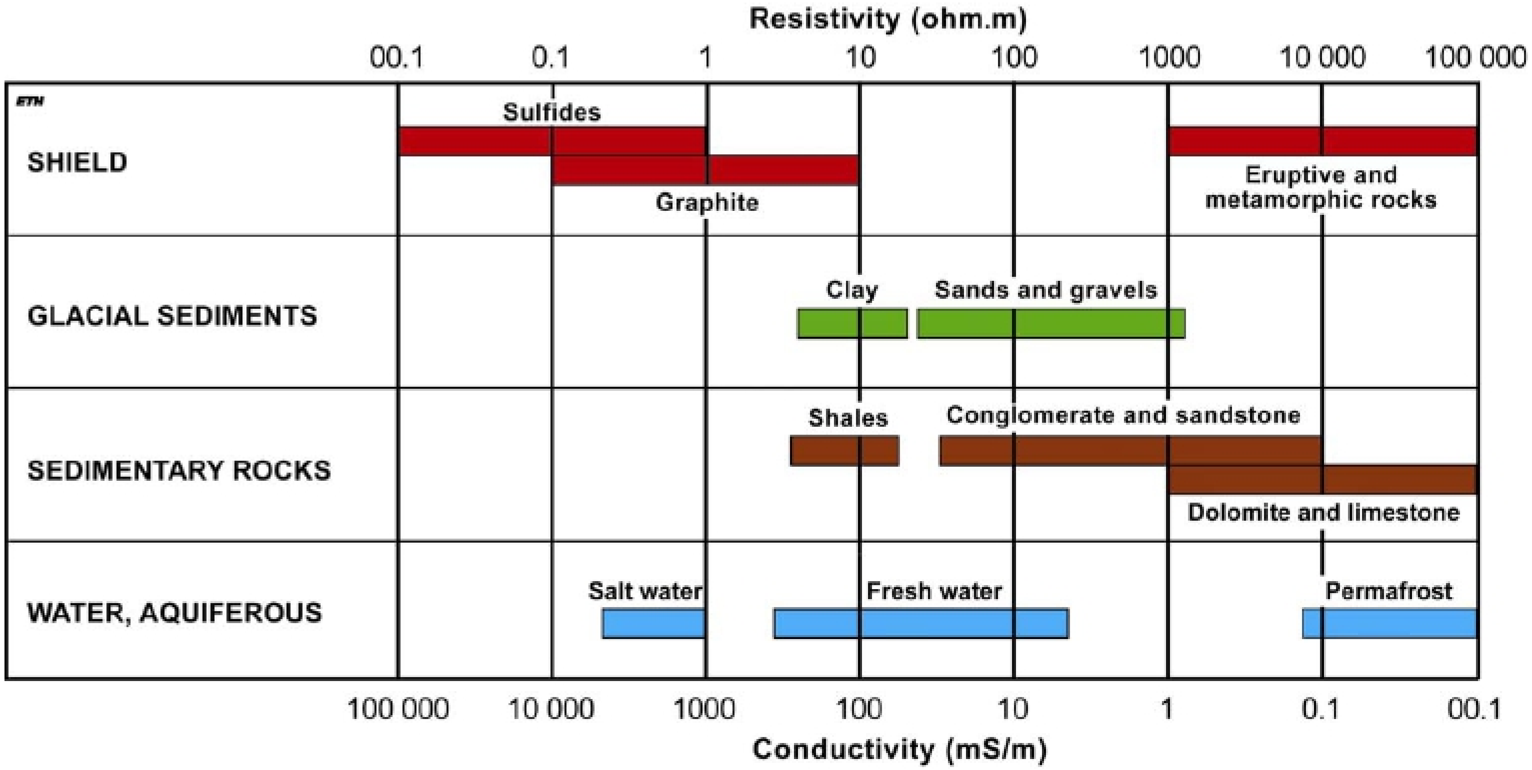
- on the resistivity of the natural pore water and consequently the quantity of dissolved salts in the electrolyte

  1g/liter=1000 ppm

- on the quantity of electrolyte contained in the unit of rock volume (saturation)

- on the mode of electrolyte distribution, porosity

Resistivity of rocks and minerals



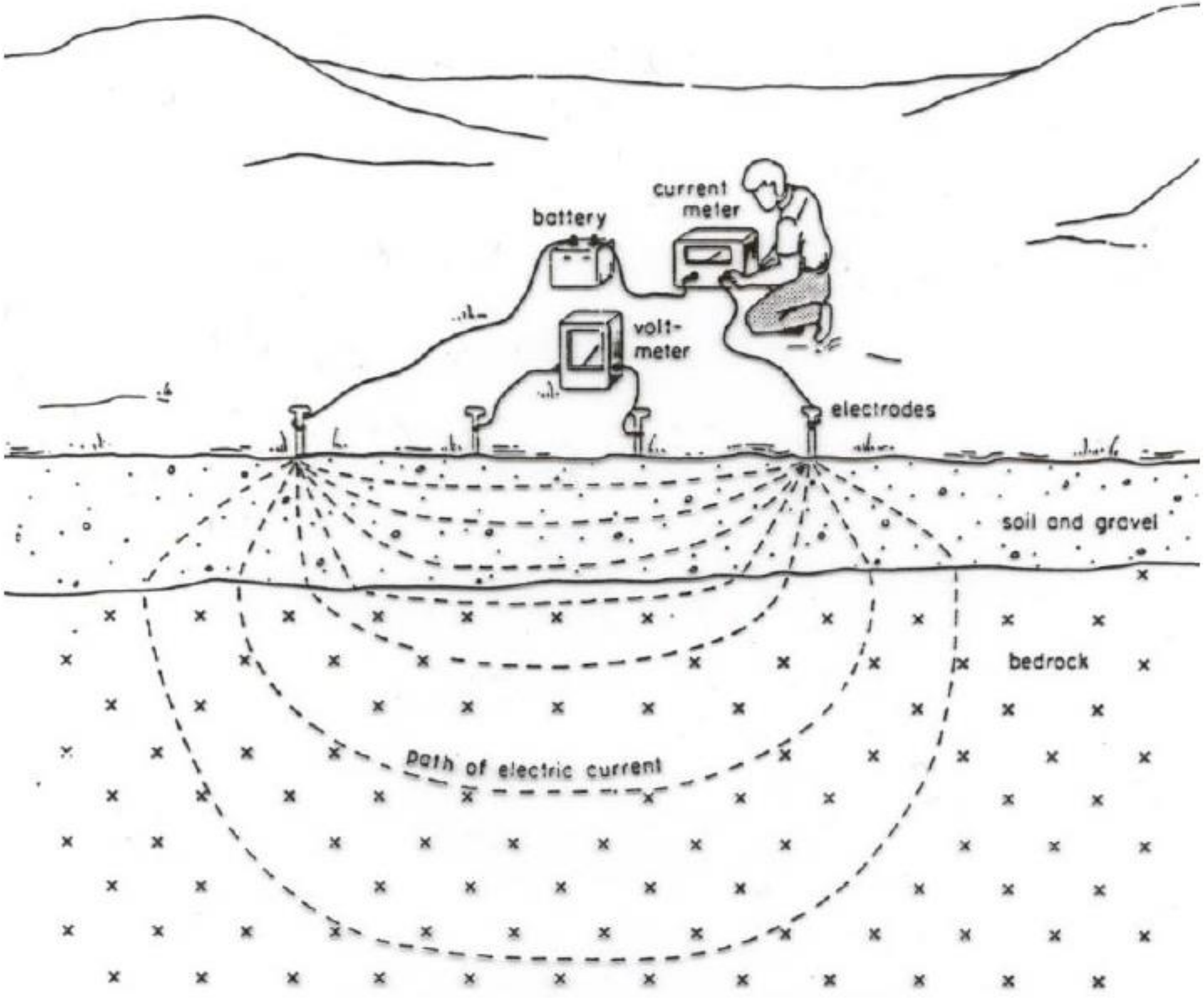
- **Air, gas or oil: infinite or very high resistivity.**
- **Liquid materials from landfills are generally conductive (<10 ohm.m)**

The resistivity of a rock **decreases** if…

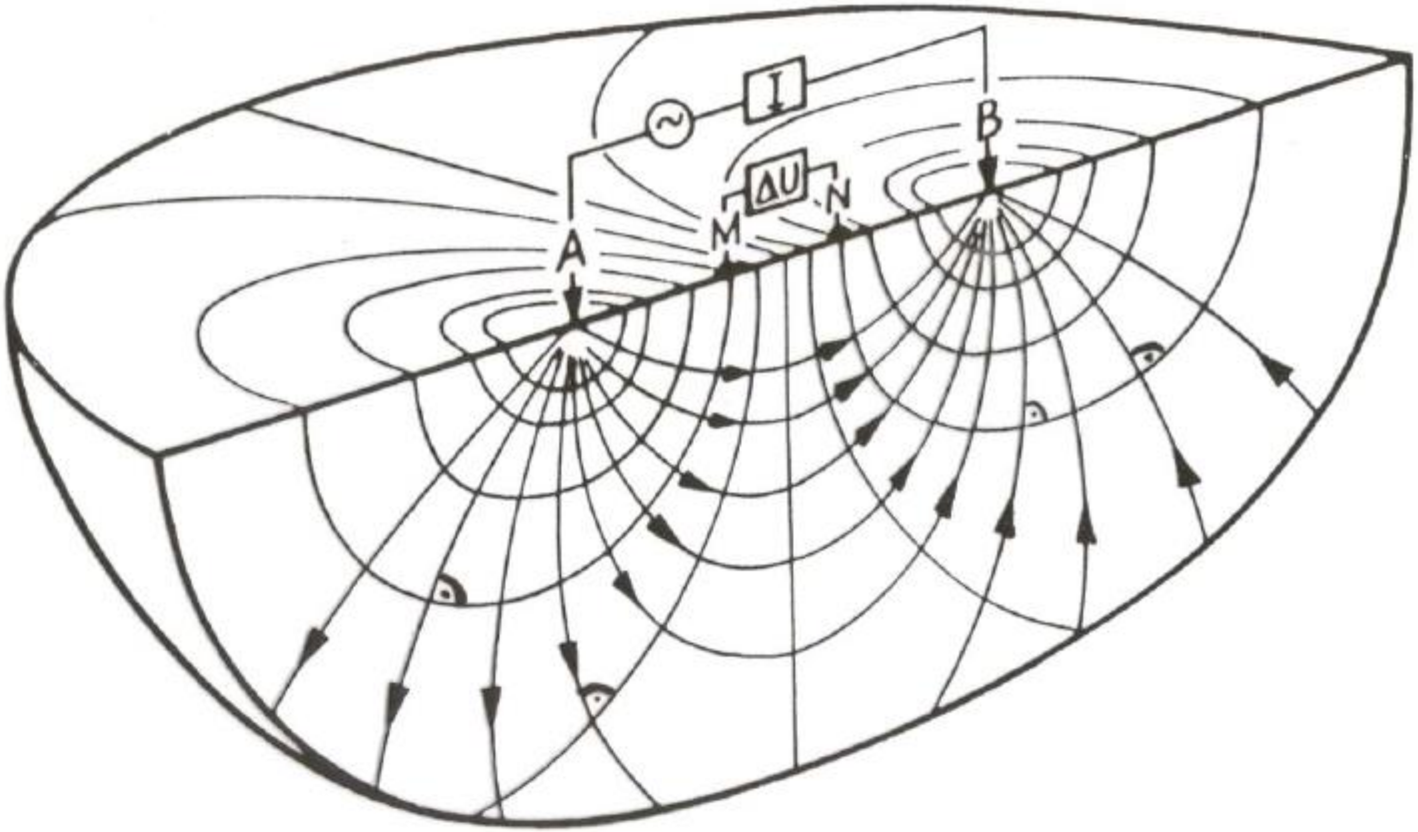
- The quantity of water **increases**
- The salinity **increases** (quantity of ions)
- The quantity of clay **increases**
- The temperature **increases**

2. General principles of resistivity surveying

Four-electrode system



Current lines, equipotential surfaces



Apparent resistivity

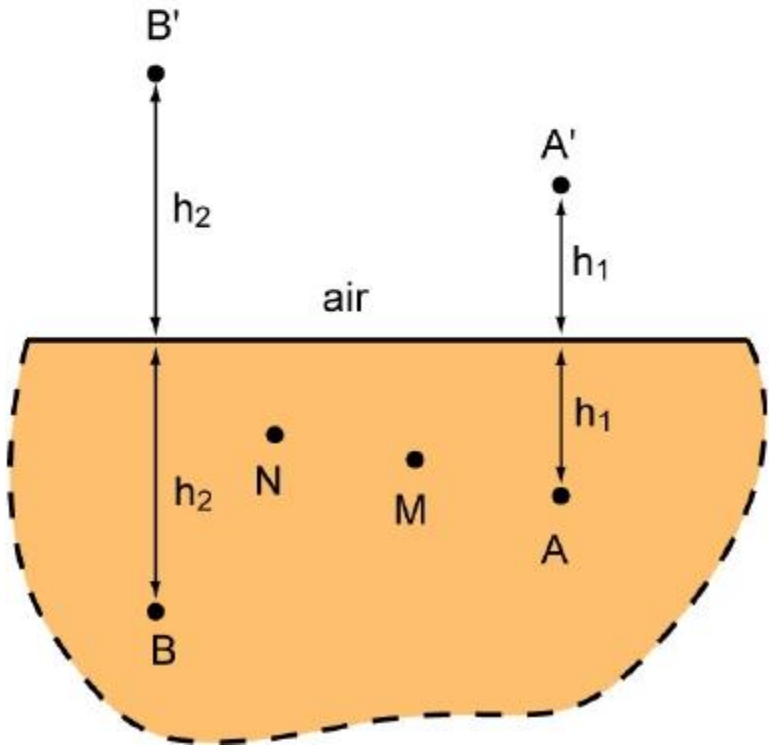
- In a heterogeneous medium, the measured resistivity is an apparent resistivity, which is a function of the form of the inhomogeneity and of the electrode spacing and surface location.

- K is named the geometric factor.

$$\rho_a = \frac{\Delta V_{MN}}{I} K$$

Geometric factor

For a half-space, a general definition for the geometric factor can be written:



$$K = \frac{4\pi}{\frac{1}{AM} - \frac{1}{AN} - \frac{1}{BM} + \frac{1}{BN} + \frac{1}{A'M} - \frac{1}{A'N} - \frac{1}{B'M} + \frac{1}{B'N}}$$

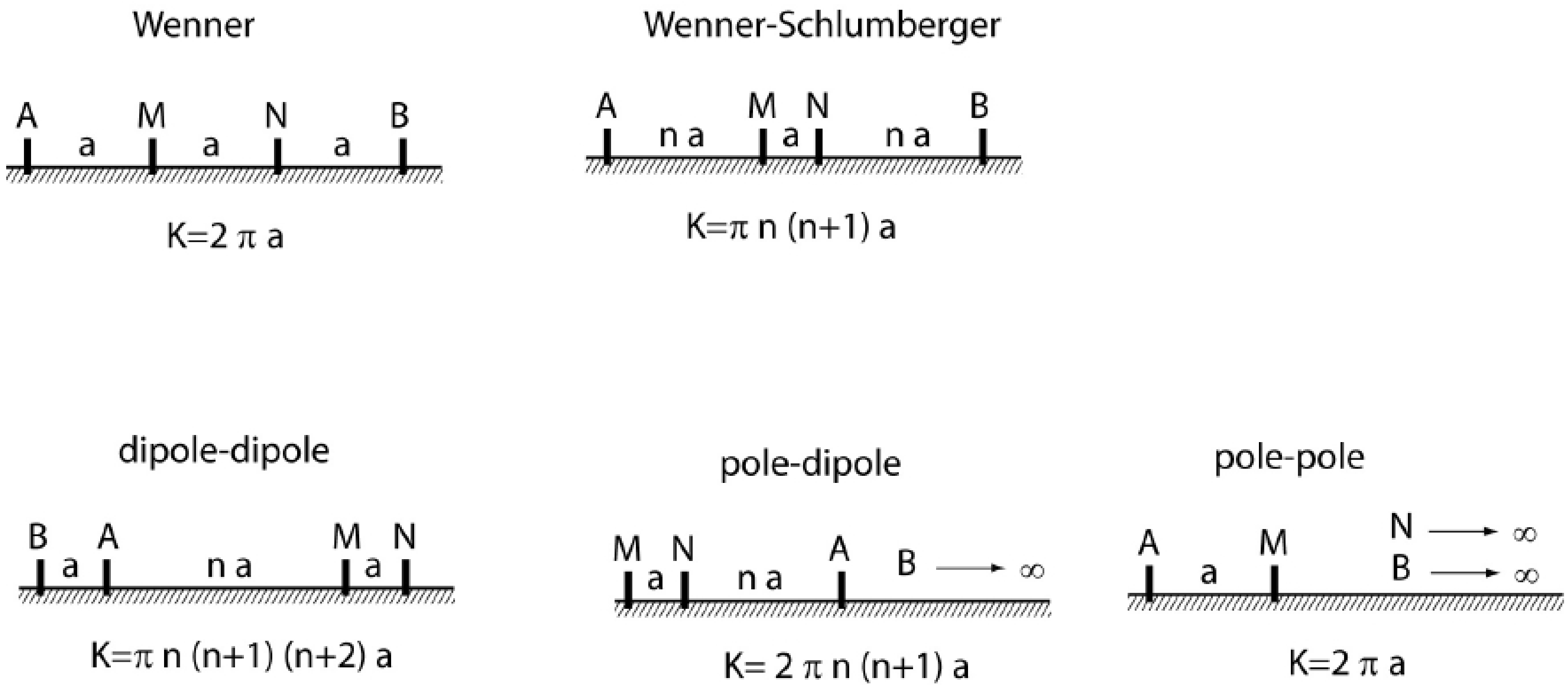
Origine of noise

- Telluric currents
- Man-made currents
- Metallic conductors in the ground (short-circuits)

Solutions:

- Use of alternating current
- Stacking operations
- Rejection filters (16-20 Hz, 50-60 Hz)

