Sapienza Università di Roma

Environmental geophysics

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3 . RADAR (high-frequency EM) methods

Electro-magnetic properties

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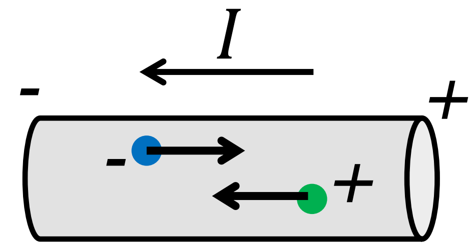
Electromagnetic properties

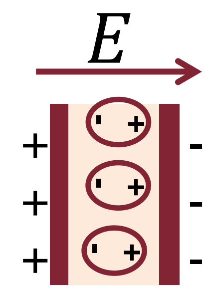
- **Electrical resistivity** ρ [Ωm] or its inverse (***Electrical conductivity*** σ=1/ρ [S/m])



Pivotal for all the EM methods

✓ Capability of a medium to resist (*favour*) an electric current flow *I*

- **Electrical permittivity** ε [F/m]



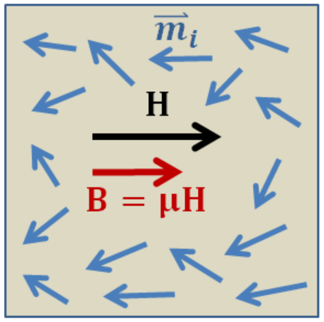
Important only for high-frequency EM methods

✓ Capability of a medium to resist the formation of an electric dipole in response to an applied electric field **E**

- **Magnetic permeability** μ [H/m]

Negligible for almost all EM methods, except for mineral exploration

✓ Capability of a medium to favour the formation of magnetic dipole in response to an applied magnetic field **H**



Resistivity vs. Resistance

Resistance is relevant only to a particular measurement circuit

Resistivity is an intrinsic property of physical materials

⇩

If we are able to directly measure or indirectly infer from other measurement the resistivity, we can assess the capability of a medium to be a good conductor or not

⇩

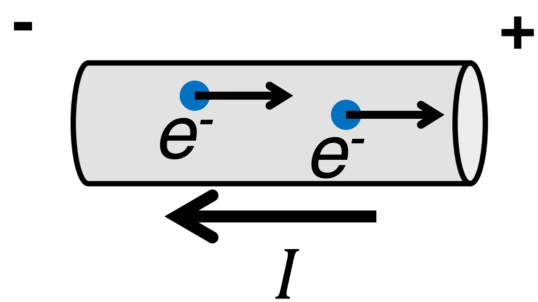
Through the resistivity distribution, we can evaluate some key physical parameters (saturation, porosity, fracturing, lithology, construction materials, etc.)

Types of conduction

1. Electronic or ohmic conduction

Electrons are charge carriers

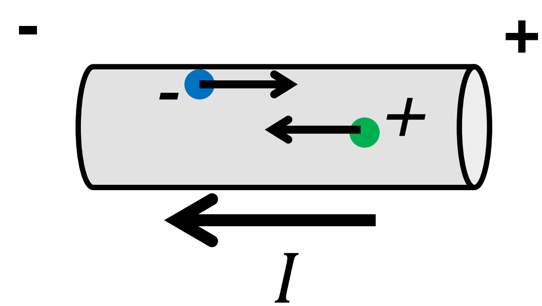
A property of metals (in geophysics this type of conduction is almost not visible – only for native metals)



2. Electrolytic or ionic conduction

Ions dissolved in a fluid are charge carriers

A property of the fluids that often occurs in geophysics because rocks and soils are often filled by water



Resistivity of minerals

Minerals can be classified into three groups:

- **conductors** (ρ **<** 10^{-7} **Ωm**)
- **semiconductors** ($10^{-7} < \rho < 10^{3}$ **Ωm**)
- **dielectrics** (or **insulators**) ($\rho > 10^{3}$ **Ωm**)

Conductors

In nature, only the native metals can be considered as conductors (copper, gold, silver, platinum etc.). Since the rates of their occurrence is low, their influence on the resistivity of rocks is generally not significant .

Semiconductors

Metal oxides and sulphides belong to the group of semiconductors.

Dielectrics

The common rock-forming minerals (quartz, feldspar, mica, pyroxene, amphibole, olivine, calcite etc.) and most of the other minerals behave as dielectrics in electric fields.

Resistivity of soils and rocks

Soils and rocks are multiphase media

The final resistivity is the combination of the resistivity of the single component

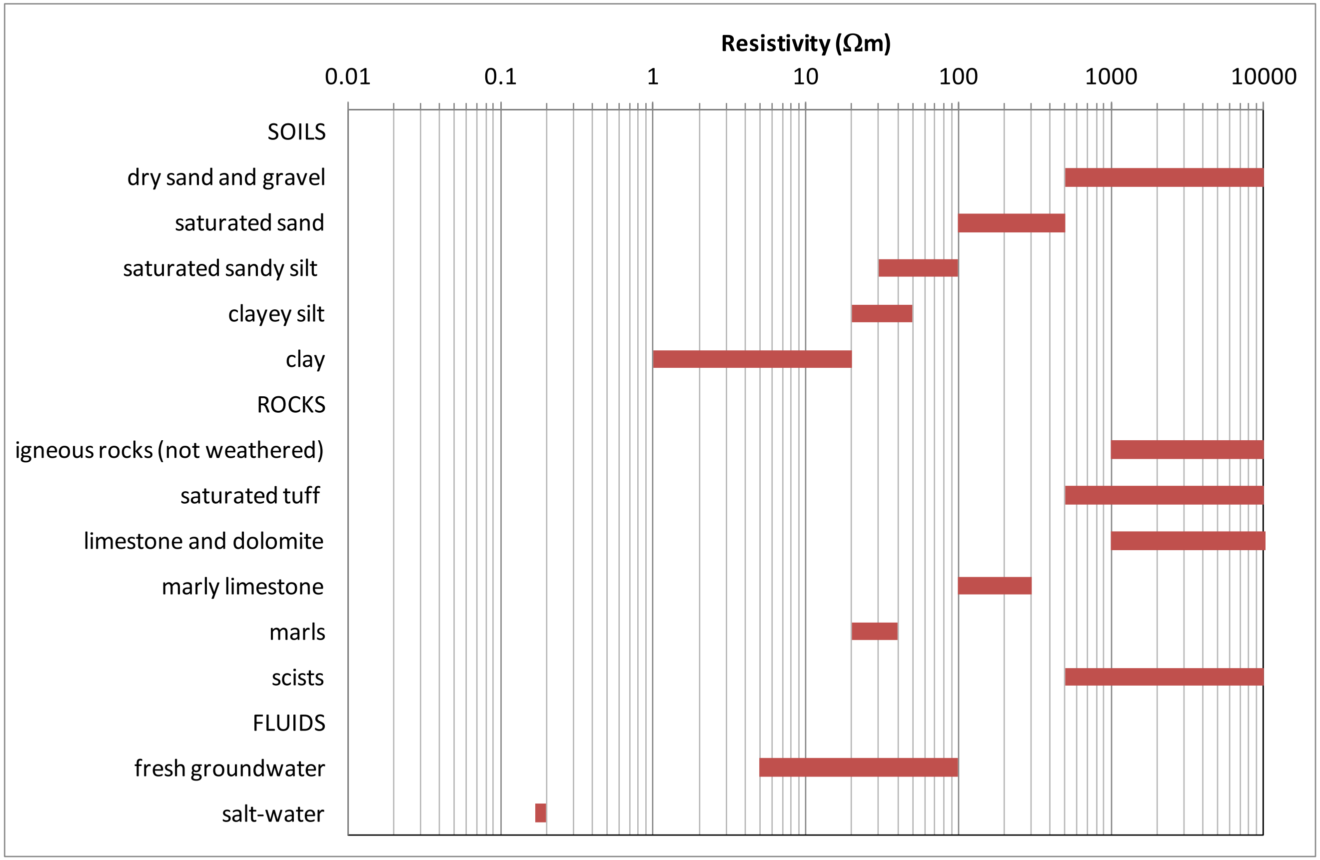
Solid
Minerals
(**high resistivity**)

