CHAPTER I
Electrical Methods

BOUFEDAH BADISSI Mohamed Salah 2025/2026
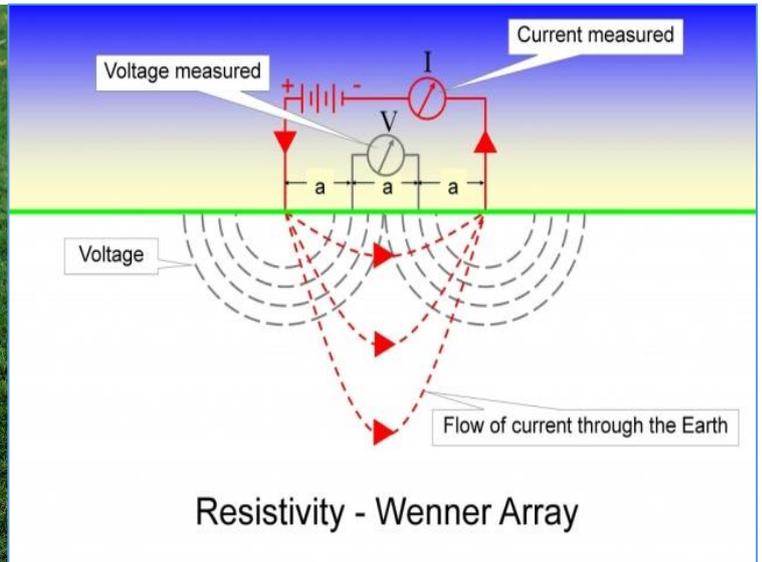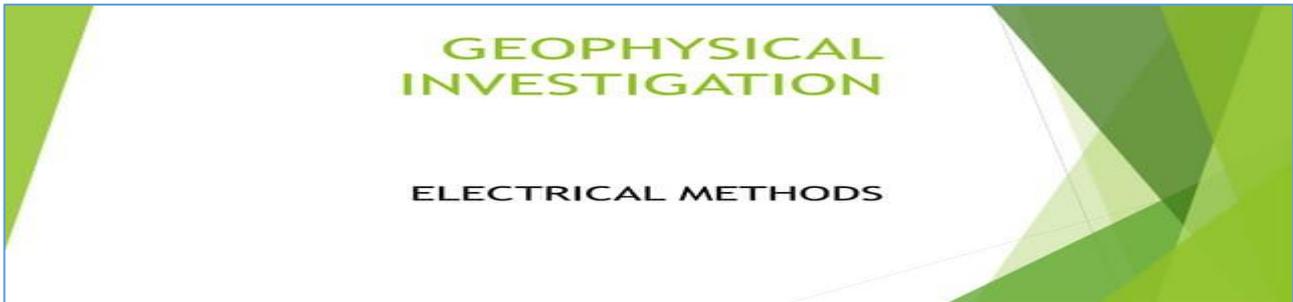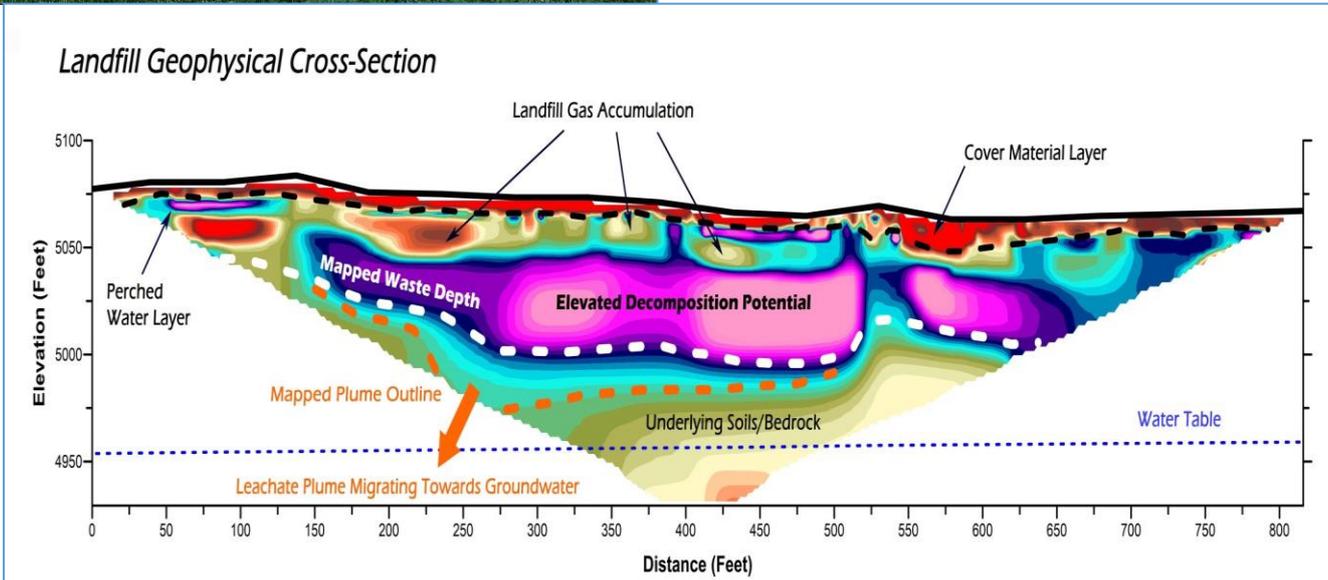
I. ELECTRICAL METHODS: PROSPECTING TECHNIQUES

I.1 Course Goals

To demonstrate the possibilities and usefulness of geophysics in solving problems arising in Geology and the environment.
Under the term, resistivity or electrical prospecting using contained current or very low frequency,
It is therefore necessary not only to choose the type of method that applies to the problem at hand, but also to choose the technique to use based on the application conditions, the size and depth of the target, etc
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I.1.1 Objectives

➢ Understand the relationships between the practical problems encountered and the associated measurable physical phenomena.
➢ Understand modern prospecting techniques and understand the principles that
drive these techniques.
➢ Be able to analyze a problem and decide on the best geophysical technique(s) to adopt.

• Develop critical thinking skills to judge the work accomplished.
• Be able to analyze and interpret the results of surveys conducted.

I.1.2 Physical Basis

Electrical prospecting is one of the oldest geophysical prospecting methods. Its implementation is relatively simple.
Direct current (often in pulsed form) is injected using two injection electrodes, and the resulting potential difference is measured with two measuring electrodes.

This depends on the electrical resistance of the subsurface.

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2

I.1.3 Reminders and Definitions
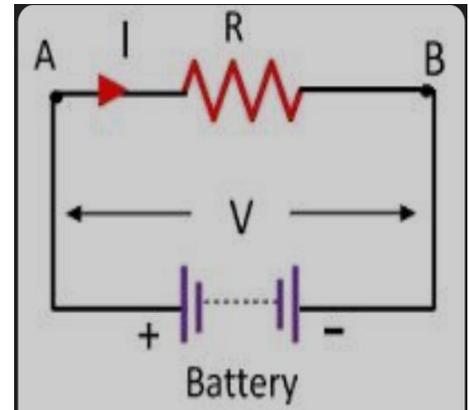
1. Ohm's Law

Ohm's Law applies to electrical circuits and to all electrical methods in geophysics:

$$\Delta V = R.I$$

Where **ΔV:** is the potential difference (in volts); I is the current (in amperes);
R is the electrical resistance (in ohms, Ω). Resistance is therefore the ratio of voltage to current:

$$R = \frac{\Delta V}{I}$$

The resistance of a medium varies linearly with the length "L" of the medium crossed, but inversely proportional to the area "S" of the surface crossed:
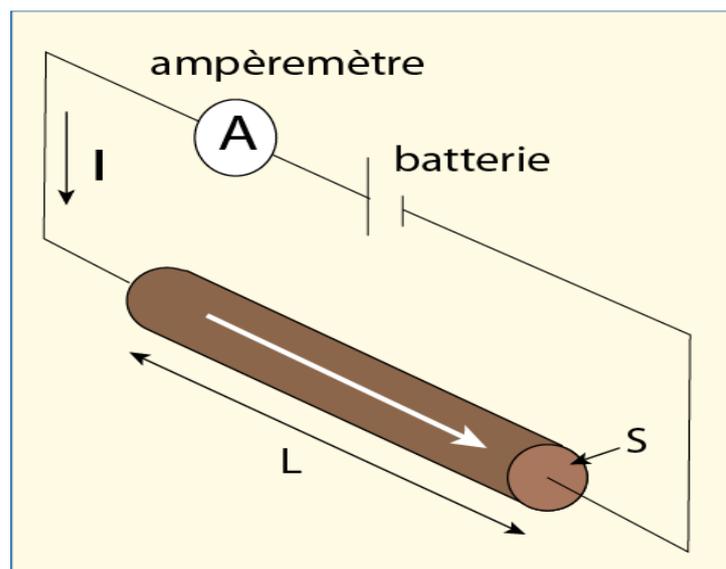
$$R = \frac{\rho.L}{S} \quad d'où \quad \rho = R.\frac{S}{L} = \frac{\Delta V}{I}.\frac{S}{L}$$

where the constant of proportionality is the resistivity (ρ) (in Ω m). It expresses the difficulty of current passing through a medium:

Conductivity (sigma) σ (in Siemens/m) is the inverse of resistivity.

Il s'agit du rapport de la densité de courant par l'amplitude du champ électrique. On mesure la conductivité électrique avec un conductimètre.

$$\sigma = \frac{1}{\rho}$$

2. Archie's Laws

Archie's Second Law (Resistivity Index)

This equation extends the model to rocks that are only partially saturated with water. It relates the resistivity index (I_R) to the water saturation (S_w).

$$I_R = \frac{R_t}{R_o} = S_w^{-n}$$

where:

- R_t is the true resistivity of the formation with partial water and hydrocarbon saturation ($\Omega \cdot m$).

- R_o is the resistivity of the rock when 100% saturated with water ($\Omega \cdot m$).

- S_w is the fractional water saturation of the pores (1.0 for a fully saturated rock).

- n is the saturation exponent, which relates to the wettability of the rock and typically has a value around 2.0.

Combined Archie Equation

The two laws can be combined to give the water saturation directly from resistivity measurements:

$$S_w = \left(\frac{aR_w}{\phi^m R_t} \right)^{1/n}$$

- a is the tortuosity factor (an empirical constant, often assumed to be 1 for many formations).

- ϕ (phi) is the fractional porosity of the rock.

- m is the cementation exponent, which depends on the degree of pore cementation and packing. It typically ranges from 1.7 to 3.0, with a common value of 2.0.

a	m	n
Fct° de la lithologie	*Fct° de la cimentation*	-
0.6 à 2	1.3 à 2.2	~ 2
(~ ↑ si φ ↓)	(↑ avec cimentation)	

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4

3. Resistivity of the most common materials

Rock	Conductivity (S m^{-1})	Resistivity (Ωm)
Granite	0.001–0.00001	1000–100000
Gabbro	0.001–0.00001	1000–100000
Basalt	0.1–0.0001	10–100000
Andesite	0.001–0.00001	1000–100000
Sand and gravel	0.05–0.002	20–5000
Sandstone	0.1–0.001	50–1000
Limestone	0.002–0.00001	5000–100000
Dolomite	0.001–0.0002	1000–50000
Conglomerate	0.01–0.0001	100–10000
Coal	0.1–0.001	10–1000
Shales	0.001–1	50–1000
Clays	0.05–0.01	20–100
Graphite	100–0.01	0.01–100
Massive sulfides	1000–1	0.001–1
Salt water	10–1	0.1–1
Brackish water	1–0.1	1–10
Freshwater	0.1–0.01	10–100
Permafrost	0.02–0.00001	500–100000
Sea ice	0.05–0.001	20–1000

Modified after Palacky GV (1987) Resistivity characteristics of geologic targets.
In: *Electromagnetic Methods in Applied Geophysics, 1. Theory*, p. 1351

Material	Resistivity (Ω*m)	Conductivity (Siemen/m)
Toneous and Metamorphic Rocks		
Granite	$5\times10^3 - 10^6$	$10^{-6} - 2\times10^{-4}$
Slate	$10^3 - 10^6$	$10^{-6} - 10^{-3}$
Basalt	$6\times10^2 - 4\times10^7$	$2.5\times10^{-8} - 1.7\times10^{-3}$
Marble	$10^2 - 2.5\times10^8$	$4\times10^{-9} - 10^{-2}$
Quartzite	$10^2 - 2\times10^8$	$5\times10^{-9} - 10^{-2}$
Sedimentary Rocks		
Sandstone	$8 - 4\times10^3$	$2.5\times10^{-4} - 0.125$
Shale	$20 - 2\times10^3$	$5\times10^{-4} - 0.05$
Limestone	$50\times10^2 - 4\times10^2$	$2.5\times10^{-3} - 0.02$
Soils and waters		
Clay	1-100	0.01 - 1
Alluvium	10 -800	1. $2.5\times10^{-3} - 0.1$
Groundwater (fresh)	10 -100	$0.01 - 0.1$
Sea water	0.2	5
Chemicals		
Iron	9.074×10^8	1.102×10^7
0.01 M Potassium Chloride	0.708	1.413
0.01 M Sodium Chloride	0.843	1.185
0.01 M Acetic acid	6.13	0.163
Xylene	6.998×10^{16}	1.429×10^{-17}

Table 1. Typical electrical resistivities of earth materials.

Material	Resistivity (Ωm)
Clay	1-20
Sand, wet to moist	20-200
Shale	1-500
Porous limestone	100-1,000
Dense limestone	1,000-1,000,000
Metamorphic rocks	50-1,000,000
Igneous rocks	100-1,000,000

4. Range of resistivities of natural materials

| The susceptablitlites of various rocks and minerals ||
Material	Susceptibility x 10^{-3} (SI)
Air	about 0
Quartz	-0.01
Rock Salt	-0.01
Calcite	-0.001 - 0.01
Sphalerite	0.4
Pyrite	0.05 - 5
Hematite	0.5 - 35
Ilmenite	300 - 3500
Magnetite	1200 - 19,200
Limestones	0 - 3
Sandstones	0 - 20
Shales	0.01 - 15
Schist	0.3 - 3
Gneiss	0.1 - 25
Slate	0 - 35
Granite	0 - 50
Gabbro	1 - 90
Basalt	0.2 - 175
Peridotite	90 - 200
Adapted from T.H. Boyd of the Colorado School of Mines	

Type of water	Resistivity [Ω·cm]	Conductivity [µS/cm]
Pure water	20000000	0,05
Distilled water	500000	2
Rain water	20000	50
Tap water	1000-5000	200-1000
River water (typical)	2500	400
River water (brackish)	200	5000
Sea-water (coastal)	30	33000
Sea-water (open sea)	20-25	40000-50000
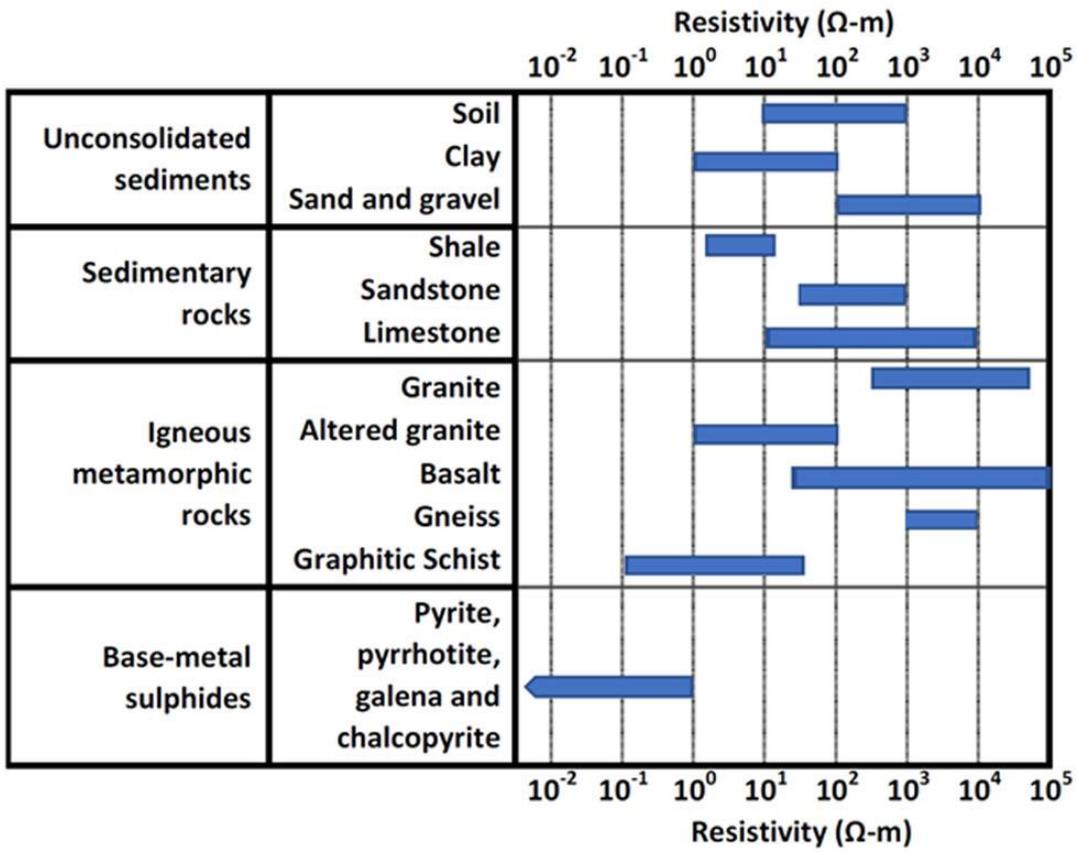
II. Distribution of electrical potential in soils

II.1. Infinite, Homogeneous, and Isotropic Medium

a. Case of a Single Electrode

Let's now examine how to measure the resistivity of rocks.

Ohm's Law allows us to predict the path of current lines in a homogeneous, isotropic medium.

Consider a homogeneous and isotropic soil with resistivity ρ bounded by a flat surface on the air side.

Let's apply a direct current I using a point electrode A.

The current will flow in rectilinear lines radiating around A and will produce potential variations in the soil due to its ohmic resistance.

The potential distribution can be represented by hemispheres centered on A.