Electrode spreads



Electrode spreads

$$\rho_a = 2\pi a \frac{\Delta V}{I}$$

Wenner array

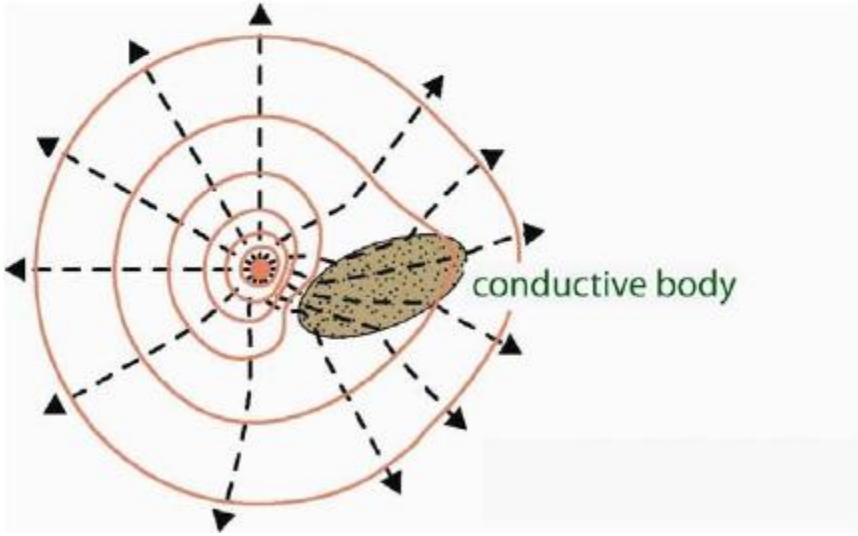
$$\rho_a = \pi n(n+1)a \frac{\Delta V}{I}$$

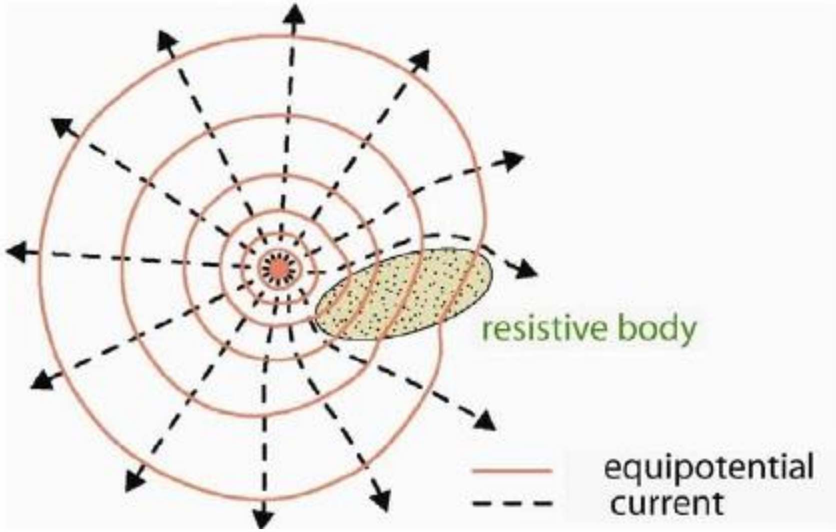
Schlumberger array

$$\rho_a = \pi n(n+1)(n+2)a \frac{\Delta V}{I}$$

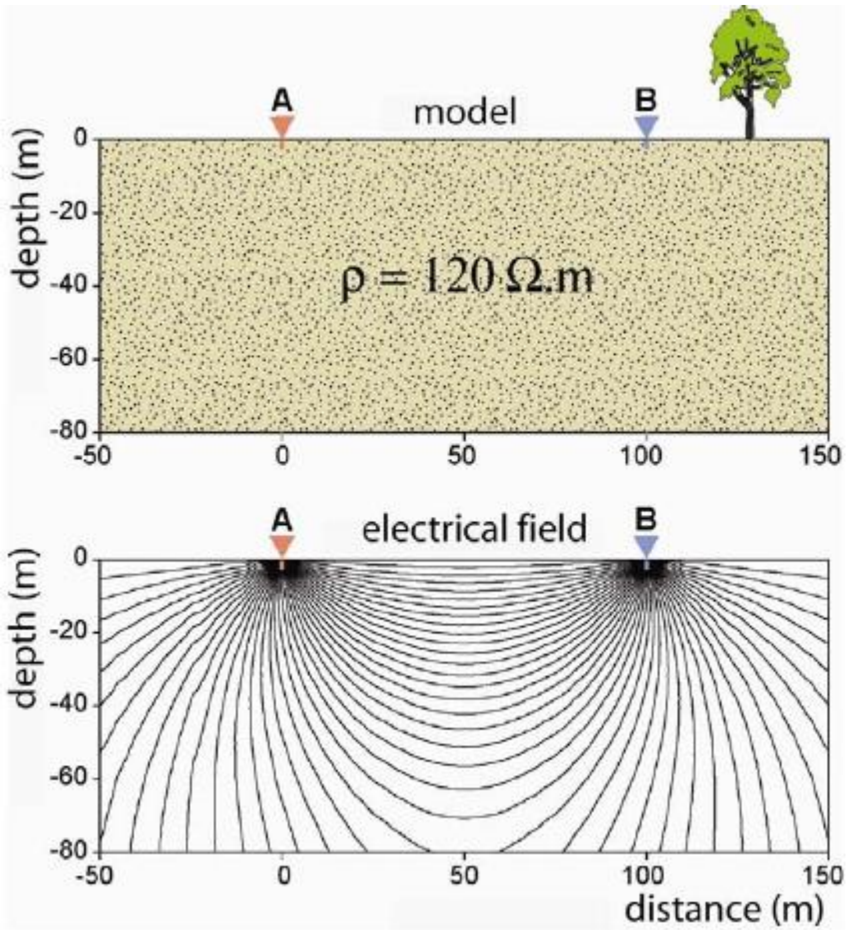
dipole-dipole array

Heterogeneous Earth

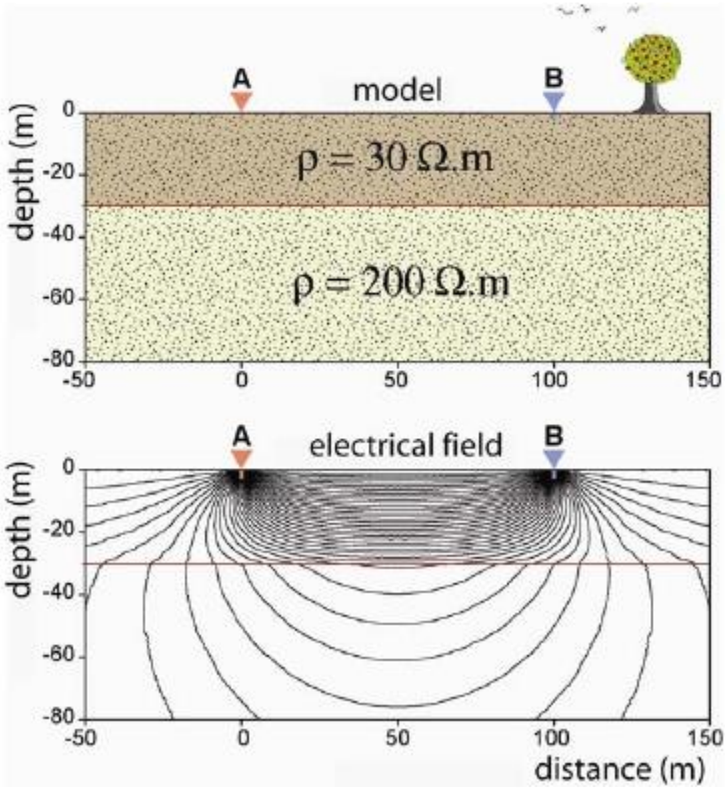


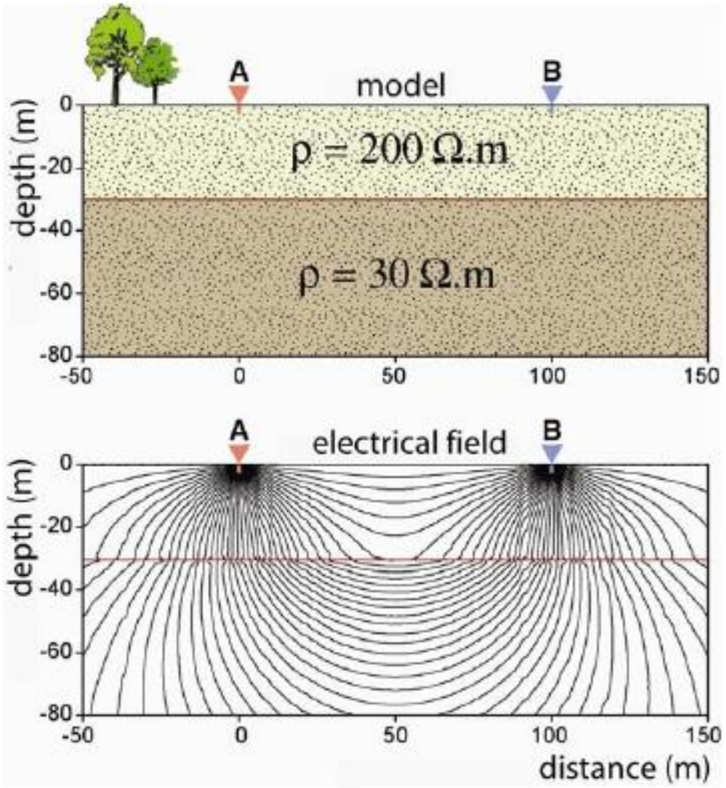


Current distribution



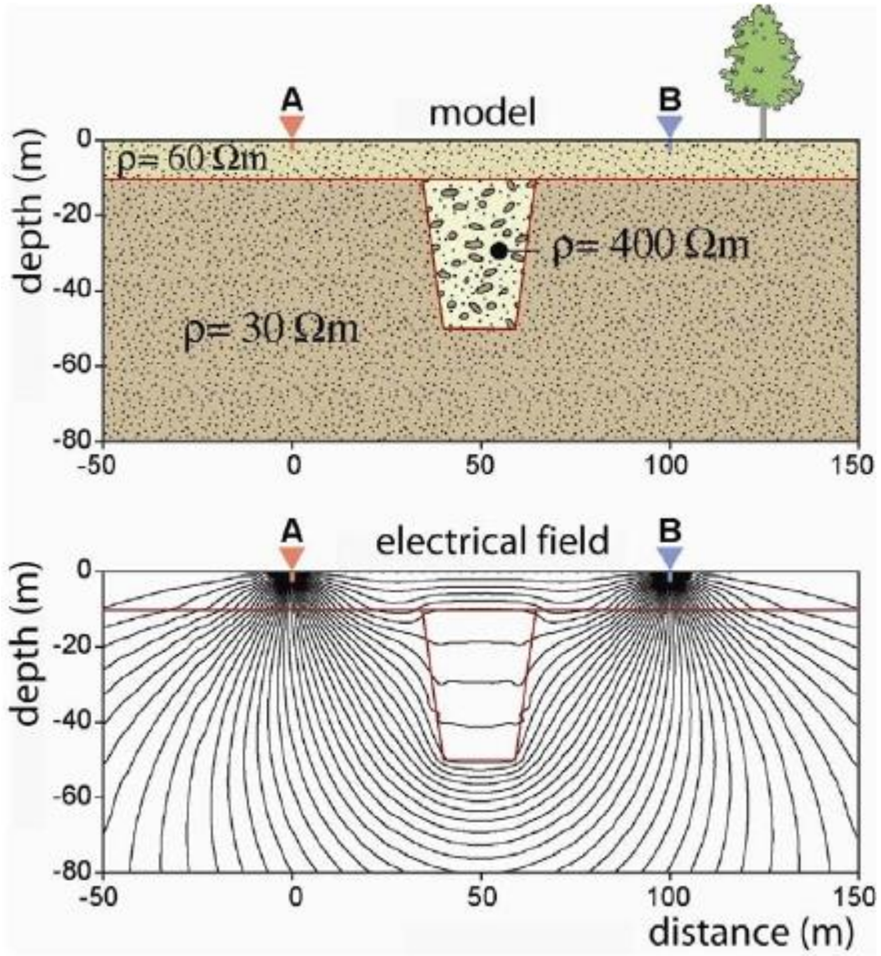
Current distribution



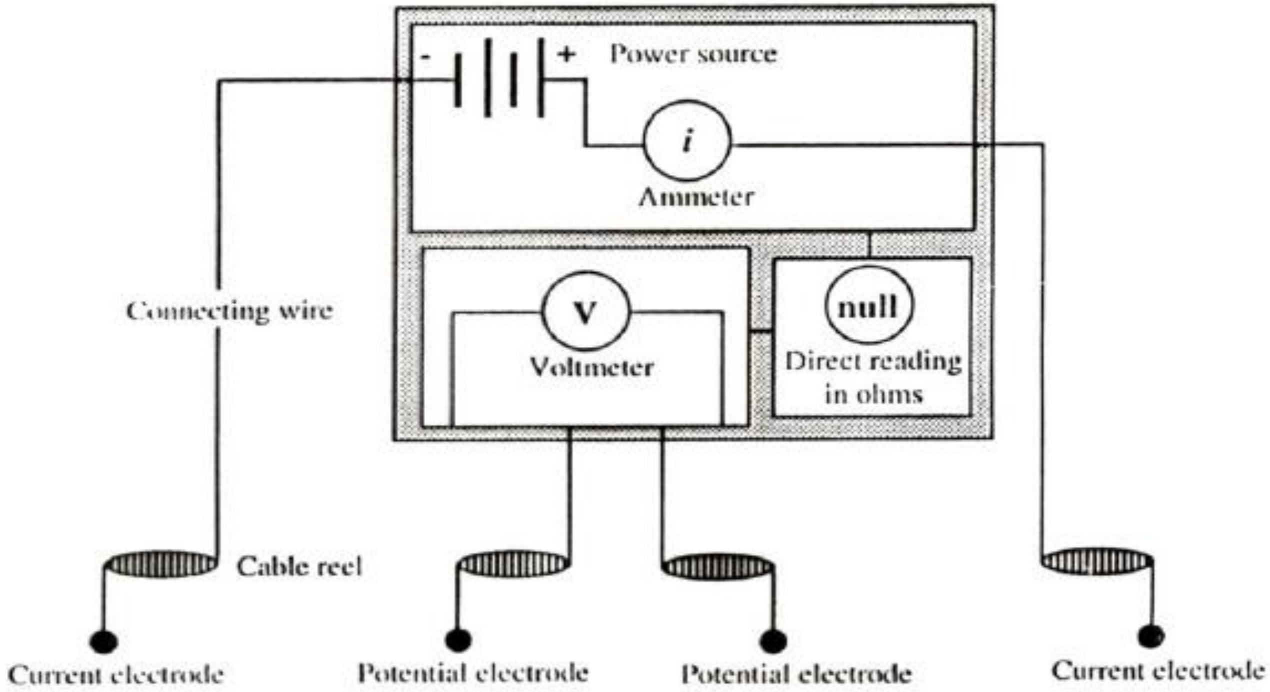


This has an influence on the depth of investigation!

Current distribution



Resistivity survey equipment



Device

- Current source: batteries in series
- Voltmeter and ammeter (resistivimeter)
- Electrodes: metallic stakes

  current electrodes: stainless steel

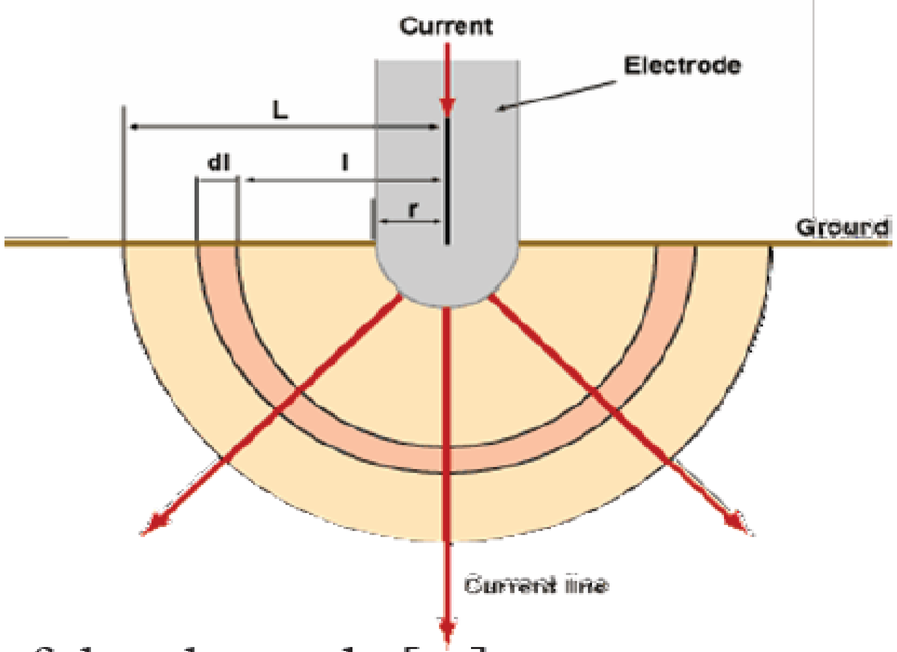
  potential electrodes: stainless steel or nonpolarizing electrodes

Polarization occurs at the contact electrode/ground: this creates an additional potential difference.