Liquid
Mainly water
(**low resistivity**)

Gas
Mainly air
($\rho = \infty$)

Resistivity of the multiphase medium
Combination of the three contributions

Resistivity of soils and rocks



Since the effective resistivity of soils and rocks is much lower than that of minerals,
electric current flows mainly through ions within pore fluids

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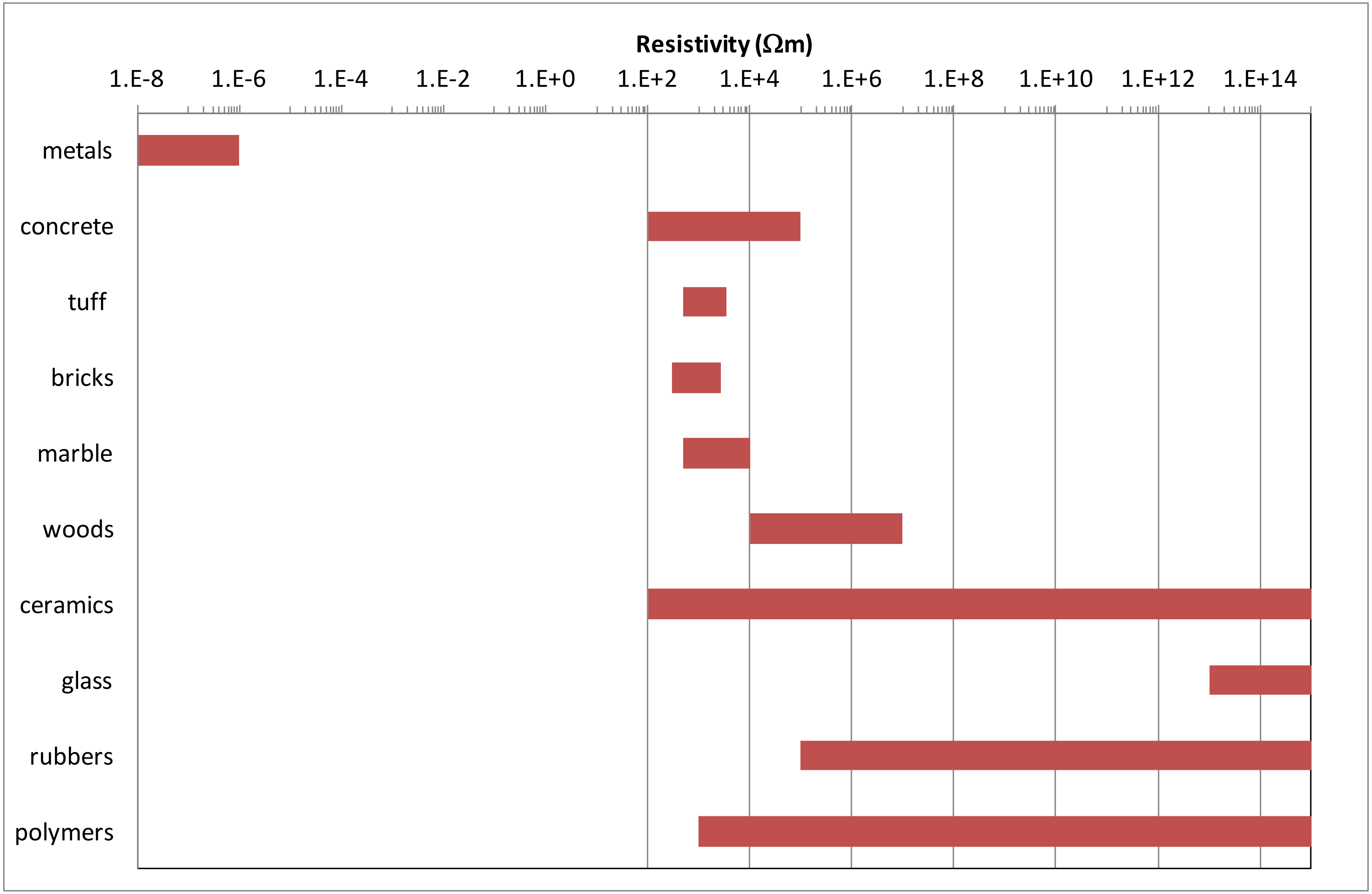
electrolytic conduction

Resistivity of anthropogenic materials



Resistivity of soils and rocks

Porosity

$$\phi = \frac{V_V}{V_T}$$

V_V pore volume

V_T bulk volume (including both solid and pores components)

ϕ is dimensionless and theoretically can vary between 0 (solid material) and 1 (only pores). Practically ϕ varies from 0.01 (solid granite) to 0.5 (clay)

Water saturation

$$S = \frac{V_W}{V_V} = \frac{V_W}{\phi V_T}$$

V_W water volume

S is dimensionless and can vary between 0 (dry material) and 1 (saturated material)

At a fixed water saturation — **Higher porosity** → **Lower resistivity**

At a fixed porosity — **Higher water saturation** → **Lower resistivity**

Resistivity of soils and rocks

In many observations resistivity ρ and porosity ϕ are strongly correlated ($\rho \sim 1/\phi^2$)

Formation factor
(depends only on soil or rock properties)

$$\rho = a\phi^{-m}S^{-n}\rho_w$$

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

Archie's law
(empirical, 1941)

in terms of conductivity

ϕ	porosity
S	degree of saturation
ρ_w	fluid resistivity (water) [Ωm]
a	tortuosity factor
m	cementation exponent
n	saturation exponent

theoretically ϕ and S range from 0 to 1 (dimensionless)

empirical coefficients (dimensionless)

<u>Hp1.</u> Rock/soil matrix is formed by non-conductive minerals
<u>Hp2</u>. The conduction is electrolytic – there is a significant amount of water

⇩

Archie's Law is not valid for rocks containing a significant percentage of clay

Resistivity of soils and rocks

Formation factor

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

The formation factor depends on:

- porosity
- pore geometry - tortuosity
- Lithology
- degree of cementation
- clay content

