GEOPHYSICS

Chapter I: Basic concepts

I. Basics:

I.1 Introduction:

Geophysics is a discipline of geology that allows the study of the subsurface by analysing the natural fields of the earth or induced fields applied to the ground in order to investigate the subsurface by exploiting the physical properties of geological formations, such as density, velocity, magnetic susceptibility, electrical conductivity and resistivity.

These physical properties are identified using geophysical methods based on the laws of physics, including gravimetric, geomagnetic, and seismic and geoelectrical methods.

I.2 What is geophysics

Geophysics is a scientific discipline that studies the Earth's physical systems using quantitative methods, such as seismology and magnetism, to understand the structure and dynamics of our planet. This field is essential for discovering natural resources, such as oil and minerals, or for predicting natural phenomena such as earthquakes and volcanic eruptions. The advanced technological tools used in geophysics help to map the earth's subsurface and provide crucial data for sustainable environmental management.

Geophysics is a multidisciplinary science that studies the Earth's physical phenomena and characteristics, and is linked to the other natural sciences (see Figure 1).

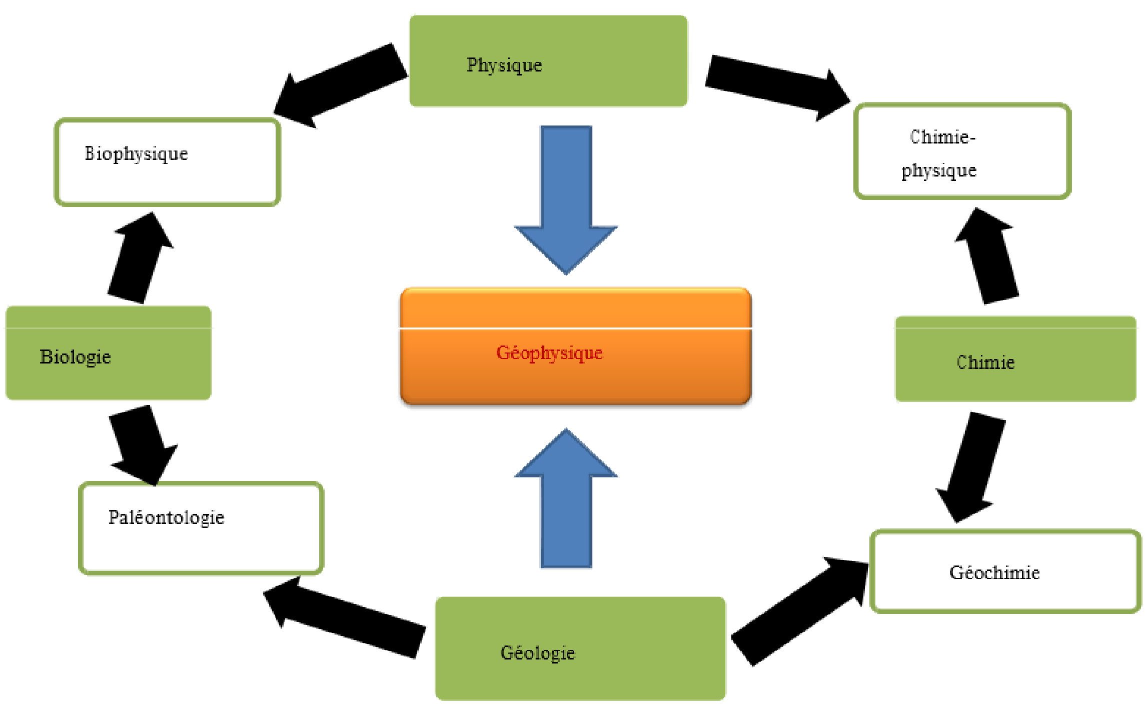

Figure 1: Position of geophysics within the natural sciences

Geophysical methods use measuring instruments to provide information about the physical properties of the subsoil. These instruments can be used directly on the ground, in boreholes, on board a plane, a vehicle, a boat or at satellite level.