Contact resistance

$$dR = \rho \frac{dL}{s} = \rho \frac{dL}{2\pi L^2}$$

$$R = \frac{\rho}{2\pi}\left(\frac{1}{r} - \frac{1}{L}\right)$$



L = distance to the centre of the electrode [m]
r = radius of the electrode [m]
R = resistance [ohm]
ρ = resistivity of the surrounding ground [ohm.m]

To decrease the contact resistance…

- Add electrodes in parallel
- Increase the current intensity
- Increase the diameter of the current electrodes
- Put electrode deeper into the ground
- Add water (with salt) near the electrodes

About 90% of the contact resistance contribution comes from a portion of the ground around the electrode that is equal to 10 times the diameter of the electrode

3. Field procedures and interpretation

Field Procedures

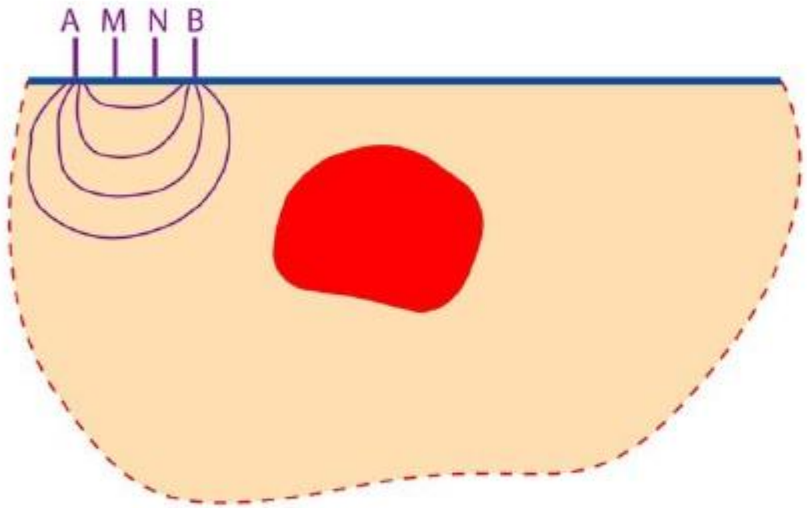
- Resistivity mapping, constant separation traversing (CST):

  used to determine lateral variations of resistivity. The current and potential electrodes are maintained at a fixed separation and moved along profiles
- Vertical electrical sounding (VES):

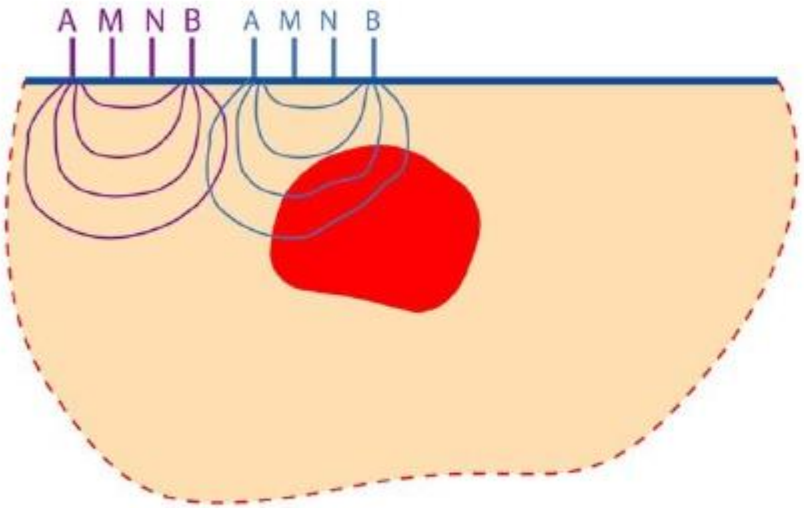
  used in the study of near-horizontal interfaces. The electrode spread is progressively expanded about a central point
- Resistivity tomography (ERT):

  is a mix between CST and VES. Also named electrical imaging

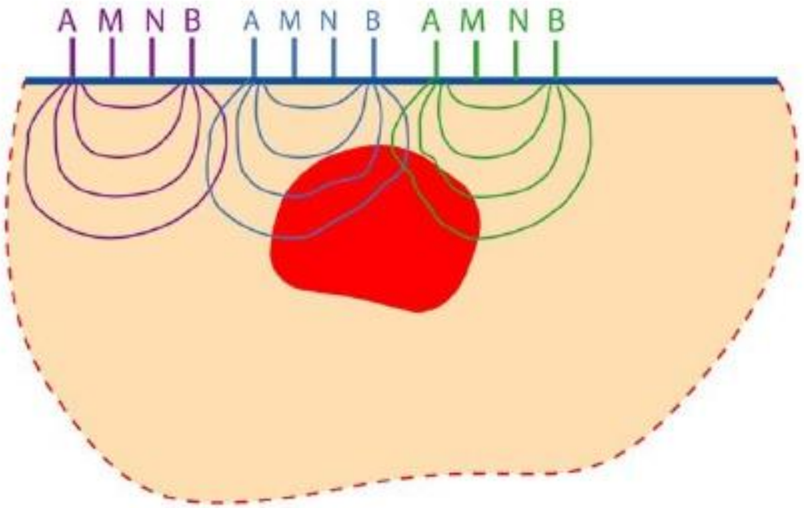
Constant separation traversing (CST)

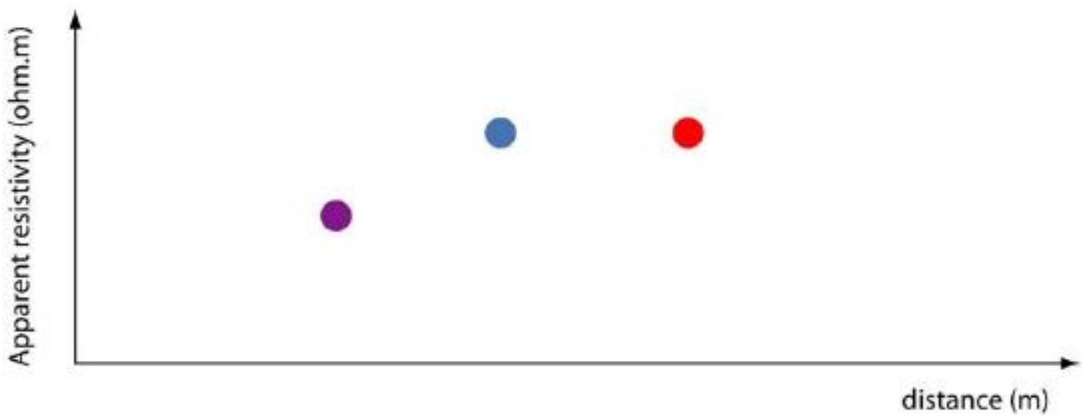


Constant separation traversing (CST)

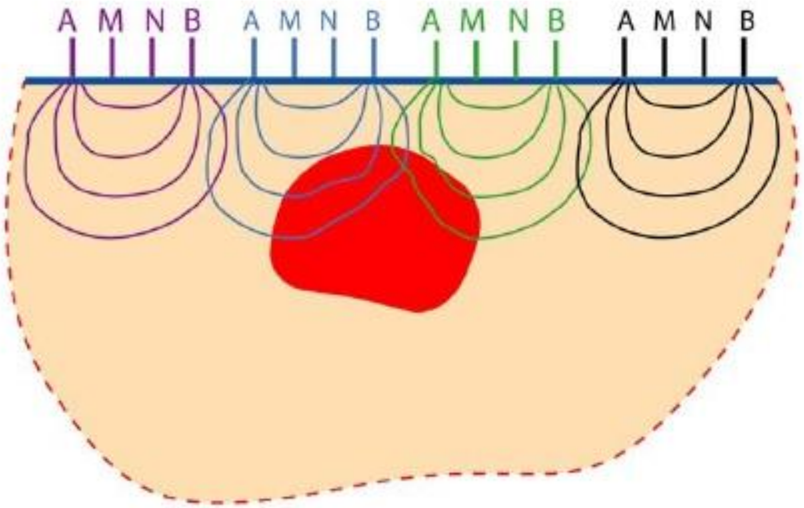


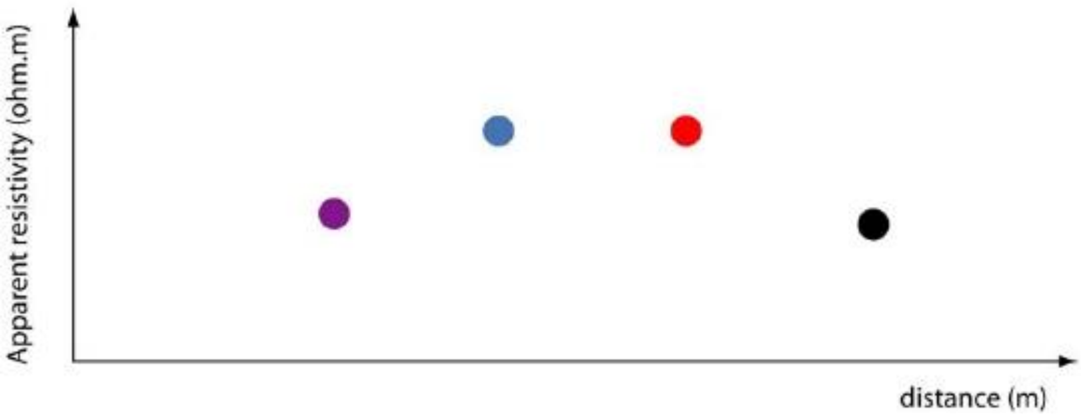
Constant separation traversing (CST)



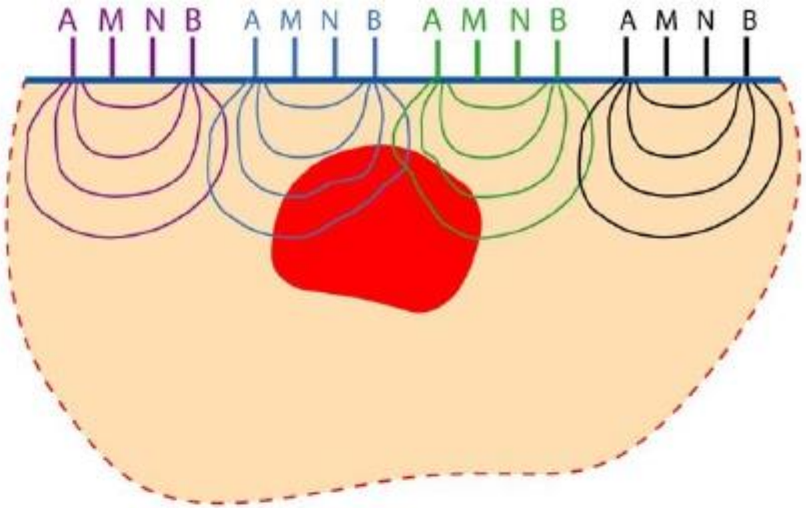


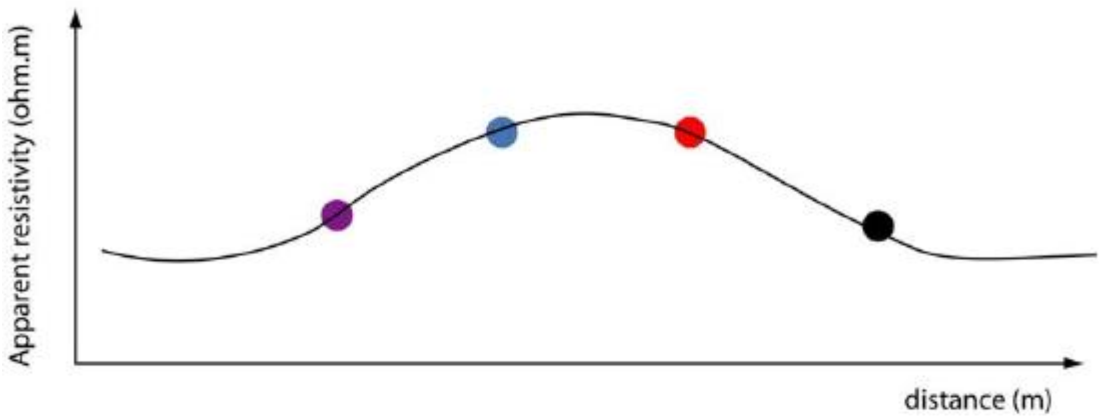
Constant separation traversing (CST)



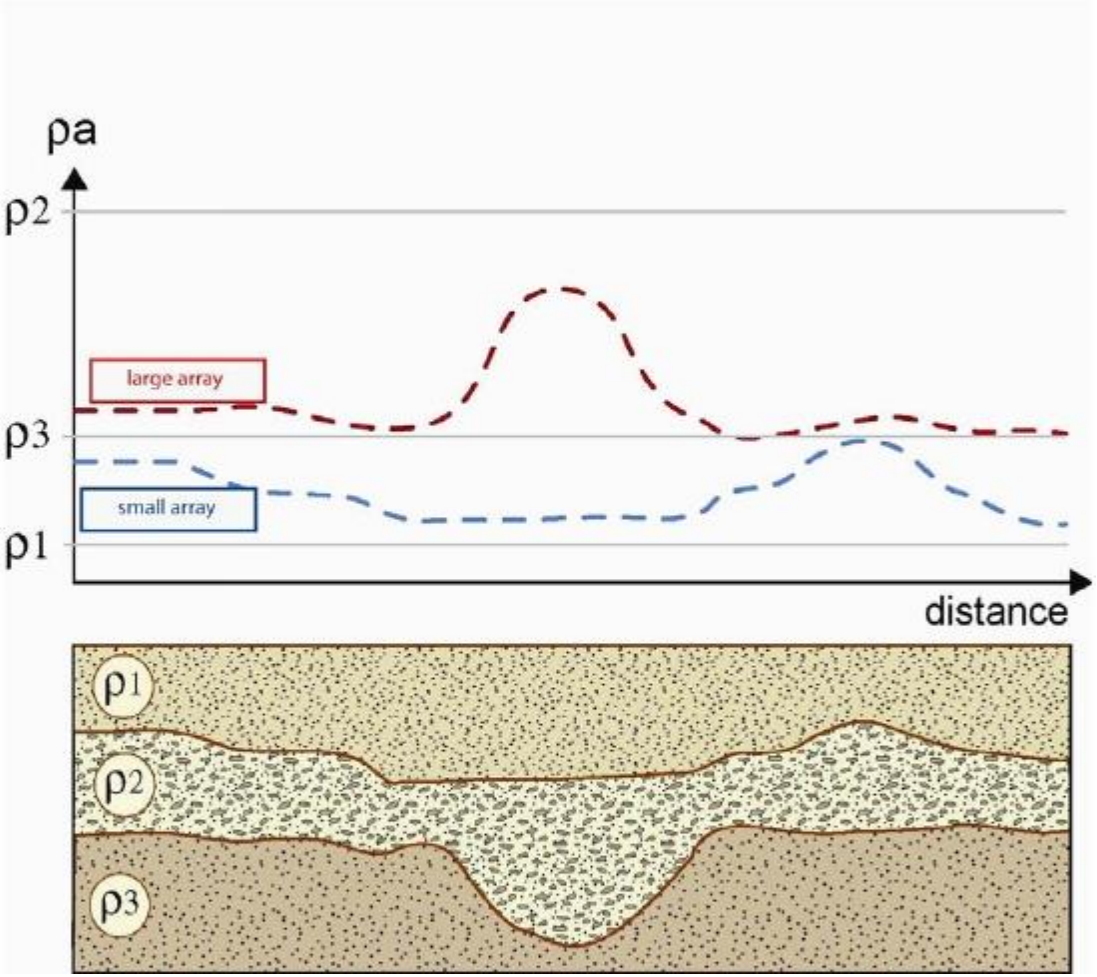


Constant separation traversing (CST)