We can set *a*=1 and *m*=2
for many rocks and soils
(first approximation value)

$$F = \frac{1}{\phi^2}$$

- *a* and *m* can vary significantly as a function of the lithology
- for an accurate estimation of *F*, *a* and *m* should be derived from laboratory tests

Lithology	*m*	*a*	References
Sandstone	1.64–2.23	0.47–1.8	Hill and Milburn (1956)
	1.3–2.15	0.62–1.65	Carothers (1968)
	0.57–1.85	1.0–4.0	Porter and Carothers (1970)
	1.2–2.21	0.48–4.31	Timur et al. (1972)
	0.02–5.67	0.004–17.7	Gomez-Rivero (1976)
Carbonates	1.64–2.10	0.73–2.3	Hill and Milburn (1956)
	1.78–2.38	0.45–1.25	Carothers (1968)
	0.39–2.63	0.33–78.0	Gomez-Rivero (1977)
	1.7–2.3	0.35–0.8	Schön (2004)

Resistivity of soils and rocks

Saturation

$$\rho = FS^{-n}\rho_w \longrightarrow S^n = \frac{F\rho_w}{\rho}$$

Saturation exponent *n* depends on:

- wettability of rock surface
- rock texture
- clay content
- fluid type

We can set *n*=2 for many rocks and soils (first approximation value)

$$S^2 = \frac{F\rho_w}{\rho} \longrightarrow S = \sqrt{\frac{F\rho_w}{\rho}}$$

Archie's law
with first approximation coefficients

$$\rho = \frac{\rho_w}{\phi^2 S^2}$$

Archie's law: examples

Ex. 1

Calculate the resistivity of the medium knowing the water resistivity and the porosity under the assumption of fully-saturated medium (S = 100%).

ρ_w =10 Ωm
ϕ = 20% (0.2)

$$\rho = \frac{10}{(0.2)^2} = 250\ \Omega\text{m}$$

Ex. 2

Calculate the porosity knowing the resistivity of the medium and the water resistivity, under the assumption of fully-saturated medium (S = 100%).

ρ_w =10 Ωm
ρ =250 Ωm

$$\phi = \sqrt{\frac{10}{250}} = 0.2\ (20\%)$$

Ex. 3

Calculate the resistivity of the medium knowing the water resistivity and the porosity for a partially-saturated medium (S = 50%).

ρ_w =10 Ωm
ϕ= 20% (0.2)
S=50% (0.5)

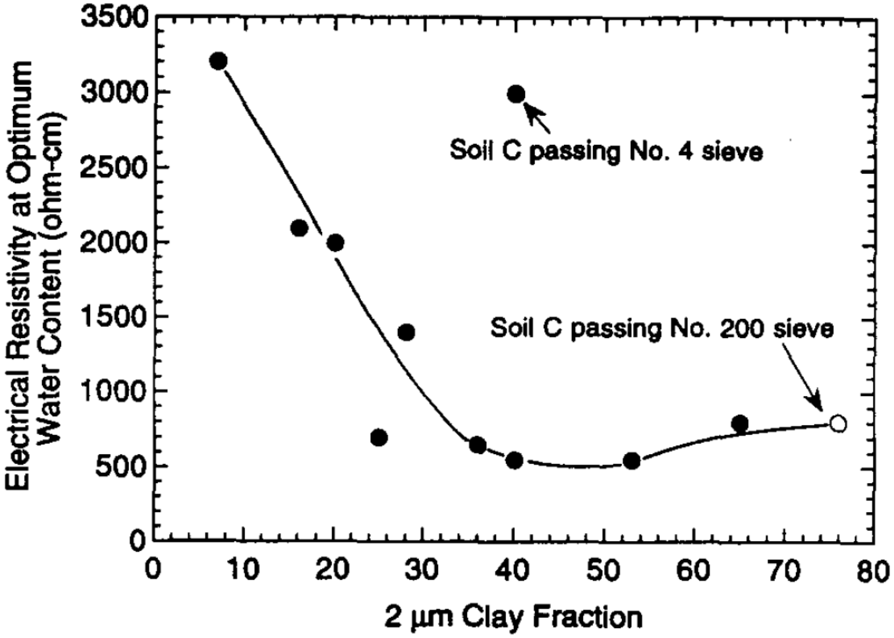
$$\rho = \frac{10}{(0.2)^2(0.5)^2} = 1000\ \Omega\text{m}$$

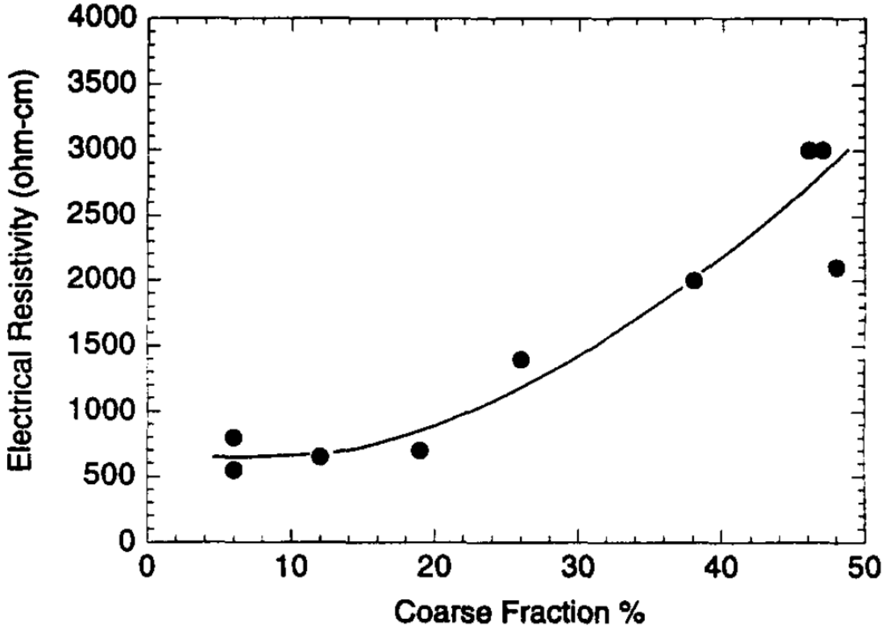
Resistivity of soils and rocks

Clay content
(% particles < 2μm)

Coarse fraction
(% particles > 75 μm)

