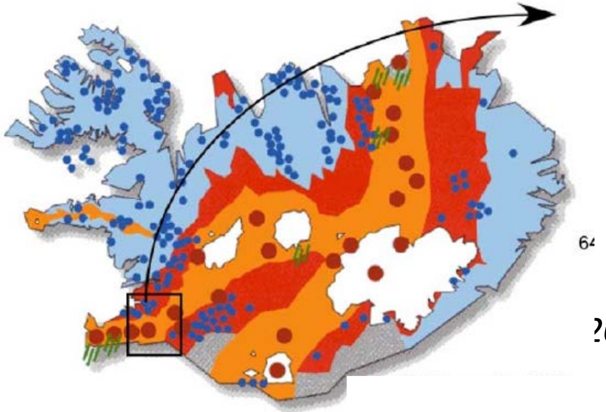
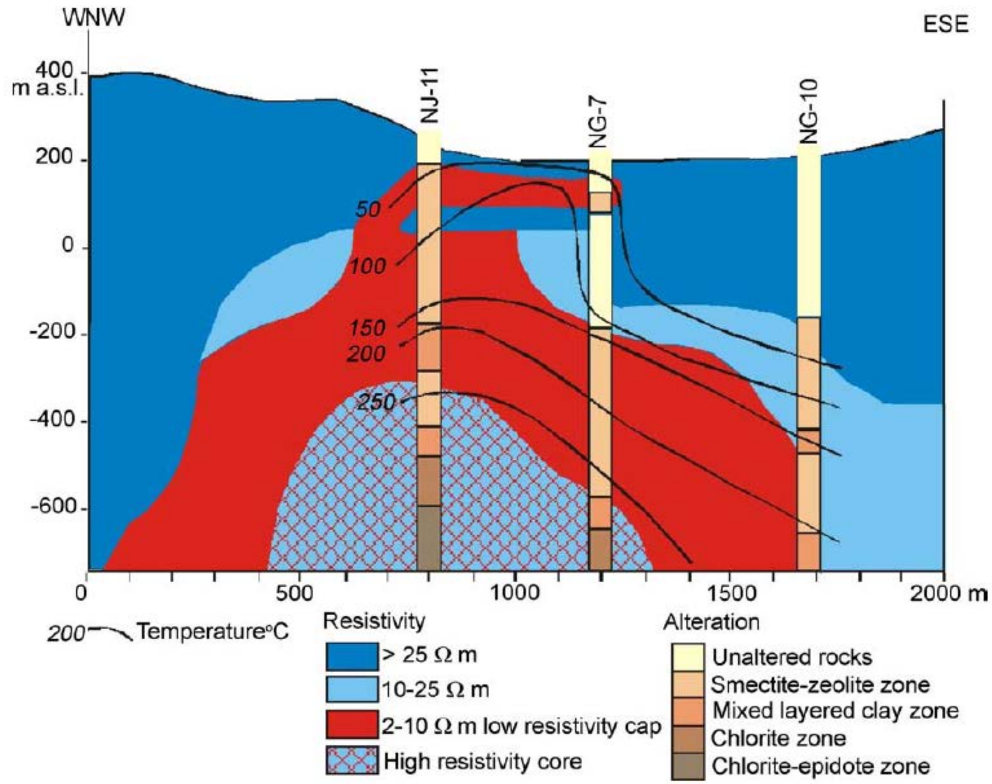
Rock Physics

prof. M. Violay

3 . Electrical properties

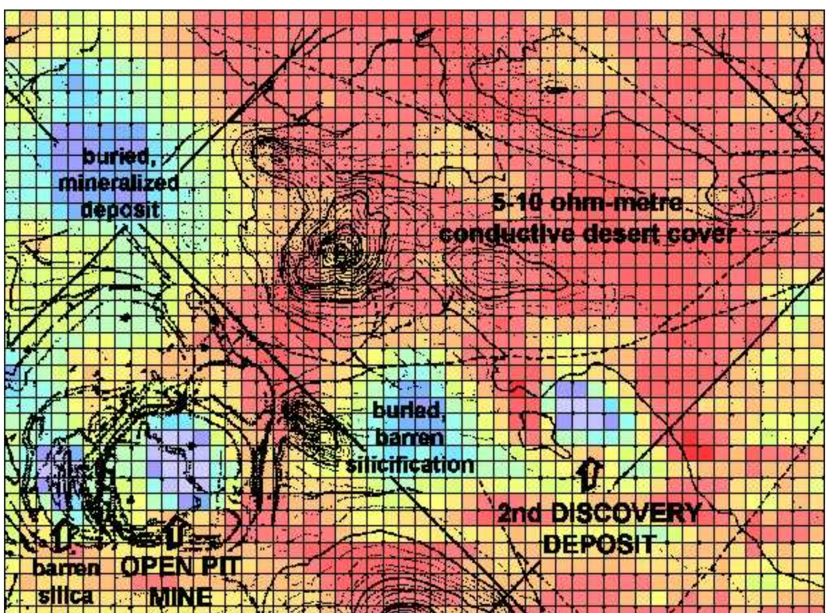
Electrical resistivity and geothermal prospecting in Iceland.





Beblo. and Björnsson,. (1978)
Flovenz et al. (1985)

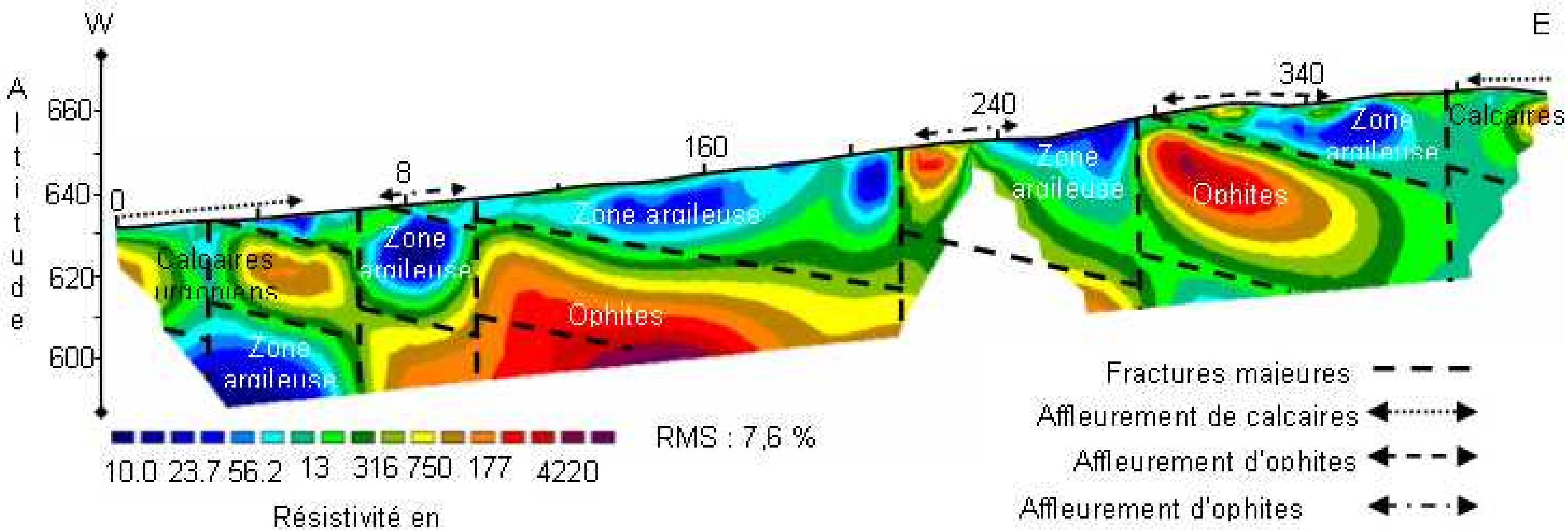
Electrical resistivity and metal (gold) detection.



Plan View # Zs6 250 to 300 feet below surface topography

Paradise Peak remained geophysically invisible during the several years it took to discover the Ketchup Flat orebody, a mile away, by drilling. About that time, 3D E-SCAN was brought in to see if it could detect any sort of useful exploration signature, based on the known orebodies.