There are two main types of method:

1. Active, which measures the underground response to energy:

    - Electromagnetic;
    - Electrical;
    - Seismic.

2. Passive, which measure the:

    - magnetic,
    - Earth's gravitational environment.

Geophysical methods can also be subdivided into surface and borehole methods.

- **Surface geophysical methods** are generally non-intrusive and can be used quickly to collect underground data.

- Geophysical drilling methods (logging) require wells or boreholes to be drilled so that geophysical tools can be introduced through the borehole.

I.3 Objectives of geophysics

The main objective of geophysics is to deduce the physical properties and constitution of the Earth (or other bodies in the solar system) from the physical phenomena associated with them, e.g. the geomagnetic field, heat flow, seismic wave propagation, the force of gravity, etc. The information provided by these tools can help locate buried objects and structures, determine geological formations and hydrogeological and hydrocarbon reservoirs, as well as determine the conditions of the Earth.

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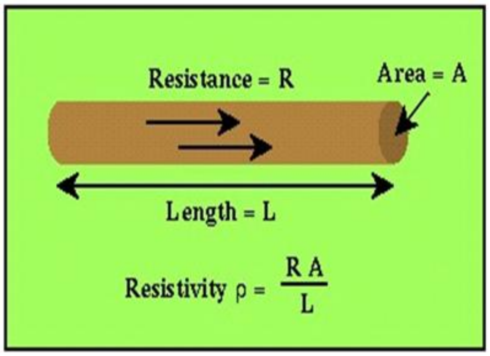
1.4. Physical properties of rocks.

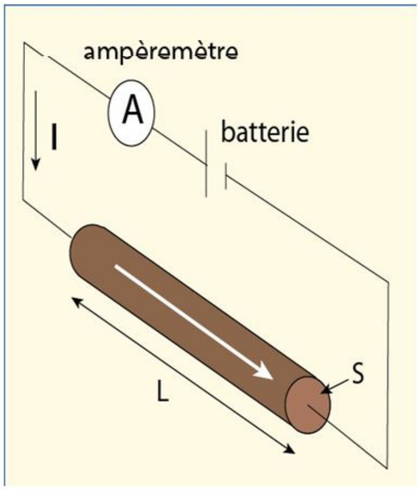
The properties or physico-chemical characteristics of rocks adopted for geophysical studies must be sufficiently differentiated or contrasted from one environment to another or from one rock to another and also be strongly felt (high amplitude) in order to ensure good signal recording by the various geophysical sensors.

a) The resistivity ρ of a medium is the physical property that determines the capacity of this medium to oppose the passage of an electric current.

Consider an electric current flowing uniformly through a cylinder from one cross-section to the next. Resistivity is the ohmic resistance of a cylinder of cross-section S and length L.

ρ: resistivity (Ohm.m)





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:

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

b) The resistance of a medium varies linearly with the length 'L' of the medium through which it passes, but is inversely proportional to the area 'S' of the surface through which it passes:

$$R = \frac{\rho.L}{S} \quad d'où \quad \rho = R.\frac{S}{L} = \frac{\Delta V}{I}.\frac{S}{L}$$

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

c) Conductivity σ (in Siemens) is the inverse of resistivity

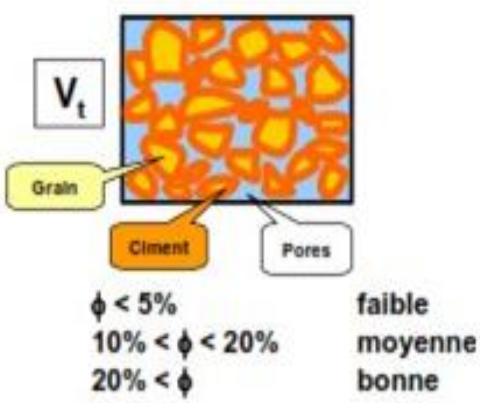
$$\sigma = \frac{1}{\rho}$$

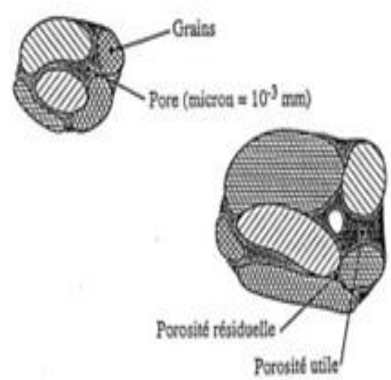
d) Porosity:

Volume of void ('pore') existing in the rock over the total volume of the rock, expressed in %.