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9
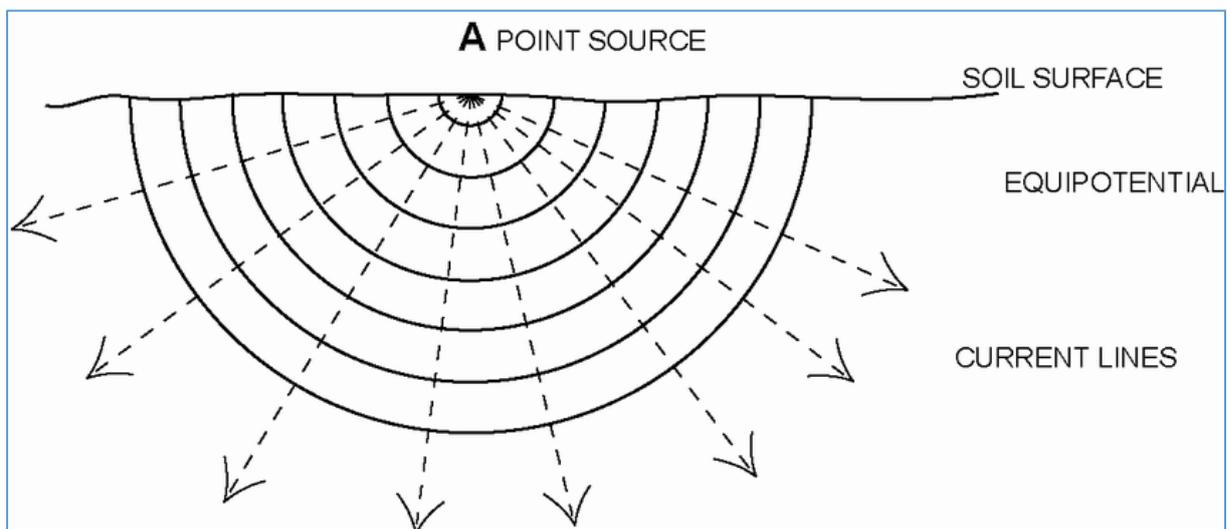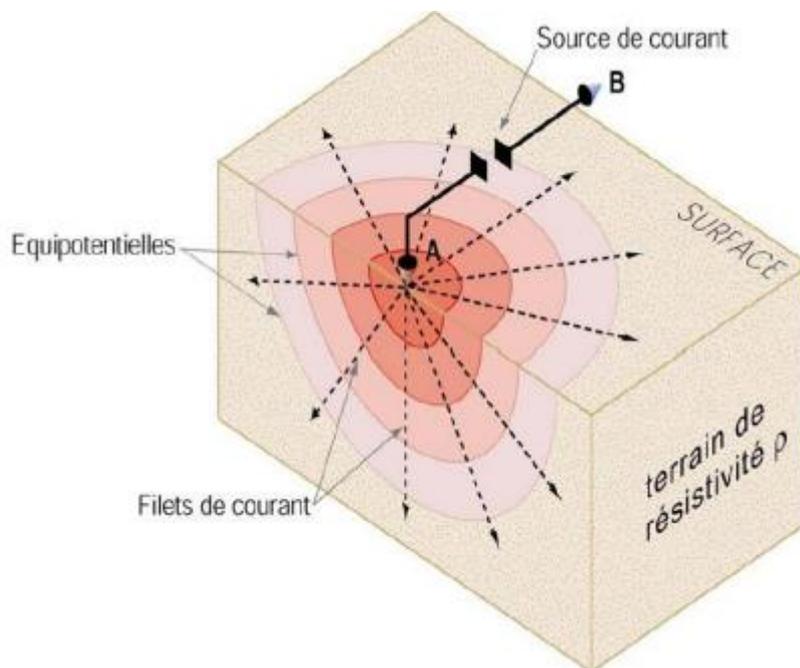
Dans un sol homogène et isotrope, le potentiel électrique autour d'une seule électrode ponctuelle à la surface suit une loi de la forme $V = \dfrac{I\rho}{2\pi R}$

Dans ce cas, l'électrode est considérée comme une source de courant ponctuelle, et le potentiel électrique (V) diminue à mesure que la distance (R) par rapport à l'électrode augmente. La formule inclut la résistivité (ρ) du sol et le courant (I) émis par l'électrode.

Le potentiel électrique (V): est mesuré en volts.

Le courant (I): est la quantité de courant émise par l'électrode, mesurée en ampères.

La résistivité (ρ): représente la résistance du matériau, mesurée en ohm-mètres (Ω.m).

La distance (R): est la distance entre l'électrode et le point de mesure, mesurée en mètres

$$dV = \rho I \frac{dl}{dS}$$

for the whole half sphere: $V = -\dfrac{\rho I}{2\pi . r^2} \cdot dr$

by integrating over the radius $V = \dfrac{\rho I}{2\pi . r} + Cste$

b. case of two (02) electrodes
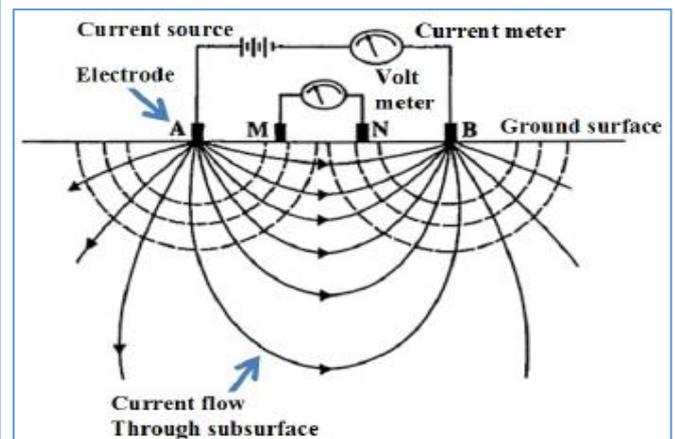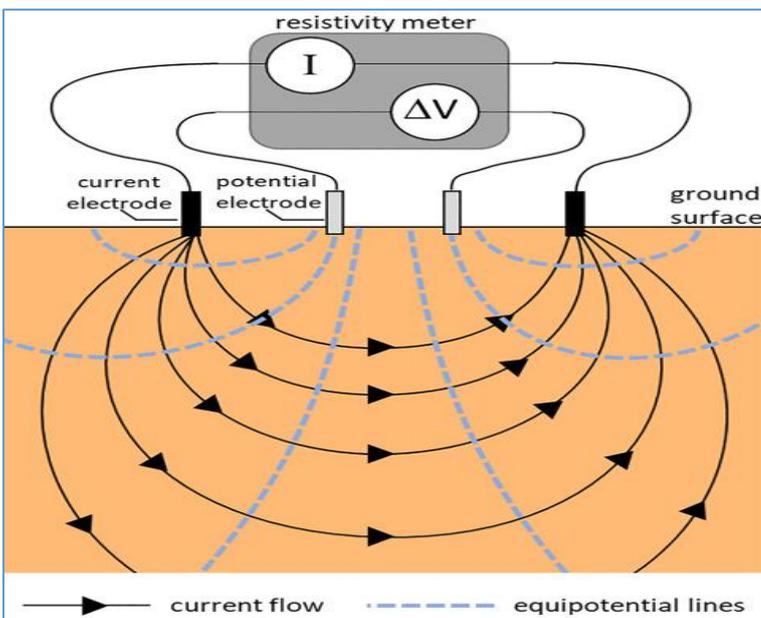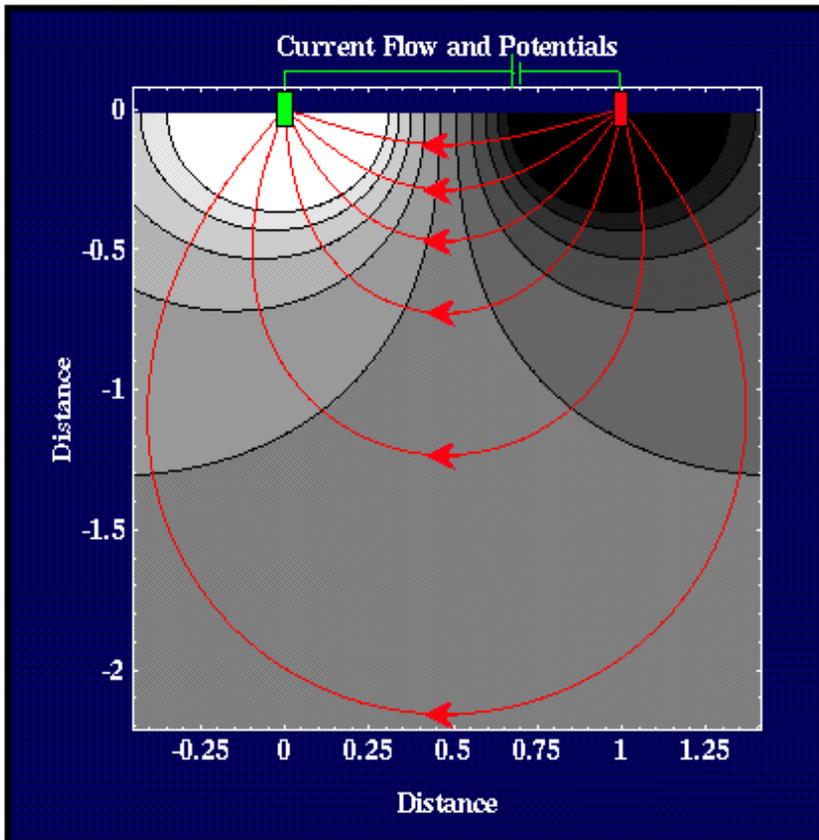

Figure: Equipotentials and current flow lines (paths) for two point current sources on the surface of a homogeneous soil

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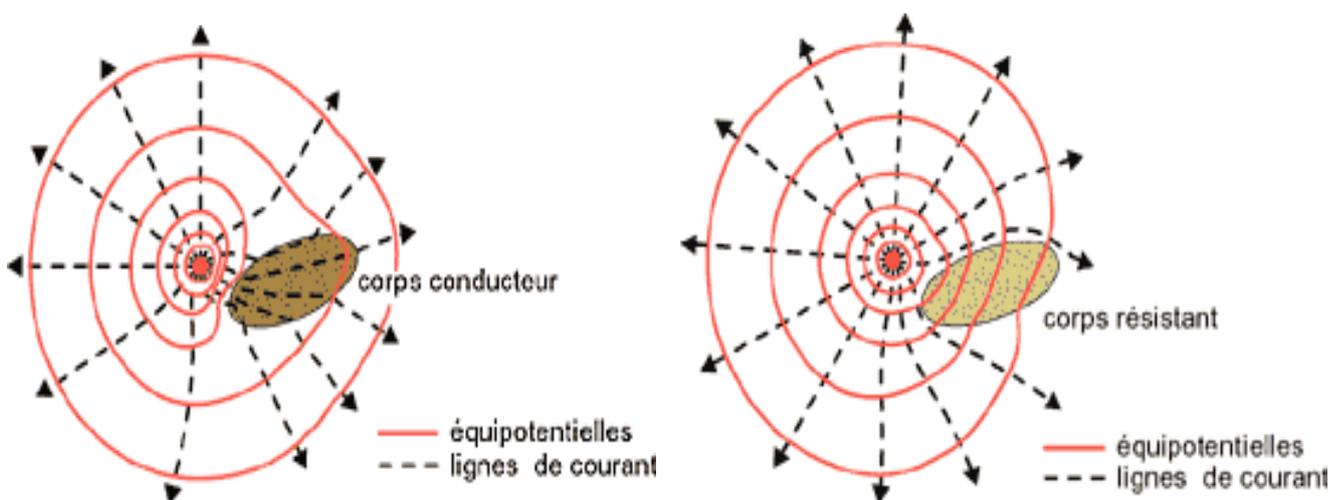## Equipotentials and streamlines

For an injection dipole:

•**Current density decreases with depth, for example (from bottom to top):**

* **According to Chouteau and Gloaguen**

Ligne de courant	% de courant
1	17
2	32
3	42
4	49
5	51
6	57

Figure: Modification of field lines and equipotentials in the presence of a resistivity anomaly
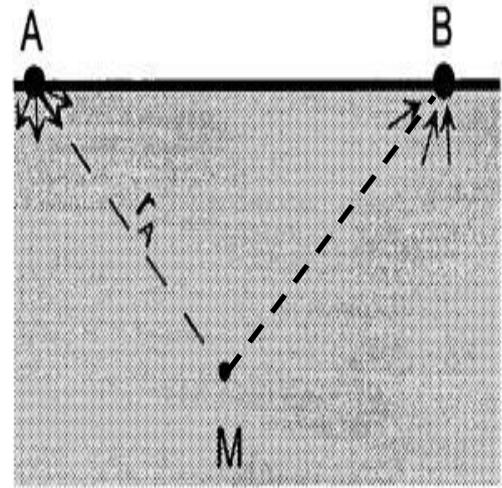
Case of two (02) electrodes (the dipoles)

In this device, the current enters at A and is recovered at B. At point M of the half-space (fig.) we will have a potential:

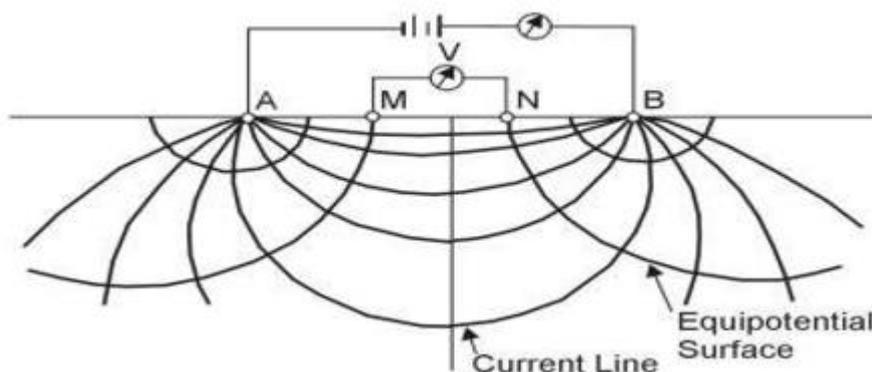the potential of the A is: $= \dfrac{\rho I}{2\pi} \dfrac{1}{r_A}$

the potential of the B is: $= -\dfrac{\rho I}{2\pi} \dfrac{1}{r_B}$

the potential of the M is: $= \dfrac{\rho I}{2\pi} \left[\dfrac{1}{r_A} - \dfrac{1}{r_B} \right]$

c. Case of four (04) electrodes (The quadrupole)

In a field experiment, current is injected into the ground using a battery or a generator connected to two electrodes, A and B (fig.).

The intensity of the injected current is read on an ammeter.

 Potential differences in the ground between two points, M and N, are measured using a voltmeter. The electrodes' contact with the ground is not perfect, and contact resistance appears at A and B. Unfortunately, their R_A and R_B values are unknown, but they can be calculated using the following calculation.

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12

At point M, on the surface, we have

$$V_M = \frac{\rho I}{2\pi}\left(\frac{1}{MA} - \frac{1}{MB}\right) - R_A I + R_B I.$$

At point N, on the surface, we have

$$V_N = \frac{\rho I}{2\pi}\left(\frac{1}{NA} - \frac{1}{NB}\right) - R_A I + R_B I.$$

The potential difference between M and N is obtained by subtracting the second equation from the first, which eliminates the unknowns R_A and R_B

$$V_M - V_N = \frac{\rho I}{2\pi}\left[\frac{1}{MA} - \frac{1}{MB} - \frac{1}{NA} + \frac{1}{NB}\right].$$

The quantity in brackets is the geometric factor of the assembly. It depends on the positions of the four electrodes on the ground. We set [ ] = f and we obtain the expression of the desired parameter, the resistivity:

$$\rho = \frac{V_M - V_N}{I} 2\pi \frac{1}{f}.$$

The ABMN points form a quadrupole. Depending on the problem to be studied, various devices are used.
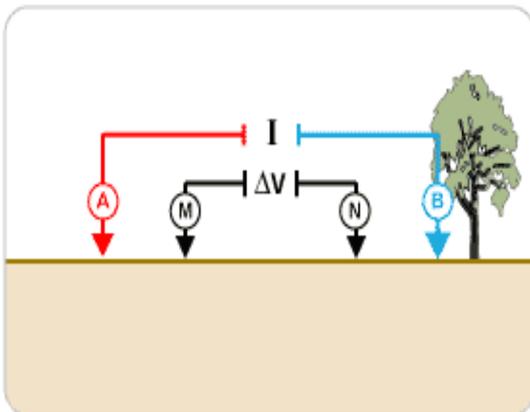
The quadrupole

Potential in M: $V_M = \frac{\rho_a . I}{2\Pi}\left(\frac{1}{AM} - \frac{1}{BM}\right)$

Potential in M: $V_N = \frac{\rho_a . I}{2\Pi}\left(\frac{1}{AN} - \frac{1}{BN}\right)$

Potential difference between M and N: $\Delta V = V_M - V_N = \frac{\rho_a . I}{2\pi}\left(\frac{1}{AM} - \frac{1}{BM} - \frac{1}{AN} + \frac{1}{BN}\right)$

Hence the apparent resistivity: $\rho_a = \frac{k.\Delta V}{I}$

With $\quad k = \dfrac{2\pi}{\left(\dfrac{1}{AM} - \dfrac{1}{BM} - \dfrac{1}{AN} + \dfrac{1}{BN}\right)}$ Geometric Factor of the devi

II. 2. Heterogeneous Medium

If, in this case, we always measure, regardless of the setup, an intensity between A and B and a potential difference between M and N, we can always calculate the resistivity of the ground. Given its inhomogeneity, we will then speak of
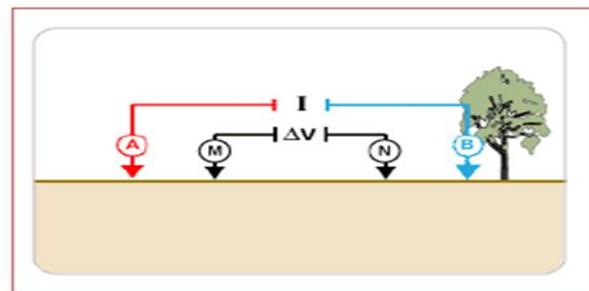
apparent resistivity and we will have: $\quad \rho_a = \dfrac{2\pi}{f}\dfrac{V_M - V_N}{I}$

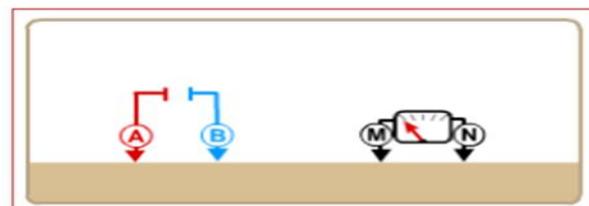This parameter has three main properties:

• ρ_a does not depend on I.