Electrical resistivity Aquifere detection



Modèle de résistivité obtenu avec un panneau électrique localisé à l'Ouest de la fontaine d'Orbe (Pyrénées). Ces mesures géophysiques couplées aux données terrain montrent bien la complexité des structures géologiques.(cf. fiche ressource en eau)

Contents :

1. Reminder on electrical resistivity

- Definition of an OHM

- An ohm is a resistance in a conductor that produces a potential difference of one volt when a current of one ampere is flowing through it.

$$\boxed{\boldsymbol{R} = \frac{\boldsymbol{V}}{\boldsymbol{A}} \left[\frac{m^2 \cdot kg}{s^3 \cdot A^2}\right]}$$

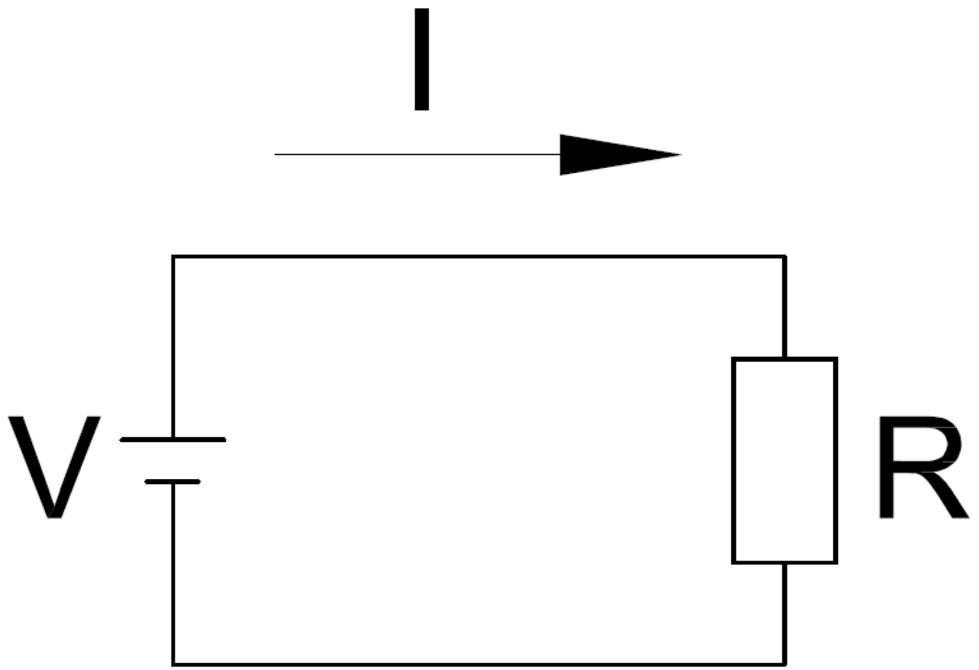
1. Reminder on electrical resistivity

➢ Ohm's law

Ohm's Law

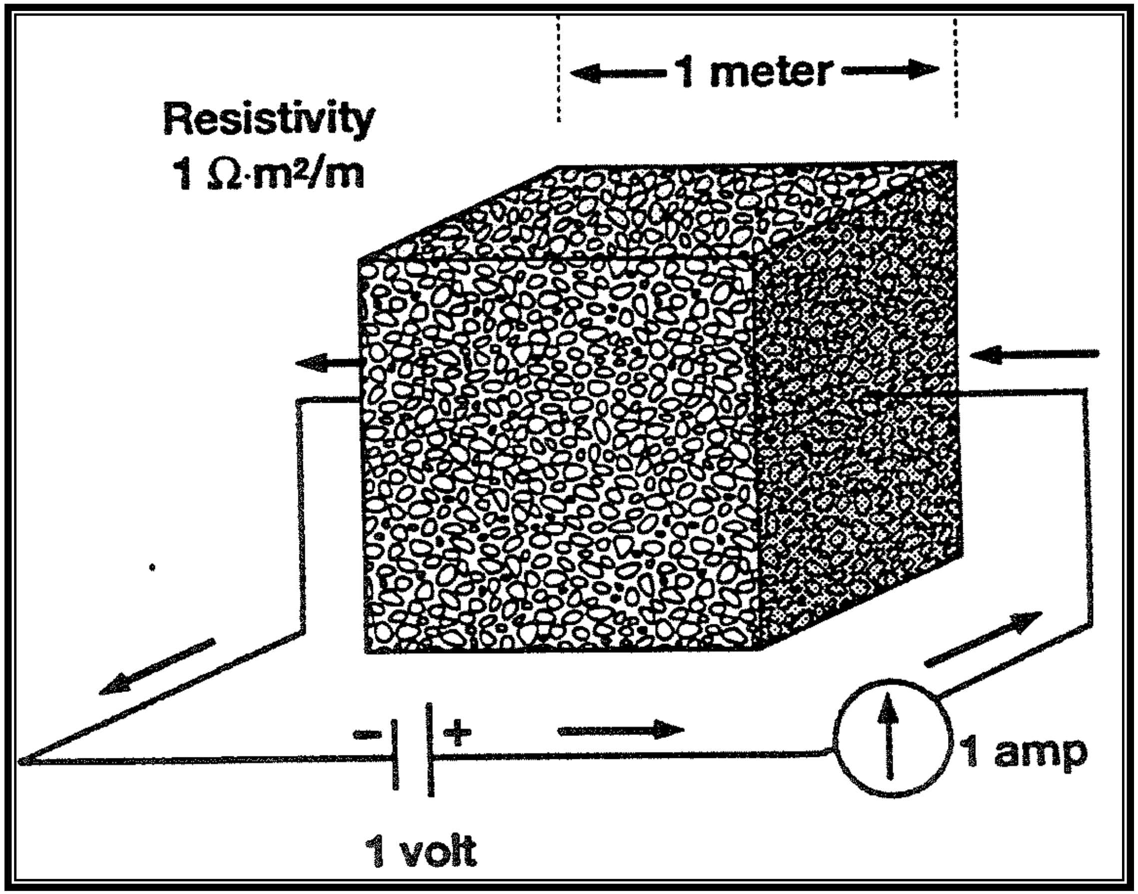
$$I = \frac{V}{R}$$

Electric current = Voltage / Resistance



1. **Reminder on electrical resistivity**

- Resistivity – definition of the ohm-meter



1. **Reminder on electrical resistivity**

- Resistivity

- Resistivity is determined by measuring the voltage required to pass a measured amount of electrical current through the rock.

- For a rock cube with sides of 1 m, if electrical potential of 1 V (Volt) is required for current flow of 1 A (Ampere), then resistivity is 1 Ω·m (Ohm ·meter)

1. **Reminder on electrical resistivity**

- Resistivity

- Resistivity is an intensive **rock/fluid property**, and is a measure of (the inverse of) the electrical flow capacity of the rock

- Resistance is extensive and for linear, 1-D electrical flow,

$$\boldsymbol{r} = \frac{\boldsymbol{R \cdot L}}{\boldsymbol{A}}$$

  - r electrical resistance, Ω
  - R electrical resistivity, $\Omega \cdot$m
  - L length of electrical flow path, m
  - A cross-sectional area perpendicular to electrical flow path, m^2

1. **Reminder on electrical resistivity**

- Resistivity

- Electrical resistance (Ω) is inverse of Electrical conductance (S, Siemens)
- $2\ \Omega = (1/2)\ S$

- Resistivity is the inverse of conductivity
- $2\ \Omega\cdot m = (1/2)\ S/m$

1. **Reminder on electrical resistivity**

- Conductivity

Resistance = ρ (ohm-meters)

Conductivity = σ = 1/ρ (mho/meters)
= Siemens/m

1. **Reminder on electrical resistivity**

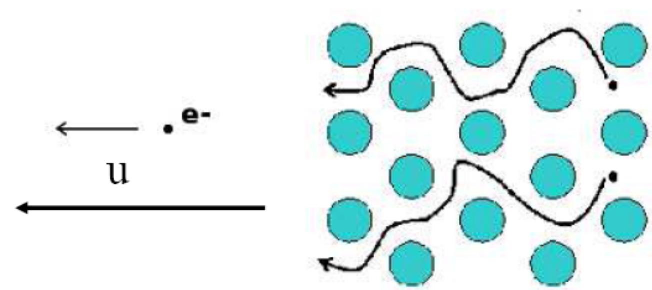
➢ Material conductivity

- Conductor (large number of free electrons)

= Metals/Graphite ➔ > 10^5s/m

- Semi conductor (Fewer mobile electron)

= most of the sulfite, oxydes 10^5-10^{-8}s/m



- Insulator (Ionic bounding)

= Most of the silicate < 10^{-8} s/m

- Electrolyte

=Water ~ $5*10^{-6}$ s/m, water with salt= 10^2s/m

1. Reminder on electrical resistivity

- Factors Affecting Electrical Resistivity

  - Resistivity of water (salinity, pore saturation)
  - Porosity of the formation,
  - Pore geometry - tortuosity
  - Lithology of the formation
  - Degree of cementation
  - Type and amount of clay in the rock (surface conductivity)
  - Metallic Sulfide Mineral Content (mineralogic conductivity)