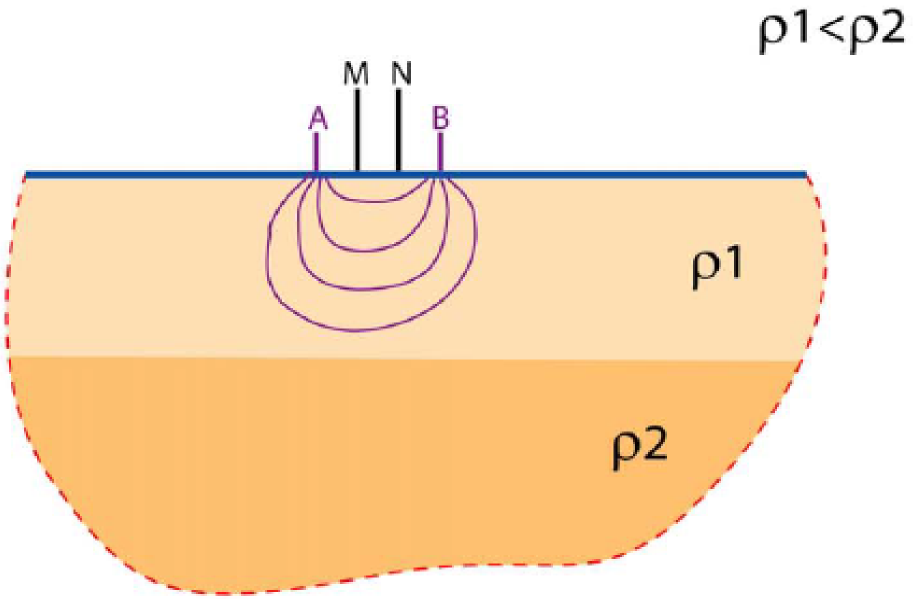


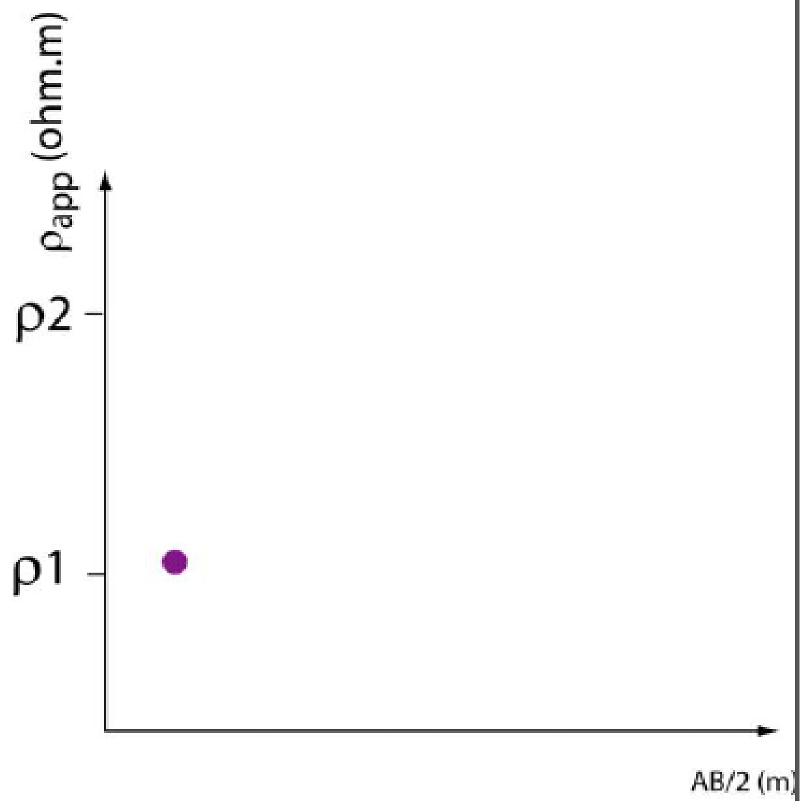


Interpretation of CST

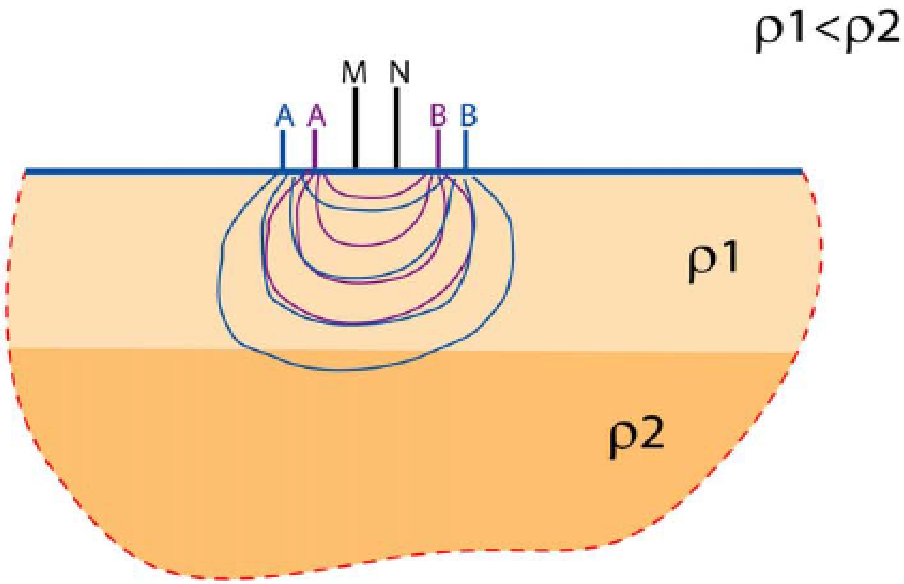


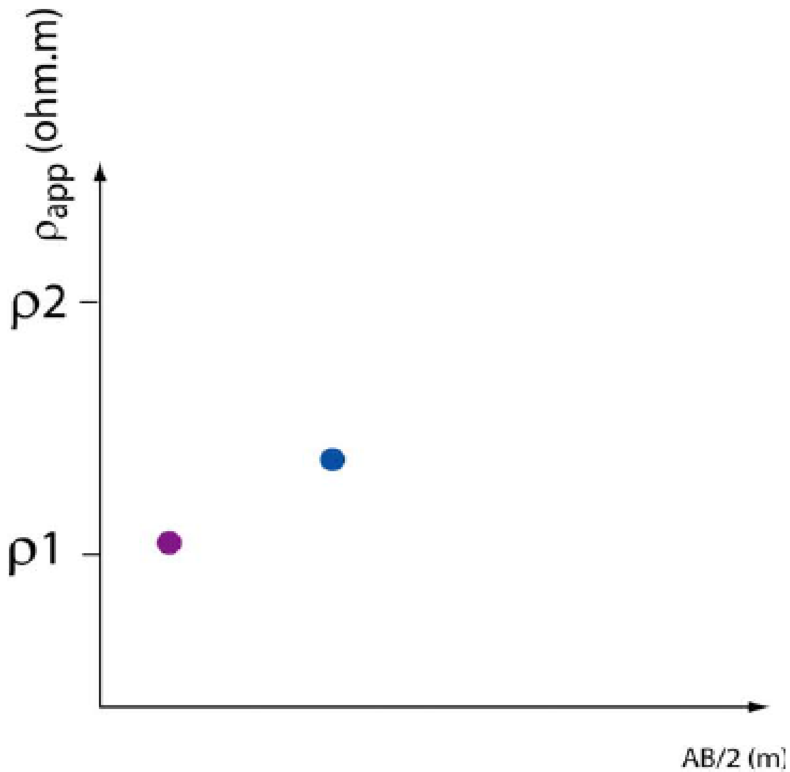
Vertical electrical sounding (VES)



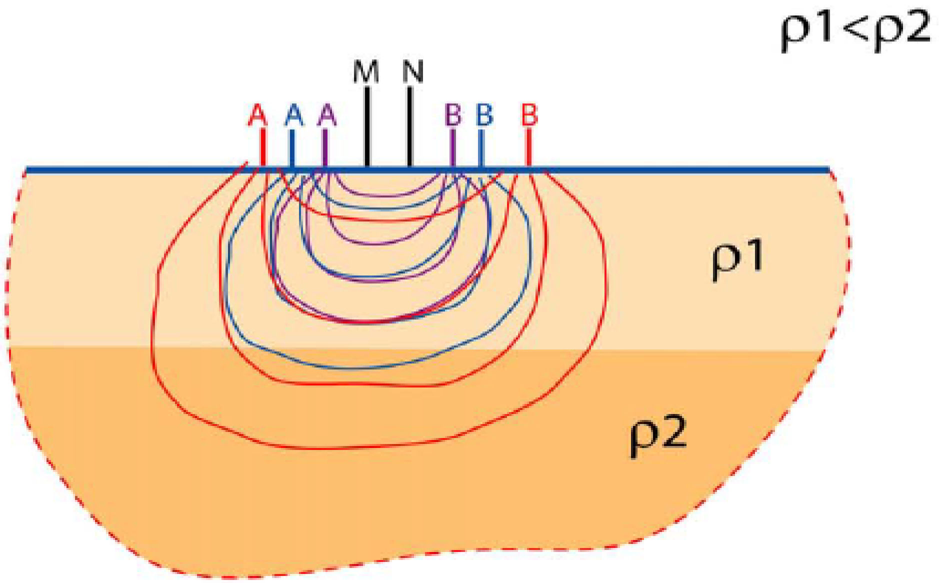


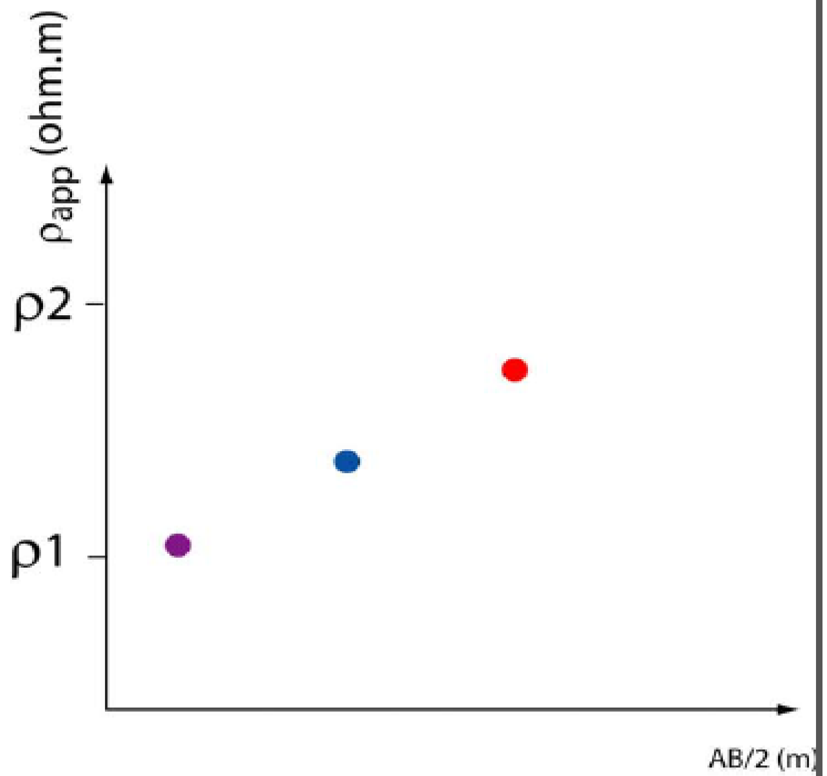
Vertical electrical sounding (VES)





Vertical electrical sounding (VES)





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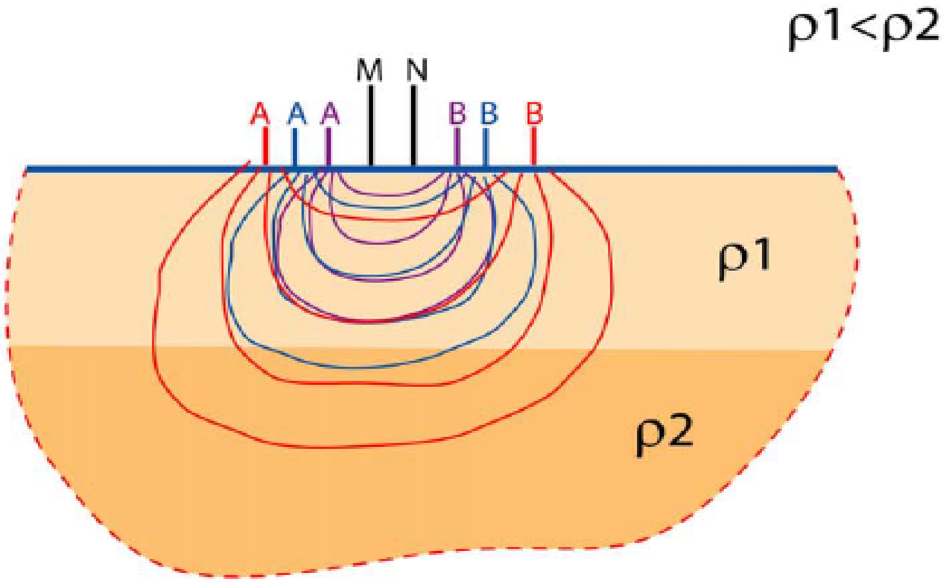
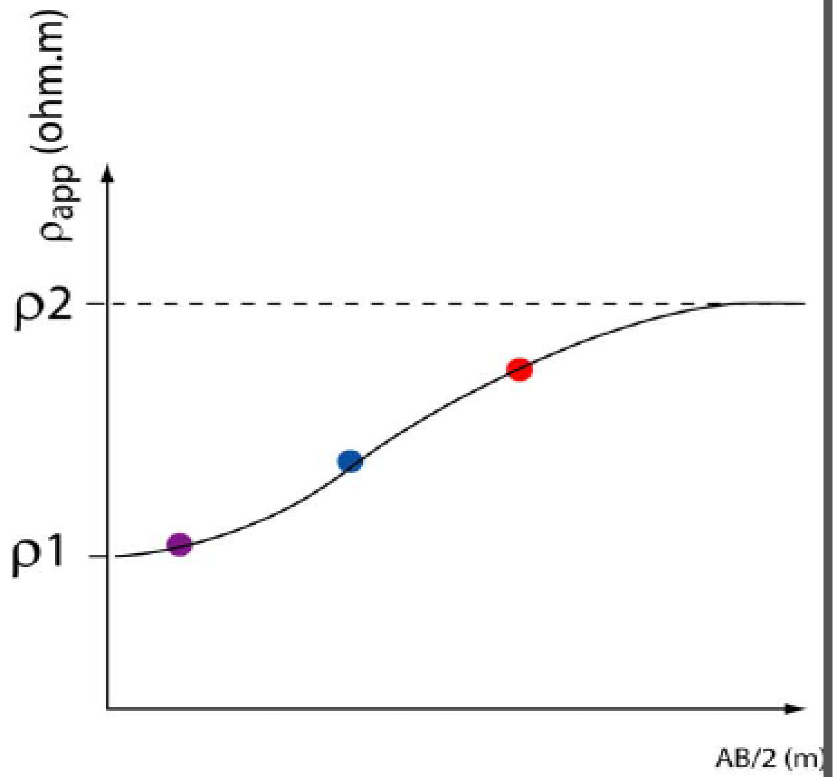




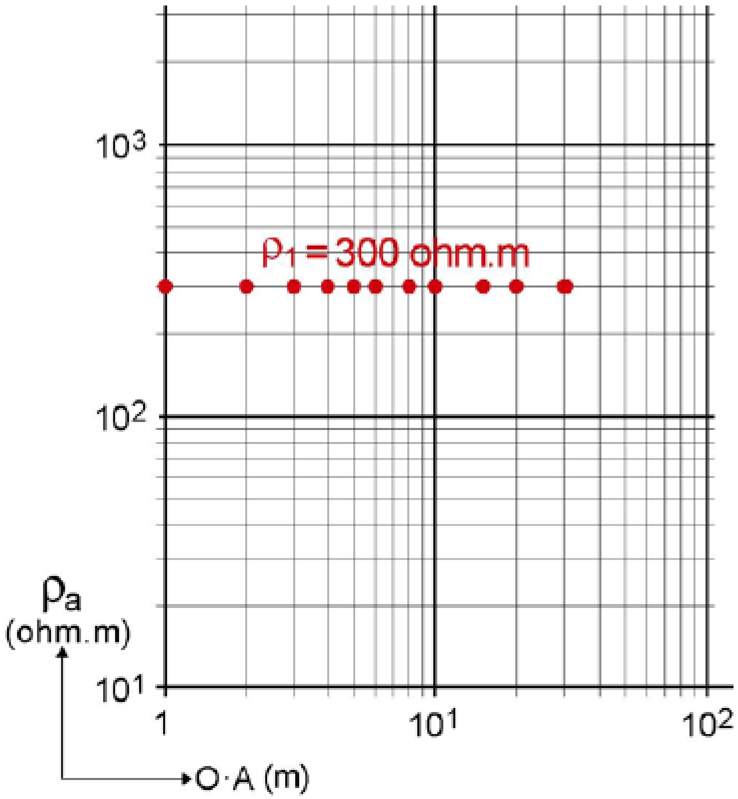
ETUDE : ______________________ SONDAGE N° : ______________________

DATE : ______________________ COORDONNEES : ______________________

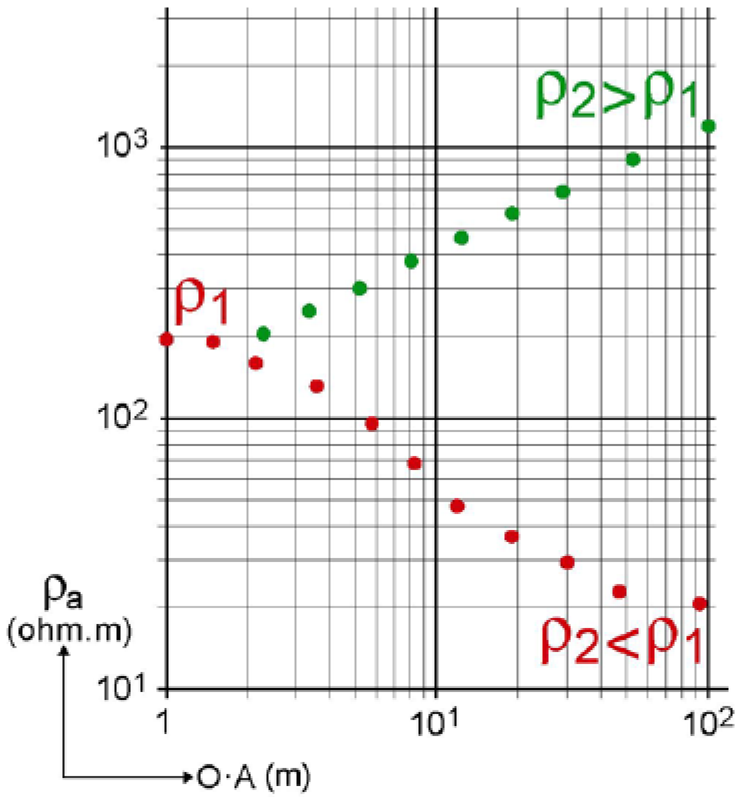
OPERATEUR : ______________________ COTE : ______________________

A — M O N — B $k = \frac{AM \cdot AN}{MN} \cdot 3,14$ $\rho a = k \frac{\Delta V}{I}$

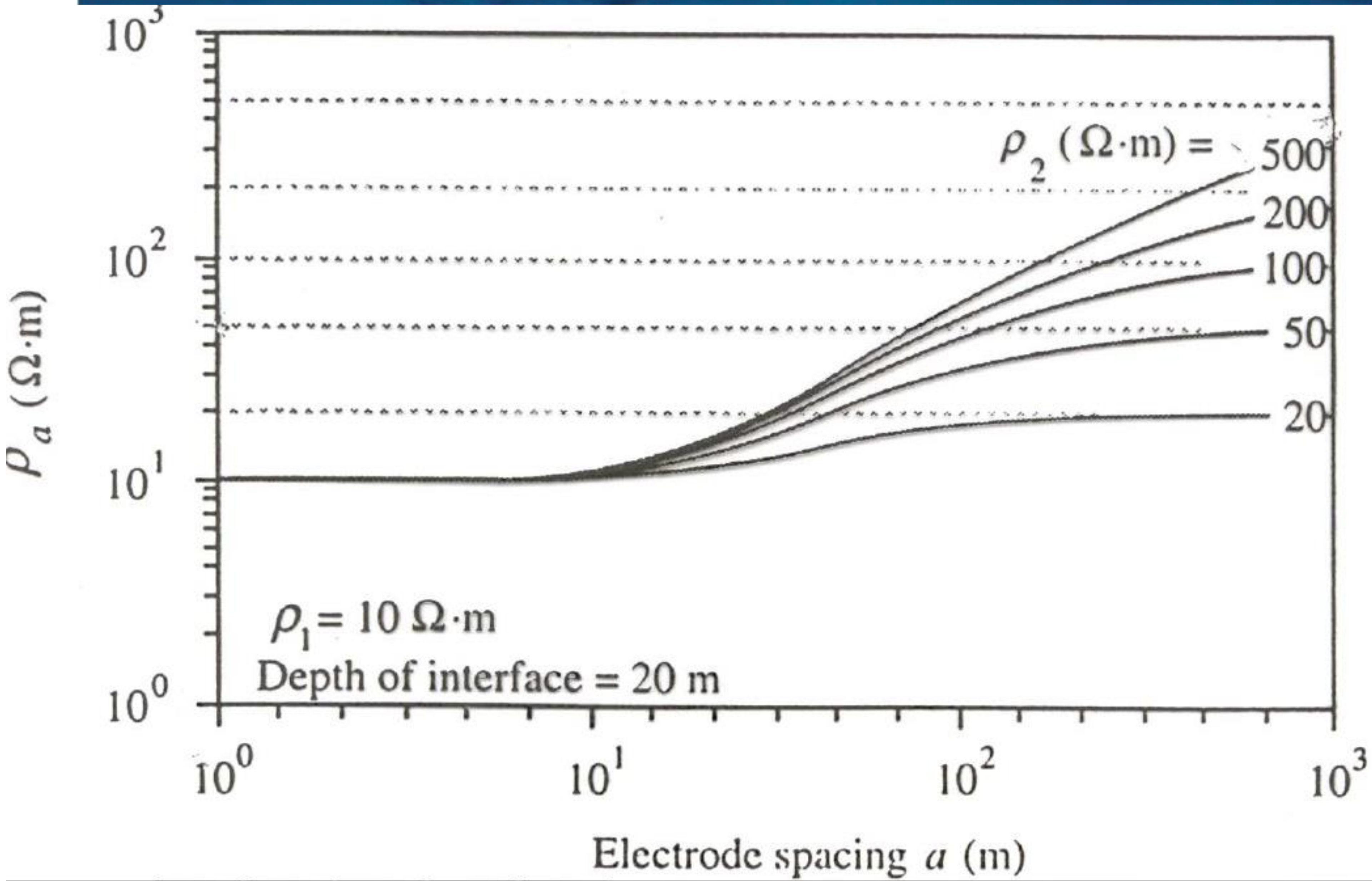
MARQUES	O-A en m	k pour M — N 1 m	M — N 10 m	M — N 60 m	M — N 200m	ΔV en millivolts	I en milliampères	ρa en ohm-m
1	1 m	2.35						
2	2	11.8						
3	3	27.5						
1	4	49.5						
2	5	77.7						
3	6	112						
1	8	200						
2	10	313						
3	15	705	62.8					
1	20	1250	118					
2	25	1960	188					
3	30	2820	275					
1	35	3850	377					
2	40	5020	495					
3	50	7850	780					
1	60	11300	1120					
2	70	15400	1530					
3	80	20100	2000	288				
1	100	31400	3130	475				
2	125		4900	770				
3	150		7050	1130				
1	175		9600	1560				
2	200		12500	2040				
3	250		19600	3230				
1	300		28200	4860				
2	350			6360	1768			
3	400			8300	2360			
1	450			10500	3000			
2	500 m			13000	3760			