• ρ_a depends on the geometric configuration used.

• ρ_a is a sort of average of the resistivities of the medium.

Types de Quadripôles
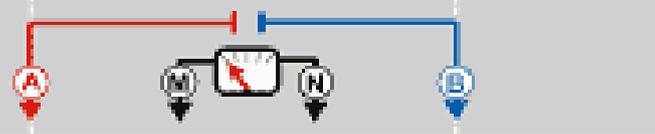
• Dispositif Wenner:

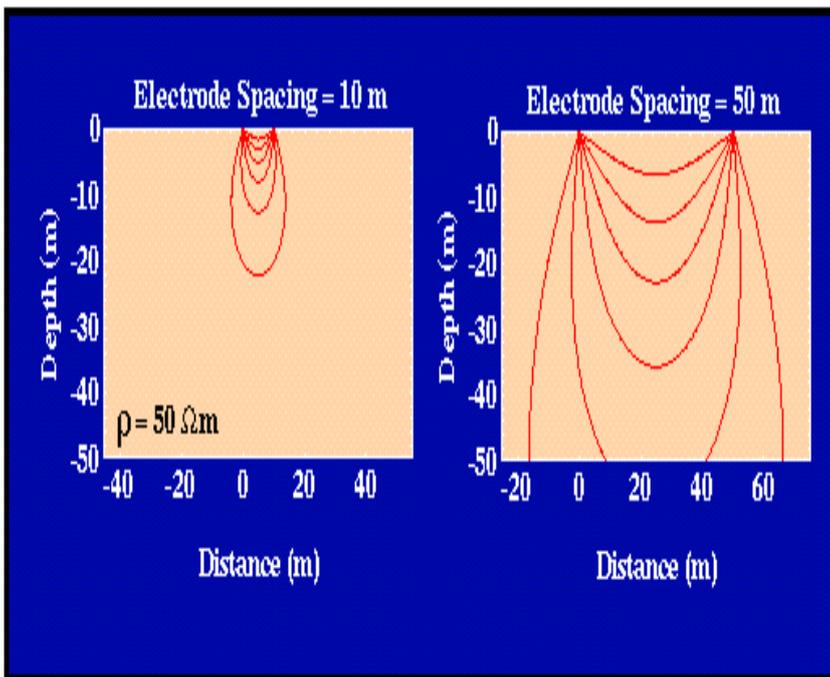pour $AM = MN = NB = a$

$k = 2\pi a$

• Dispositif dipôle-dipôle:

pour $AB = MN = a$

$k = \pi.n.(n+1)(n+2).a$

Penetration depth of the main devices

According to Chouteau & Gloaguen

Dispositifs	L	Prof. d'investigation	
		Roy (1971)	Barker (1989)
Wenner	(A) (M) (N) (B)	0.11L	0.17L
Schlumberger	(A) (M) (N) (B)	0.125L	0.19L
Dipôle-Dipôle	(A) (B) (M) (N)	0.195L	0.25L
Pôle-Pôle	(A) (B)∞ (M) (N)∞	0.35L	

Penetration (investigation) depth and electrode spacing

50% of all current flows at a depth less than the electrode separation.

To increase penetration, the electrode separation is increased.
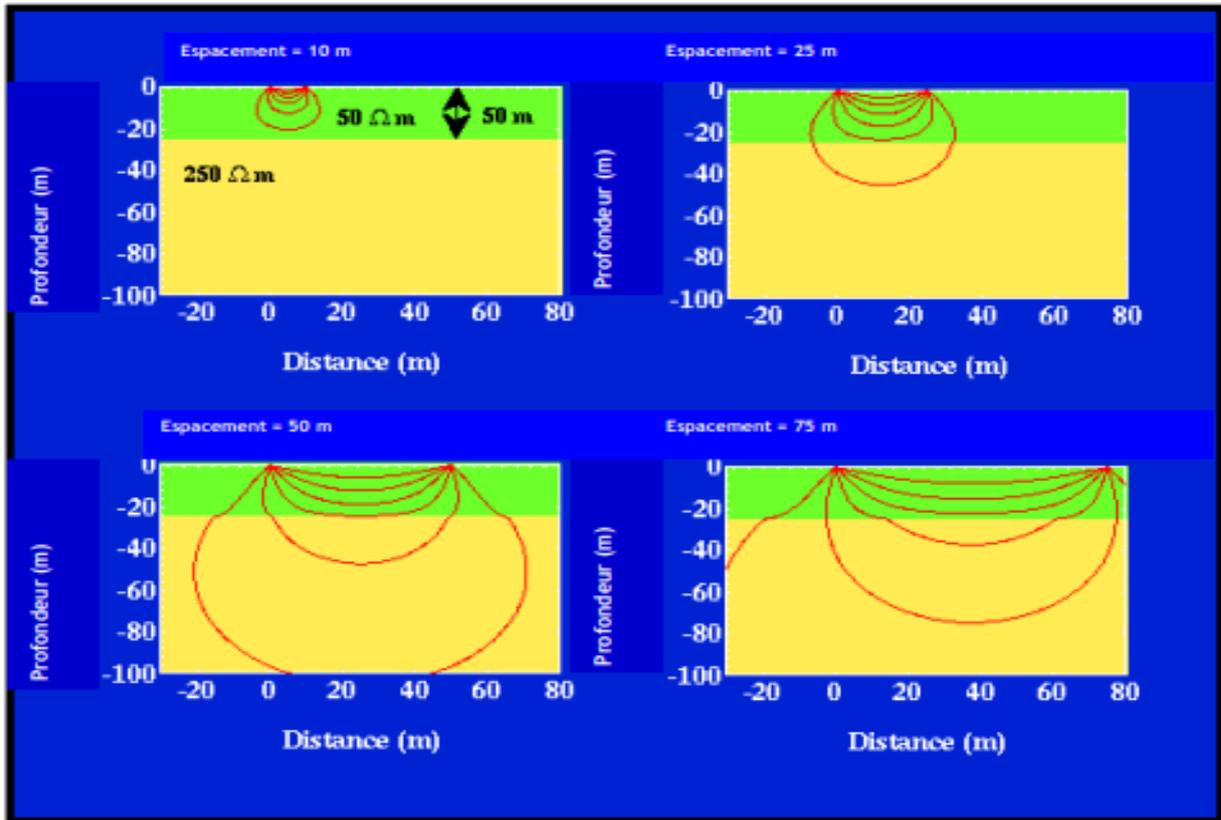
Sensitivity of the main devices

Measurements and equipment

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II.2 Direct current resistivity methods
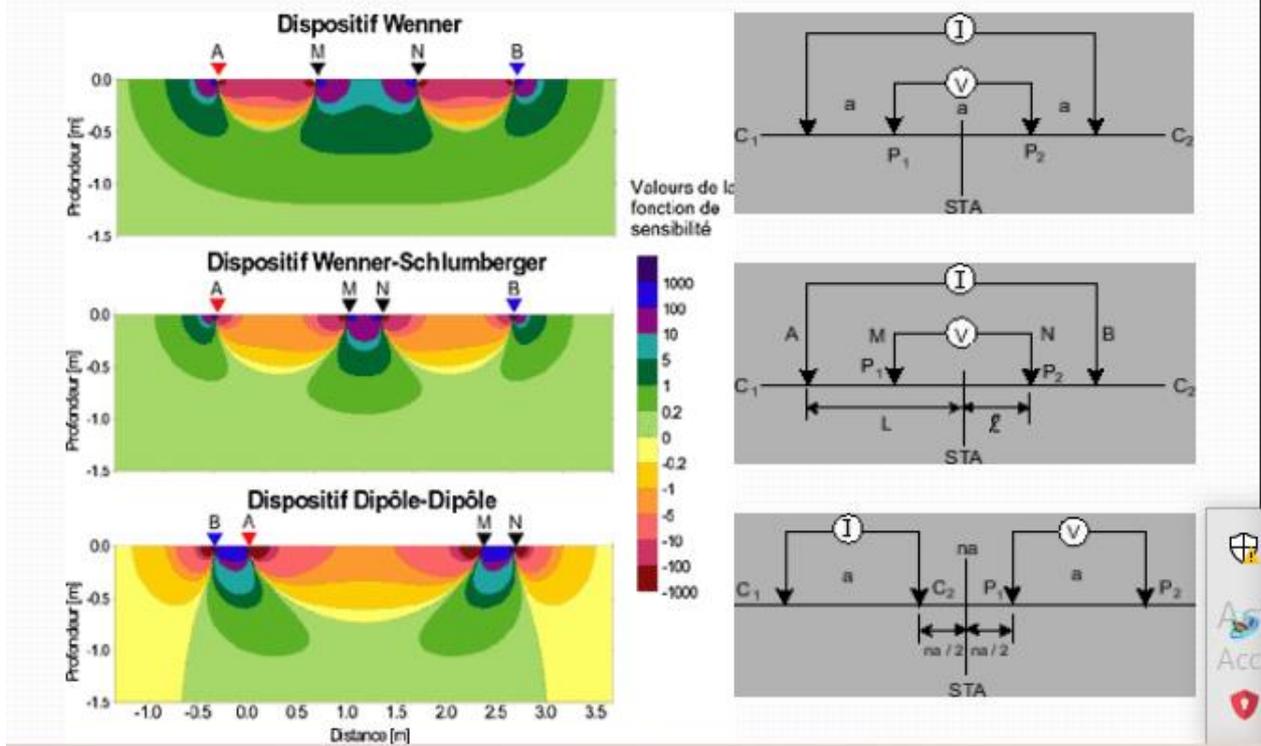
II.2.1 Current Distribution

At the midpoint of electrodes A and B and for a **homogeneous subsoil**, the quantity of current passing under a certain depth z is:

$$I_f = \left(\frac{2}{\pi}\right) tan^{-1}\left(\frac{2z}{AB}\right)$$

This current penetration is illustrated by the following figure:
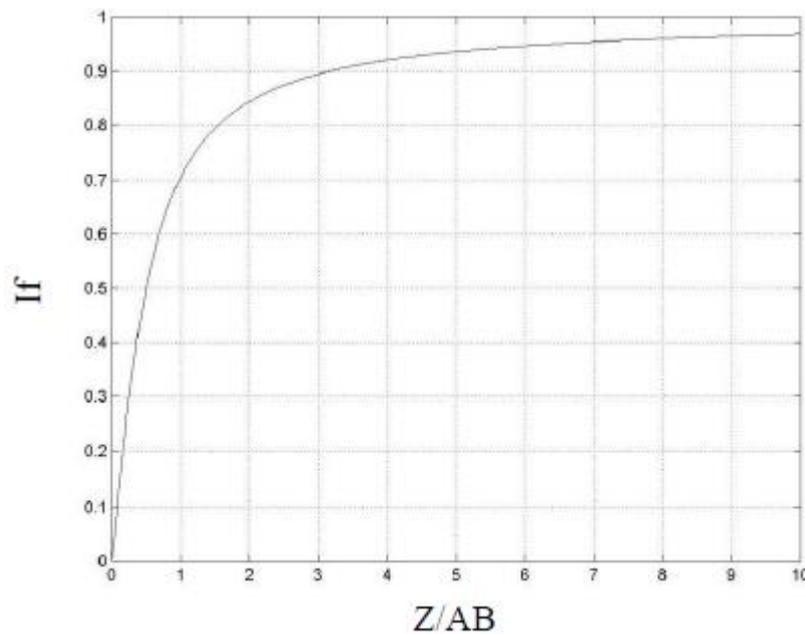

Figure: Relationship between current density and the investigation depth of an electric current

It is assumed that for a homogeneous terrain, 30% of the current is between the surface and a depth Z = AB/4, 50% of the current is between the surface and Z = AB/2, and 70% of the current is between the surface and Z = AB.

These results allow us to assess the extent to which the current emitted at the surface by two point electrodes penetrates into the subsurface and can be affected by rocks located at depth.

II.2.2 Potential and Electric Field for a Heterogeneous Terrain

The existence of a relatively conductive or resistant mass in the subsurface will disrupt the distribution of current flows and equipotential lines. Here, we will address this problem more qualitatively. In the case of a heterogeneous subsurface, it is indeed difficult to obtain simple equations describing the behavior of the electric field, and advanced numerical techniques (finite differences, finite elements) must be used. Let us begin by providing an image of the distribution of the electric current

(or electric field) in a homogeneous terrain between two electrodes A and B (this situation is similar to the one described above).

The geological example used for the modeling is a sandstone level with a resistivity of 120 Ohm.m.
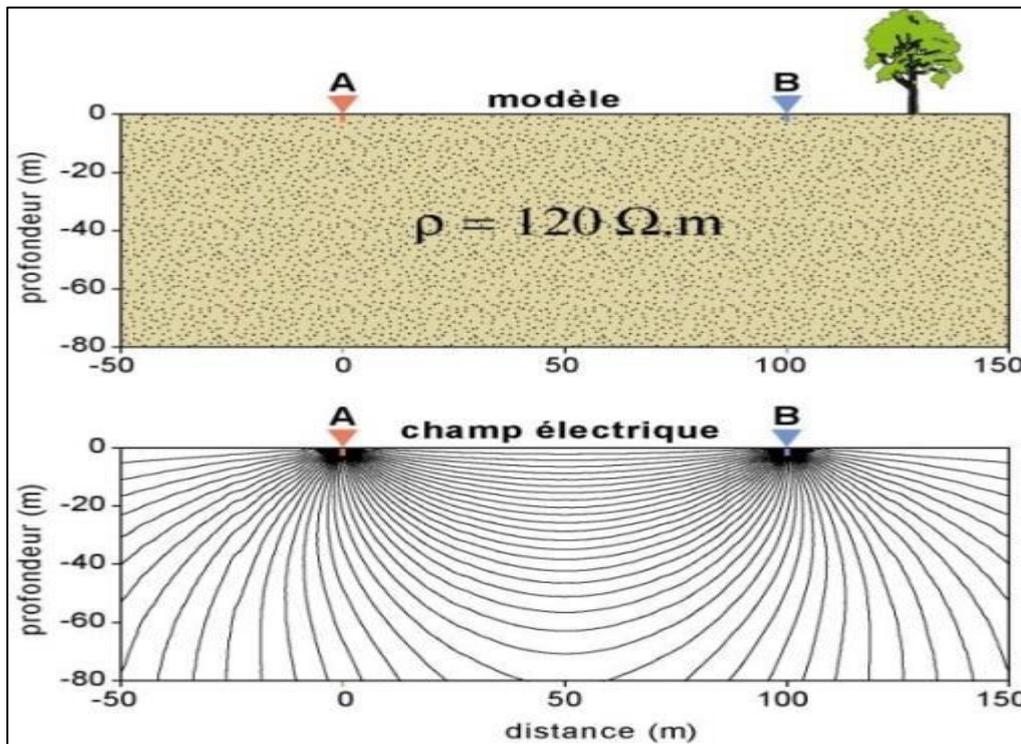
Figure: Geological model used for modeling is a sandstone level with resistivity 120 Ohm.m

II.2.2.1 Two-terrain model $\rho_1 < \rho_2$ with

The geological example used for modeling shows (below left):

- An upper marl terrain with a resistivity of 30 Ohm.m
- A lower sandstone level with a resistivity of 200 Ohm.m

II.2.2.2 Two-terrain model $\rho_1 > \rho_2$ with

The geological example used for modeling shows (below right):

- An upper level of sandy gravel with a resistivity of 200 Ohm.m
- A lower level of sandstone-marl with a resistivity of 30 Ohm.m

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19
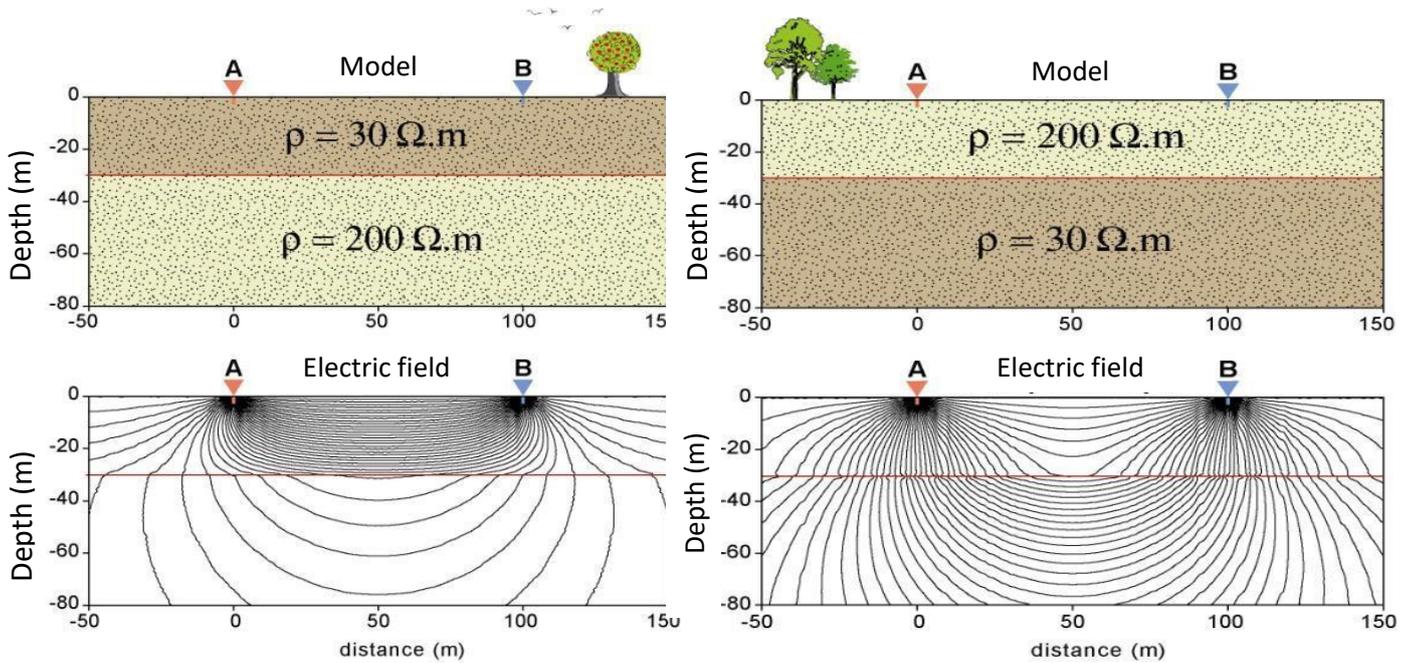
Figure: Two-terrain geological models