Resistivity strongly decreases (1/6) passing from 10 to 40% of clay content

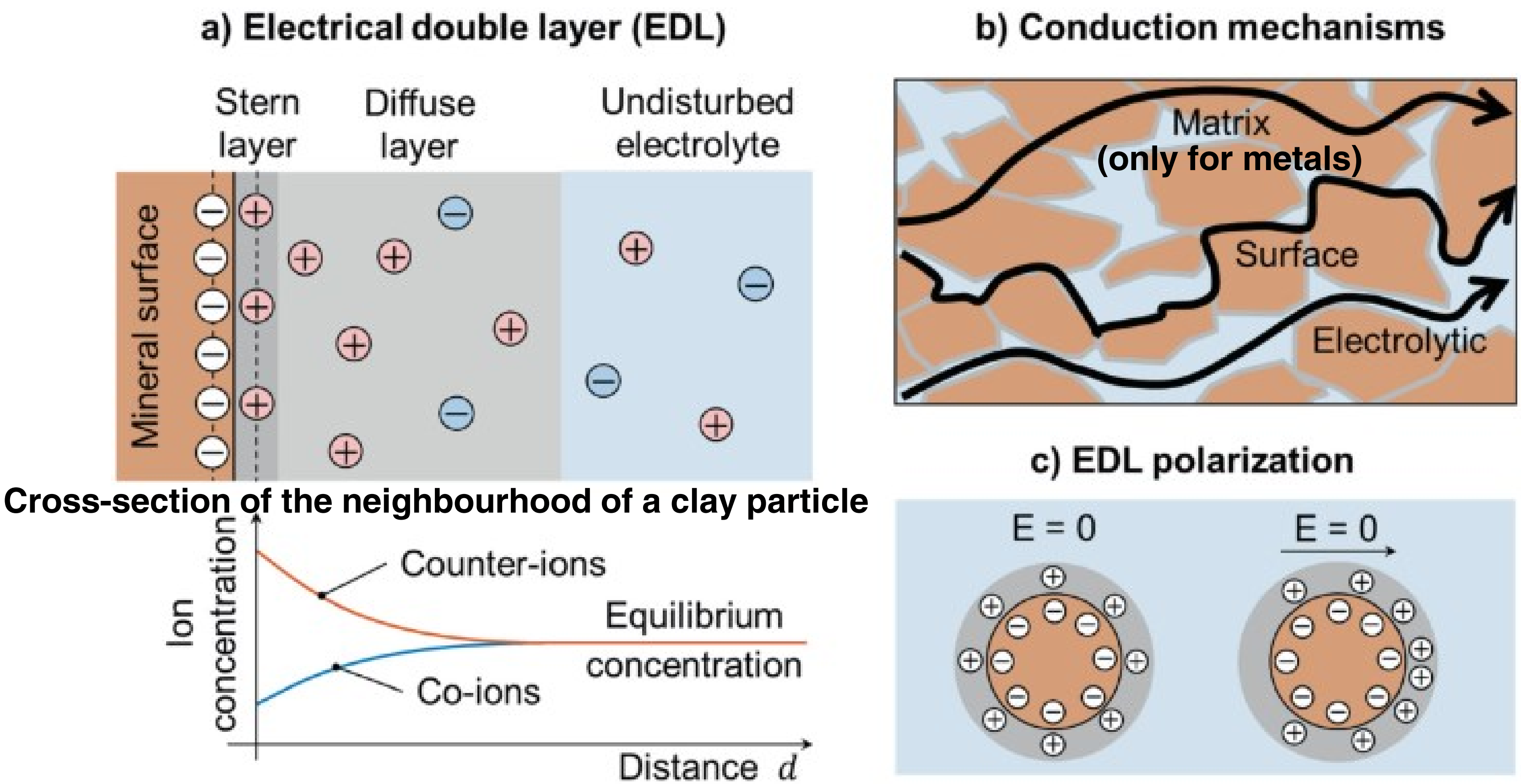




1. The clay soils are rich in water
2. The clay minerals can absorb cations in an exchangeable state on the surface (**surface conductivity**)

Resistivity of soils and rocks

Clay particles has a **net negative charge** on their surface (for structural reasons). Therefore, **positive** dissolved **ions can be adsorbed** on clay surface. This effect create a huge increase of ions concentration near the grain surface and therefore of the electric conduction. The same is valid also for a metal particle.



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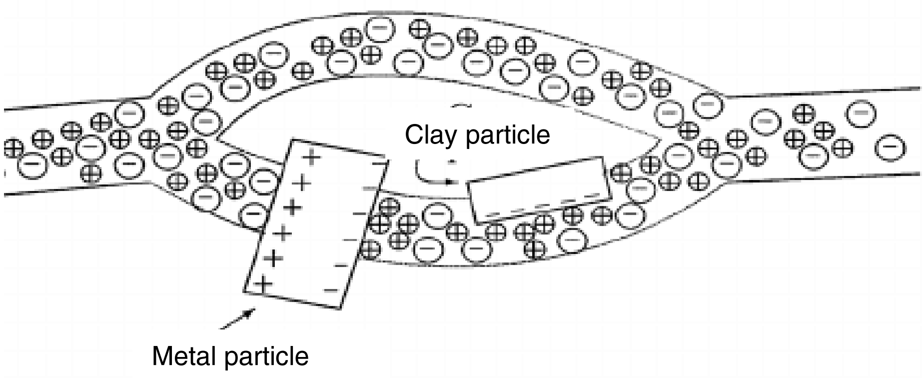
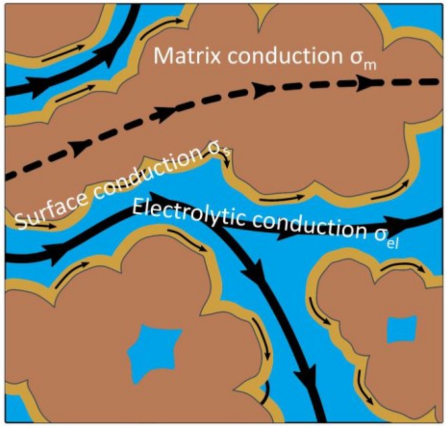




electrolytic conduction (Archie's Law)

surface conduction (for clays and few other special cases)