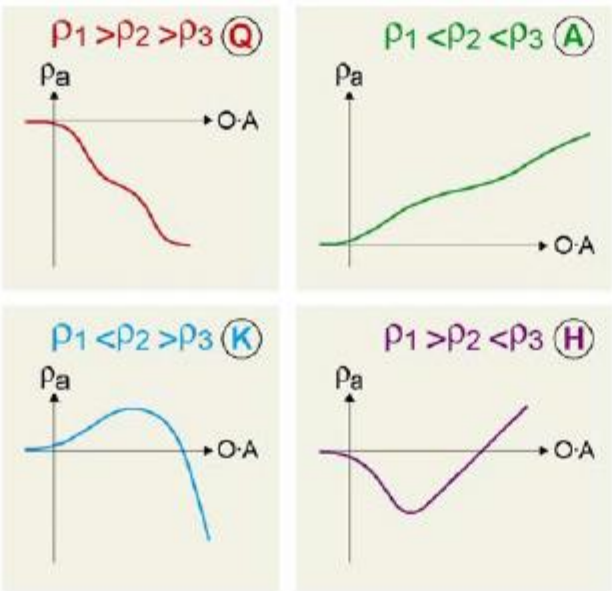
10^3
$\rho_1 = 300$ ohm.m
10^2
ρ_a
(ohm.m)
10^1
1
10^1
10^2
O·A (m)

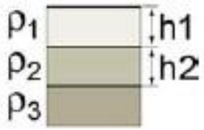


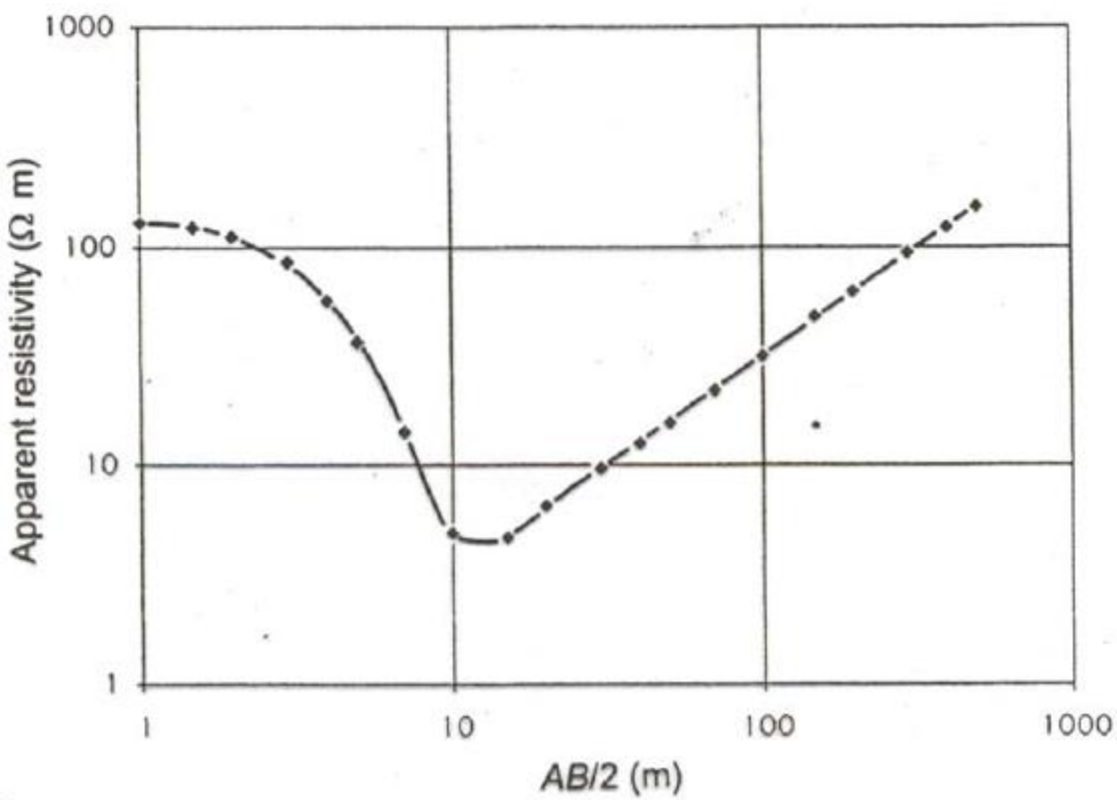
$\rho_2 > \rho_1$
10^3
ρ_1
10^2
ρ_a
(ohm.m)
$\rho_2 < \rho_1$
10^1
1
10^1
10^2
O·A (m)

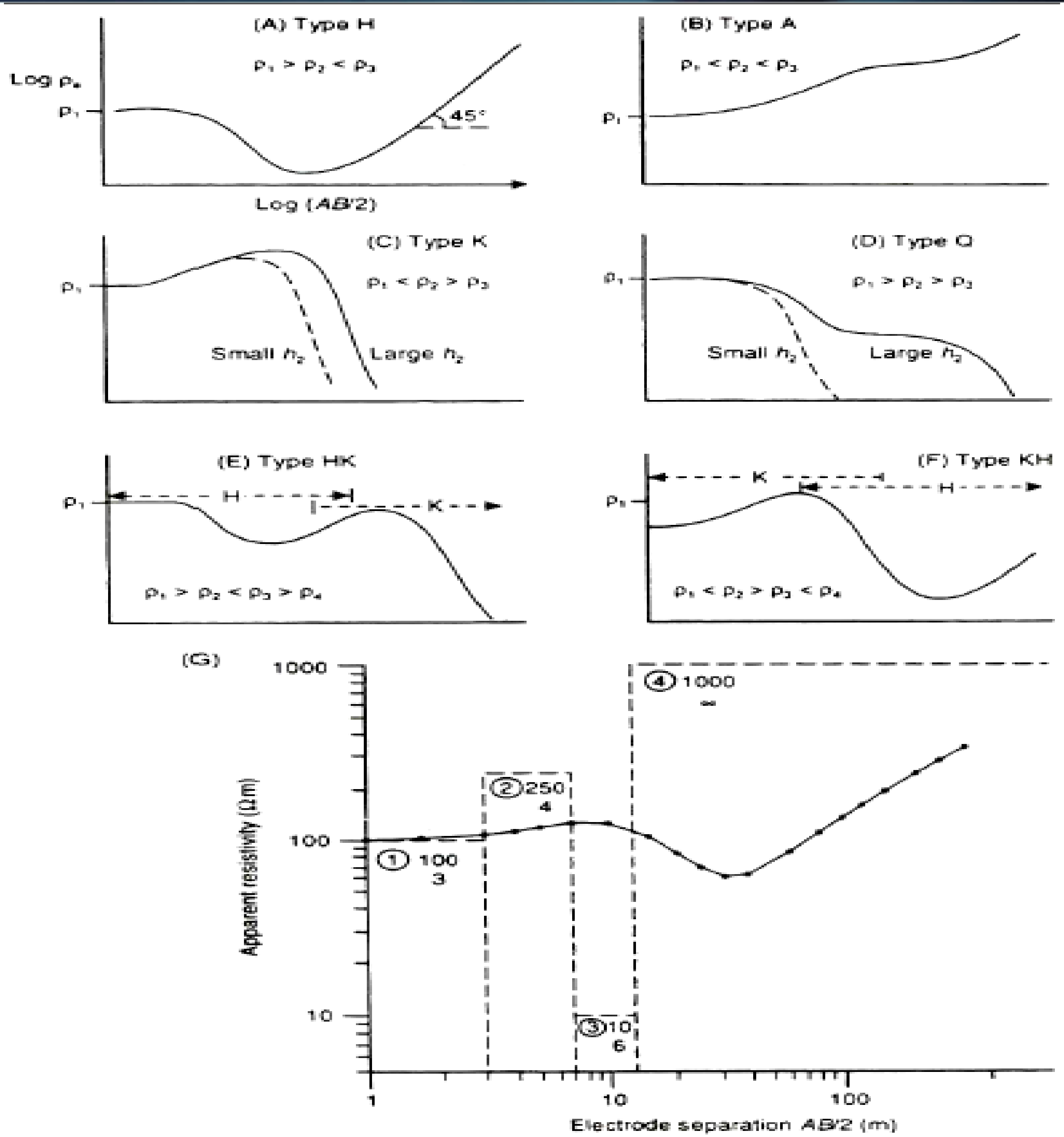

10^3
10^2
10^1
10^0
ρ_a (Ω·m)
ρ_2 (Ω·m) =
500
200
100
50
20
ρ_1 = 10 Ω·m
Depth of interface = 20 m
10^0
10^1
10^2
10^3
Electrode spacing a (m)

Three layers and more…

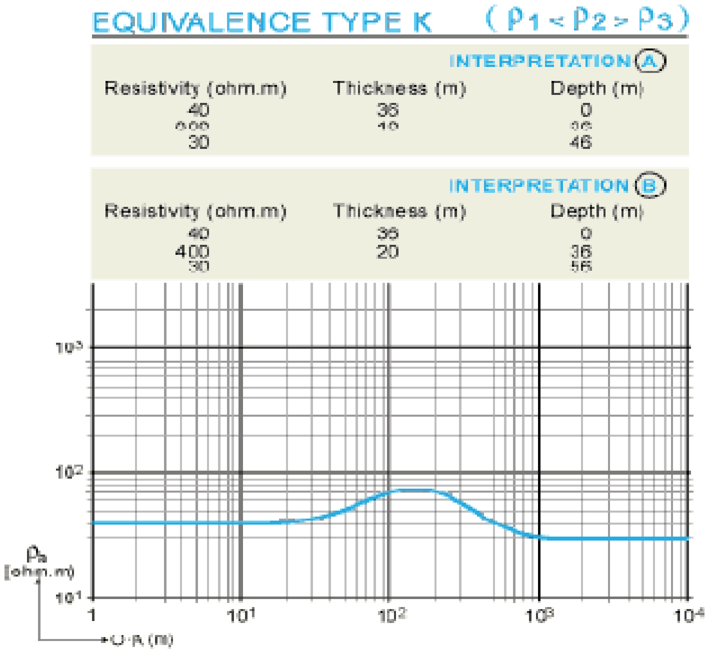


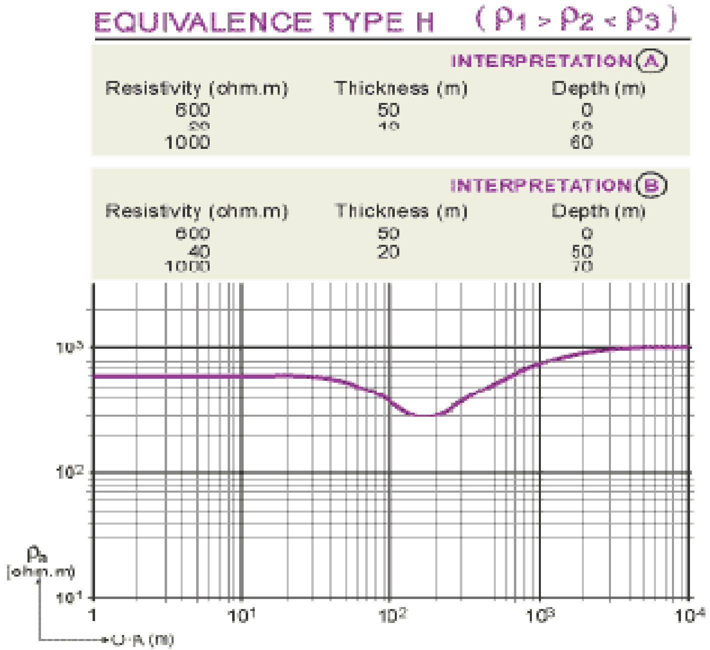





(A) Type H
ρ1 > ρ2 < ρ3
Log ρa
ρ1
45°
Log (AB/2)
(B) Type A
ρ1 < ρ2 < ρ3
ρ1
(C) Type K
ρ1 < ρ2 > ρ3
ρ1
Small h2
Large h2
(D) Type Q
ρ1 > ρ2 > ρ3
ρ1
Small h2
Large h2
(E) Type HK
ρ1
H
K
ρ1 > ρ2 < ρ3 > ρ4
(F) Type KH
ρ1
K
H
ρ1 < ρ2 > ρ3 < ρ4
(G)
1000
100
10
Apparent resistivity (Ωm)
1 100 3
2 250 4
3 10 6
4 1000 ∞
1
10
100
Electrode separation AB/2 (m)

Equivalence





$$R = h\rho$$

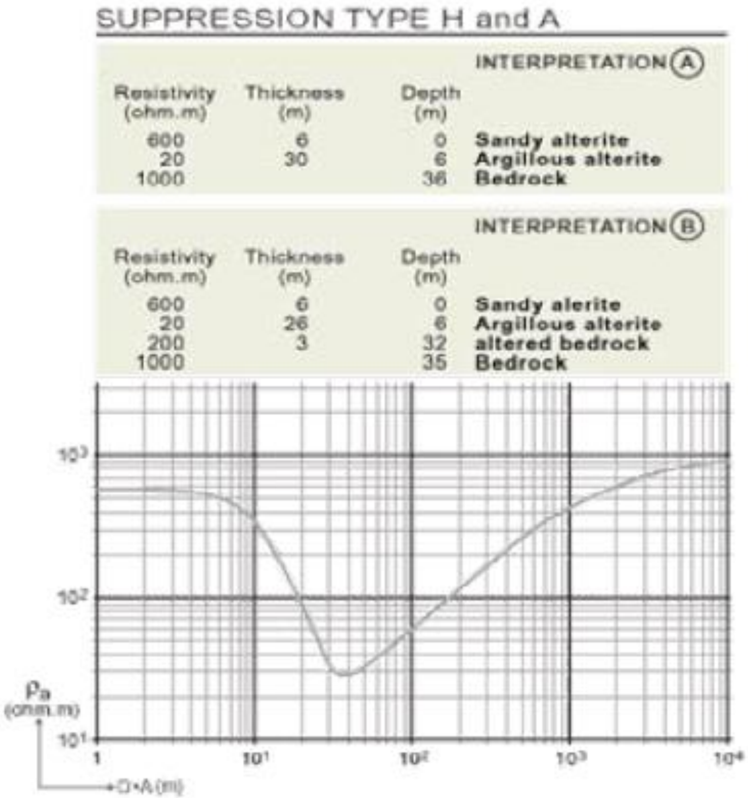
$$R = \frac{h}{\rho}$$

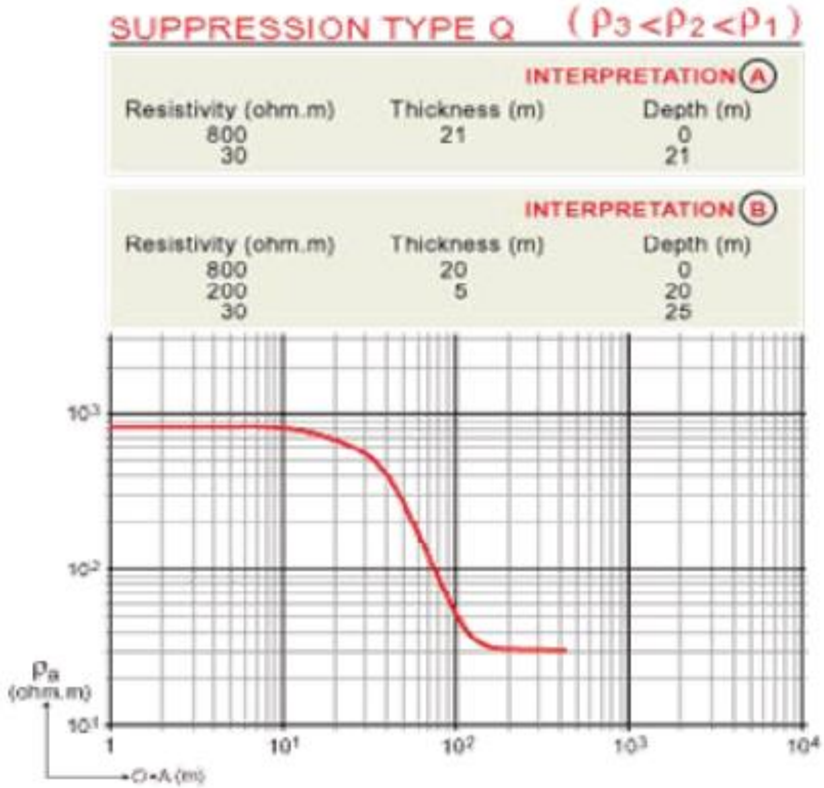
Parametric sounding

A parametric sounding is a VES carried out on an outcrop or near a borehole to precisely determine the resistivity of a geological formation.