All the interconnected pores are the useful porosity. The remaining porosity is the residual porosity.

Reservoir rocks have widely varying porosities, generally between 10% and 35%.





$$\Phi = \frac{V_{pore}}{V_{total}} = \frac{V_{total} - V_{solid}}{V_{total}}$$

- Primary porosity: This is inherited from the original sediment deposition.

- Secondary' porosity: This is due to diagenetic changes in the sediment during burial or the existence of fractures in the rock.

Porosity is the ability of a rock to store a fluid (air, water) in its interstices, also known as pores. It does not depend essentially on the size of the grains, but above all on their arrangement. It is the ratio of the volume of voids v_v in the rock to the total volume v_t:

$$n = \frac{V_v}{V_t}$$

Or in relation to the volume of the skeleton Vs:

$$n = \frac{V_t - V_s}{V_t} = 1 - \frac{V_s}{V_t}$$

The pore space can be studied directly by observation with an optical or electron microscope, possibly after filling with a colouring agent. Image analysis techniques can then be used to estimate porosity quantitatively.

Porosity varies from a few % to over 40% in sedimentary rocks. In magmatic rocks, porosity is lower, often less than 1%. Rocks are classified according to porosity as:

Tableau. 2.1. Types de roches selon la porosité.	
Roche de faible porosité	$0 < P < 5$ %
Roche de porosité moyenne	$5 < P < 10$ %
Roche de porosité élevée	$10 < P < 20$ %
Roche de porosité très élevée	$P > 20$ %

Some porosity in loose sediments

Type de sédiments	Diamètre (mm)	porosité totale (%)
Gravier moyen	2.5	45
Sable gros	0,250	38
Sable moyen	0,125	40
Sable fin	0,09	40
Sable très fin	0,045	40
Sable silteux	0,005	32
Silt	0,003	36
Silt argileux	0,001	38
Argile	0,0002	47

e) Saturation (S)

The water saturation Sw, i.e.

$$S_w = \frac{Volume\ des\ pores\ remplis\ d'eau}{Volume\ total\ des\ pores}$$

Note that this is the water saturation. For a mixture of water and air (partially saturated rock) we have:

$$S_w + S_{air} = 1$$

f) Temperature (T):

An increase in temperature decreases viscosity, the mobility of ions becomes greater and dissociation increases, which has the effect of decreasing resistivity or conversely increasing conductivity. The following relationship is generally used to evaluate the resistivity of a rock at a temperature t, knowing its resistivity at 18°C:

$$\rho_t = \frac{\rho_{18}}{1 + 0.025(t - 18)}$$

RELATIONSHIP BETWEEN RESISTIVITY, POROSITY AND WATER SATURATION

ARCHIE'S FORMULA - FORMATION FACTOR F

- A rock containing 100% water (Sw = 1) has a resistivity Rt, also called Ro.

- This resistivity Ro is proportional to the water resistivity Rw

$$R_o = FR_w$$

Porosité ϕ

$R_{o1} = FR_{w1}$

Porosité ϕ

$R_{o2} = FR_{w2}$

- The proportionality factor F is called the Formation Factor and is equal to the ratio between Ro resistivity and Rw water resistivity.