1. **Reminder on electrical resistivity**

➢ Factors Affecting Electrical Resistivity

$$\boxed{\boldsymbol{C_{0(T,P)} = \frac{C_{w(T,P)}}{F_{(T,P)}} + C_{s(T,P)} + C_{min(T,P)} + C_{oxi} + C_{melt(T,P)}}}$$

With :

$\boldsymbol{C_0}$ = rock electrical conductivity

$\boldsymbol{C_w}$ = pore fluid electrical conductivity

$\boldsymbol{F}$ = formation factor (~ 3D topology of pore volume)

$\boldsymbol{C_s}$= pore surfaces electrical conductivity (~ CEC, Ø, ρ_m, … i.e. alteration)

$\boldsymbol{C_{min}}$ = min conduction (>300°C)

2. **Ionic Conduction**

- Electricity and earth materials

- Primarily, conduction is by ions in water
  - Na^+ and Cl^- are very common
  - Other monovalent ions K^+ and OH^-
  - Bivalent ions, too: Ca^{++}, Mg^{++}

- But, clays can conduct electricity also

2. **Ionic Conduction**

➢ Resistivity of earth materials

Resistivity ↑

(1) Rock
(2) Gas
(3) Oil
(4) Fresh Water
(5) Salt Water

Conductivity ↓

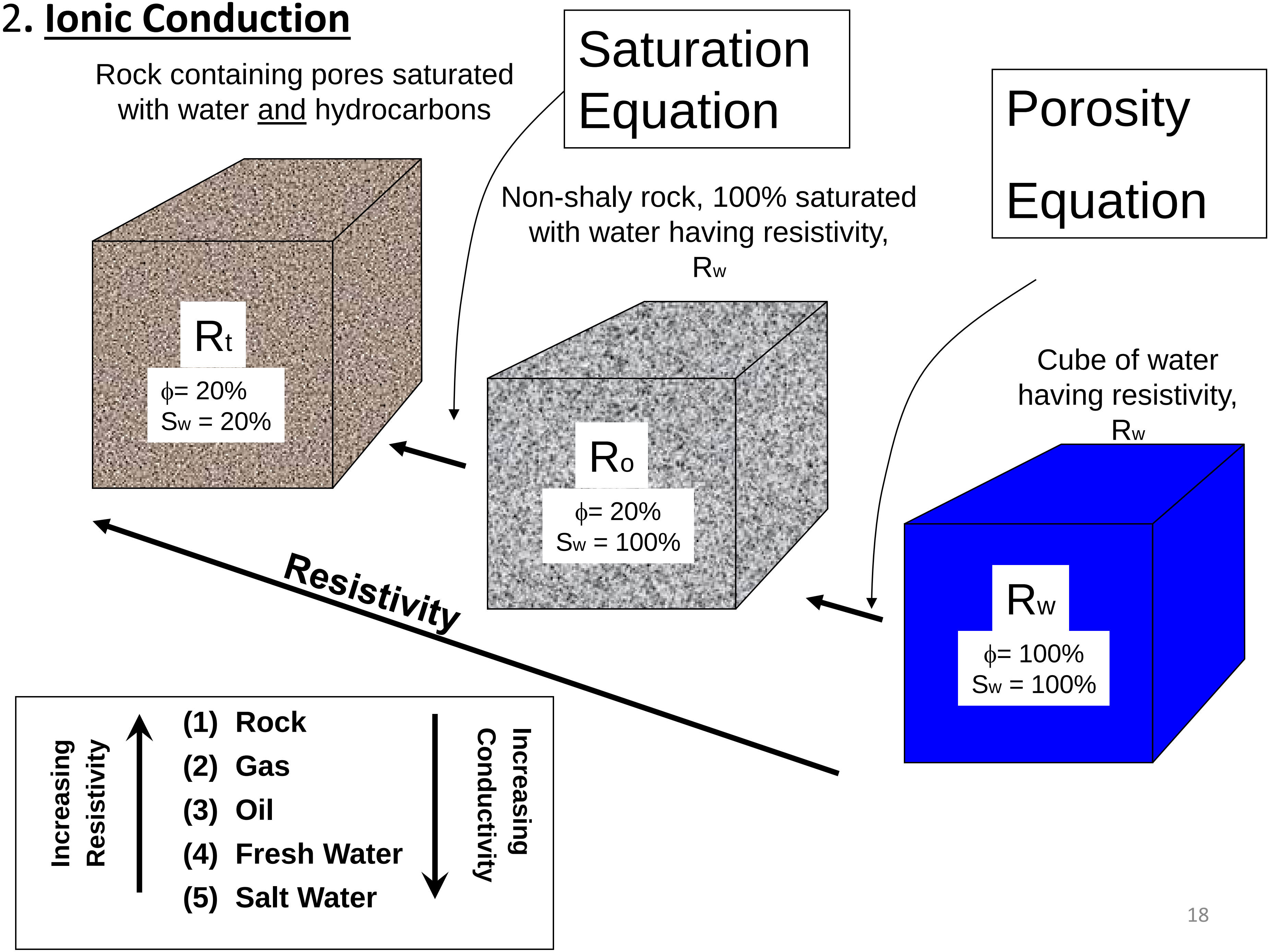
Common Notations

R_o = Resistivity of non-shaly rock saturated (Sw=1) with formation water (ohm-m)

R_t = True formation resistivity (ohm-m)

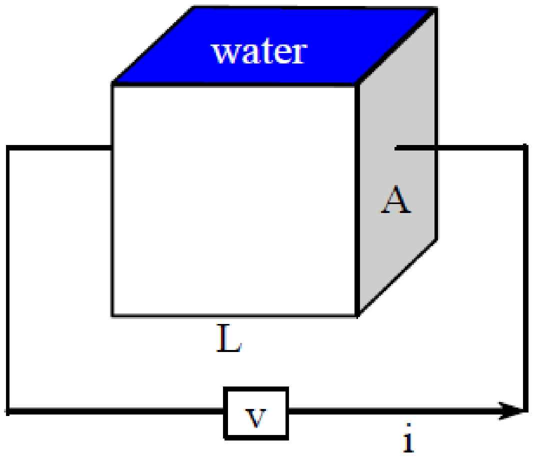
R_w = Formation water resistivity (ohm-m)

2. **Ionic Conduction**



2. **Ionic Conduction**

Consider the following tank completely filled with brine water,



→ apply a voltage, v

→ measure a current, i

→ calculate a resistance, r

by **Ohms Law:**

v = i r

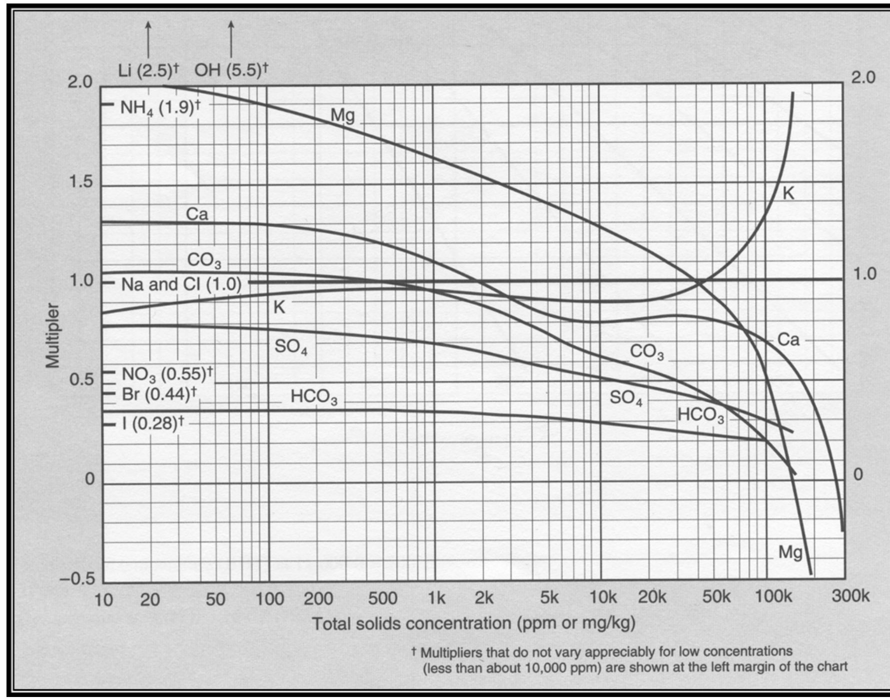
→ Define water resistivity, Rw, as:

$$\boxed{R_w = r_w \frac{A}{L} \;\rightarrow r_w = R_w \frac{L}{A}}$$

2. **Ionic Conduction**

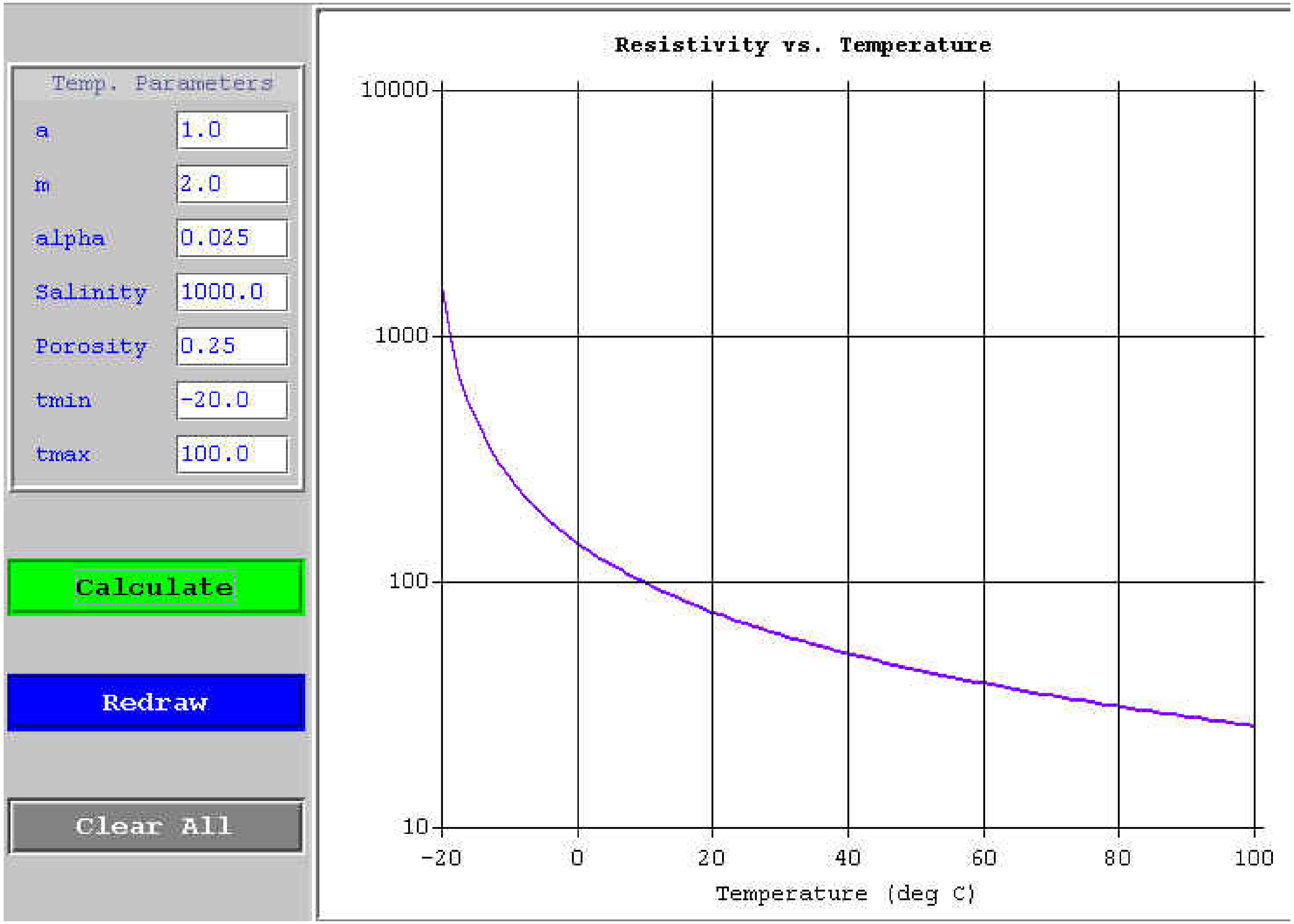
➢ ELECTRICITY AND EARTH MATERIALS

- Water resistivity controlled by
  - Ion concentrations
  - Type of ions
  - Temperature
- Chart GEN-4 to convert to NaCl equiv
- Chart GEN-5 for temp/resist for NaCl



2. Ionic Conduction

➢ Effect of Water Temperature



http://appliedgeophysics.berkeley.edu:7057/dc/figures/fig43_7.jpg

2. <u>Ionic Conduction</u>

Consider the tank completely filled with 100% brine saturated, porous sand:

- Resistance with respect to the water phase :

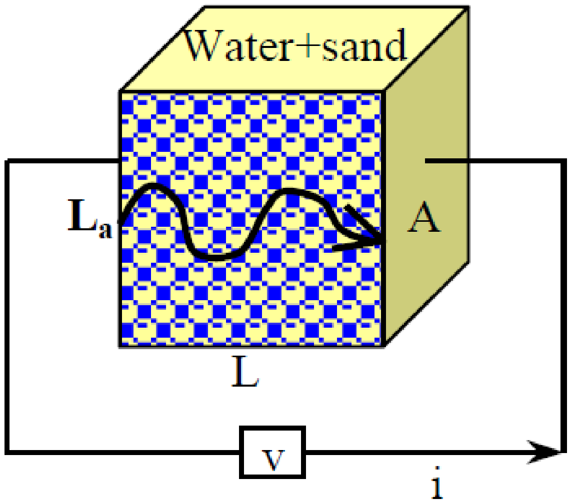
  $\mathbf{r_w} = \mathbf{R_w} \frac{L_a}{A_p}$

  with L_a apparent length
  and A_p the pore Area

- Resistance of the rock filled by water

  $\mathbf{r_0} = \mathbf{R_0} \frac{L}{A}$

- Since ro ≈ rw $\boxed{\frac{R_0}{R_w} = \frac{A}{A_P} \cdot \frac{L_a}{L}}$



2. **Ionic Conduction**

- Definitions

Define the **Formation Resistivity Factor F** $\rightarrow$ $\boxed{F = \frac{R_0}{R_w}}$

Define **porosity** $\boldsymbol{\phi}$ $\rightarrow$ $\boxed{\phi = \frac{A_P}{A}}$

Simplified theoretical relationship between F and φ does not account for heterogeneity.

2. **Ionic Conduction**

- Formation factor

Since the conduction of current in soil and rock is through the electrolyte contained in the pores, resistivity is governed largely by the porosity, or void ratio, of the material and the geometry of the pores. Pore space may be in the form of intergranular voids, joint or fracture openings, and blind pores, such as bubbles or vugs. Only the interconnected pores effectively contribute to conductivity, and the geometry of the interconnections, or the tortuosity of current pathways, further affects it. The resistivity ρ of a saturated porous material can be expressed as

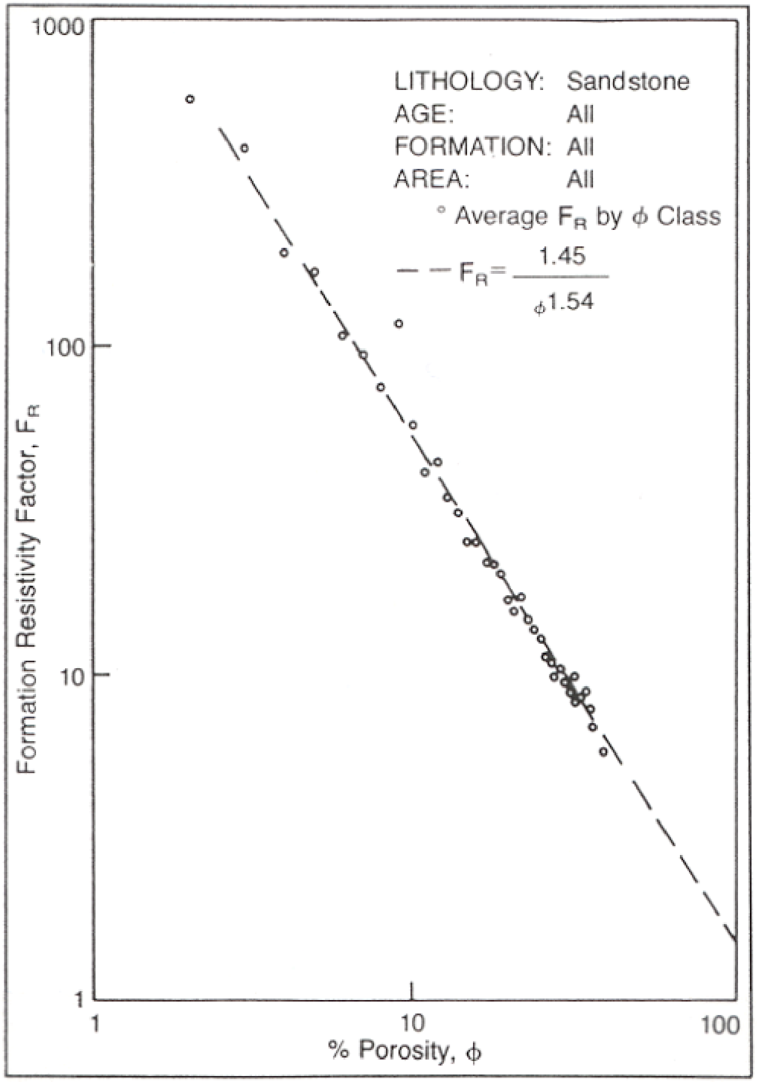
$$\boxed{\boldsymbol{\rho = F\rho_w}}$$

F = formation factor,

ρ_W = resistivity of pore water.