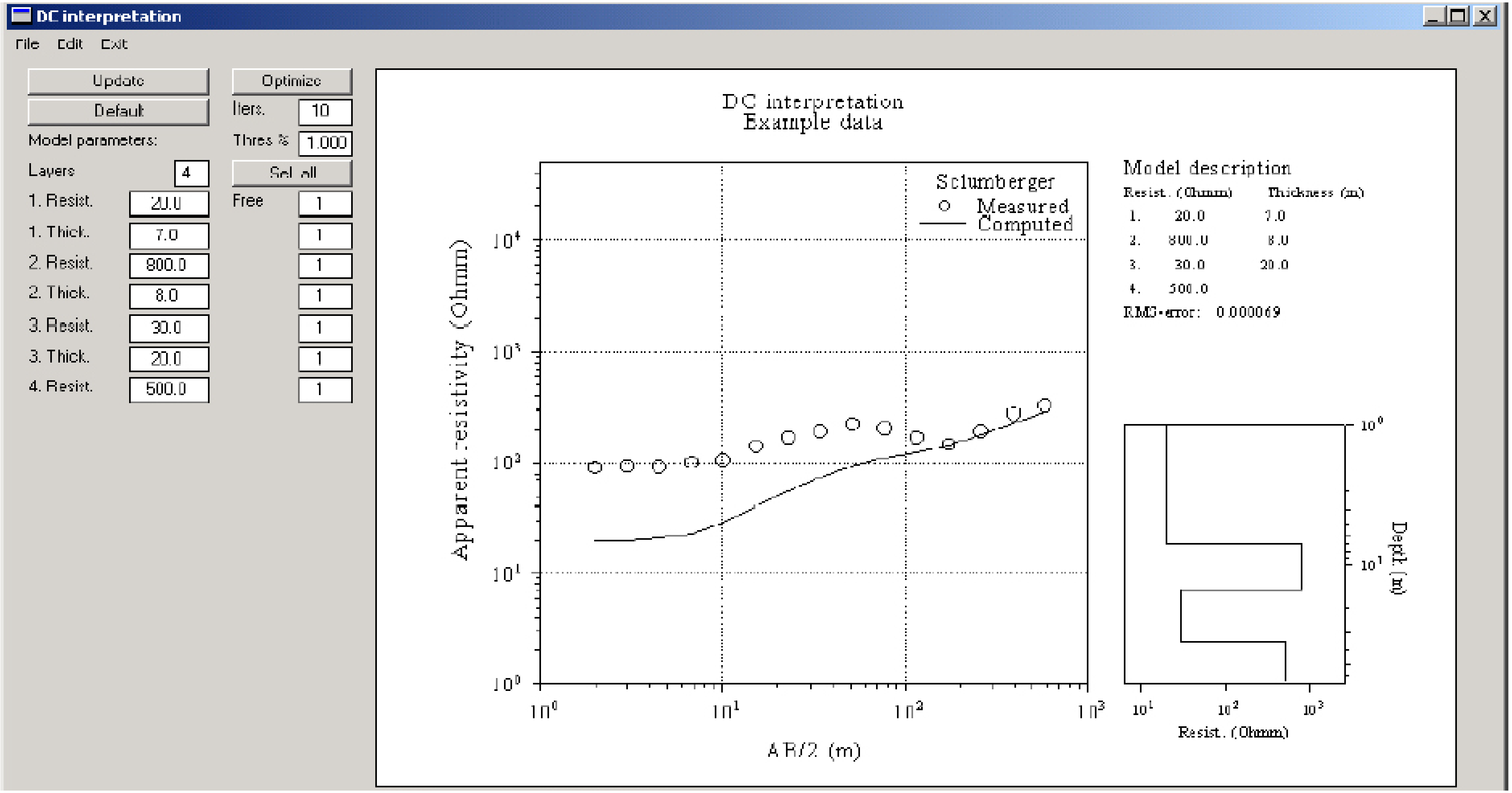
A precise determination of resistivity reduce the problem of equivalence

Suppression

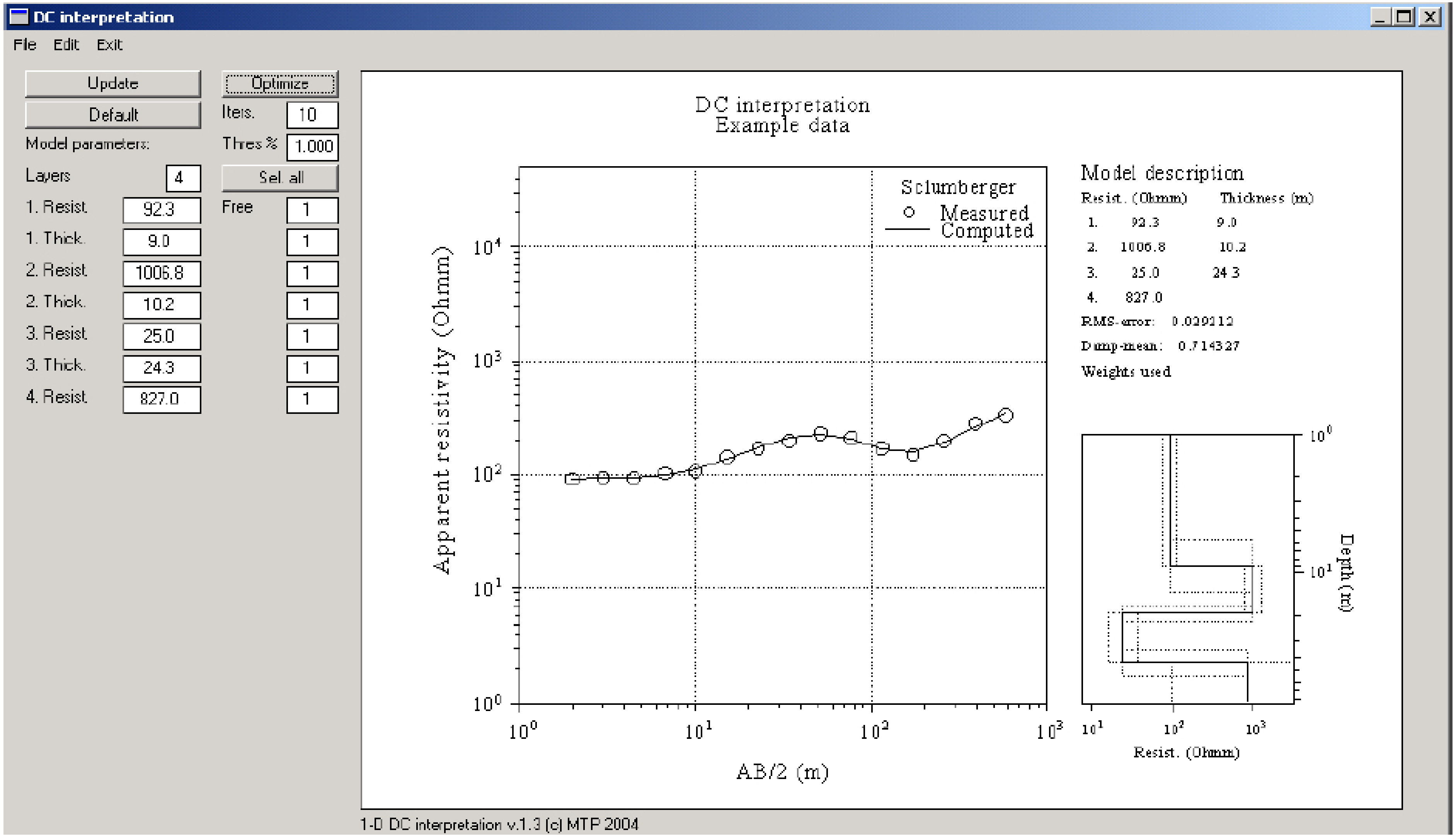




Interpretation of VES



Interpretation of VES



Interpretation of VES

Study : Isérables

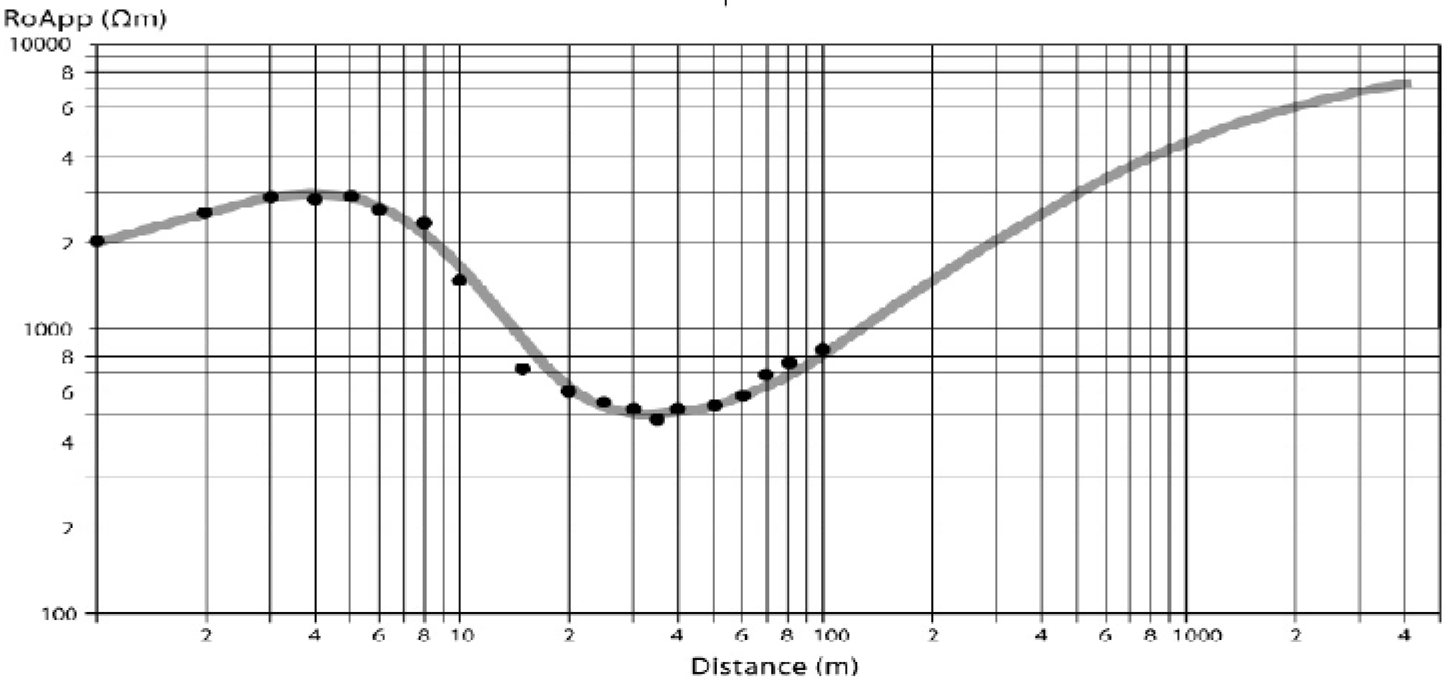
VES N° : 23

Operator :

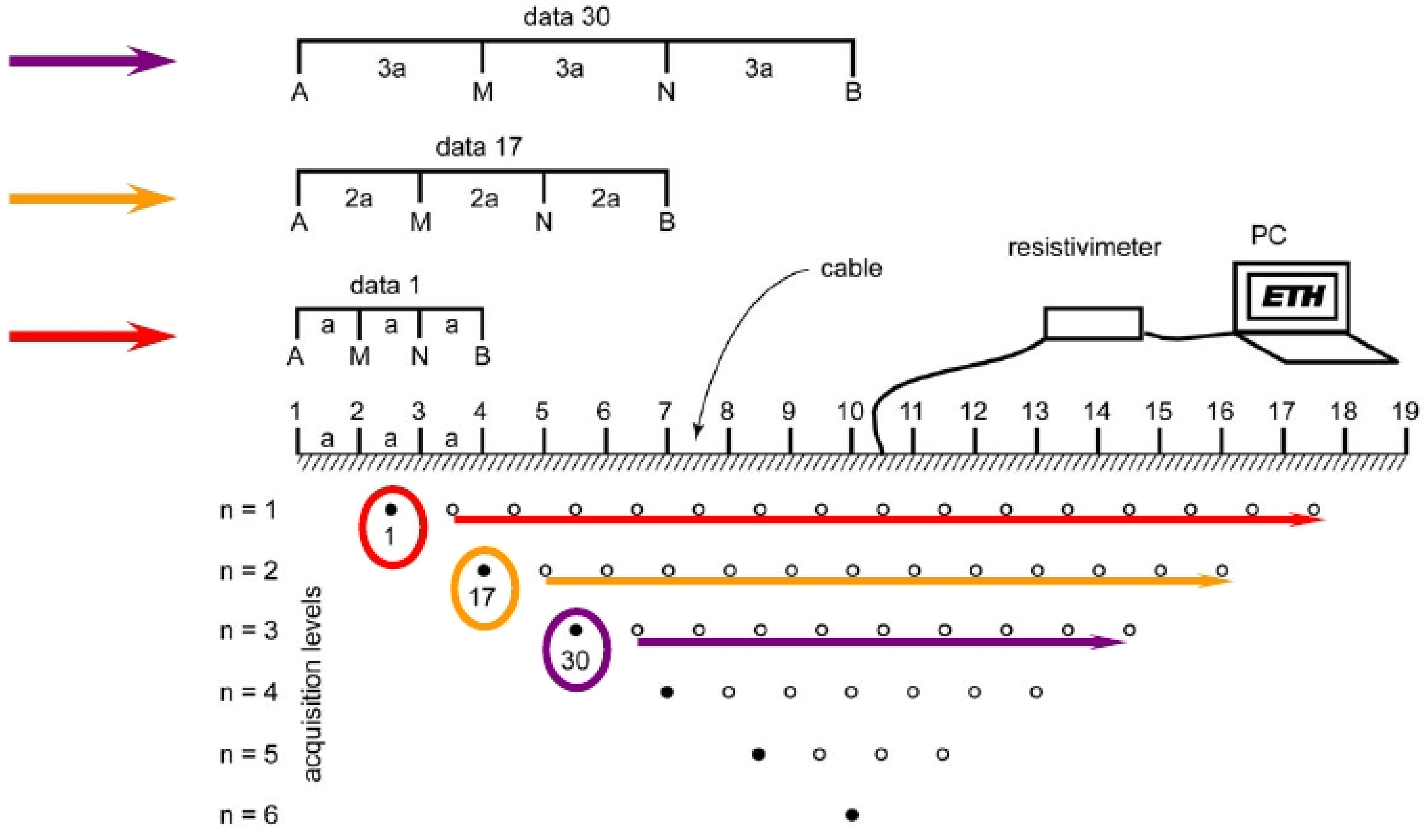
Date : 21.05.2003

Coord X : 110300
y : 588320
z : 2100
Azimute : 0

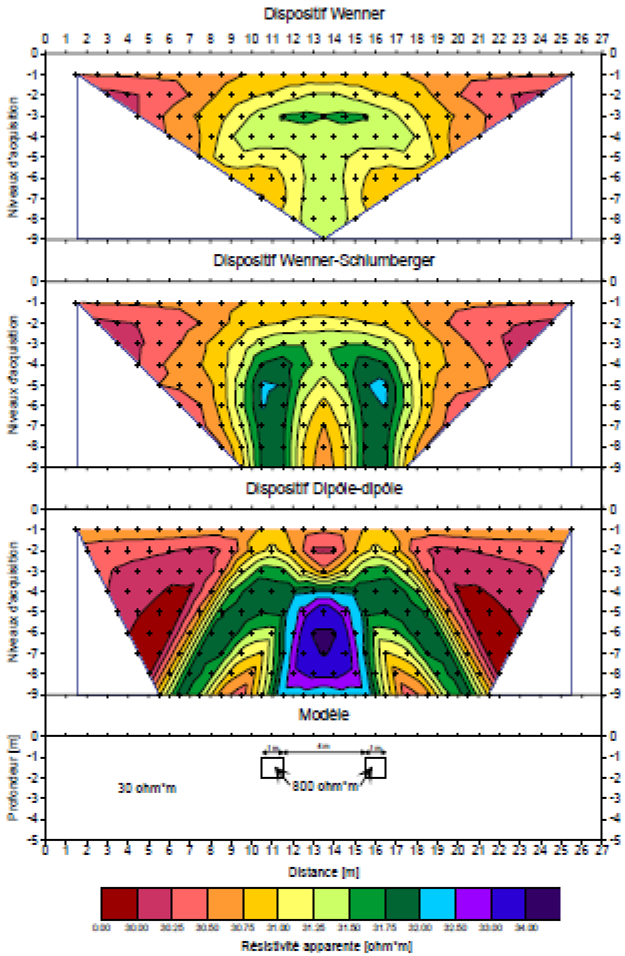
Unit N°	Resistivity (Ω·m)	Thickness (m)	Depth (m)
1	1800	0.9	
2	5300	2.3	0.9
3	440	50	3.2
4	8000		53.2



2D resistivity tomography



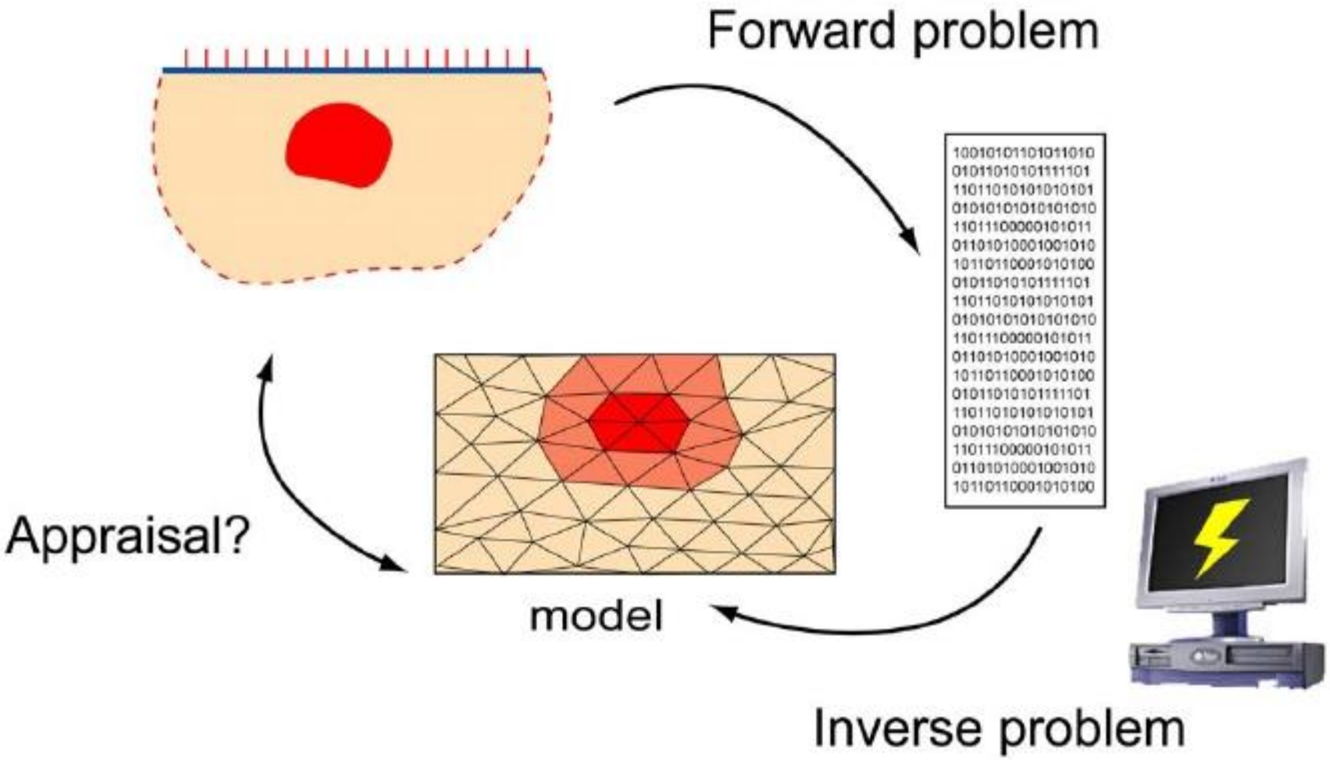
2D ρ_{app} pseudosection



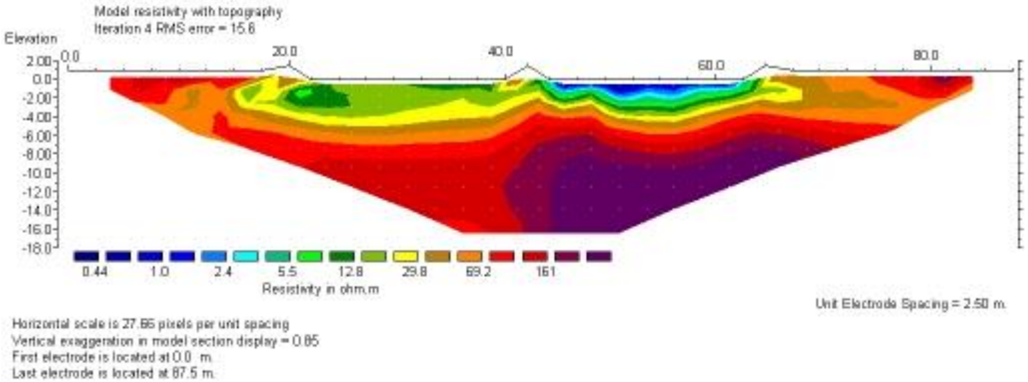
The apparent resistivity pseudosection is different depending on the array used!