- The Formation Factor is a function of reservoir porosity and lithology:

$$F = \frac{R_o}{R_w} \qquad F = \frac{a}{\phi^m} \qquad \text{donc :} \qquad R_o = \frac{a}{\phi^m} \times R_w$$

Porosité ϕ_1

$R_{o1} = \frac{a}{\phi_1^m} \times R_w$

Porosité ϕ_2

$R_{o2} = \frac{a}{\phi_2^m} \times R_w$

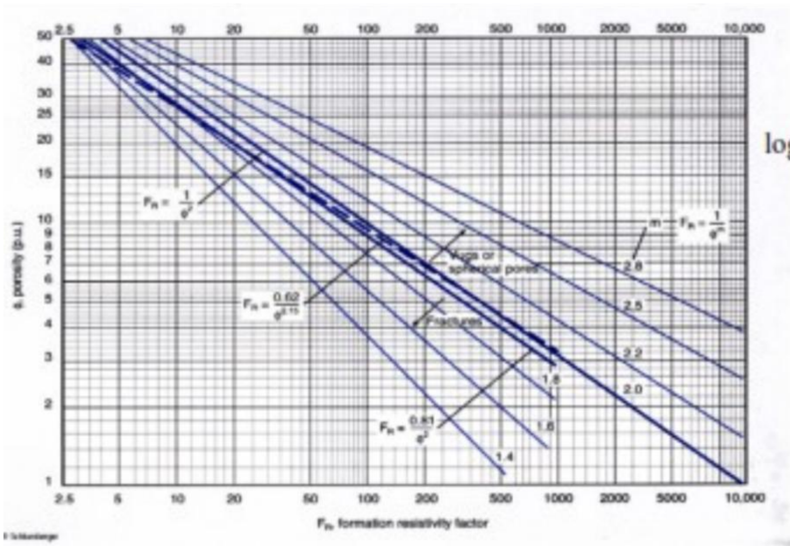
ARCHIE'S FORMULA - FORMATION FACTOR F

In general, the constant à is close to 1 and the cementing factor m is close to 2.

- For sandstone in general: $F = \frac{0.81}{\phi^2}$ ou $F = \frac{0.62}{\phi^{2.15}}$

- For Carbonates, in general, a = 1 and m = 2, but m is variable: 1.3 < m < 2.5

Formation Resistivity Factor versus Porosity (Chart Por1 – Schlumberger)

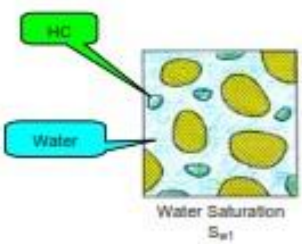


$$F = \frac{a}{\phi^m}$$

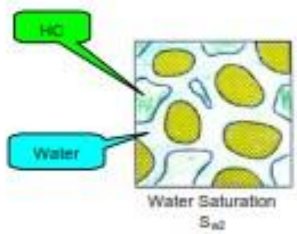
$$\log(F) = \log(a) - m\log(\phi)$$

- A rock with water saturation S_w has resistivity R_t
- Rt varies with water saturation S_w and is inversely proportional to S_{wn}
- n is the saturation exponent, usually close to 2.

$$R_t = \frac{R_o}{S_w^{\ n}} = \frac{a}{\phi^m} \times \frac{R_w}{S_w^{\ n}} \quad \text{ou} \quad S_w = \sqrt[n]{\frac{a}{\phi^m}\frac{R_w}{R_t}}$$



$$R_{t1} = \frac{F * R_w}{S_{w1}^{\ n}}$$



$$R_{t2} = \frac{F * R_w}{S_{w2}^{\ n}}$$

This is Archie's formula. It is only valid for clean, clay-free formations (clay volume Vsh = 0).