II.2.2.3 Resistant Ditch Model (Modèle de fossé résistant)

The archaeological example used for the modeling shows three terrains (note the more complex distribution of current flows):

- An upper moraine level with a resistivity of 60 Ohm.m
- A lower sandstone-marl level with a resistivity of 30 Ohm.m
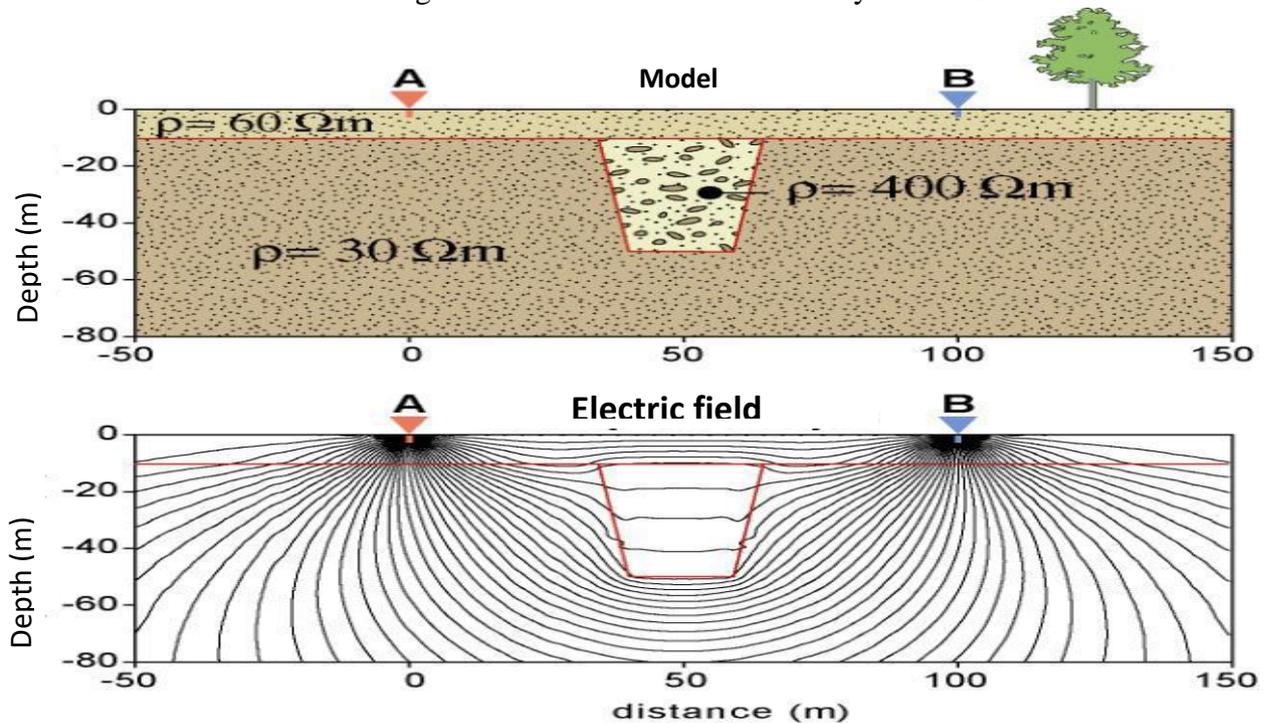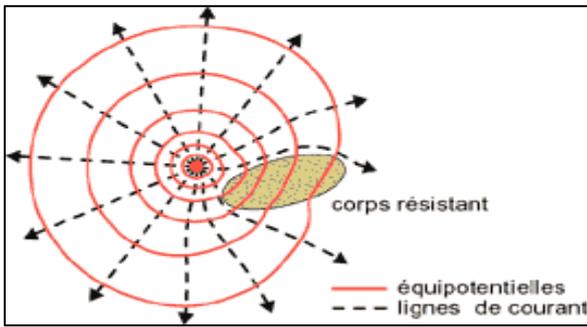 - An old gravel-filled ditch with a resistivity of 400 **Ohm.m**

Figure: Geological model of resistant ditch

II.2.2.4 Local heterogeneities in the plane

When we are dealing with more or less local variations in resistivity, a conductive body, for example, will attract and concentrate the current lines. The equipotential lines will be repelled by the conductor. Here is this situation in the form of maps viewed in the plane (on the surface) and around a single positive current source:
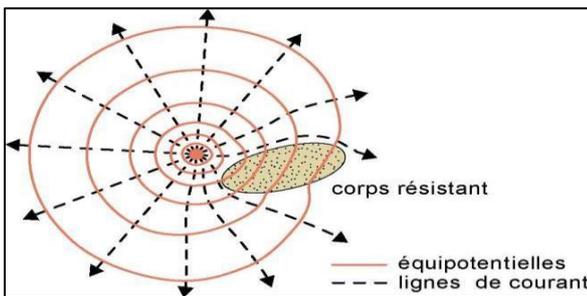
Conversely, for a resistive body, the current streams will tend to go around the resistive obstacles and the equipotentials will tighten in the vicinity and inside this body:

II.2.2.5 Influence of Relief

Topography disrupts the distribution of potentials. The following example shows that the equipotentials will be closer together at valley bottoms and further apart at mountain tops (even though in this example the subsoil is homogeneous!). Note that the equipotentials are perpendicular to the surface. This effect can become problematic in mountainous regions. It also depends on the contrast in resistivities in heterogeneous terrain. When the conductive surface terrain remains on a very resistant substrate, almost all of the current flows are concentrated in the conductor, and even the slightest differences in height will have a significant effect. It is therefore necessary to take the topography into account when interpreting the results.
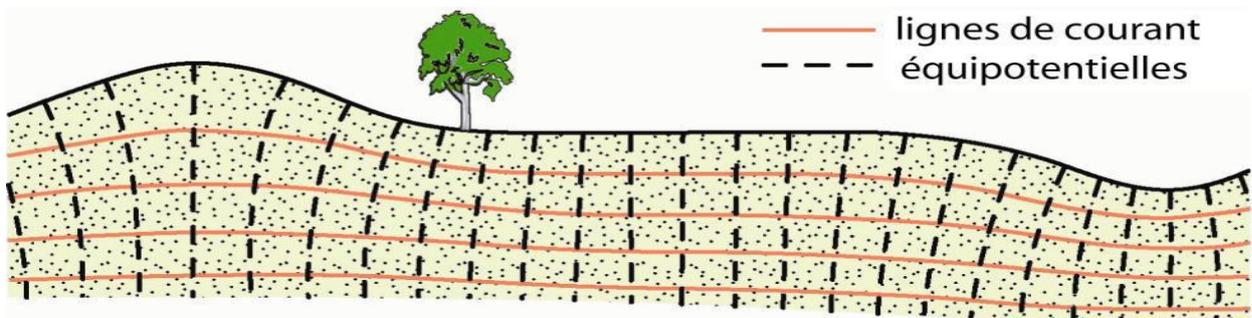

Figure: Model representing the influence of relief on resistivity measurements

II.3 Measurement Technique

II.3.1 The Measuring Quadrupole

We saw above that measuring the resistance between two taps leads to a dead end (we only measure the contact resistance). It is therefore necessary to separate the injection circuitfrom the measurement circuit. In practice, four AMNB electrodes are used for this. If ΔV we close a current circuit I using two electrodes A and B, we can measure the potential difference created by the current flowing between two electrodes M and N.

As we have seen, this must be measured ΔV in the central third of the device (with some exceptions) in order to measure the effect of deep structures and not the direct environment of the electrodes.

A complete measurement circuit then consists of:

II.3.2 The Current Source

We generally use 90-volt dry batteries in series. More rarely, a gasoline generator

coupled with a rectifier or a car battery.

II.3.3 Emission Electrodes A and B

These electrodes are generally made of stainless steel rods.

Current I is measured using an ammeter (ampèremètre).

Current Circuit

These are insulated steel cables.

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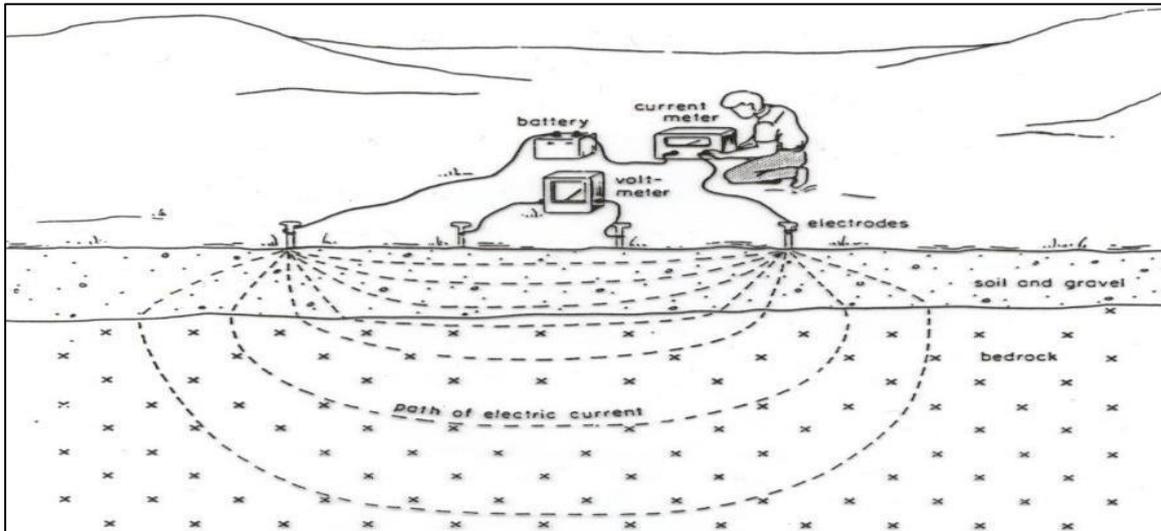*BOUFEDAH BADISSI Mohamed Salah 2025/2026*

22

Figure: Simplified diagram of implementation on the ground

II.3.4 Electrodes for Measuring Potential M and N

While measuring I does not pose any real problems, measuring ΔV is more delicate. Indeed, in the soil, M and N oxidize differently and are polarized. This is referred to as spontaneous polarization of the electrodes. To limit the polarization phenomenon of the electrodes as effectively as possible, chemically stable metals (copper, lead) are chosen. However, due to the different oxidation states on the surfaces of the two electrodes, a potential difference appears between M and N in the absence of any external current. This difference must be eliminated. For example, non-polarizable electrodes are used, but this parasitic potential is most often compensated for using a small adjustable auxiliary voltage source or by repeating the measurements while reversing the polarity of A and B.

II.3.5 Measuring the Potential Difference ΔV

Once this compensation is made, we can measure the ΔV due to the flow of the current sent between A and B. In some cases, the ΔV becomes too small to be measured properly.

This difficulty is overcome as follows:

- Increase the sensitivity of the device
- Increase the distance between M and N. Indeed, on the graph of the evolution of the field and

the potential, we note that enlarging MN corresponds to increasing ΔV. However, a very large MN becomes very receptive to all kinds of stray currents (noise) such as:

- ✓ A variable component of the 50 hertz network
- ✓ Another 16 hertz component coming from the railway lines

✔ Currents that vary greatly over time, non-periodic, due to the activation of various machines
✔ Currents due to natural phenomena, telluric, lightning, etc.

II.3.6 Principle of Reciprocity مبدأ التبادلية

The principle of reciprocity states that in any medium, homogeneous or heterogeneous, isotropic or anisotropic, the potential created at a point M by a current sent to A is equal to that which would be measured at A if M became a source of emission.
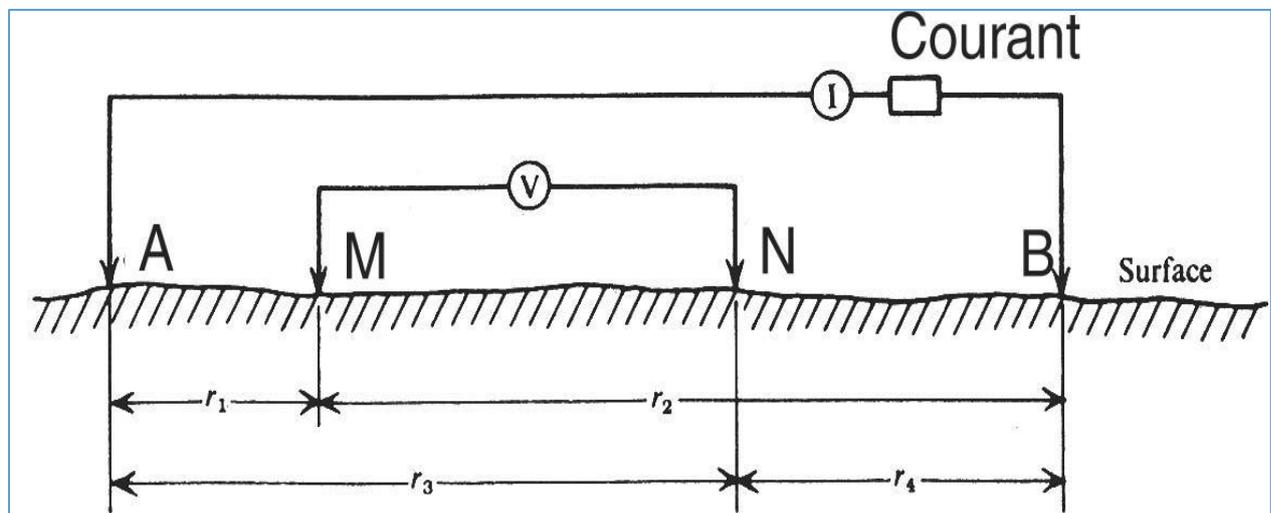
Figure: Dimensioning of the resistivity measuring quadrupole

In practice, the current is sent between two poles A and B and the potential difference

ΔV is measured between the two points M and N. The principles of superposition and reciprocity then show that this potential difference is the same as that which would be observed between A and B if the current were sent between M and N.

Calculating Resistivity and Apparent Resistivity

Having measured ΔV and I, all that remains is to calculate the resistivity. In a homogeneous medium with two poles A and B, the combined action of A and B will give, following the equation obtained above:

potentiel en M

$$V_M = \frac{\rho I}{2\pi}\left(\frac{1}{AM} - \frac{1}{BM}\right)$$

Potentiel en N

$$V_N = \frac{\rho I}{2\pi}\left(\frac{1}{AN} - \frac{1}{BN}\right)$$

ΔV entre M et N

$$\Delta V = V_M - V_N = \frac{\rho I}{2\pi}\left(\frac{1}{AM} - \frac{1}{BM} - \frac{1}{AN} + \frac{1}{BN}\right)$$

and $\quad \rho = K\frac{\Delta V}{I}\quad$ with $\quad K = 2\pi\left(\frac{1}{AM} - \frac{1}{BM} - \frac{1}{AN} + \frac{1}{BN}\right)^{-1}$

ΔV in millivolts, I in milliamps, in ohm.m, K in meters, which is the geometric factor dependent on the spacing between the electrodes.

If the subsurface is homogeneous and isotropic, using this type of device, we will obtain the true resistivity. If, on the other hand, the subsurface is heterogeneous, we will measure the apparent resistivity, which depends on the nature of the subsurface (true resistivity) and the geometry of the device used.

II.4 First electrical prospecting technique: Maps and profiles of apparent resistivities

II.4.1 Principle

The results obtained by maintaining a constant distance between A, B, M, and N, while moving the assembly along a profile, are used to create apparent resistivity profiles and maps. Since a cable is "dragged" across the field, this is also referred to as electrical dragging.

An apparent resistivity map drawn from several profiles is a map of relative anomalies that relates to a substantially constant length and orientation of the entire measuring device. Indeed, a given AMNB line length corresponds to a

roughly constant investigation depth, and therefore to the study of a section of ground of a given thickness and width. Horizontal variations in resistivity will be observed. The dimensions of the device will therefore be chosen according to the problem to be addressed. It is often necessary to draw maps with several line lengths to be able to correctly interpret the results.

II.4.2 Some Devices

A wide variety of devices can be considered to create an apparent resistivity map. Each measuring device actually comprises four electrodes: two, A and B, for sending current (transmission circuit) and two, M and N, for measuring the potential ΔV (measuring circuit).

A. Dipoles or pole-pole
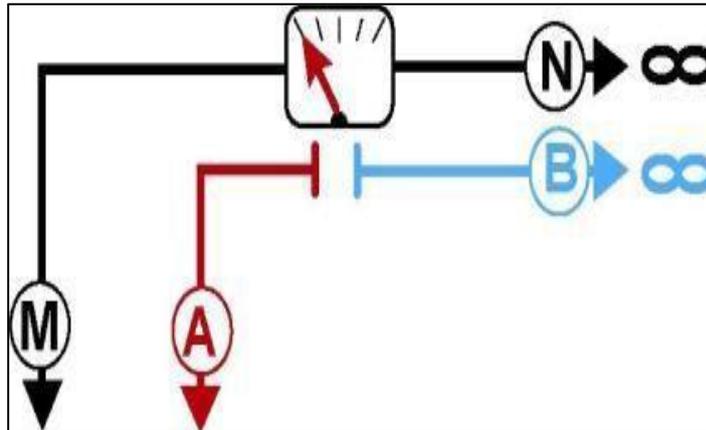
Electrodes B and N are placed at "infinity" (in theory); only A and M are considered. This device is theoretically simple since the potential measured at M is due to A alone. In practice, h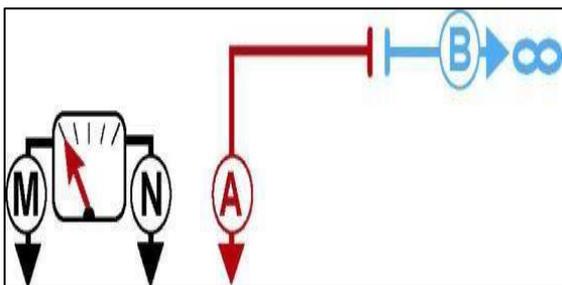owever, this device is cumbersome due to the length of the cables required to negligible the effect of the electrodes placed at "infinity" (in reality, very far from the measurement site, since four electrodes are always needed to complete the circuit).

B.\ Tripoles or Pole-Dipoles

Tripoles have the advantage of requiring the movement of only three electrodes and less cable length, which can sometimes be advantageous. However, their asymmetrical nature generally makes them preferable to complete quadrupoles.