2. **Ionic Conduction**

- Formation factor



Helander (1983)

2. Ionic Conduction

$$\boxed{\frac{\sigma_w}{\sigma_f} = F = a\phi^{-m}}$$

σ_w = conductivity of the water,

σ_f = conductivity of the formation as a whole,

a = empirical constant, typically 1 for unconsolidated sediments,

m = empirical constant, typically 2 for unconsolidated sediments,

ϕ = effective porosity, the fraction of interconnected pore space,

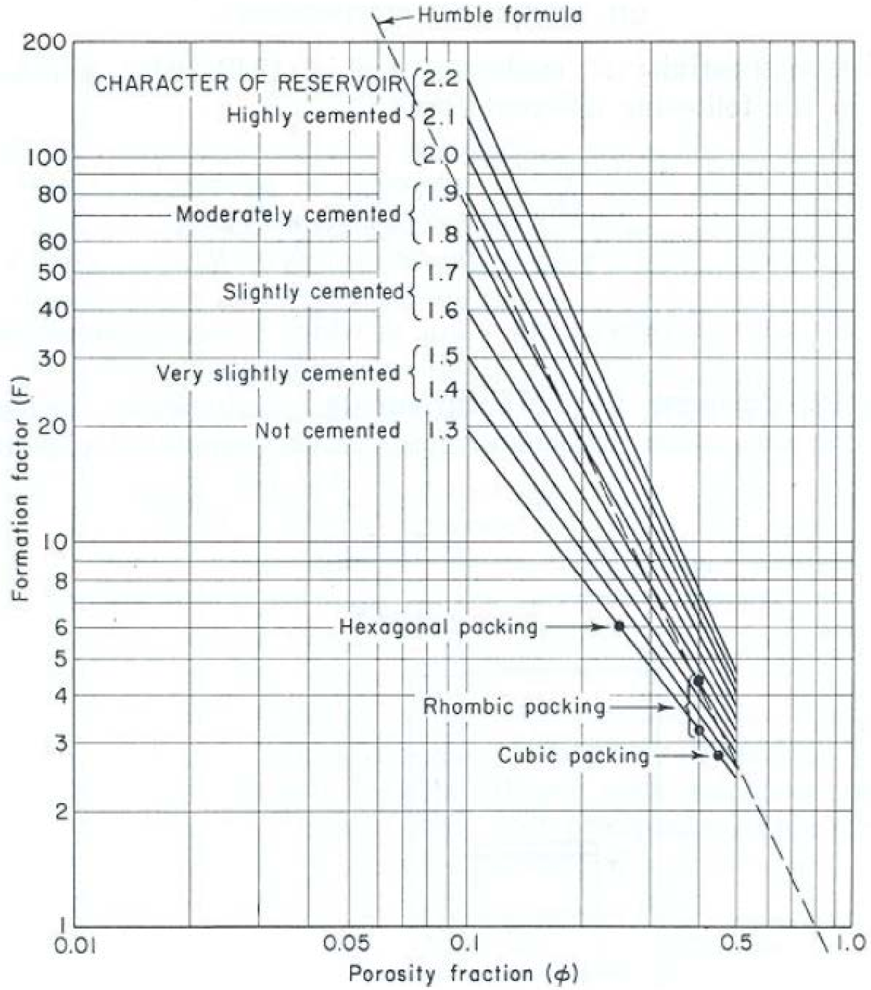
F = "formation factor," related to the volume and tortuaosity of the pore space.

The conductivity of most geological formations can be fit to Archie's Law

2. **Ionic Conduction**

- Cimentation exponent :

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



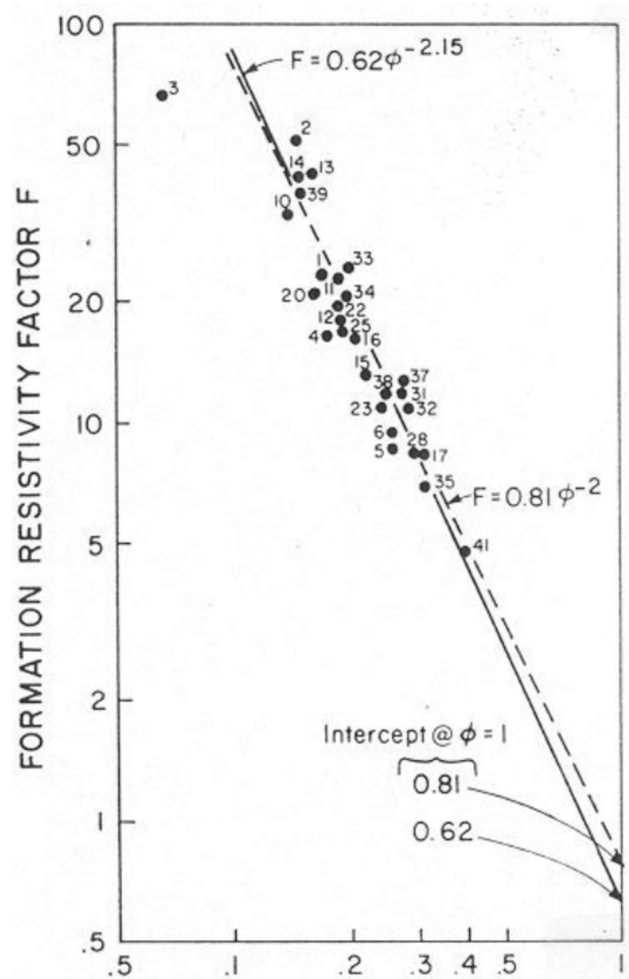
F dependent on degree of cementation, thus *m* originally defined as “cementation exponent”.

2. **Ionic Conduction**

- Cimentation exponent :

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

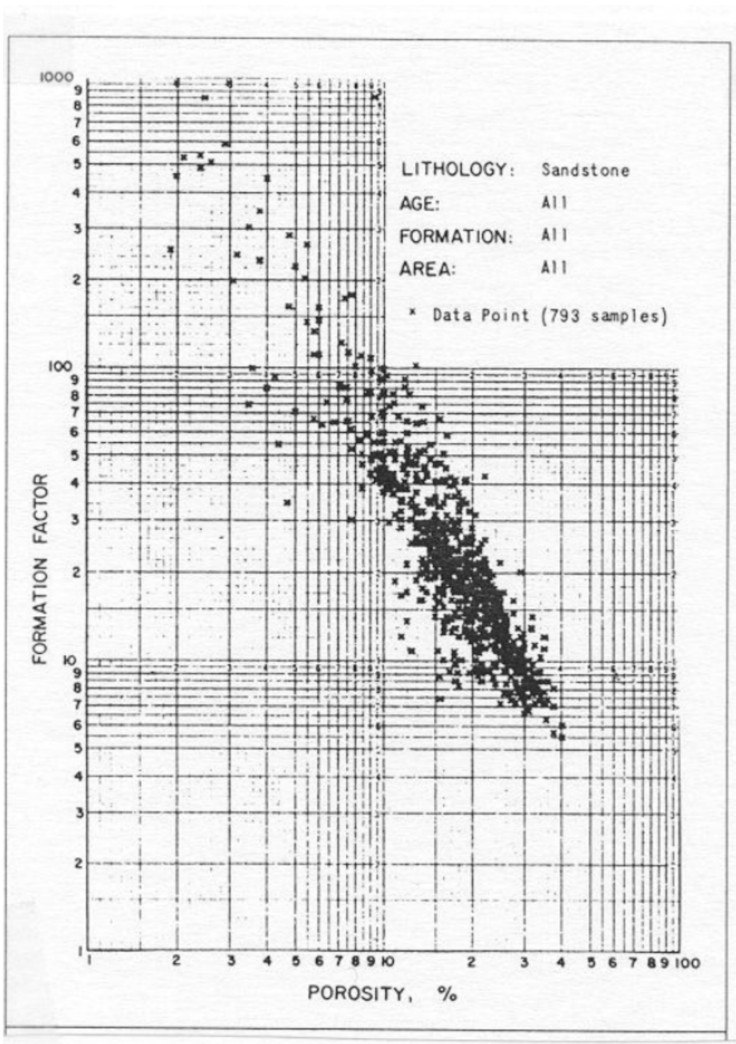
Winsauer, et al (1952) - analyzed data from 30 samples (28 ss, 1 lms, 1 unconsolidated ss) Developed correlation known as “Humble Eq.” $F = 0.62\phi^{-2.15}$
Tixier (1979) – simplified equation using same data $F = 0.81\phi^{-2}$