Estimation of water saturation in clean formations

$$S_w = \sqrt[n]{\frac{a}{\phi^m}\frac{R_w}{R_t}}$$

- Resistivity logs (Laterolog, Induction) → Rt
- Porosity logs (Density, Neutron, Sonic, NMR) →φ
- SP, Resistivity Ratio, Rwa → Rw

- Laboratory petrophysical measurements → a, m, n

Default values: a = 1, m = 2, n = 2

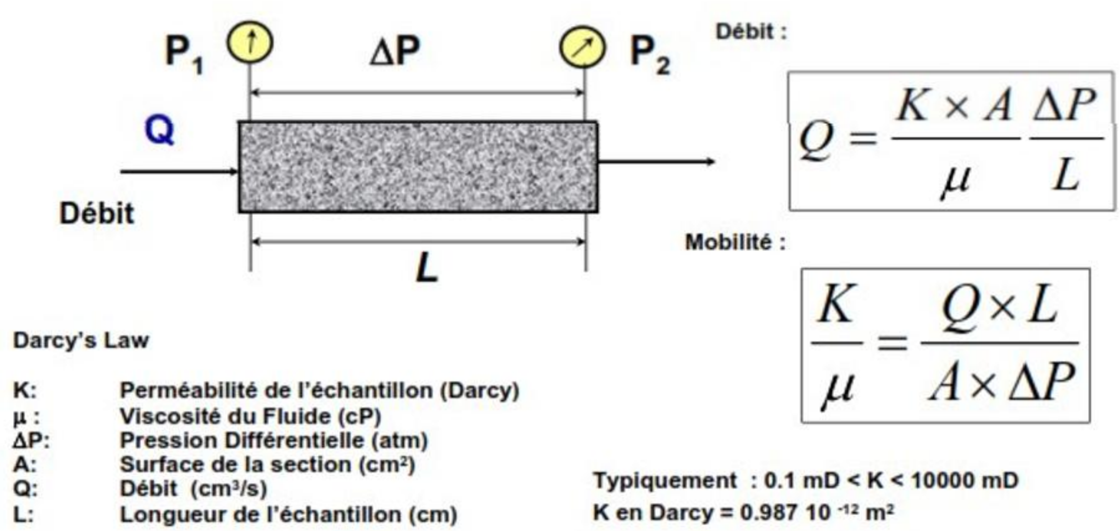
Formula valid only for clean, clay-free formations (Vsh = 0)

G) **Permeability**

Permeability characterizes the ability of a rock (or any other porous medium) to let fluids circulate within its pore space. A rock's permeability is entirely determined by the geometry of its porosity network.

- Permeability is the capacity of a porous formation to allow fluid flow when a pressure gradient is applied.

- It is expressed in m Darcy or Darcy.



h) Density

Density is a physical parameter that varies according to the nature of the geological environment. By definition, the density of a body is the ratio of its density to the density of water. Density is therefore a dimensionless quantity, unlike density, which is expressed in $kg.m^{-3}$. Note that the distinction between density and density does not exist in English, where density is always given with a unit and corresponds to density. The following table gives some density values for terrestrial materials.

$$d = m/V$$

Different densities of earth materials.

matériaux	densité	matériaux	densité
Densité moyenne de la Terre	5,5	Gabbros	2,7 à 3,3
Densité moyenne de la croûte continentale	2,67	Péridotite	3,1 à 3,4
Sédiments non consolidés	1,8 à 2,0	Charbon	1,2 à 1,8
Sables « secs »	1,4 à 1,65	Pétrole	0,6 à 0,9
Sables « humides »	1,9 à 2,05	Eau de mer	1,01 à 1,05
Grès	2,0 à 2,5	Glace	0,88 à 0,92
Sel	2,1 à 2,4	Chromite	4,5 à 4,8
Marnes	2,1 à 2,6	Pyrite	4,9 à 5,2
Calcaires	2,4 à 2,8	Hématite	5,0 à 5,2
Granites	2,5 à 2,7	Magnétite	5,1 à 5,3
Dolérite	2,5 à 3,1	Fer	7,3 à 7,8
Serpentine	2,5 à 2,6	Cuivre	8,8 à 8,9
Gneiss	2,65 à 2,75	Argent	10,1 à 11,1
Basaltes	2,7 à 3,1	Or	15,6 à 19,4

The density of the same rock will vary according to various parameters such as porosity, water content, temperature and pressure. Sediments that are deeply buried, and therefore compacted, will have a higher density than those that remain close to the surface.