C.\ Complete Quadrupoles

In most quadrupoles used, the four electrodes are arranged in the same alignment. The two measuring electrodes M and N are most often within the interval AB and are generally symmetrical about the midpoint O of this interval. The three most commonly used quadrupoles are:

- **The Wenner alpha:** all electrodes are equidistant, AM = MN = NB = AB/3
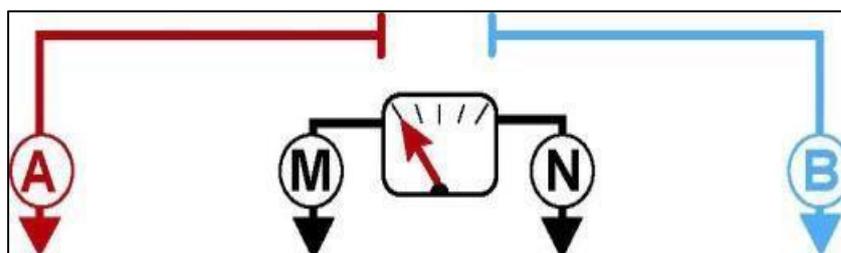
- **The Schlumberger**: The distance MN is small compared to AB. In general MN < AB/5

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BOUFEDAH BADISSI Mohamed Salah 2025/2026

26
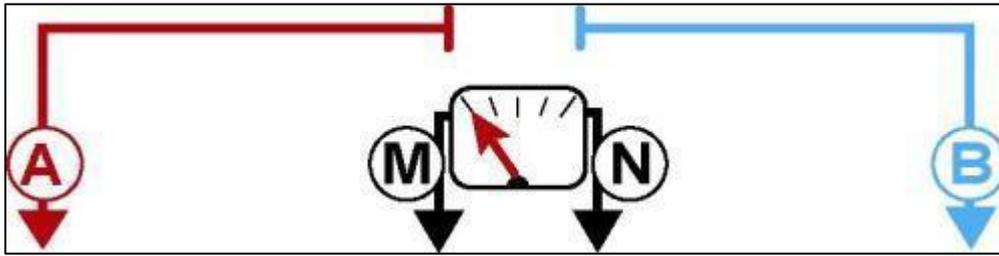
The dipole-dipole: The MN dipole is outside the AB dipole

The dipole-dipole is a device where MN is outside AB. The advantage of this is that it requires only very short cable lengths for a given investigation depth. However, it requires very sensitive equipment, because while the investigation depth increases with the distance between A and B, the ΔV measured between M and N decreases with the cube of this distance (in a Schlumberger, the ΔV decreases with the square of this distance).

These three quadrupoles also differ in their ability to image horizontal (slab) or vertical (wall) structures. A Wenner will be more sensitive to a vertical variation in resistivity (well-suited for detecting horizontal structures such as slabs), while a dipole-dipole will be influenced by a horizontal variation in resistivity (well-suited for detecting vertical structures such as walls). A Schlumberger exhibits intermediate behavior. This is especially true at a great distance from the electrodes.

II.4.3 Multiple dragging (Le traîné multiple)

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BOUFEDAH BADISSI Mohamed Salah 2025/2026

27

Measurements with a single length of line are often insufficient, especially since their investigation depth can vary with the succession of resistivities in the subsurface. Instead of repeating measurements several times, simultaneous trails can be used over several lengths of line. The same MN is used successively to measure **ΔV** for the current transmission between A', B', and AB. The entire device is then shifted along the profile. Of course, these multiple devices require the use of special cables with multiple conductors, and many other configurations are possible.
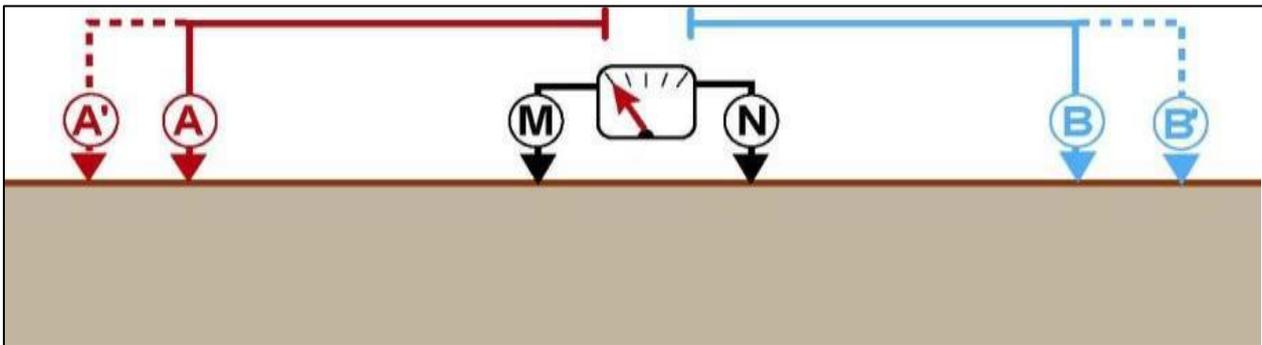
The **following figure** shows an example of a "Twin Probes" device that allows multiple resistivity measurements to be performed using only five electrodes. Note that electrodes A, B, M, and N are swapped for each measurement. A total of six apparent resistivity maps can be measured in a single setup (four pole-pole, one Wenner, and one dipole-dipole).

A single person can perform these measurements by simply moving the device along thea series of profiles. A multiplexer allows rapid switching from one device to another, which makes the measurement fast.

II.4.4 Device Investigation Depth

The figure below gives the investigation depths and resolving power for some devices. According to Roy, the investigation depth is the depth of the infinitely thin layer that contributes most to the potential measurement.

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BOUFEDAH BADISSI Mohamed Salah 2025/2026

28

For Barker, it is the depth at which the portion of terrain located above this limit has the same influence as the portion of terrain located below it ("median investigation depth").
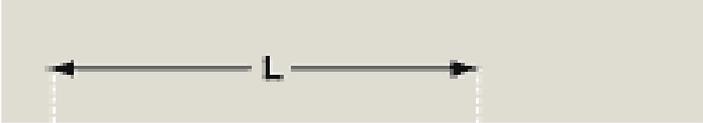

Dispositifs	L	Prof. d'investigation	
		Roy (1971)	Barker (1989)
Wenner		0.11L	0.17L
Schlumberger		0.125L	0.19L
Dipôle-Dipôle		0.195L	0.25L
Pôle-Pôle		0.35L	

Figure II.11 : relation entre dispositifs et profondeur d'investigation et pouvoir de résolution

Note that resolving power and investigation depth vary inversely. For the dipole-dipole, the investigation depth depends on the spacing between the two outermost electrodes.

II.4.5 Measurement Spacing (Espacement des mesures)

Whether using either of these devices, the entire system is moved along the alignment of the electrodes while dragging the entire cable assembly. The interval between successive measurements will depend on the precision with which accidents are to be located. It is generally equal to AB for reconnaissance studies; for precision studies, a measurement interval equal to MN can be used, which leads to a continuous exploration of the profile. The same work is then repeated on parallel and equidistant profiles. Here again, the distance between profiles will depend on the precision; this distance can be greater than or equal to the distance between successive measurements. Most often, the profiles will be oriented normally to the direction of the structures being studied.

II.4.6 Interpretation of Profiles and Apparent Resistivity Maps

The representation of the results obtained poses no particular problem. For symmetrical devices, the apparent resistivity value obtained is plotted at the center of the device. In

the case of asymmetrical devices, such as external MNs, the results are plotted vertically above the center of the MN electrodes. This convention is arbitrary. The results of a set of profiles are represented in the form of apparent resistivity maps, each corresponding to a well-defined line length that must be indicated. At the locations of all MN centers, the apparent resistivity value obtained is recorded, and curves of this apparent resistivity are then interpolated between the measurement points.

It is important to have the raw data (the data sheet, with the line length, measurement spacing, and measured values) available at all times. The file should also include a location plan of the study with the scale, coordinates, topographic information, etc. In all cases, an apparent resistivity map must be accompanied by the length of the AB line used, the scale, measurement spacing, and a legend to locate the study.

The interpretation of apparent resistivity maps and profiles is essentially qualitative. It is often beneficial to create several resistivity maps for the same region with AB devices of different lengths, with the smaller ones highlighting the action of the surface terrain and the larger ones for exploring the subsurface more deeply. This allows us to obtain additional qualitative information on the variation of resistivity with depth. In the case of measurements carried out with mobile devices, the large amount of data collected may require computer and statistical processing to filter the data.

Below is a schematic example of resistivity profiles for a very simple geological model (3 layers).

The relationship between the evolution of apparent resistivity and the geology in the subsurface is clearly visible(for example, the ditch filled with material of resistivity 2 cannot be detected with the short line length AB, but is clearly visible with a longer AB).

The apparent resistivity maps or profiles that reflect the results are similar to the maps taken by geologists, except that these are no longer purely superficial observations but rather the measurement of a physical parameter of interest, on average, over a slice of ground of a certain thickness.

It is often useful to measure apparent resistivities on the same profile with several line lengths. This gives results for several slices of soil, some thicker than others.
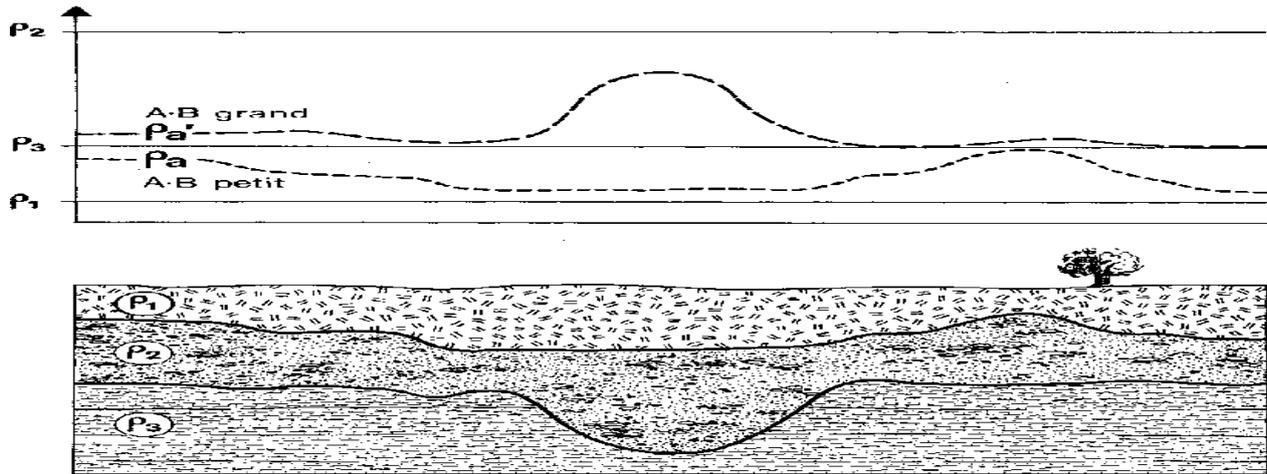
Figure: Example of electrical response to a geological model

Resistivity maps have the advantage of allowing **continuous exploration**, which can be very useful for detailed studies such as the identification of fractured zones in village hydraulics in basement areas in Africa, for example. It is a very useful method in reconnaissance studies aimed at highlighting anomalous zones that can then be studied in more detail. Its usefulness is also evident when locating shallow **faults or facies variations: faults, conductive pockets, the nature of alluvium, etc.**

This method also makes it possible to interpolate the values of a parameter, resistivity or depth, precisely determined at a number of isolated points: boreholes, outcrops, electrical soundings. In certain simple cases, it is even possible to provide isobath maps, such as the bedrock roof under a cover using two different line lengths.
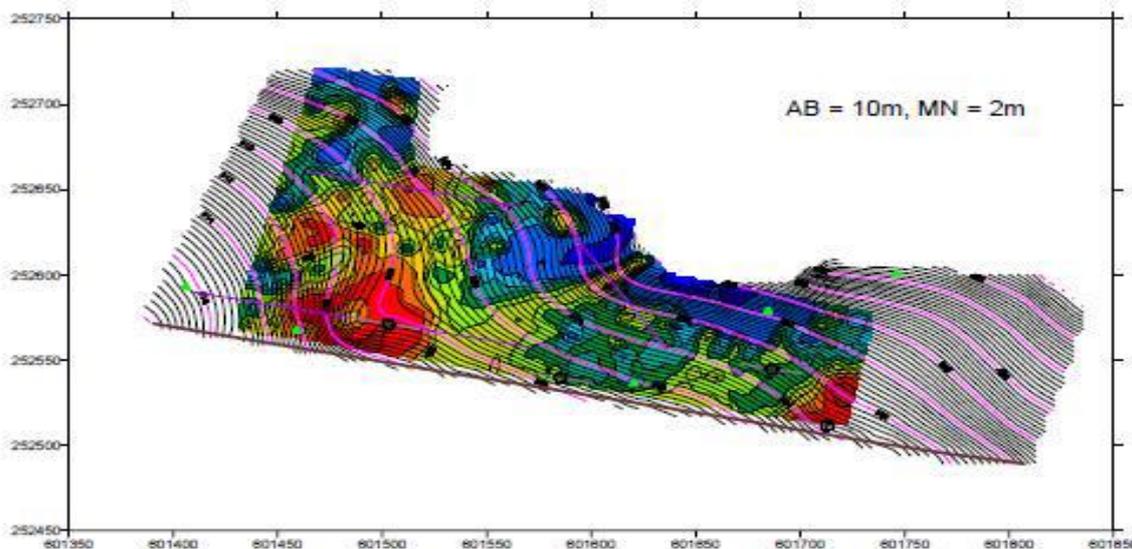

Figure: Example of an apparent resistivity map (Basel 1999, AB = 10 m) in a karst environment. Low resistivities reveal different flow directions that are invisible on the surface.

II.5 Second electrical prospecting technique: vertical electrical surveys

II.5.1 Principle

When performing an electrical survey, we investigate how the subsurface resistivity varies vertically at a given point on the surface. To do this, a series of measurements are performed at the same location, each time increasing the dimensions of the device and thus the investigation depth, which is proportional (the longer the device, the deeper the current propagates). At this location, an increasingly thicker section of the ground is explored, thus highlighting changes in the geological structure along the vertical axis.

Measurements can be made with conventional devices, such as Schlumberger, Wenner, dipole-dipole, etc. In practice, however, only symmetrical quadrupoles are used, most often the Schlumberger device. In practice, the distance MN is kept fixed and as small as possible for a certain number of measurements, thus reducing manual labor. However, it is hardly possible to conduct a complete survey with a single MN position, as for very long line lengths the measured ΔV would be too small. This MN distance must therefore be increased from time to time.
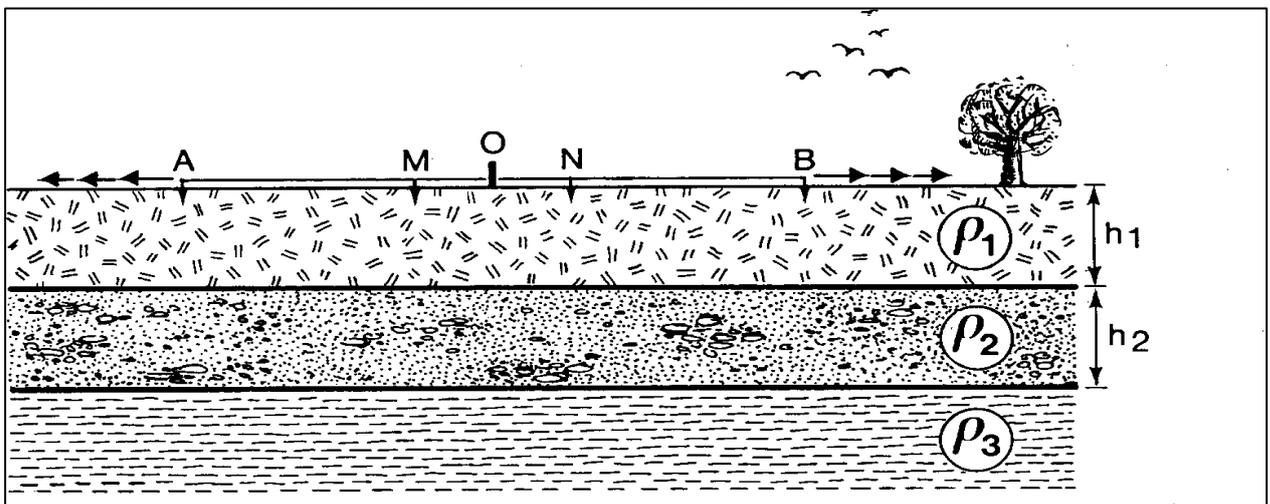

Figure: Implementation of an electrical survey

The measured apparent resistivity ρ_a is plotted as a function of the device spacing (OA) on logarithmic paper, where the two axes are plotted on logarithmic scales (see figure below). The resulting curve is called the "electrical sounding curve." Various interpretation methods can be used to reconstruct a geoelectrical cross-section of the subsurface from this curve, where each formation is defined by its thickness and true resistivity.

This method is only applicable with any rigor when the ground consists of laterally uniform horizontal layers. Indeed, for an electrical sounding to reflect resistivity variations with depth, the measurements must not be affected by horizontal variations. It is therefore important when performing electrical soundings to avoid horizontal variations in resistivity as much as possible. Apparent resistivity maps prepared beforehand allow for the judicious placement of electrical soundings.

The figure below illustrates an acquisition sheet for an electrical survey. It shows the columns intended to receive the measured ΔV and I values. The geometric factor is given for different MNs, the consistency of the measurements.

ETUDE : _____   SONDAGE   N° : _____

DATE : _____   COORDONNEES : _____

OPERATEUR : _____   COTE : _____

$k = \dfrac{AM \cdot AN}{MN} \cdot 3{,}14$ $Pa = k \dfrac{\Delta V}{I}$

k pour

MARQUES	O·A en m	M____N 1 m	M____N 10 m	M____N 60 m	M____N 200m	ΔV en millivolts	I en milliampères	Pa 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	4660				
2	350			6360	1766			
3	400			8300	2360			
1	450			10500	3000			
2	500 m			13000	3760			

Figure: Vertical Electrical Survey Sheet

II.5.2 Different Types of Electrical Soundings (Survey)

The shape of the curves obtained by electrical sounding over stratified media is a function of the resistivity, the thickness of the layers, and the configuration of the measuring device.