2. **Ionic Conduction**

- Cimentation exponent :

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



Carothers (1968) - analyzed 793 sandstone data points. Generalized correlation:
$F = 1.45\ \phi^{-1.54}$

2. **Ionic Conduction**

- Relation ϕ-F

- Humble - granular or soft rocks, e.g. sandstone

  $F = 0.62\ \phi^{-2.15}$

- Tixier - granular or soft rocks, e.g. sandstone

  $F = 0.81\ \phi^{-2}$

- Archie- most types of carbonates

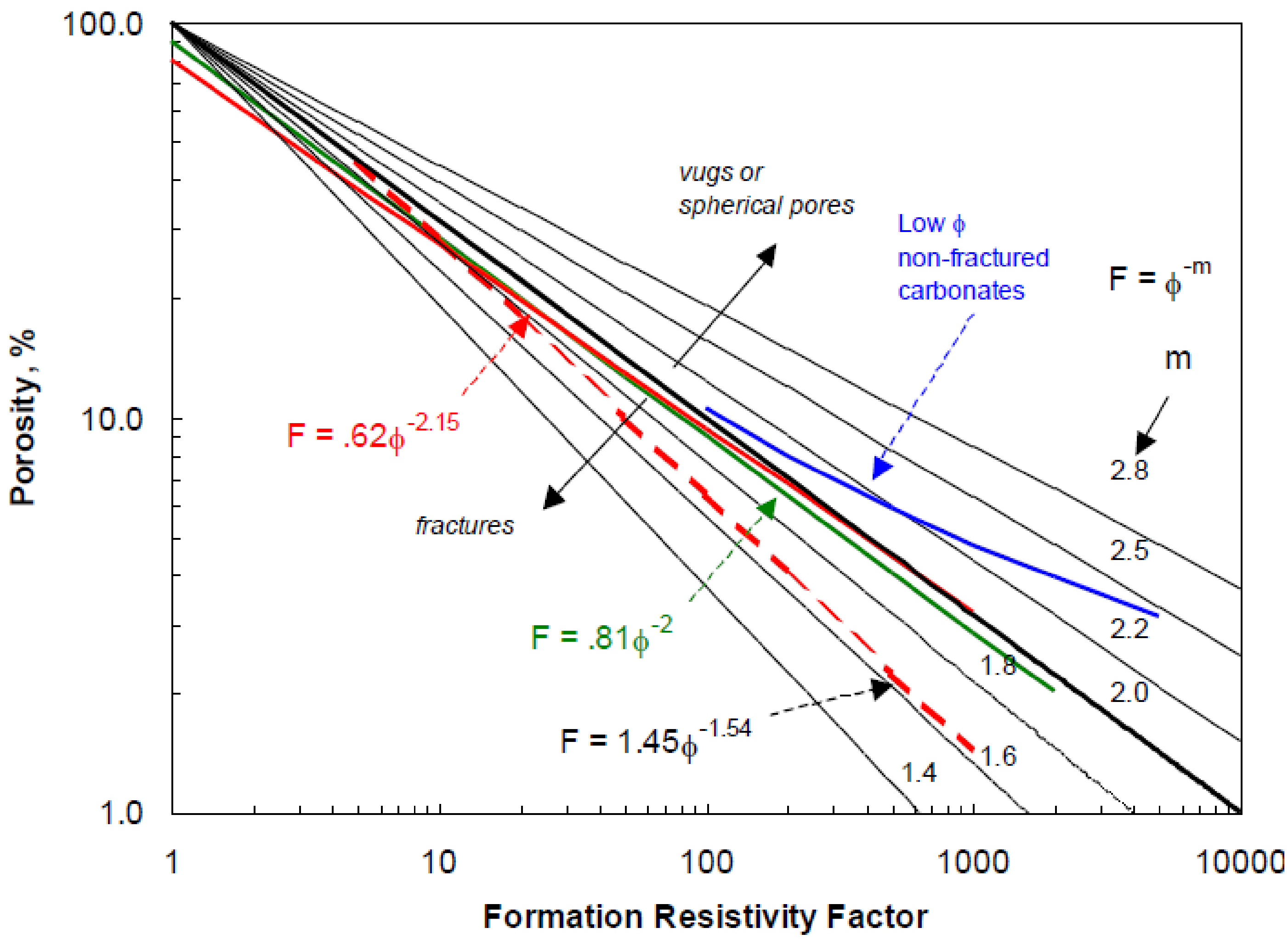
  $F = \phi^{-2}$

- Shell - low ϕ (<9%) carbonates, not fractured

  $F = \phi^{-m}$ with $m = 1.87 + 0.019/\phi$

2. **Ionic Conduction**

- Relation ϕ-F



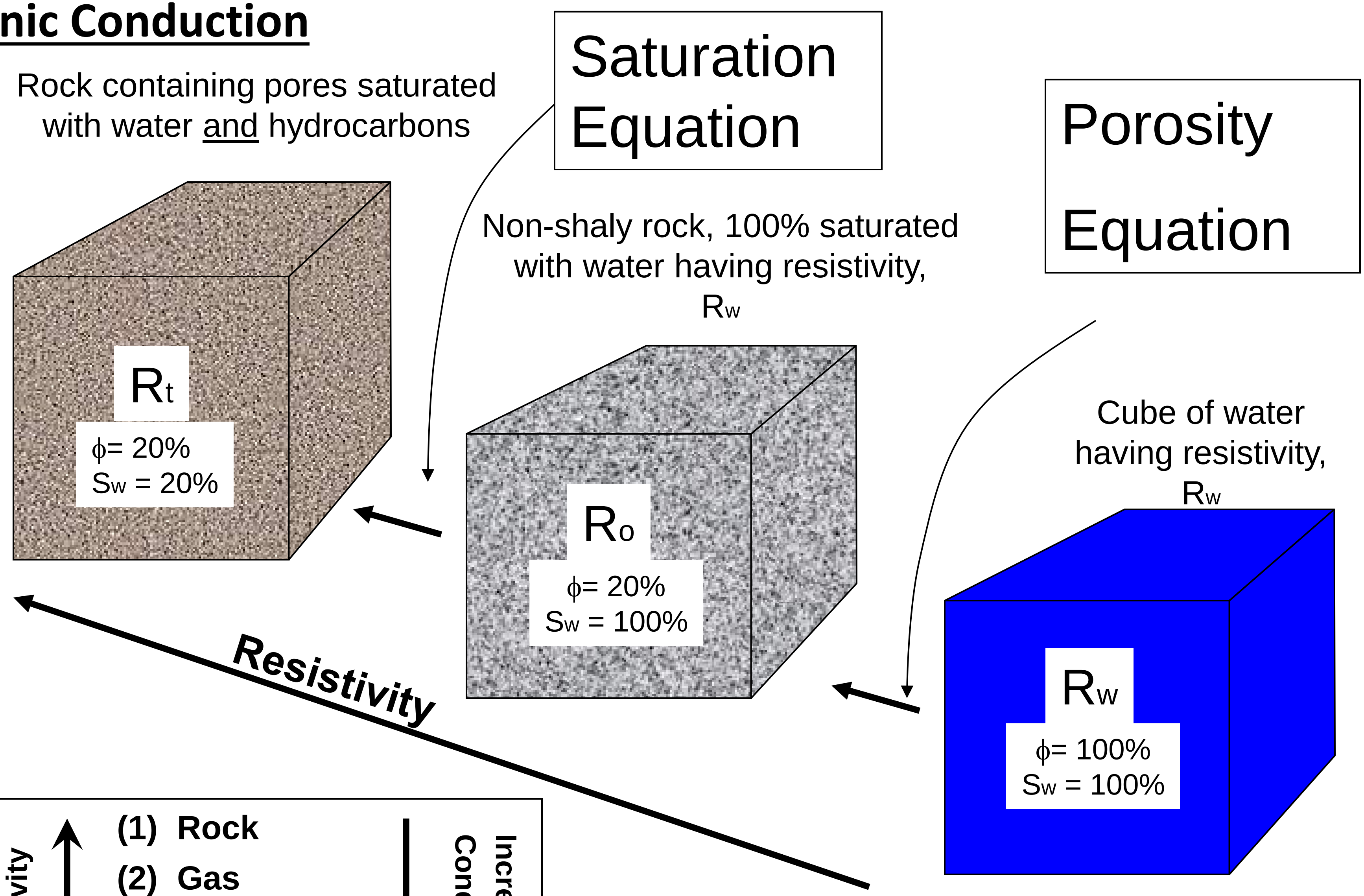
2. **Ionic Conduction**

- Tortuosity

- In low porosity igneous rocks, the electrical tortuosity is preferentially used to the cementation index (Walsh and Brace,1984; Pape et al., 1985; providing an alternate view at relationships between pore space and electrical transmissivity with:
- $\boxed{F = \frac{\tau}{\phi}}$

Where τ relates to the geometrical complexity of the path followed by the electrical current in the fractured pore space or, in a more general sense, to the efficiency of electrical flow processes (e.g., Guéguen and Palciauskas, 1992; Clennell, 1997).

2. Ionic Conduction



Increasing Resistivity ↑

(1) **Rock**
(2) **Gas**
(3) **Oil**
(4) **Fresh Water**
(5) **Salt Water**

↓ Increasing Conductivity

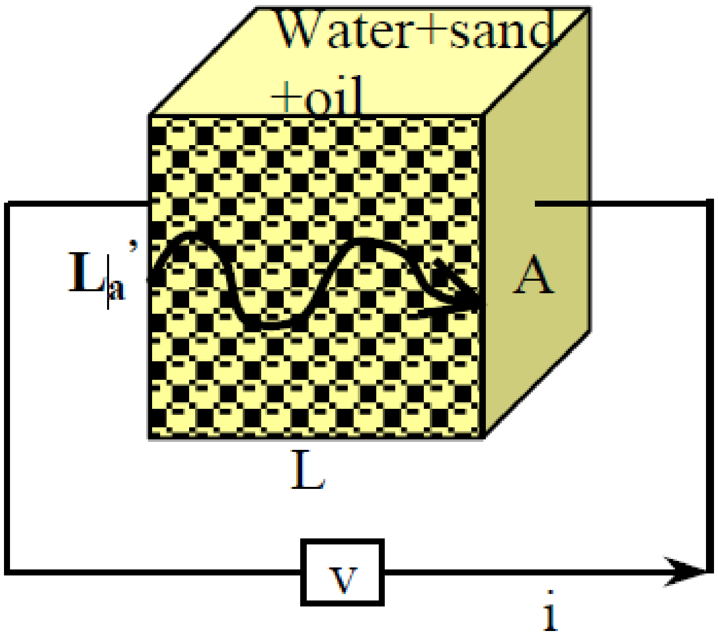
$$R_t = R_w \phi^{-m} S_w^{-n}$$

2. **Ionic Conduction**

➢ Effect of saturation

Consider the tank filled with a porous sand and partially saturated.