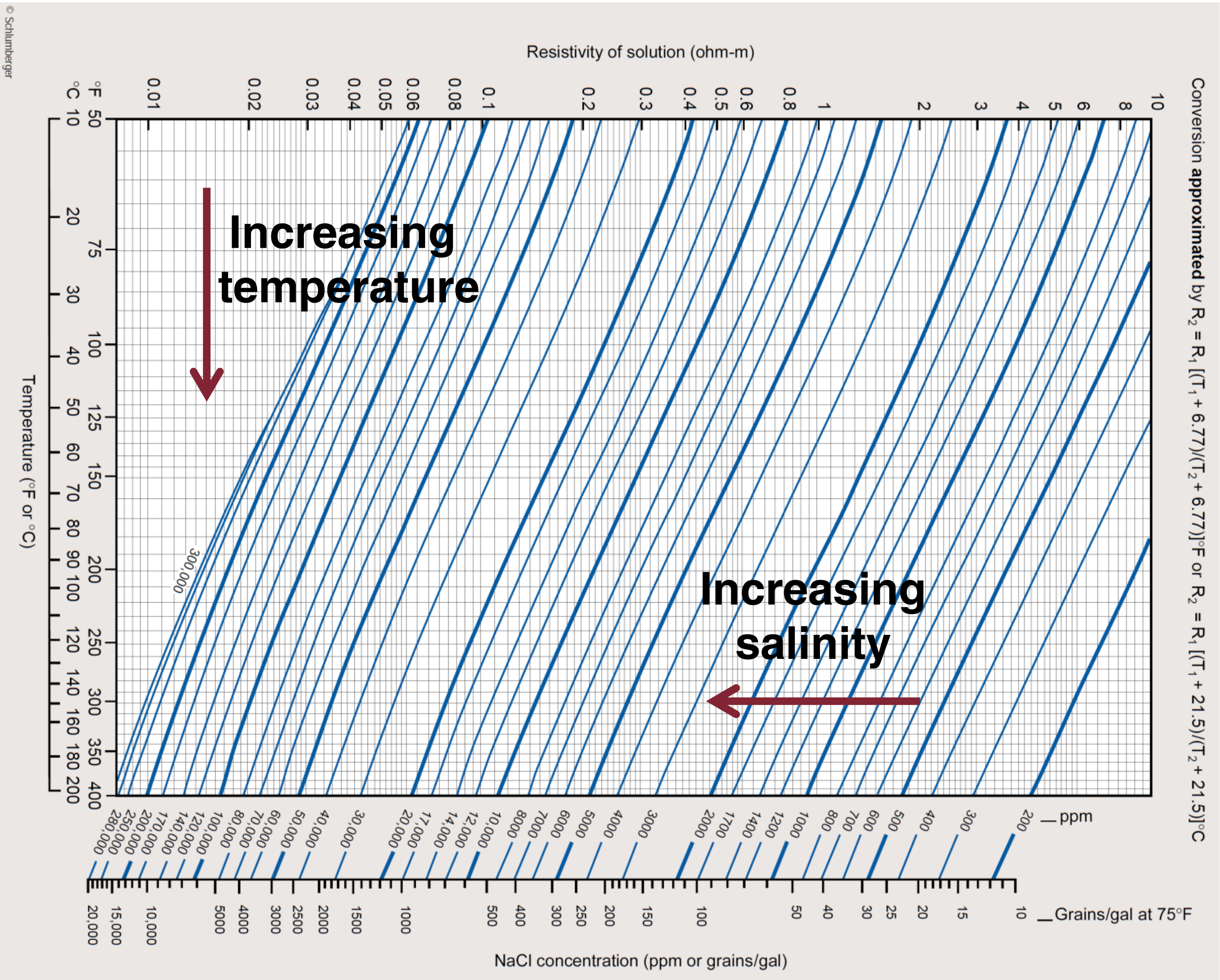
matrix conduction (almost always negligible – except than for metal grains)

Total conduction

$$\sigma = \frac{\phi^m S^n \sigma_w}{a} + \sigma_s + \sigma_m$$

Resistivity of soils and rocks

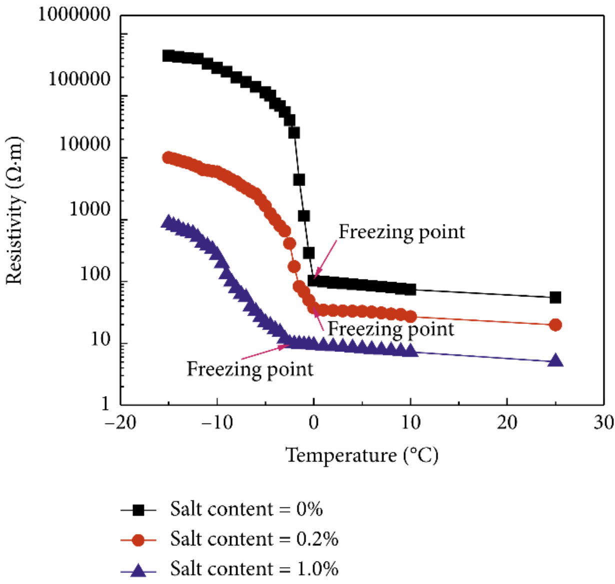
Temperature and salinity of fluids



$$\rho_w(T) = \frac{\rho_{w,0}}{[1 + \alpha(T - T_0)]}$$

$$\alpha \cong 0.02\ °C^{-1}$$

However, ice has a completely different behaviour



Electrical permittivity

The **electrical permittivity** is a measure of resistance encountered when applying an electric field in a medium

$$\varepsilon = \varepsilon_0 \varepsilon_r$$

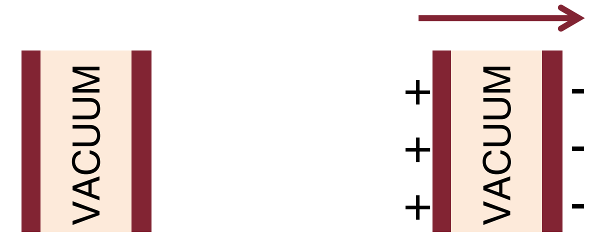
ε_r: **relative permittivity** or **dielectric constant**

ε_0: **electrical permittivity** of free space ≈ $8.8 \cdot 10^{-12}$ F/m

$$\varepsilon_r = 1 \quad \text{vacuum}$$
$$\varepsilon_r > 1 \quad \text{medium}$$

Before the application of an electric field

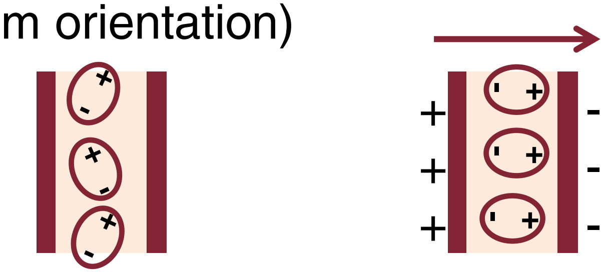
After the application of an electric field



The plates are **instantaneously charged**

Before the application of an electric field (random orientation)

After the application of an electric field



The electric charge arrives at the positive plate after a certain **delay time** proportional to the medium **polarization**

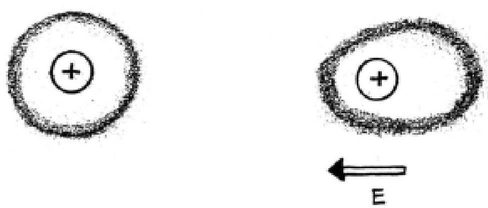
Polarization mechanisms

- Polarization
  - High-frequency $f_0 > 10^6$ Hz
    - Electronic
    - Atomic (or Ionic)
    - Dipolar (or Orientational)
  - Low-frequency $f_0 < 10^6$ Hz
    - Maxwell-Wagner (or Interfacial)
    - EDL
    - Electrode
    - Membrane
    - Biochemichal
    - Pore throats

Electrical permittivity – High-frequency polarization

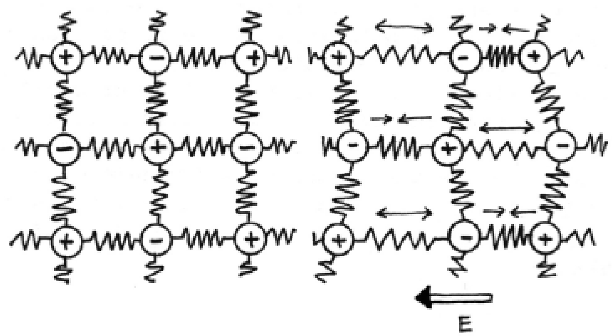
High-frequency polarization mechanisms

Electronic



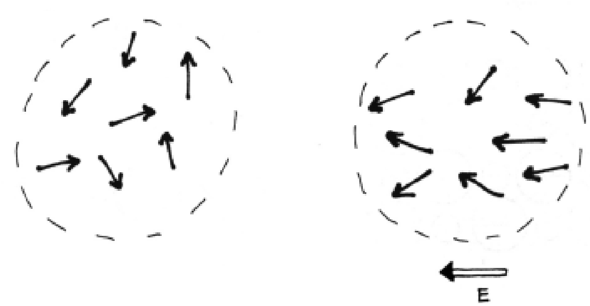
Shift of the electronic cloud under the action of an external field