II.5.2.1 Homogeneous and Isotropic Media

If the media consists of a homogeneous, isotropic layer of infinite thickness and finite resistivity, the measured apparent resistivity will be a straight line whose ordinate is the resistivity 1 of this media.
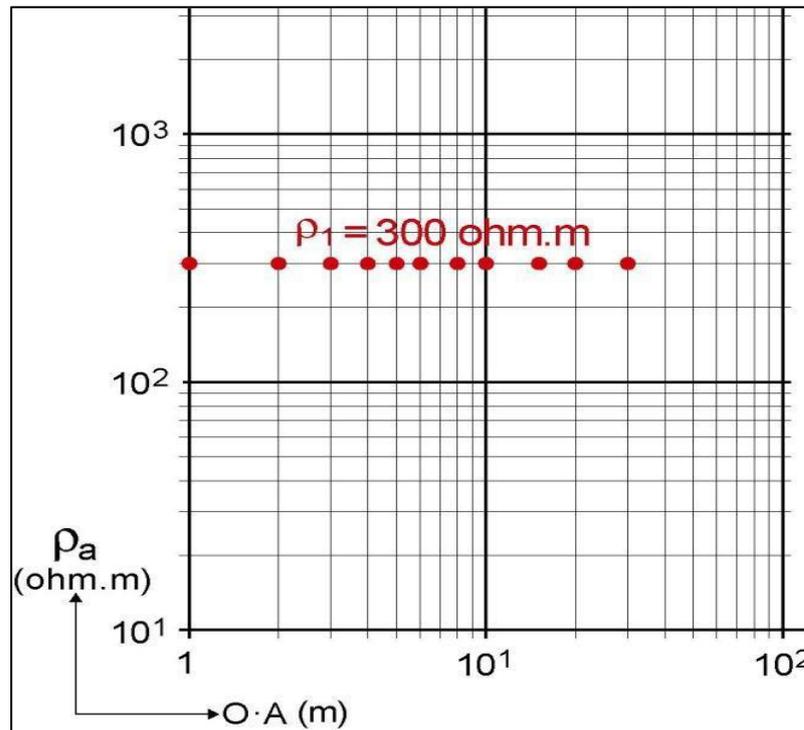

Figure: Survey curve for homogeneous terrain

II.5.2.2 Two-Layer Medium

If the subsoil is composed of two layers, a first layer of thickness h1 and resistivity ρ_1 overlying a substratum of infinite thickness and resistivity ρ_2, then the electrical sounding begins, for small spacings, with a portion of a straight line where the apparent resistivity ρ_1 is more or less equal to the resistivity ρ_2 of the first substrate.

Then, as the spacing increases, the curve rises or falls depending on ρ_2 whether is greater or smaller than and ρ_1 finally reaches an asymptotic value, which is that of ρ_2. The spacing OA at which the value of ρ_2 is reached depends on three factors:

- The thickness of h1
- The value of the resistivity ratio
- The device used.

....
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34

The effect of the thickness of h1 is quite obvious. The greater the thickness of the first layer, the greater a spacing will be required to obtain the resistivity of the second layer. This is true for any device and for any ratio of ρ_2/ρ_1. However, regardless of the device used, larger OA are required to obtain the resistivity ρ_2 of the second layer when ρ_2 it is $(\rho_2/\rho_1 > 1)$ resistant ρ_2 than when it is $(\rho_2/\rho_1 < 1)$ conductive. The current is indeed channeled in the first layer if .

To interpret the electrical sounding (i.e., to obtain the true thicknesses and resistivities of each layer from the measured apparent resistivities), two methods are used: the first is graphical, and the other uses an inversion (modeling) program called Winsev or others.

Both interpretation methods are based on solving the general potential equationon the surface of two parallel, homogeneous, and isotropic terrains, a series of curves representing the apparent resistivity can be constructed, called the CH-1 Abacus.

$$\frac{\rho_a}{\rho_1} = 1 + 2\sum_{n=1}^{\infty} \frac{K^n L^3}{[L^2 + (2n)^2]^{\frac{3}{2}}}$$

Avec, $K = \frac{\rho_2 - \rho_1}{\rho_2 + \rho_1}$ et $L = \frac{OA}{h_1}$

Ainsi on a, si $\rho2 = \rho1$, $K = 0$ et $\rho a = \rho1 = \rho2$

Si $OA \rightarrow 0$, $L \rightarrow 0$ et $\rho a = \rho1$

Si $OA \rightarrow \infty$, $L \rightarrow 0$ et $\rho a = \rho2$

The set of these curves is called the **CH1 chart** (Figure). These curves represent $\rho a/\rho1$ as a function of OA/h1 for different values of ρ_2/ρ_1 (OA = AB/2). These curves are plotted on a bilogarithmic scale. Each curve in this chart corresponds to the curve of an electrical sounding carried out on a subsurface composed of two layers where the first layer has unit thickness and resistivity.

Recall that an electrical sounding consists of a series of apparent resistivity measurements carried out with progressively increasing lines, the center and direction of the device remaining fixed. The variation in the apparent resistivities obtained is essentially due to the increasing current penetration.
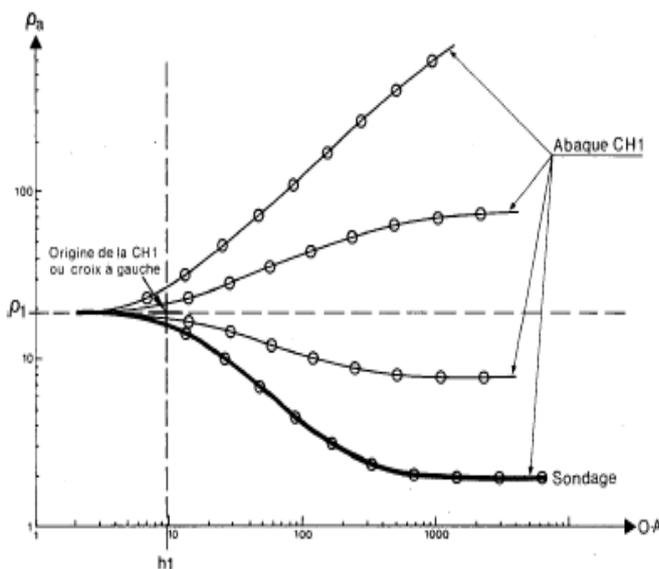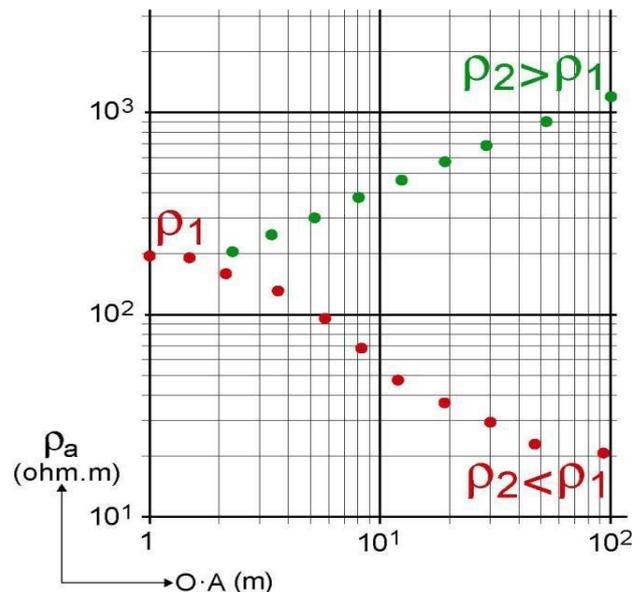

Figure: Two-layer sounding curves
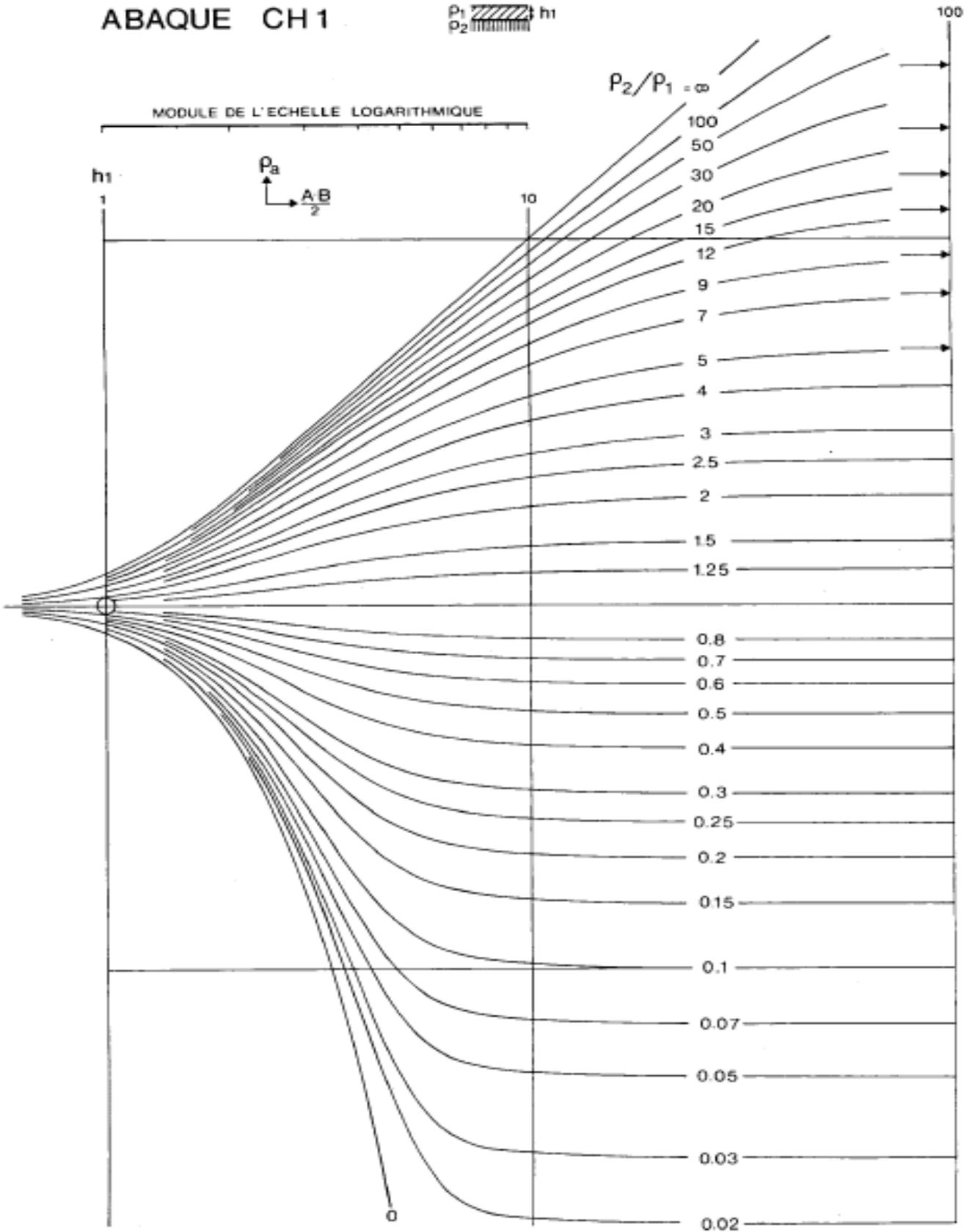
Figure: CH-1 abacus
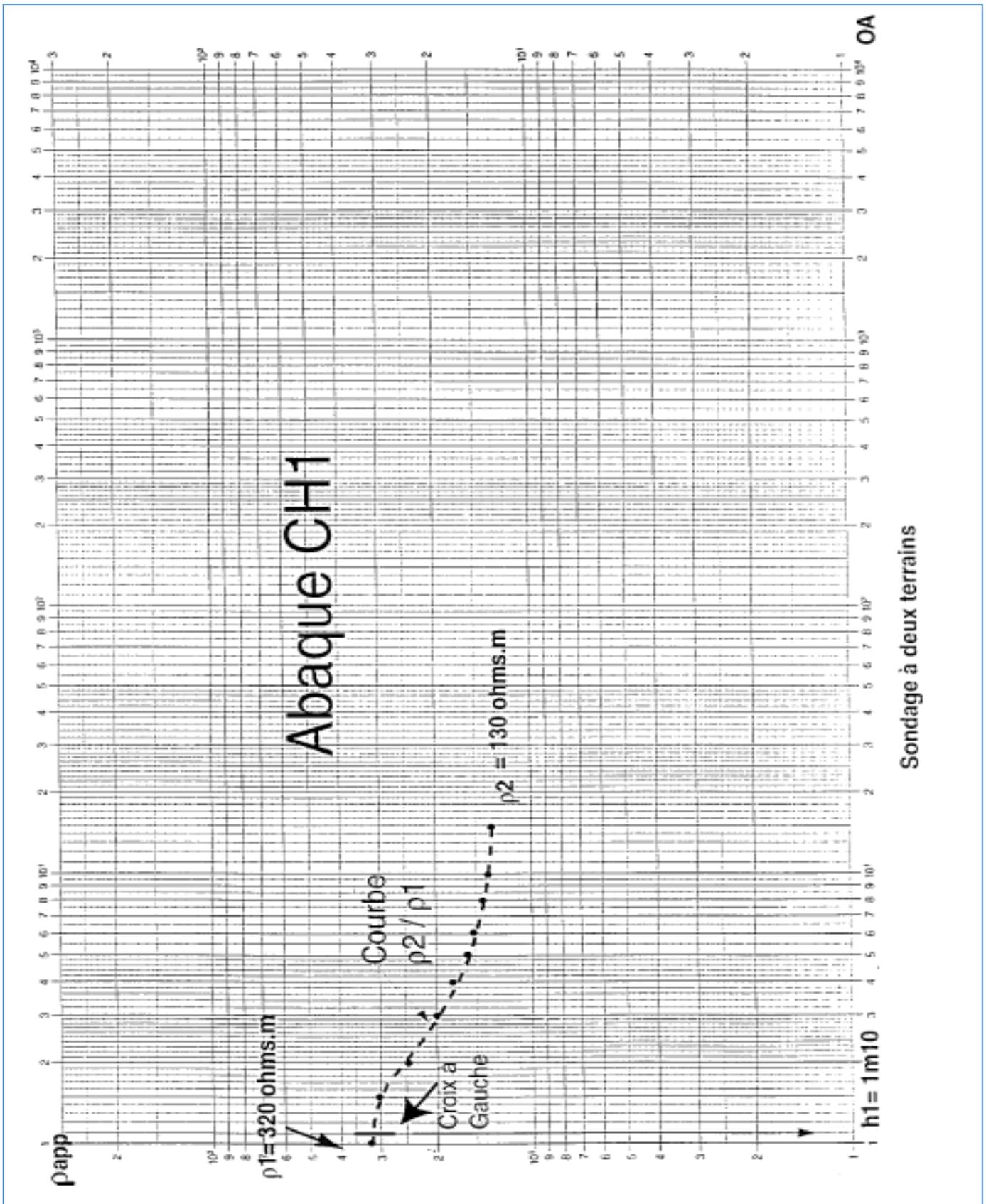
Figure: Bilogarithmic Sheet

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II.5.2.3 Three-layer medium (and more...)

If the subsoil is composed of three layers of resistivity ρ_1, ρ_2, ρ_3 and thickness h1, h2, then four possible combinations exist (figure below):

- Conductor between two resistors, type **H** borehole
- Resistivity between two conductors, type **K** borehole
- Resistivity increasing in stages, type **A** borehole
- Resistivity decreasing in stages, type **Q** borehole

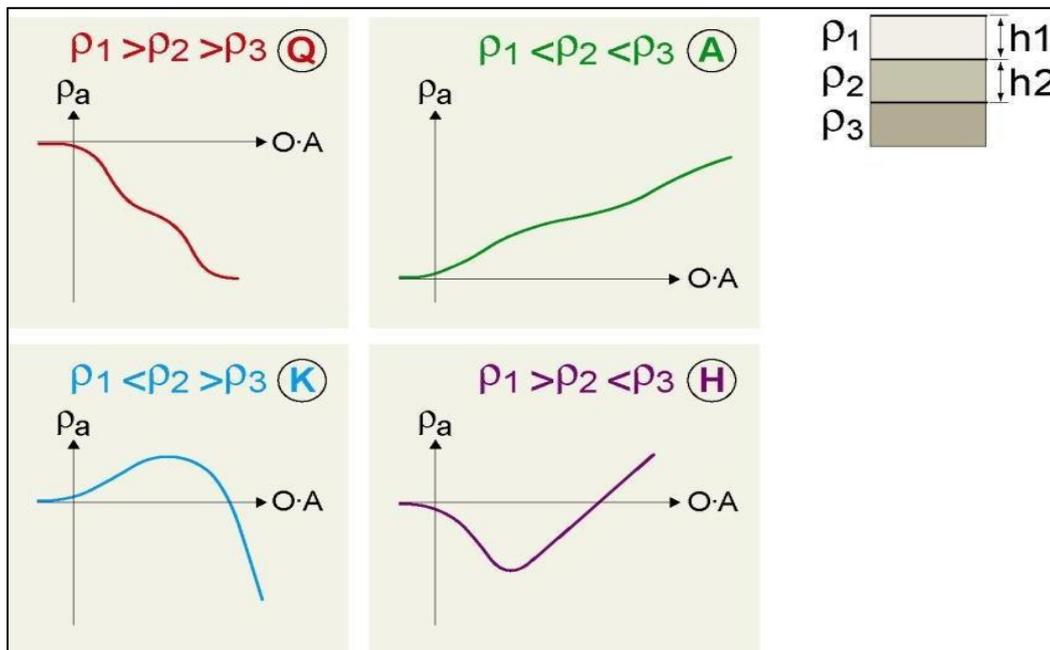Again, a program must be used to interpret these multi-layer boreholes.

Figure: Electrical sounding curves for three layers

II.5.3 Interpretation of Electrical Soundings

Electrical sounding interpretation programs are available free of charge on the Internet.

These programs allow for automatic interpretation (inversion by iterations).

The measured apparent resistivities (field data) are plotted in graph (A) in the following figure. The goal of this operation is to create a model of the subsurface consisting of a succession of horizontal layers, each with a specific resistivity and thickness (B), and then to calculate the response of this model (C). This is the model's response, or the calculated apparent resistivities (based on the model). The interpretation is only correct when the curve calculated for the model coincides with the field measurements. In this case, the model is a possible approximation of the subsurface reality because it generates data similar to the measured data.