- Resistance with respect to the water phase only: → $r_w = R_w \frac{L_a'}{A_p}$;
- Resistance with respect to the porous rock partially saturated: → $r_T = R_T \frac{L}{A}$
- Since rt≈rw $\boxed{\frac{R_T}{R_w} = \frac{A_P}{A'_P} \cdot \frac{L'_a}{L_a}}$



2. **Ionic Conduction**

- Archie's law

The minerals comprising a rock are almost always electrical insulators. Thus, electrical conduction occurs because of the moisture contained within the pores of the rock or soil. The resistivity of soil or rocks depends on several parameters. These include the clay content, moisture salinity, degree of saturation of the pores, and the number, size, and shape of the interconnecting pores. For soils, the degree of compaction (influencing porosity) is also an important factor. Archie (1942) developed an empirical formulae relating resistivity to porosity, degree of saturation and resistivity of the saturating moisture, shown below.

$$\boxed{\boldsymbol{\rho_e = a\phi^{-m} S^{-n} \rho_w}}$$

where ϕ is the fractional pore volume (porosity), s is the fraction of the pores containing water, ρ_w is the resistivity of the water, n is approximately 2, a and m are constants with a varying between 0.5 and 2.5 and m varying between 1.3 and 2.5.

2. **Ionic Conduction**

- Definition of resistivity index (second Archies's law)

Resistivity index : $\boxed{\mathbf{I} = \frac{R_T}{R_0}}$

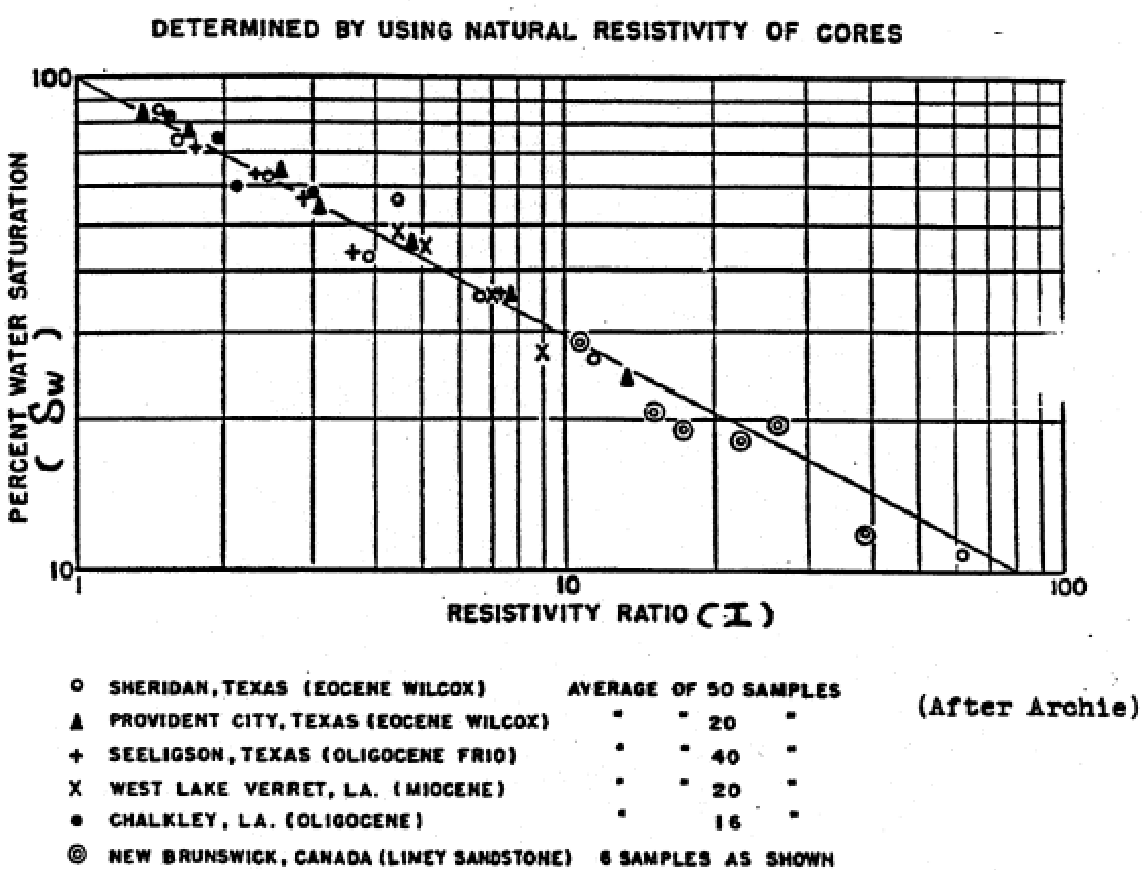
From Archie : $\boxed{\mathbf{I} \propto \frac{c}{S_w^n}}$

$$\boxed{\log(S_w) = \frac{1}{n}\log(C) - \frac{1}{n}\log\left(\frac{R_T}{R_0}\right)}$$

- With S_w = percentage of water saturation
- N a saturation exponent and C a constant