Ionic



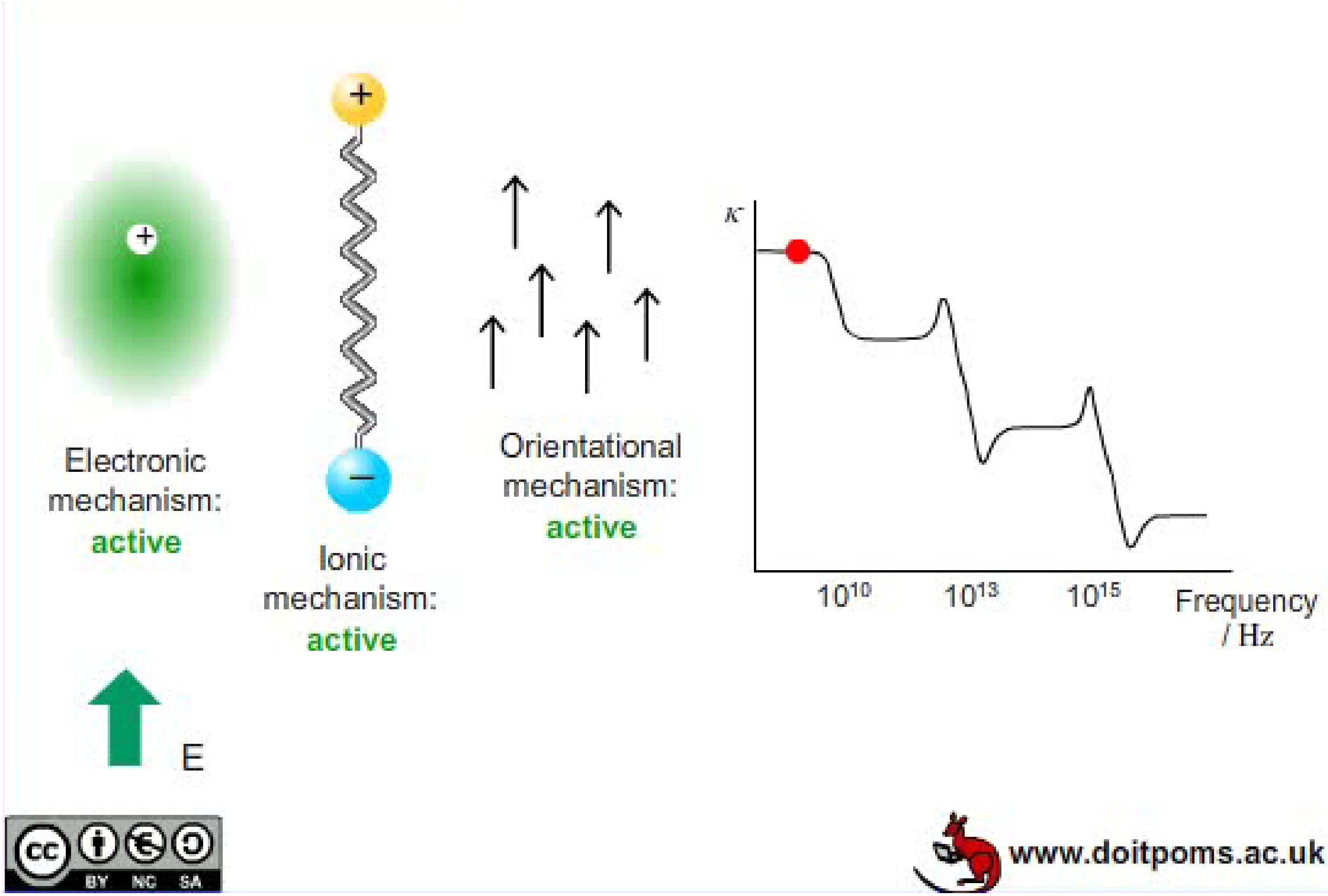
Deformation of molecules in the direction of the applied field

Dipolar

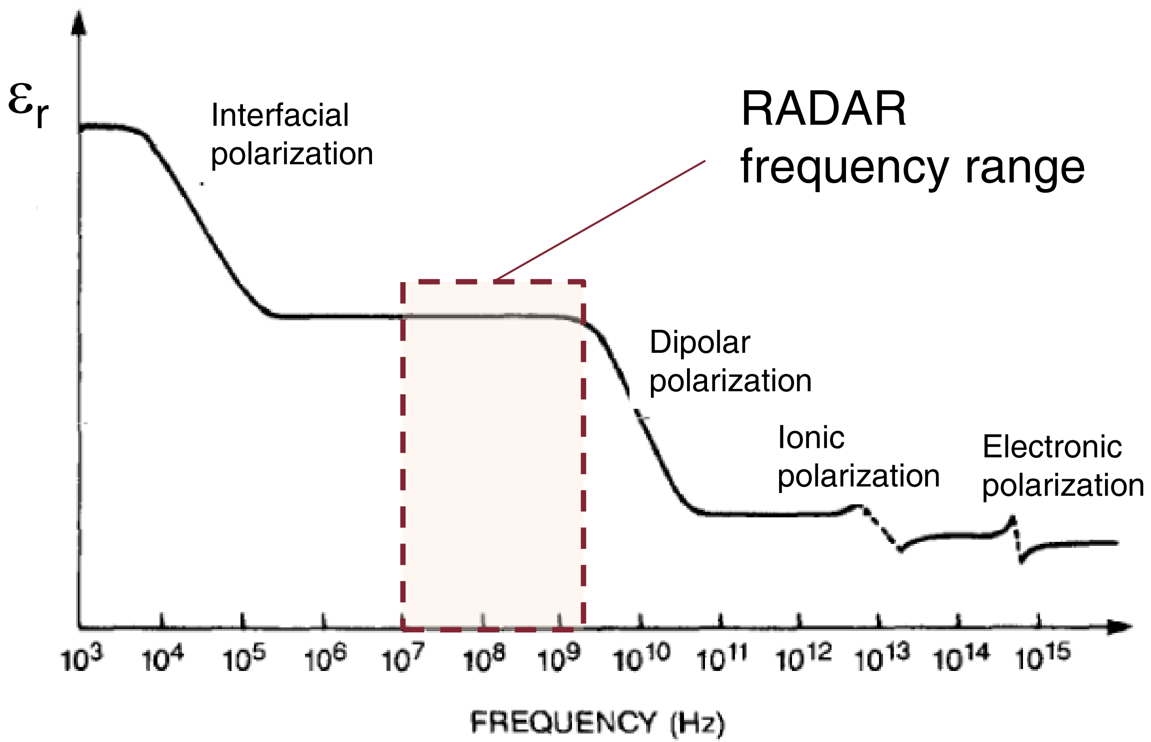


Gradual orientation of dipoles towards the field direction

Polarization (*video*)



High-frequency polarization vs. dielectric constant



The whole contribution in polarization for each frequency is the sum of the contributions of each type of polarization at one frequency.