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BOUFEDAH BADISSI Mohamed Salah 2025/2026

38

However, the inversion must first be constrained in terms of resistivities and thicknesses, which are the a priori information (data measured on outcrops, boreholes). Without constraints, the inversion algorithm only seeks to converge toward a minimal error between the apparent resistivities measured and calculated on its model, sometimes to the detriment of geological relevance (infinitely conductive or excessively thin layers).
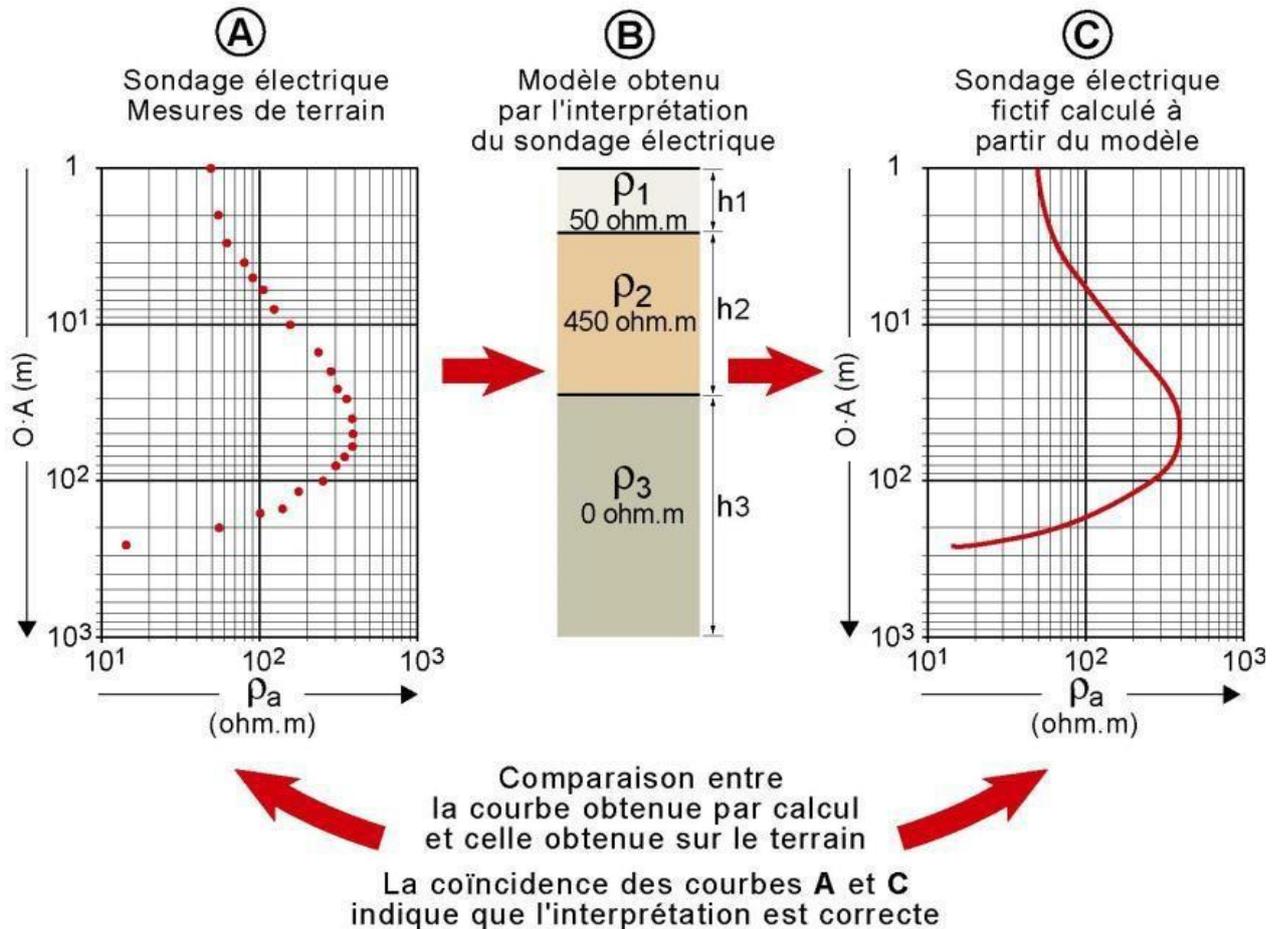

Figure: Inversion of electrical sounding data

An electrical sounding curve with measurements containing noise can correspond to very different distributions of resistivities and thicknesses, which can lead to uncertainty. The interpretation is multifaceted (several possible solutions). This uncertainty manifests itself in two specific forms, known as the principle of equivalence (the impossibility of independently determining the resistivity and thickness of a layer, under certain conditions of resistivity contrast) and of suppression (a layer of intermediate resistivity may disappear). A priori information (e.g., outcrop measurements) is often necessary to correctly interpret electrical soundings.

The figure below shows an example of an electrical sounding carried out in the Fribourg region (Grangeneuve). The measurements are marked by black dots and the curve calculated on the model

by a black line. The geological model, in terms of resistivities and depths, is given below the figure. We can clearly see the conductive soil, then the more resistant gravel, and finally the more conductive Burdigalian Molasse.
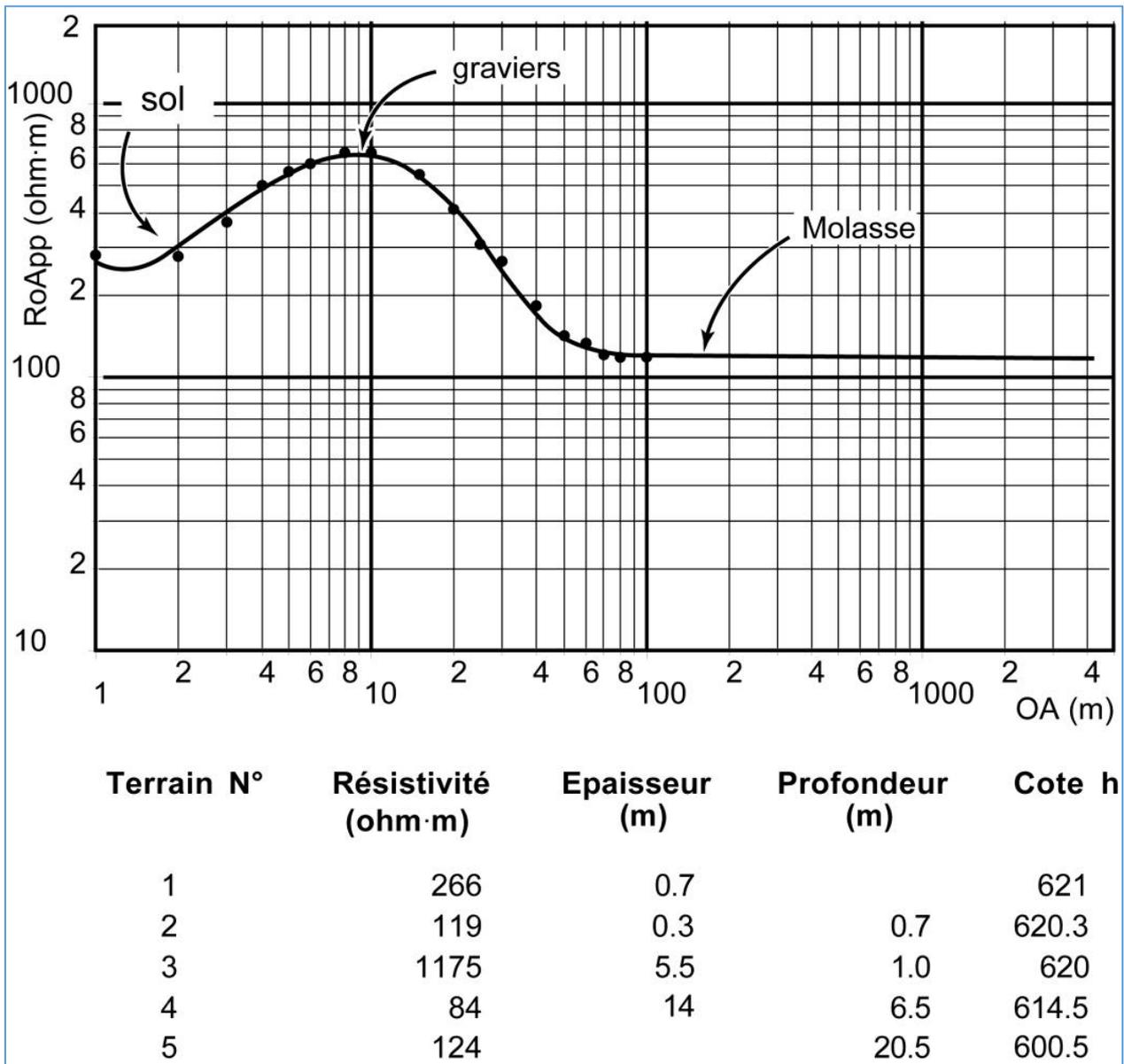
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BOUFEDAH BADISSI Mohamed Salah 2025/2026

39

Terrain N°	Résistivité (ohm·m)	Epaisseur (m)	Profondeur (m)	Cote h
1	266	0.7		621
2	119	0.3	0.7	620.3
3	1175	5.5	1.0	620
4	84	14	6.5	614.5
5	124		20.5	600.5

Figure: Interpreted vertical electrical survey

II.6 Third Electrical Prospecting Technique: Electrical Tomography (Imagery)

II.6.1 Purpose of Electrical Tomography (Imagery)

One of the limitations of electrical surveys is that they do not take into account lateral variations in subsurface resistivity. The electrical tomography method (sometimes called electrical imaging, or ERT) was developed to obtain a model of the subsurface in which the resistivity distribution varies vertically and horizontally. In the case of 2D tomography, it is assumed that the resistivity does not change in the direction perpendicular to a profile. This assumption is reasonable for many elongated bodies (e.g., walls), and in this case, the method can be applied. It will then be necessary to attempt to place the profiles perpendicular to the body to be studied, which will also allow us to determine the true dimensions of this body. For more complex subsurface geometry, a 3D survey should be used. While a few dozen points are used for a survey, between 100 and 1,000 will be required for a

2D profile and several thousand for a 3D acquisition. This development, while enabling a considerable improvement in our knowledge of the subsurface, poses several problems: the long acquisition time, the relatively high cost of the equipment, and the interpretation of the increasingly large amount of data.

2D tomography therefore currently appears to be a good compromise between obtaining reliable data

while maintaining reasonable acquisition and processing costs.

II.6.2 2D Measurement Procedure

A 2D acquisition generally uses a large number of electrodes connected to a multi-conductor cable and positioned along a profile. A laptop computer, in which the measurement sequence is programmed (or a resistivity meter with a hard drive), is connected to a switching box and automatically selects the electrodes used for current injection and potential measurement (figure below). Each electrode has a unique digital address in the device, allowing it to be identified by the computer. The measurement sequence is generally created as a text file containing various information. The formats of these files depend on the manufacturer. The multi-conductor cables are connected to the switching box. Galvanic contact with the ground is ensured using metal stakes (stainless steel) or special electrodes that eliminate spontaneous polarization. A constant spacing is generally used from one electrode to the next.
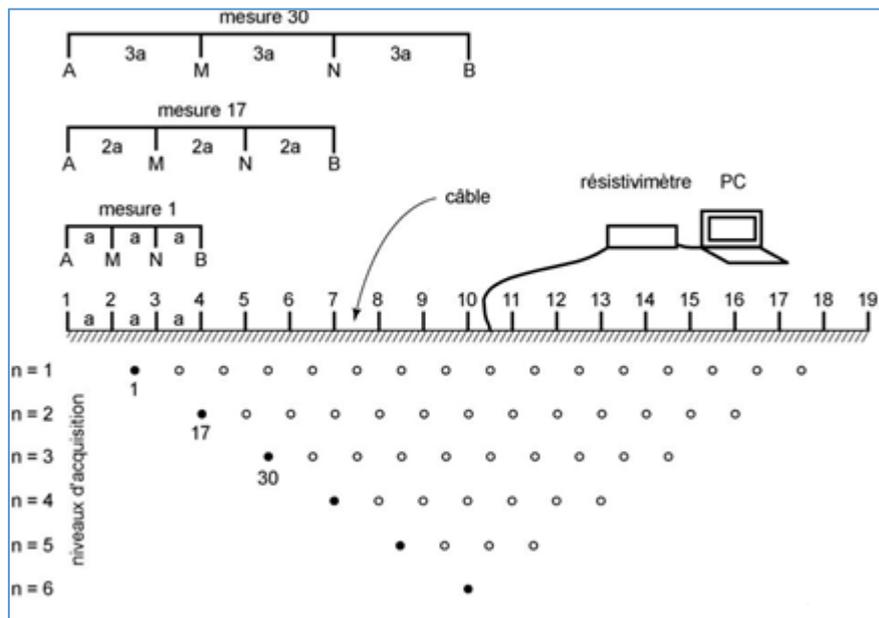

Figure: mise en oeuvre d'une Tomographie 2D

When the acquisition is launched, the program automatically selects the electrodes used for current injection and potential measurement based on the programmed measurement sequence.

The measurement is then stored in the computer's (or resistivity meter's) memory.

To obtain a good 2D image of the subsurface, the measurement coverage must be

also 2D and uniform. Let's take a Wenner device with 19 electrodes as an example. The distance between two electrodes is denoted a. In a Wenner device (figure below), the first measurement in the acquisition file will be made using electrodes 1, 2, 3, and 4; electrodes 1 and 4 will be used for current injection (A and B), and 2 and 3 for potential measurement (M and N). The entire device will then

move by switching through a distance a. Electrodes 2 and 5 will then be used to inject the current, and 3 and 4 will be used to measure the potential. The process is repeated up to electrode 19. Therefore, for the first acquisition level, there are 16 possibilities (19-3).

Since the Wenner device maintains a constant distance between all electrodes, we will therefore use a distance equal to 2*a for the next level. The first measurement of the second level will therefore involve electrodes 1 and 7 for current injection and 3 and 5 for potential measurement. The process is repeated again up to electrode 19. The second level will then include 13 possibilities (19-2*3). Measurements for each acquisition level are thus performed with 3*a, 4*a, etc. (there are 6 for 19 electrodes in Wenner). It is obvious that the greater the inter-electrode distance, the smaller the number of possibilities. The number of measurements will depend on the type of device used. To obtain good results, it is essential to perform measurements systematically to avoid areas without measurements. The Wenner device has the lowest number of measurements compared to other commonly used devices.
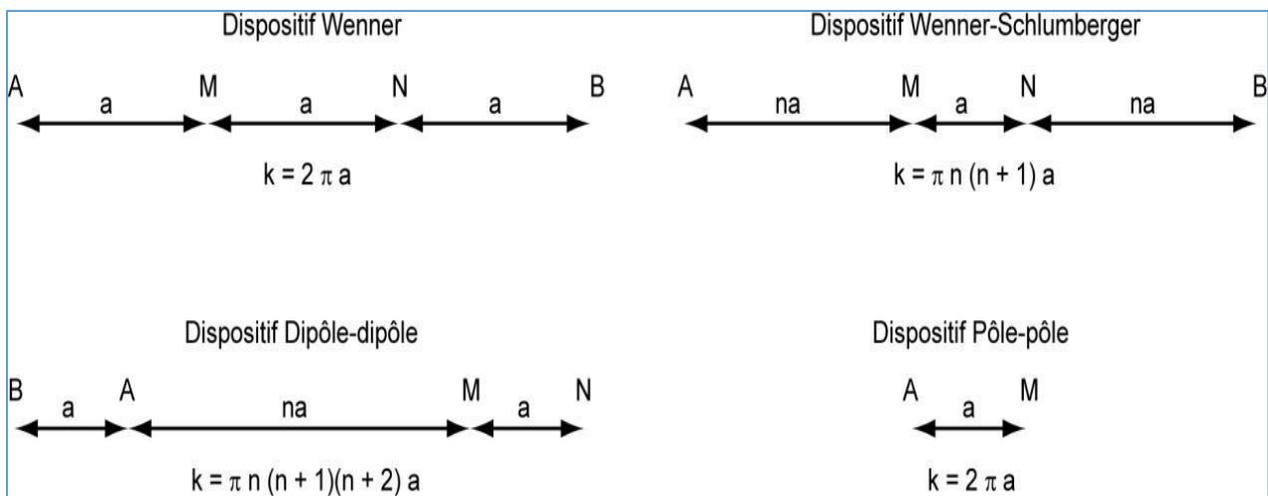

Figure: Devices used in electrical tomography

For the pole-pole system, a procedure similar to the Wenner method is used. For a system with 19 electrodes, 18 measurements are first made with a distance of 1*a between A and M, then 2*a, and so on.

For a dipole-dipole, a Wenner-Schlumberger, or a pole-dipole system, the measurement sequence is slightly different (see figure below). For a dipole-dipole, for example, measurements usually begin with a distance of 1*a between the current injection (A and B) and potential measurement (M and N) electrodes. The first measurement sequence is then performed by giving a value of 1 for the factor n (which is the ratio AM/MN) and then a value of 2 while keeping the distance AB and MN fixed at 1*a. When n is 2, the distance AM is therefore twice the distance AB (or MN). For subsequent measurements, the value of n is usually

incremented up to 6. From n=6, the measured potential value is no longer accurate because it is too low. To increase the depth of investigation, the distance AB is increased to 2*n and the same measurement sequence is performed in a similar manner. If necessary, this operation can be repeated.

For the Wenner-Schlumberger and a pole-dipole, different combinations of a and n are used. It is therefore clear that in the case of a Wenner-Schlumberger, the exact type of device will therefore be somewhere between a Wenner in the strict sense and a Schlumberger device.