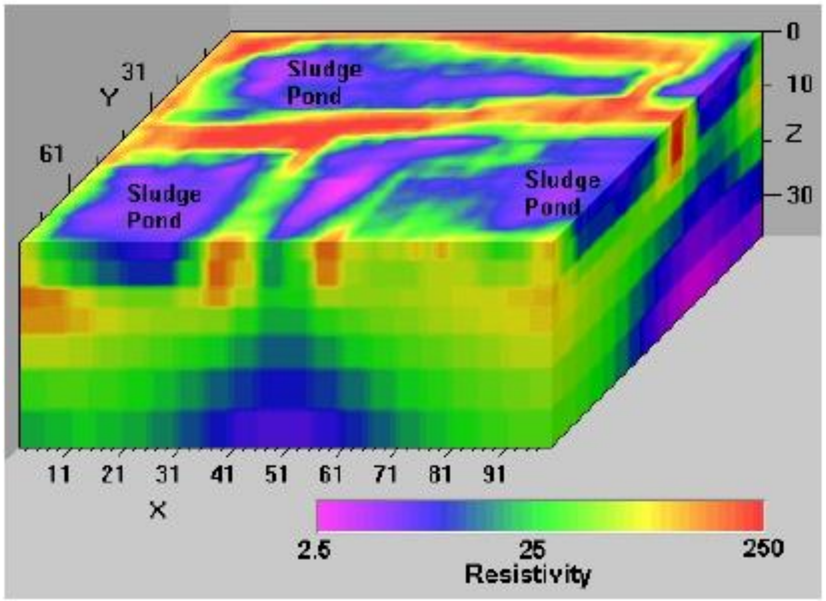
Need for processing the data, i.e. inversion…

Forward / inverse problems

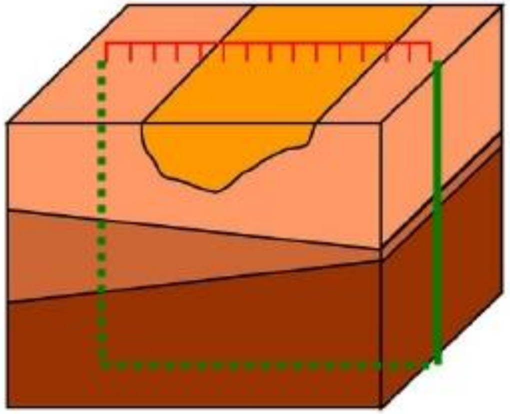


2D and 3D models

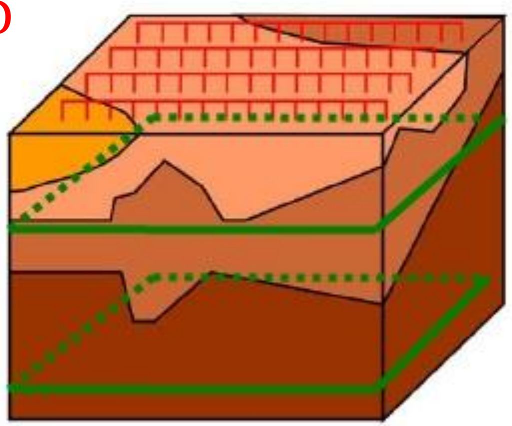




2D



3D



Advantages

- Resistivity surveys are simple and robust
- Non expensive
- Allows for a rapid qualitative mapping of the underground
- Can be used for a 2D or 3D investigation of the subsurface
- Resistivity contrasts are often present in geological deposits

Drawbacks

- Sensitive to non-unicity in the modeling solutions
- Sensitivity to noise and metallic bodies such as pipes (urban area)
- Method mainly sensitive to the fluid in rocks. Good for hydrology but a problem in archeology and soil investigations: the signature of a feature can dramatically change with the seasons or weather conditions!

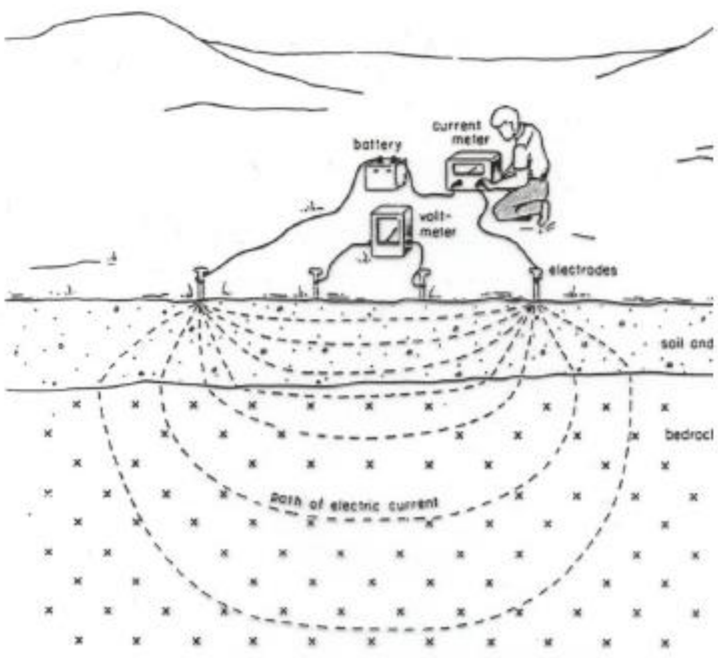
Induced Polarization Method

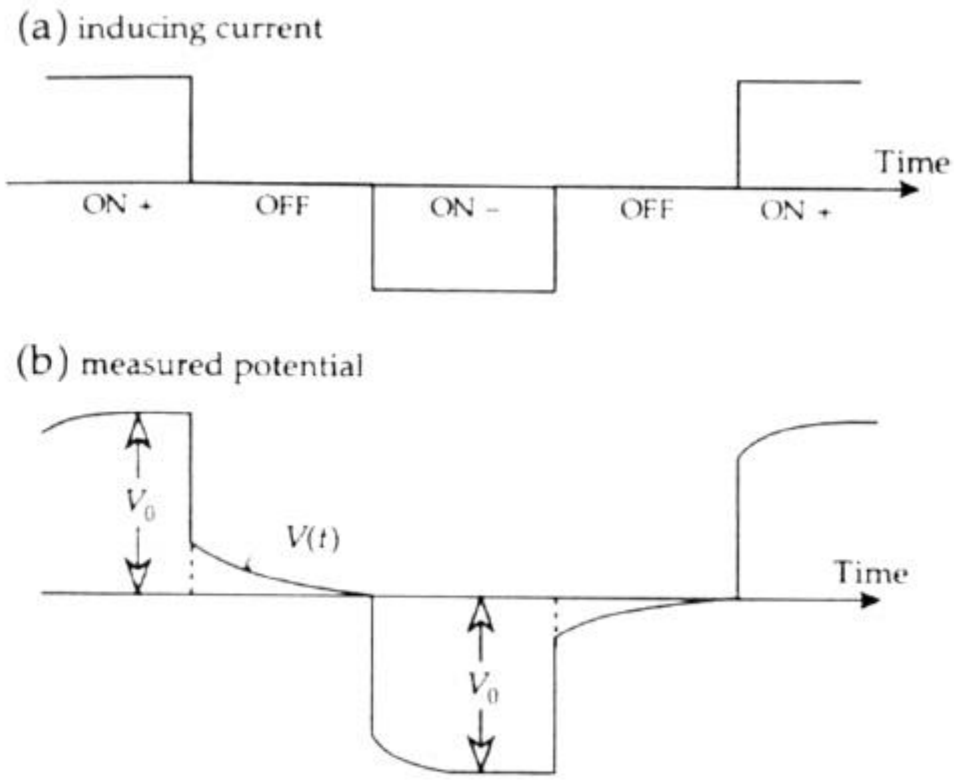
- **Induced polarization (IP)** is an electromagnetic method that uses electrodes with time-varying currents and voltages to map the variation of electrical **Permittivity** (dielectric constant) in the Earth at low frequencies.
- Induced polarization is observed when a steady current through two electrodes in the Earth is shut off: the voltage does not return to zero instantaneously, but rather decays slowly, indicating that charge has been stored in the rocks. This charge, which accumulates mainly at interfaces between **clay** minerals, is responsible for the **IP** effect.
- The IP effect can be measured in either the time **domain** by observing the rate of decay of voltage, or in the **frequency domain** by measuring **phase** shifts between sinusoidal currents and voltages.

- Induced Polarization (IP) effect is seen primarily with metallic sulfides, graphite, and clays. For this reason, IP surveys have been used extensively in mineral exploration.
- Recently, IP has been applied to hazardous waste landfill and groundwater investigations to identify clay zones.

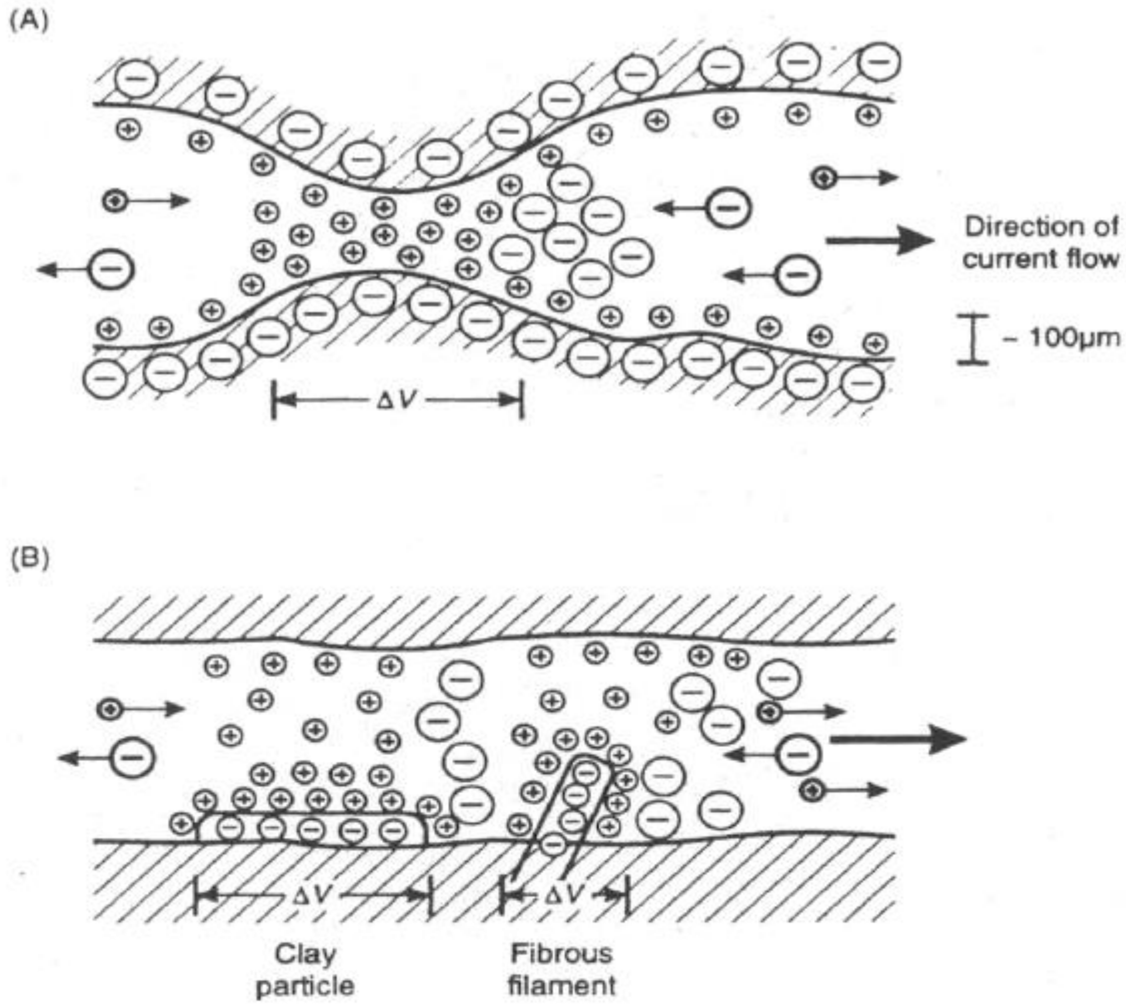
5. General principles of IP and measured parameters

Basic theory





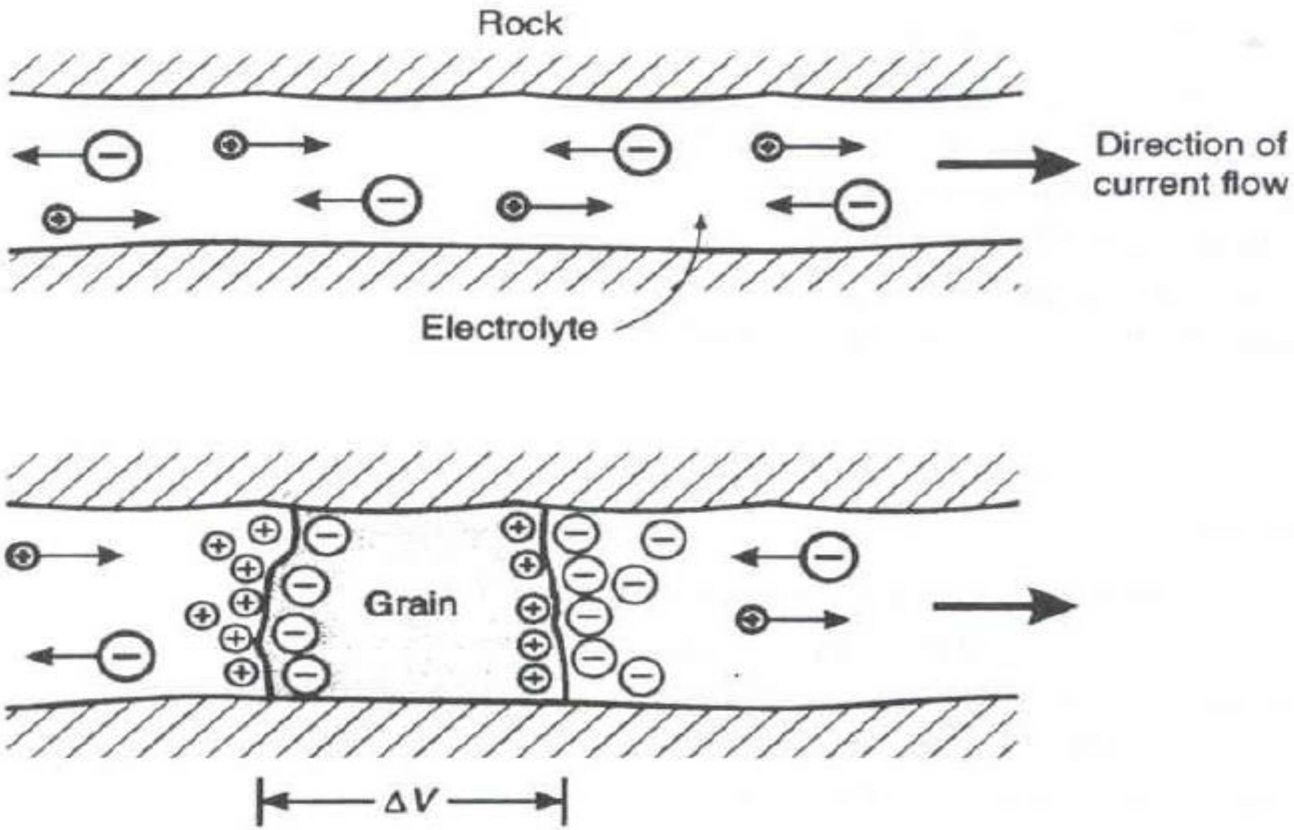
Membrane polarization



Membrane polarization occurs when pore space narrows to within several boundary layer thicknesses.