At high frequencies we have only dipolar, ionic and electronic polarization

Classification of materials for polarizability

Not all materials display the three mechanisms

Nonpolar materials: only displacement of the electron cloud: **electronic polarization**. Such materials are generally referred to as **elemental materials.**

Polar materials: displacement of electron clouds and of the relative positions of ions: **electronic and ionic polarization**. The total polarizability is:

$$\alpha = \alpha_e + \alpha_i$$

α - polarizability

An example of such materials is **salt** (NaCl).

Dipolar materials: displacement of electron clouds, of the relative positions of ions and of dipoles: **electronic, ionic and dipolar polarization**. The total polarizability is:

$$\alpha = \alpha_e + \alpha_i + \alpha_d$$

An example of such materials is **water** (H_2O).

Electrical permittivity – Low-frequency polarization

a) **EDL polarization**: ions re-distribution through tangential and/or normal displacements at the fluid/grain interface

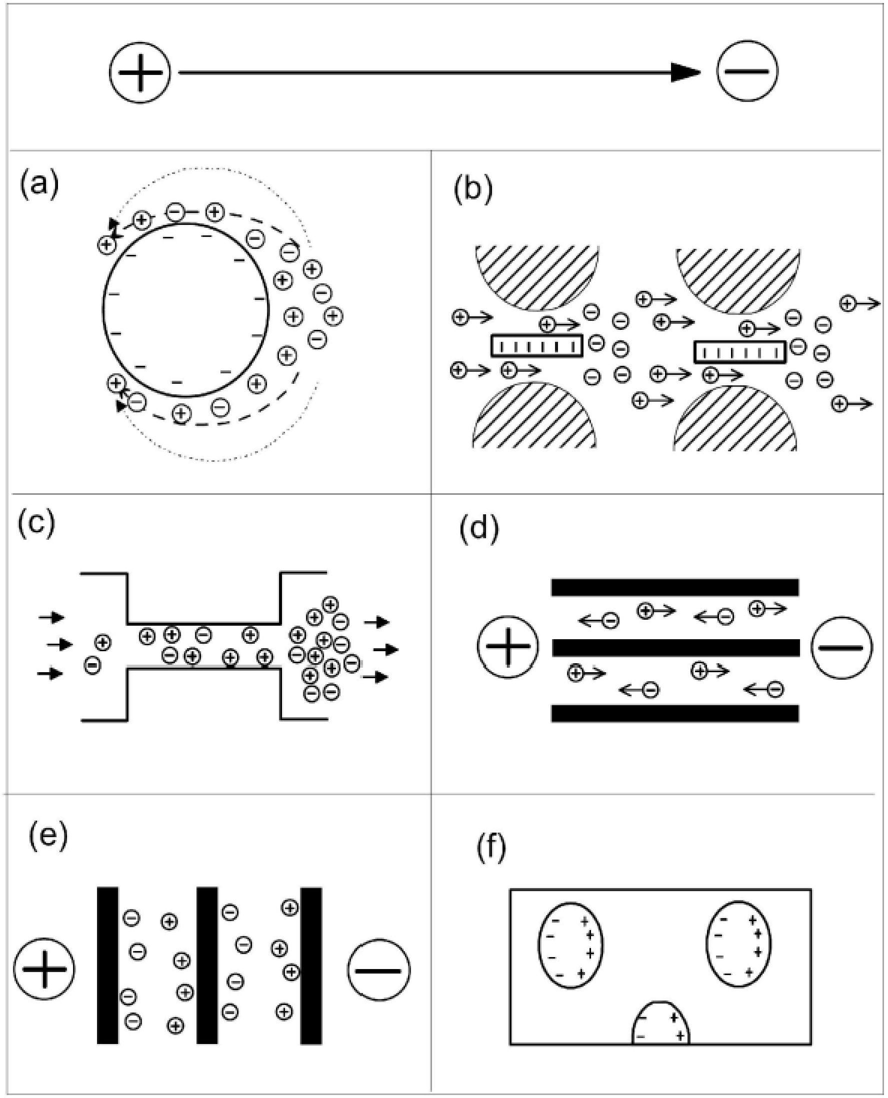
b) **Membrane polarization**: inclusions act as a semi-permeable membrane, creating ion accumulation and deficiency zones

c) **Polarization associated with pore throats**: throats can favour the ion-selective behaviour

d) **No interfacial polarization**: layering is parallel to the electric field

e) **Maxwell (interfacial) polarization**: layering is normal to the electric field

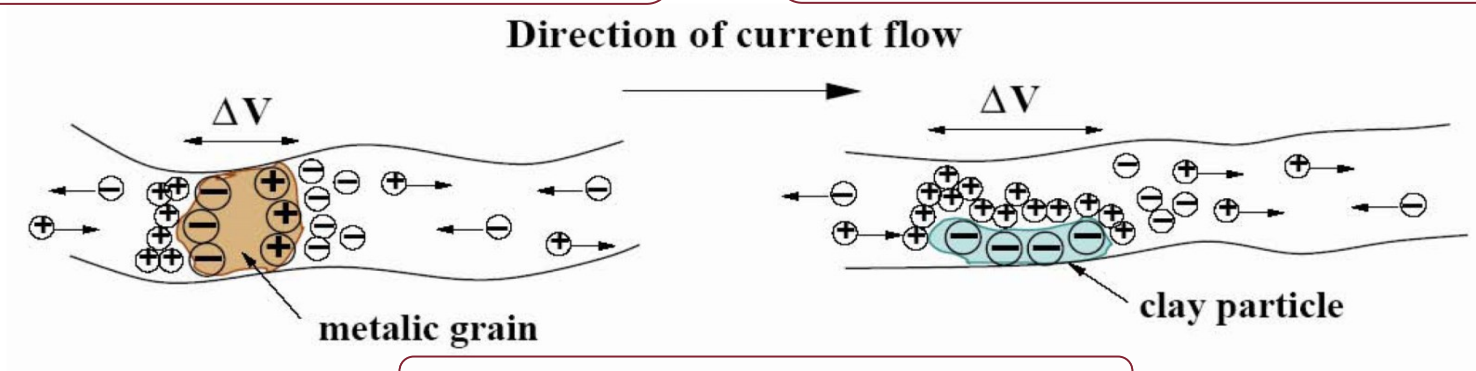
f) **Wagner (interfacial) polarization**: dielectric medium with conductive inclusions (e.g. metals)