BOUFEDAH BADISSI Mohamed Salah 2025/2026

II.6.3 3D Measurement Procedure

Given that geological and archaeological structures are naturally 3D, a true 3D device should yield better results. However, this type of acquisition has not yet reached a level of development equivalent to that of 2D. A 3D acquisition requires more data and is therefore more expensive. However, there are two main developments currently making 3D studies possible. These are the recent emergence of multi-channel resistivity meters, which allow multiple measurements to be taken simultaneously, and the rapid advancement of computer hardware, making it possible to process a large amount of data in a reasonable amount of time. The procedure described for 2D acquisitions remains valid in 3D. However, the electrodes are usually arranged in a square or rectangle on the surface (although this is not mandatory). The shape of the grid can therefore vary depending on the shape of the body being studied. The interelectrode is also identical along the x and y axes of the device (figure below). Pole-pole, pole-dipole, and dipole-dipole devices are mainly used in 3D surface tomography. Other devices have insufficient data coverage towards the edges of the grid.
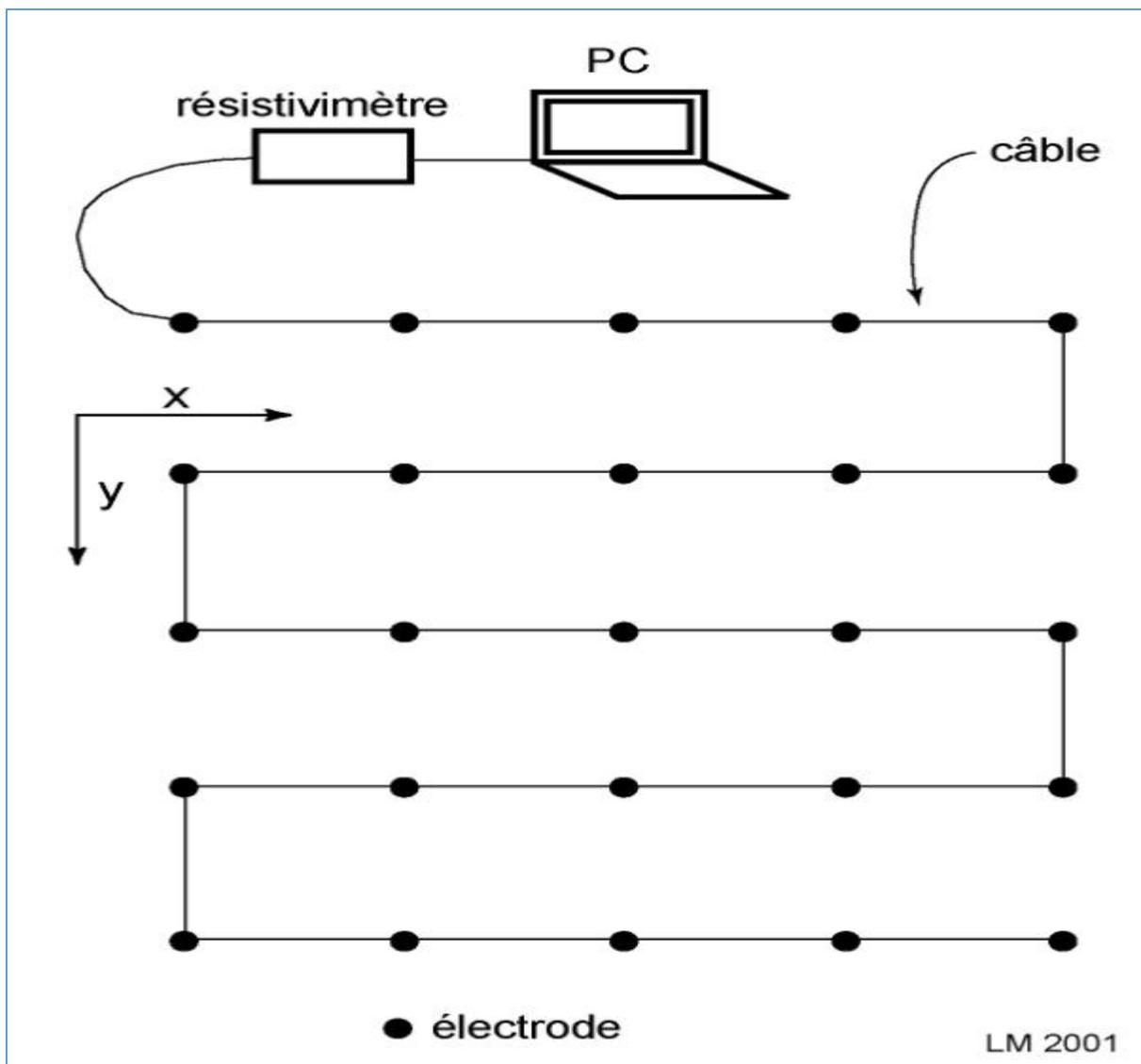

Figure: Procedure for implementing 3D tomography

BOUFEDAH BADISSI Mohamed Salah 2025/2026

II.6.4 Pseudo-sections

Measurement points are usually represented in 2D in the form of pseudo-sections (electrical cross-sections of the subsurface in apparent resistivities). The measurement points are plotted perpendicular to the center of the device and at an arbitrary depth proportional to the distance separating the electrodes.

A pseudo-section produces a distorted image of the subsurface because this image depends on the distribution of resistivities in the soil but also on the device used (concept of apparent resistivities). A pseudo-section is therefore only a convenient way to represent apparent resistivities. It is therefore completely incorrect to use a pseudo-section as a final image of the true resistivity of the subsurface! This pseudo-section must be interpreted (inverted, see below). One of the uses of the pseudo-section is the ability to eliminate incorrect apparent resistivity data from these profiles. These are marked by points of apparent resistivity that are abnormally high or low compared to the surrounding points.

The figure below shows the pseudosections obtained with three different devices on a model consisting of two identical bodies (walls), infinitely long perpendicular to the device and four times their width apart. The figure allows for some interesting observations. The shapes generated by an identical object differ greatly depending on the device used. This is why it is almost impossible to correctly interpret a pseudosection. The number of measurement points and their location also vary with the different devices. This phenomenon is clearly visible by comparing the acquisition performed with Wenner and the dipole-dipole. The apparent resistivity values of the anomaly are very low, despite the high resistivity of the two bodies (800 Ohm.m) and an environment at 30 Ohm.m.

II.6.5 Interpretation of Electrical Tomography

The interpretation of the data (i.e., the determination of a model from the measurements)

is called inversion. The inversion method is described schematically here. A starting model (composed of blocks or cells of homogeneous resistivity) is first developed either automatically from the measured apparent resistivity data or from a priori information entered by the user. The program then calculates the response of this model by solving the direct problem (i.e., the calculation of apparent resistivities calculated from the model's true resistivities, by numerically simulating the same series of field measurements on the model) (step 1). The algorithm then determines the degree of difference between the measured and calculated apparent resistivities on the model (step 2).

The model is then modified to minimize this degree of difference (error) (step 3). The operation is then repeated iteratively until the process converges (the error no longer decreases significantly). In this case, the model is a possible approximation of the actual subsurface. The model is represented in the form of blocks or sometimes in a smoothed form (contouring the block values).
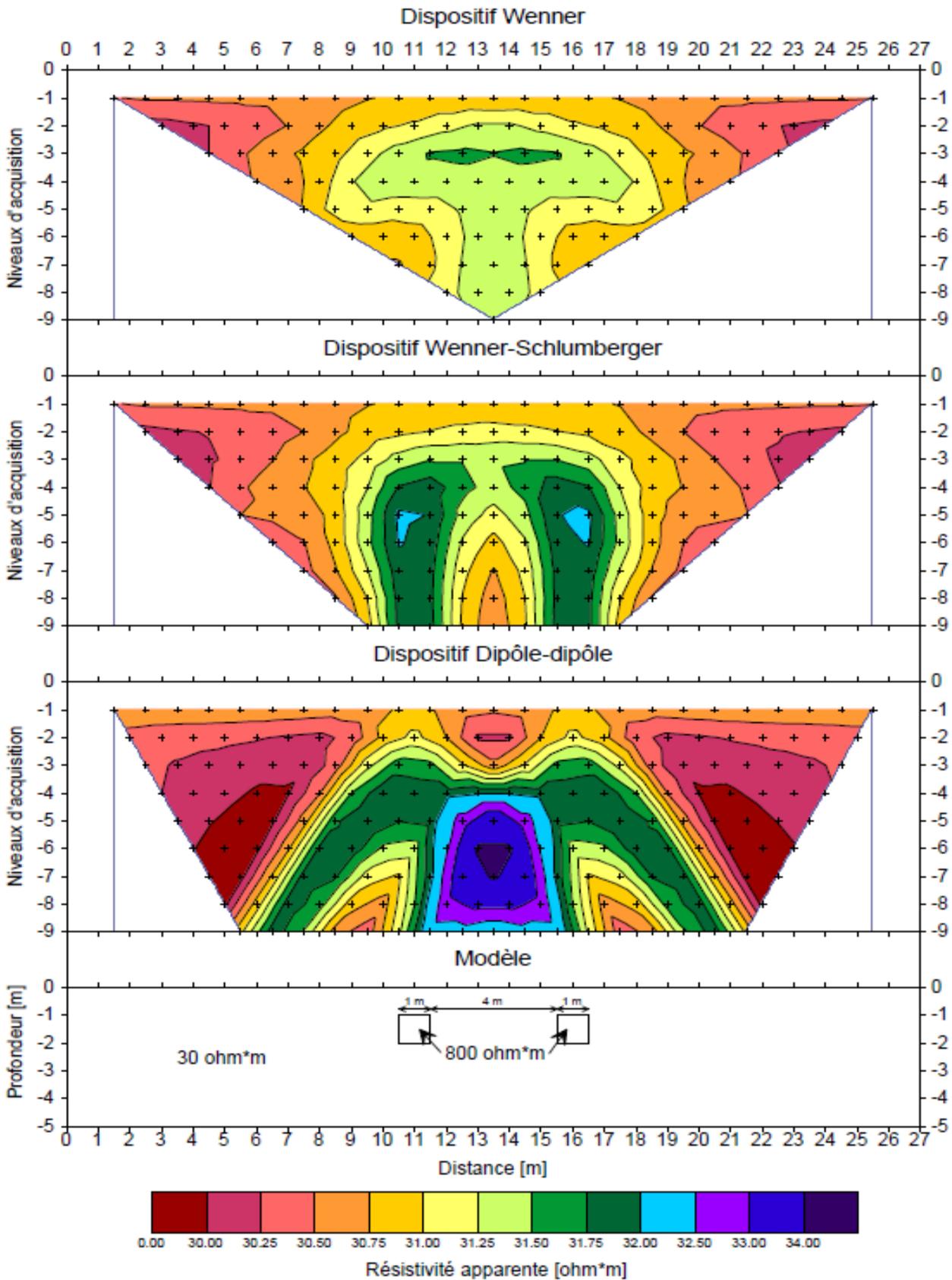
Figure: Resolving power of different devices

Note that the current distribution in the model depends on the model's resistivities:

This is why we use iterative inversion for electrical tomography, because at each iteration, the model and therefore the current distribution will be modified. It will therefore be necessary to recalculate the model's response at each iteration. In this case, the inversion is said to be nonlinear. You can find more information on inversion here.

The figure below shows the result of the inversion of the pseudosections measured above on the two walls. The 2D model represents a cross-section of the electrical properties of the subsurface.

It can be noted that the results are relatively similar regardless of the devices used (Wenner, Schlumberger, dipole-dipole), but they are not exactly identical: as we saw above, each device has a different resolution which is also reflected in the inversion result.
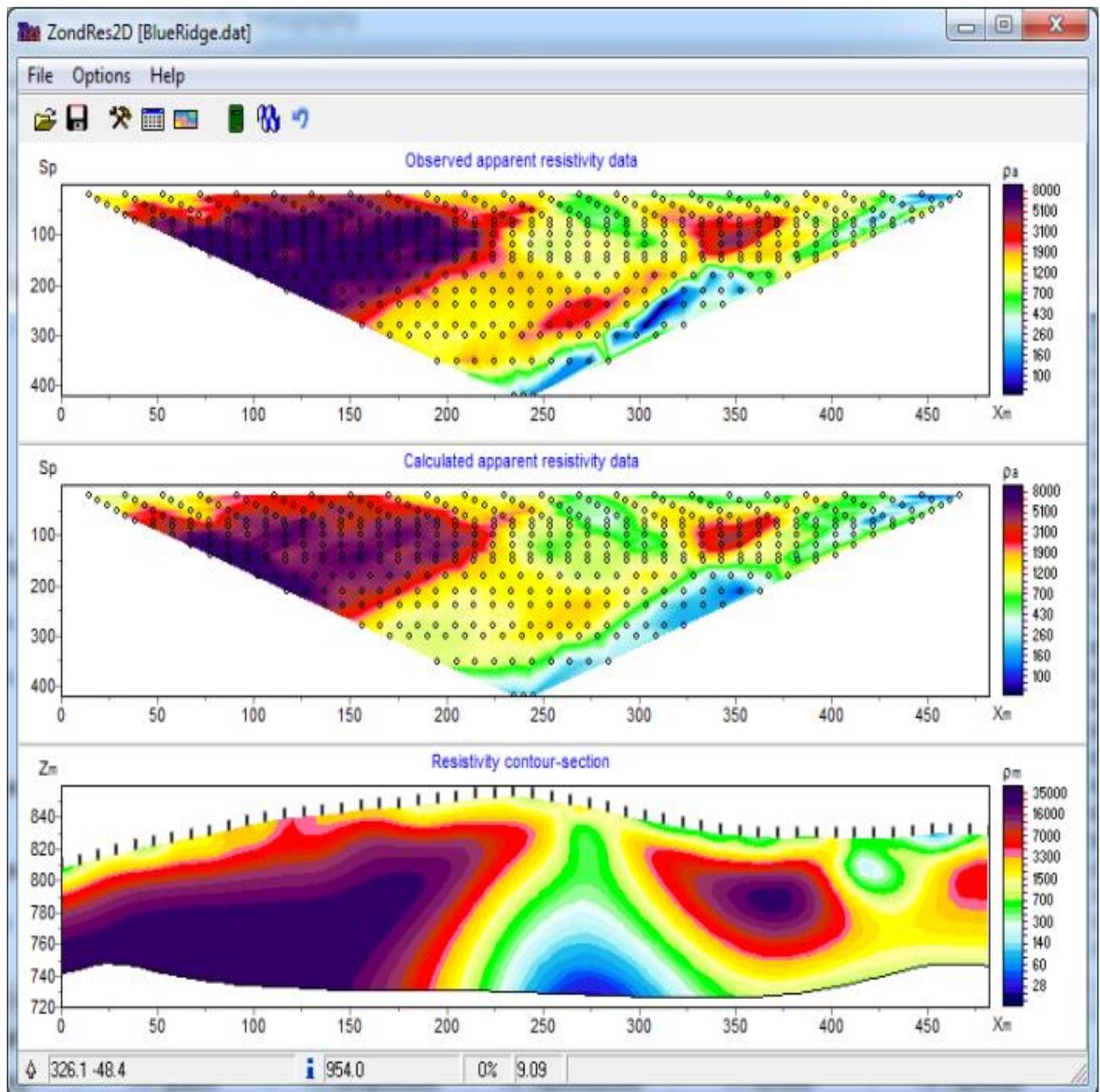

Figure: Procedure for inverting electrical data (example of 2D electrical tomography)

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BOUFEDAH BADISSI Mohamed Salah 2025/2026

46

3D inversion follows a similar strategy. The model is no longer a cross-section composed of cells, but a resistivity volume composed of small cubes. This volume is represented as horizontal sections (at the same depth) through it (see figure below).
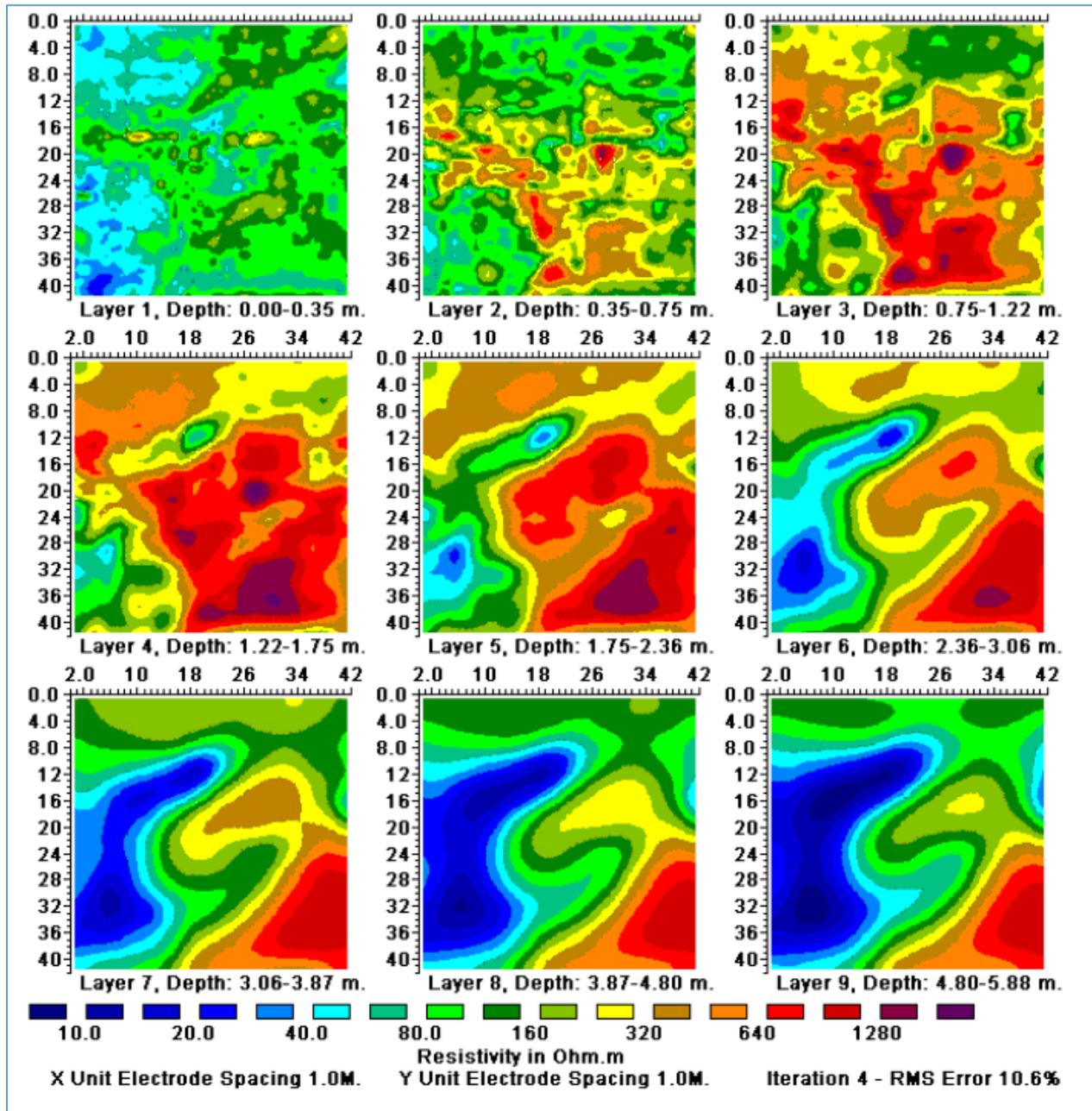

Figure: Example of Electrical Tomography 3D