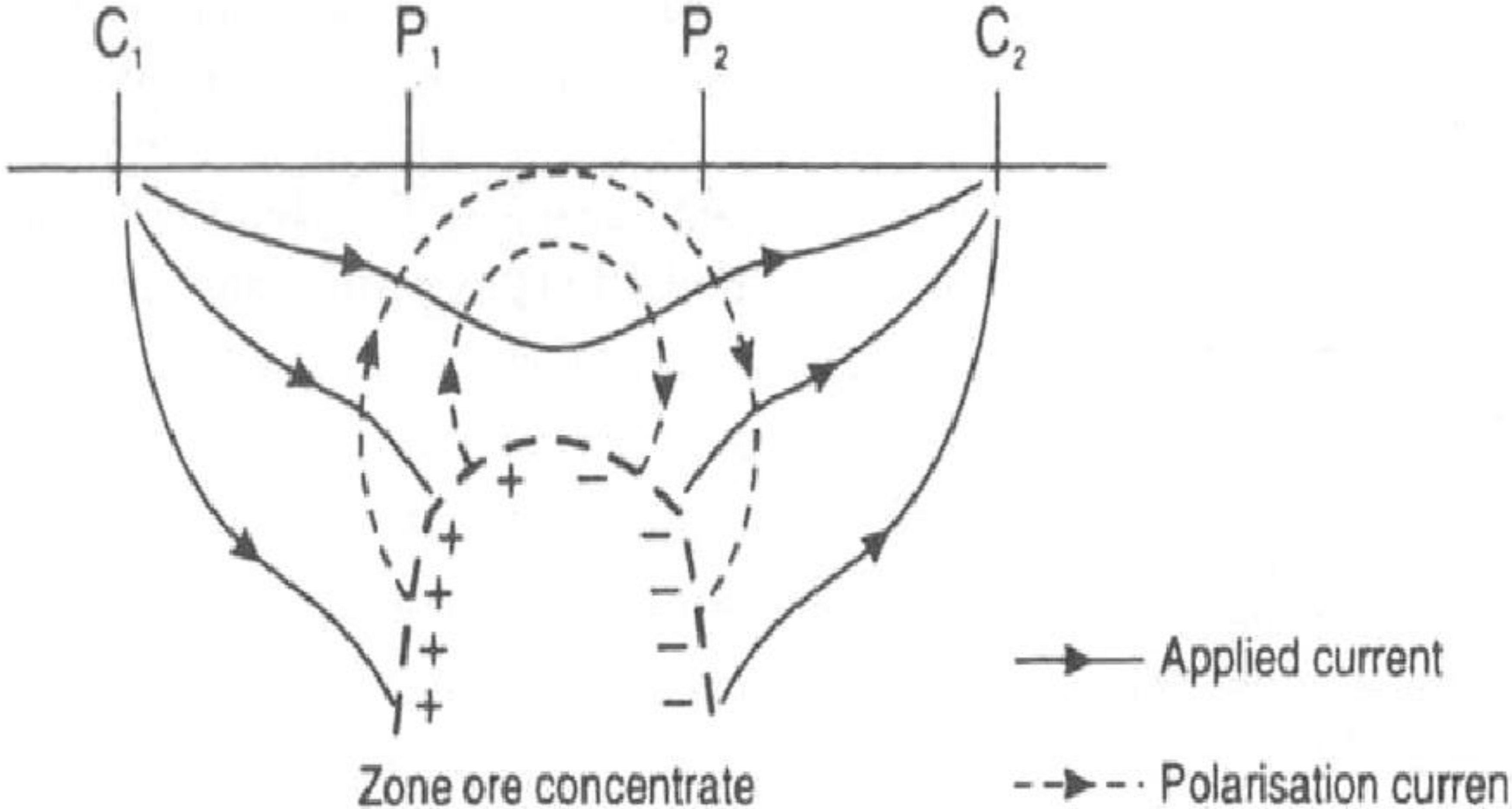
Charges accumulate when an electric field is applied.

Electrode polarization



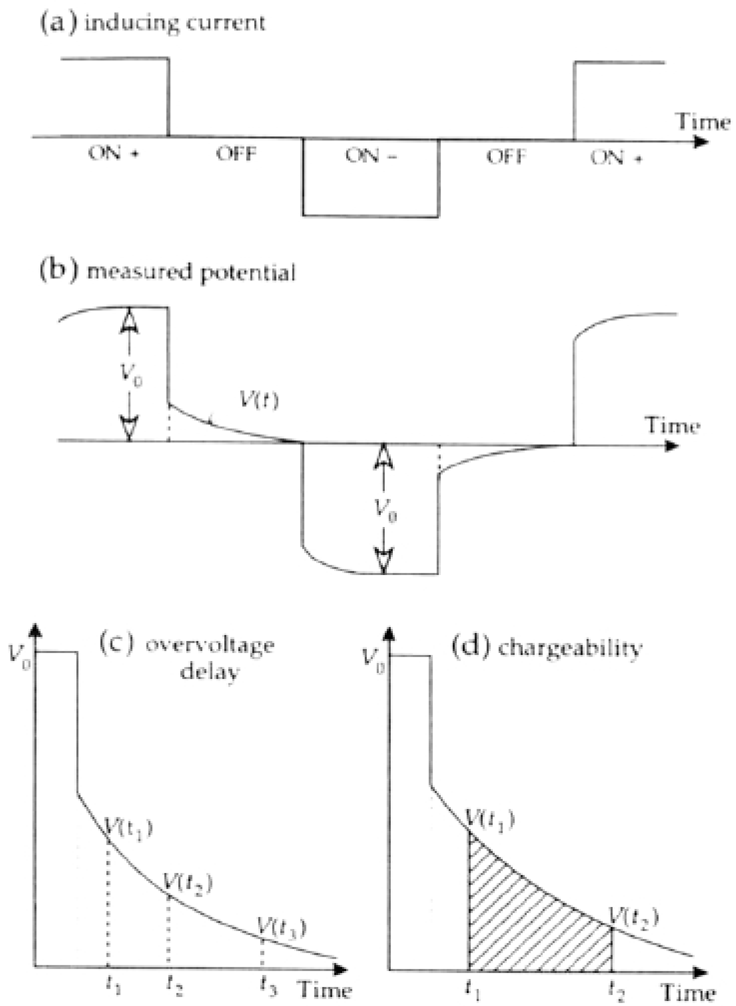
Electrode polarization occurs when pore space is blocked by metallic particles. Again charges accumulate when an electric field is applied.

The result is two electrical double layers which add to the voltage measured at the surface.



Note that membrane and electrode polarizations cannot be separately identified!

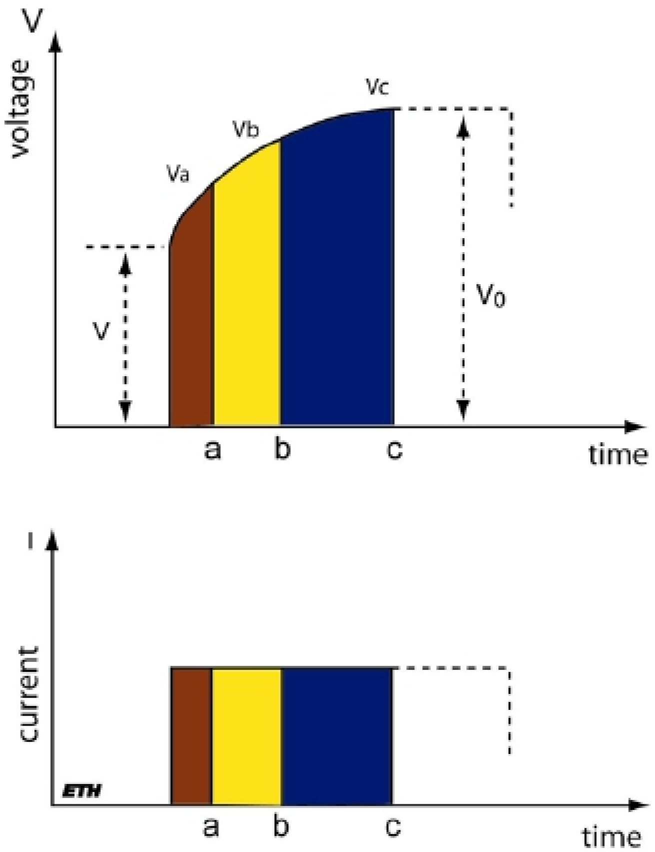
Time-domain IP



$$M_a = \frac{1}{V_0}\int_{t_1}^{t_2} V(t)\,dt$$

M_a is the apparent chargeability in milliseconds (ms)

Frequency-domain IP



$$PFE = 100\frac{\rho_{a\,DC} - \rho_{aAC}}{\rho_{aAC}}$$

PFE is the percent frequency effect (in %)

ρ_{aDC} is the apparent resistivity mesured at low frequency (0.05-0.5 Hz)

ρ_{aAC} is the apparent resistivity mesured at higher frequency (1-10 Hz)

Frequency-domain IP

$$MF = 2\pi \cdot 10^5 \frac{(\rho_{aDC} - \rho_{aAC})}{\rho_{aDC}\rho_{aAC}} = 2\pi \cdot 10^5 \frac{PFE}{\rho_{aDC}}$$

MF is the metal factor in Siemens per meters (S/m)

This normalization removes to a certain effect the variation of IP effect with the effective resistivity of the host rock (ρ_{aDC})

6. IP properties of rocks

Chargeability of minerals

Mineral	Chargeability (ms)	Mineral	Chargeability (ms)
Pyrite	13.4	Erubescite	6.3
Chalcocite	13.2	Galena	3.7
Copper	12.3	Magnetite	2.2
Graphite	11.2	Malachite	0.2
Chalcopyrite	9.2	Hematite	0.2

Concentration 1 %, current injection time 3 s, integration time 1 s

Chargeability of rocks

Rock	Chargeability (ms)	Rock	Chargeability (ms)
Aquifer	0	Schist	5 to 20
Alluvion	1 to 4	Sandstone	3 to 12
Gravel	3 to 9	Argilite	3 to 10
Volcanic	8 to 20	Quartzite	5 to 12
Gneiss	6 to 30		

Current injection time 3 s, integration time 0.02 s to 1s

IP effect…

- … is **higher** for **disseminated** than massive clay and metallic particles
- … **depends** on the **concentration** of clay and metallic particles
- …**increases** if water in the ground has a **low conductivity**
- … **increases** with **decreasing porosity**
- …**varies** with the **amount of water** in the ground
- …**depends** on the **current intensity** and the **current frequency**

7. Field procedures, interpretation and examples

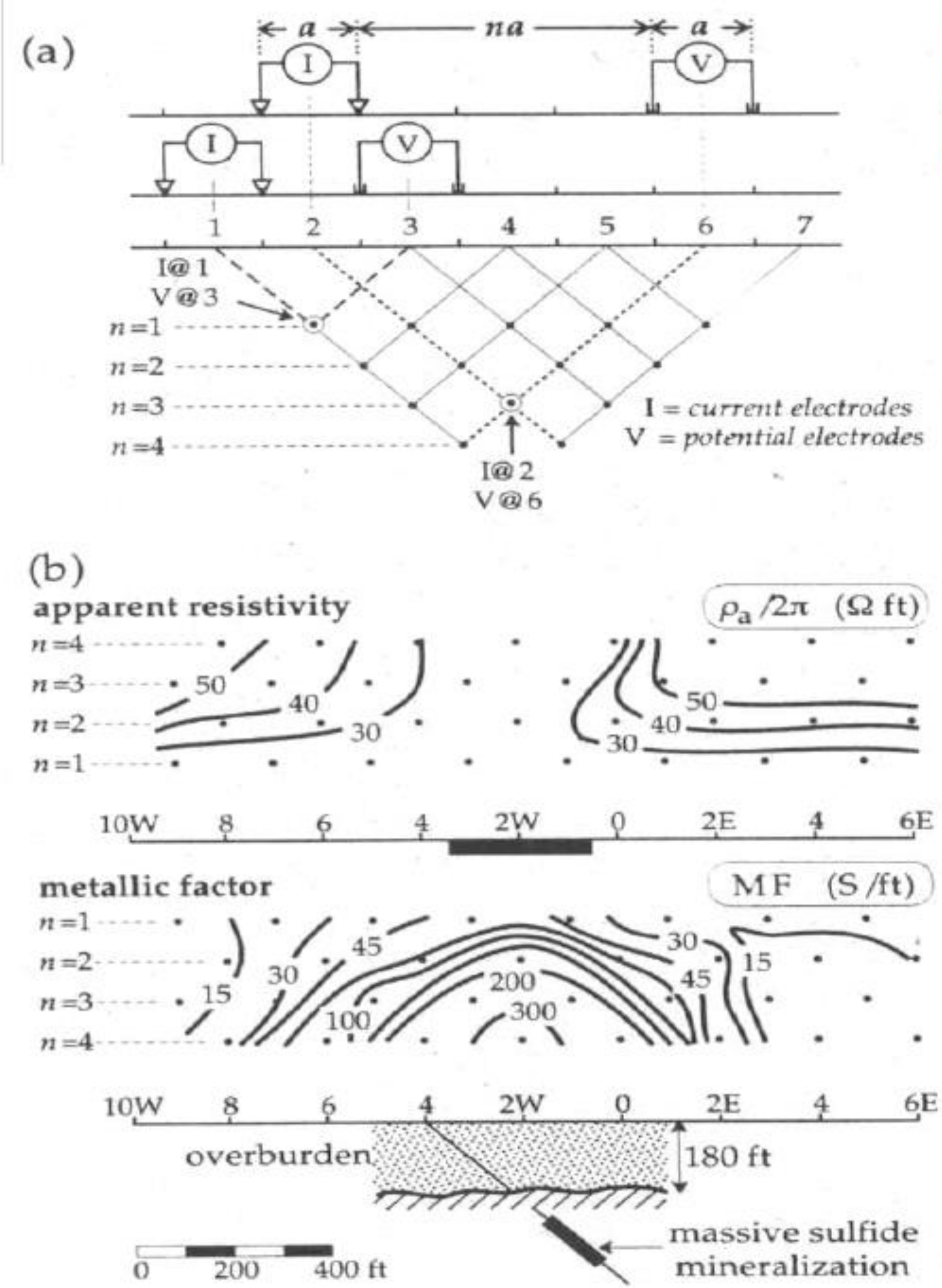
IP measurements

- Different measurement devices for Time-domain IP and Frequency-domain IP
- Same electrode arrays (for mapping and sounding) as in conventional resistivity
- **Sensitive** to **telluric noise**
- **Sensitive** to noise resulting from **electromagnetic coupling between adjacent wires** (dipole-dipole array very useful)
- Stability of potential measurements can be a problem (use non polarizable electrodes)

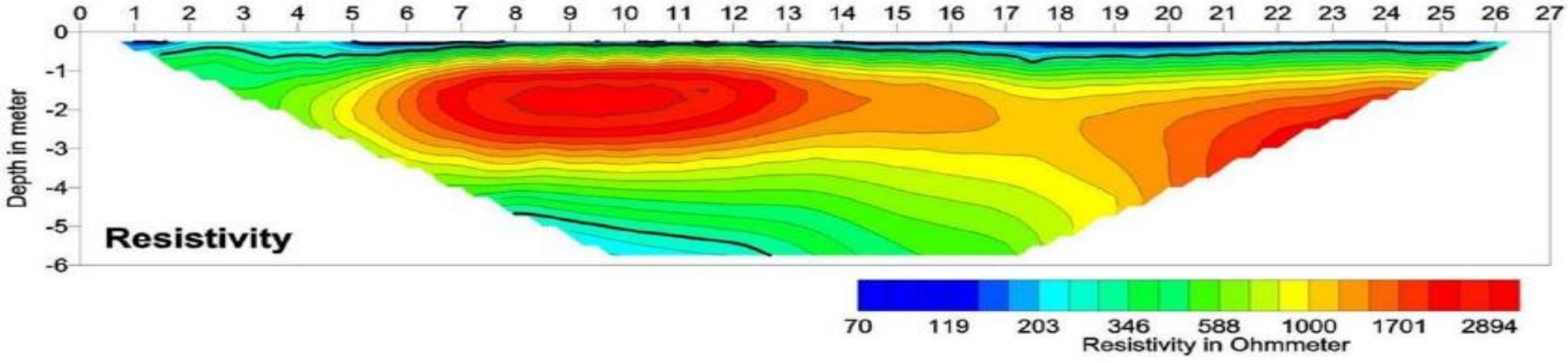
Interpretation

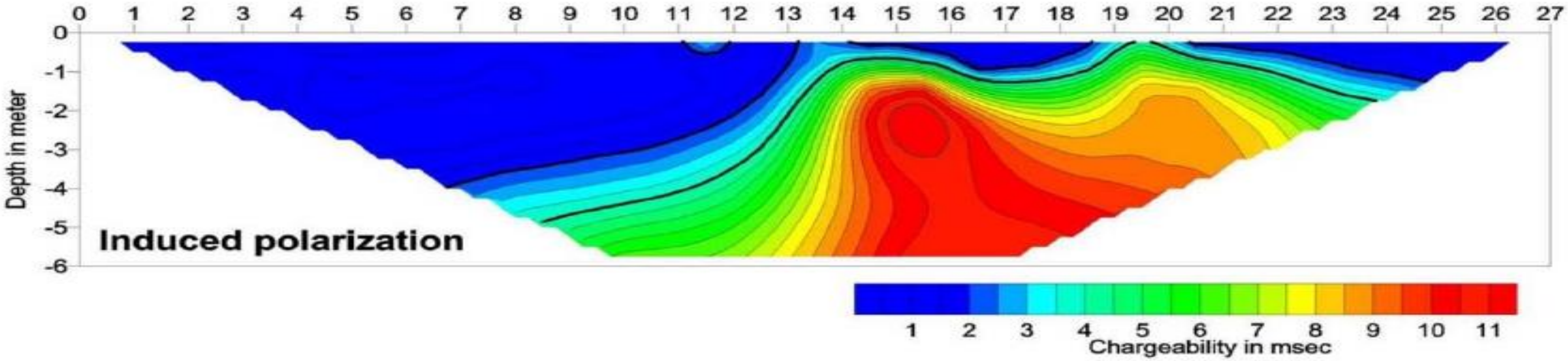
- Mainly qualitative, more complex than for resistivity
- Inversion using iterative algorithms (similar to resistivity)

Mining geophysics



Resistivity and Induced Polarization Survey





Objective:	To investigate a karstic limestone area using resistivity and induced polarization
Survey date:	October 21, 1999
Survey site:	Austin, Texas
Electrode array:	Schlumberger
Instrument:	Sting/Swift, 28 stainless steel electrodes at 1 meter spacing
Units:	Meter, Ohmmeter and msec

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Advantages

- Detection of disseminated mineral (difficult with resistivity)
- Method sensitive to clay in aquifers

Drawbacks

- Same disadvantages as resistivity method
- IP surveys is slow and more expensive than resistivity surveys