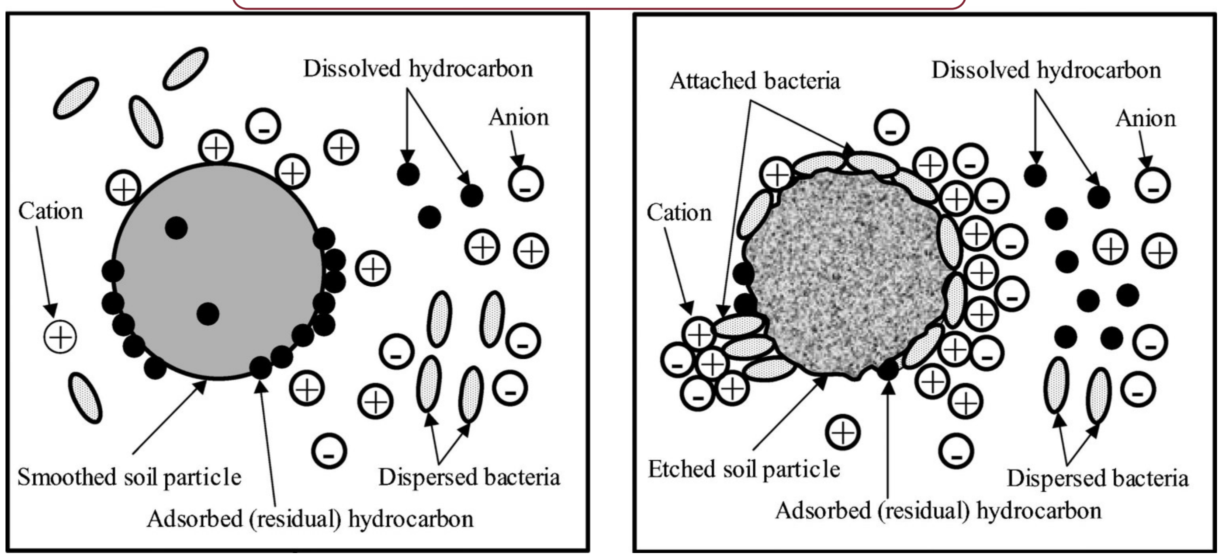
Electrical permittivity – Low-frequency polarization

Electrode polarization (metalic grains)

Membrane polarization (clay particles)



Biochemical polarization



Electrical permittivity of soils and rocks

Soils and rocks are multiphase media

The global dielectric constant is the combination of the values of the single component

Solid	**Liquid**	**Gas**
Minerals	Mainly water	Mainly air
(low ε_r**)**	($\varepsilon_r \sim 80$)	($\varepsilon_r \sim 1$)

Dielectric constant of the multiphase medium
Combination of the three contributions

Electrical permittivity of soils and rocks

Material	ε_r	σ [S/m]
Air	1.00034	0
Distilled water	80	10^{-6}
Freshwater	80	0.01 - 0.2
Saltwater	80	5
Ice	3-4	10^{-5} - 10^{-8}
Dry sand	3-5	10^{-3}
Saturated sand	20-30	$2 \cdot 10^{-2}$ - $5 \cdot 10^{-3}$
Limestone and dolomite	4-8	10^{-3} - 10^{-4}
Silt	5-30	$2.5 \cdot 10^{-2}$ - $5 \cdot 10^{-2}$
Clay	5-40	0.05 - 0.5
Granite	4-6	10^{-4} - $5 \cdot 10^{-5}$

Electrical permittivity of soils and rocks

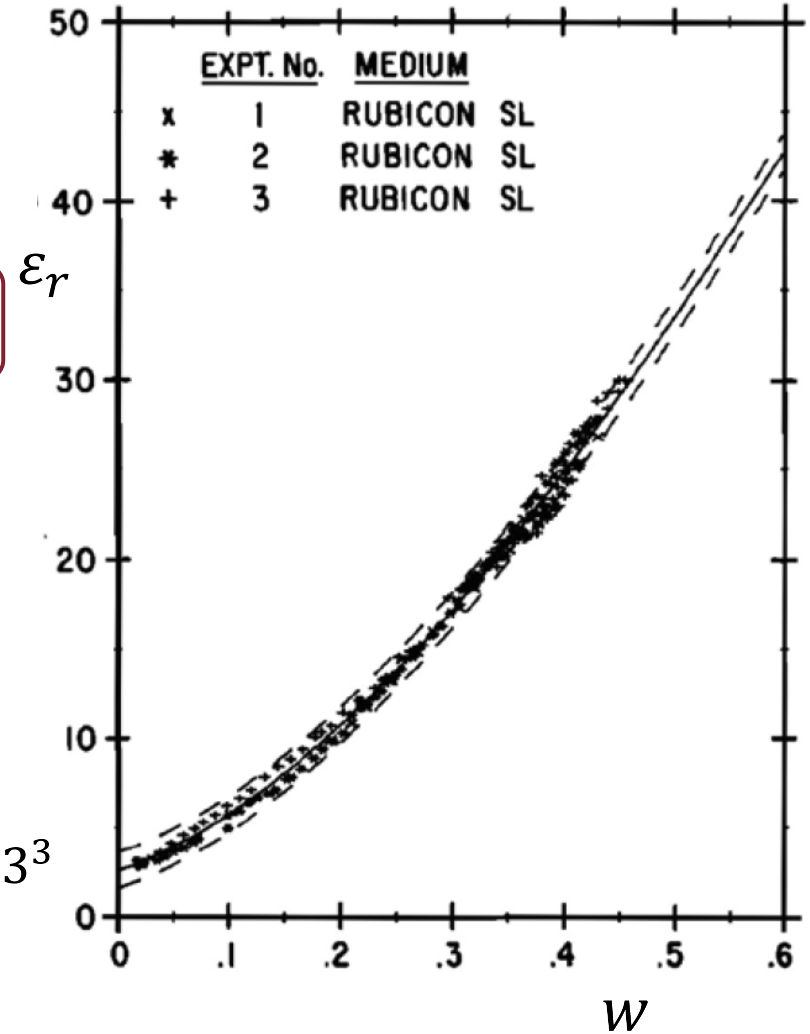
Topp's law
(empirical, 1980)

Hp. only for three-phase media

$$\varepsilon_r = 3.03 + 9.3w + 146w^2 + 76.7w^3$$

$w = \frac{P_w}{P_s}$ water content

ε_r dielectric constant



Ex. 1 Calculate the dielectric constant for a medium having *w*=30%

$$\varepsilon_r = 3.03 + 9.3 \cdot 0.3 + 146 \cdot 0.3^2 + 76.7 \cdot 0.3^3$$

$$\varepsilon_r \cong 21$$

Magnetic permeability

The **magnetic permeability** is the ability of a medium to support the formation of a magnetic field

$$\mu = \mu_0 \mu_r$$

μ_r → **Relative permeability** or **magnetic constant**

μ_0 → **magnetic permeability** of free space ≈ 4π10[-7] H/m

$\mu_r = 1$ vacuum
$\mu_r \approx 1$ non-magnetic materials
$\mu_r > 1$ paramagnetic materials
$\mu_r < 1$ diamagnetic materials
$\mu_r \gg 1$ ferromagnetic materials

For most rocks and soils → $\mu_r \approx 1$