2. **Ionic Conduction**

- Effect of saturation



From plot, n=2 and c = 1, thus,

$$S_w = \sqrt{\frac{R_o}{R_T}}$$

2. **Ionic Conduction**

- Effect of saturation

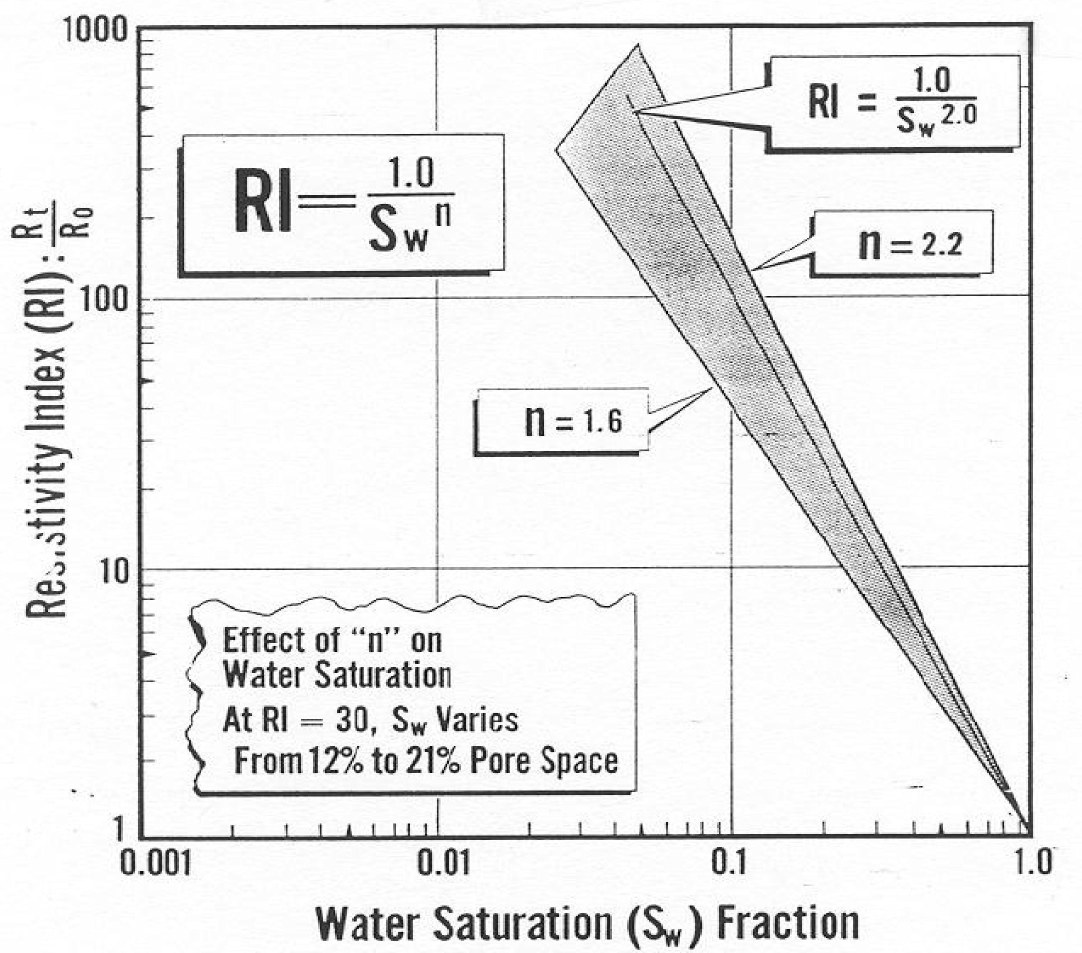
- General form known as **Archie's Law**.

- $$\boxed{S_w = \sqrt{\frac{F R_w}{R_T}}}$$

- *Fundamental relationship which the entire well logging industry is based!!*

2. **Ionic Conduction**

- Significance of saturation exponent S_w



Resistivity Index vs Water Saturation
For Range of Measured Saturation Exponents

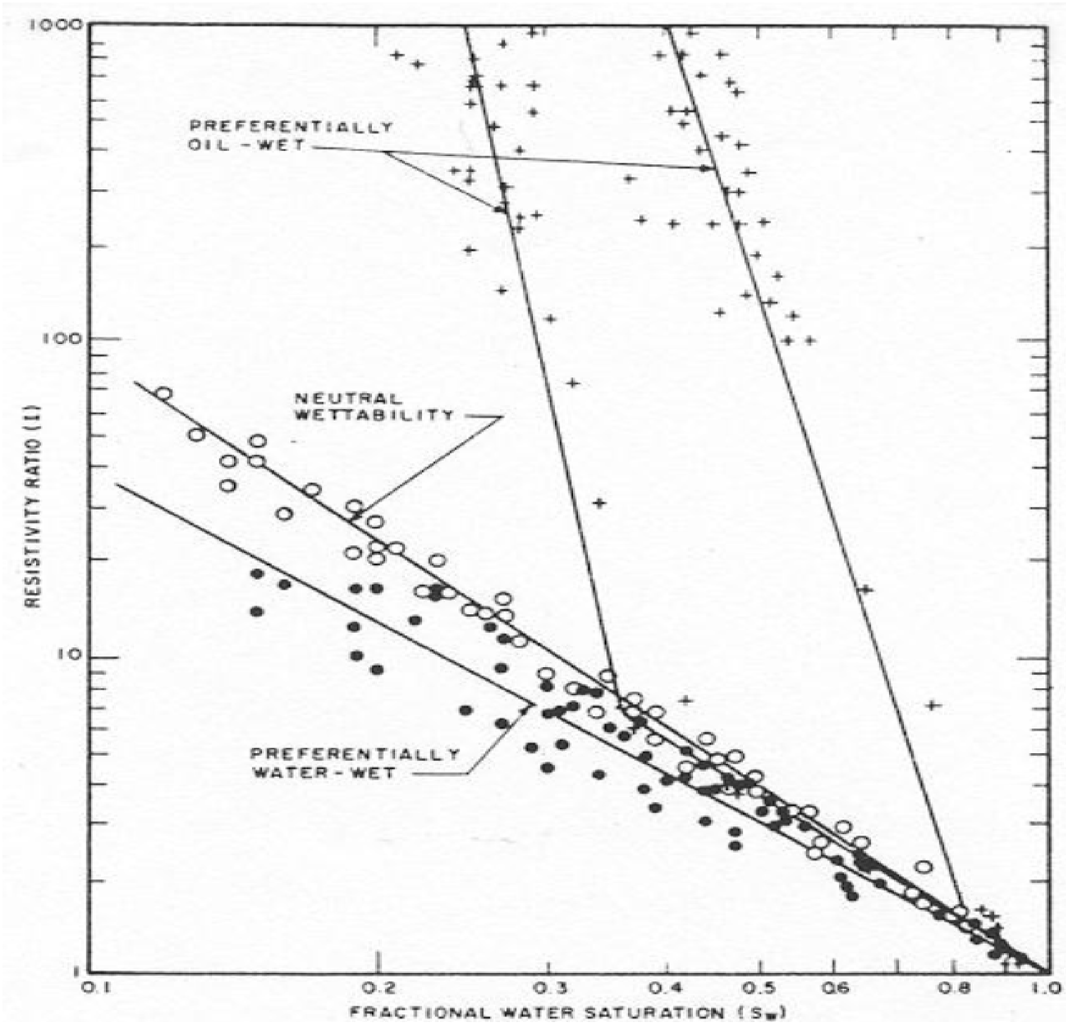
2. **Ionic Conduction**

➢ Significance of saturation exponent S_w

- Wettability of rock surface
- Rock texture
- Presence of clays
- Measurement techniques; i.e., static vs dynamic
- Nature of displacing fluid
- resistivity-Saturation Relationship
- fluid distribution in the pore spaces as a function of fluid
- wettability. Water and oil saturations in (a) a water-wet sand and (b) an oil-wet sand. Pirson (1958)

2. **Ionic Conduction**

- Significance of saturation exponent S_w



Resistivity Ratio vs. water saturation in carbonate cores
Anderson, JPT, (Dec 1986)

2. **Ionic Conduction**

➢ Influence of permability

A rock with a non-conducting matrix must be permeable (connected pores) as well as porous to conduct electricity.

Darcy's Law: $\boxed{\boldsymbol{q = -k \frac{dV}{dh}}}$

Ohm's Law: $\boxed{\boldsymbol{j = -\sigma \frac{dV}{dh}}}$

where q = fluid density

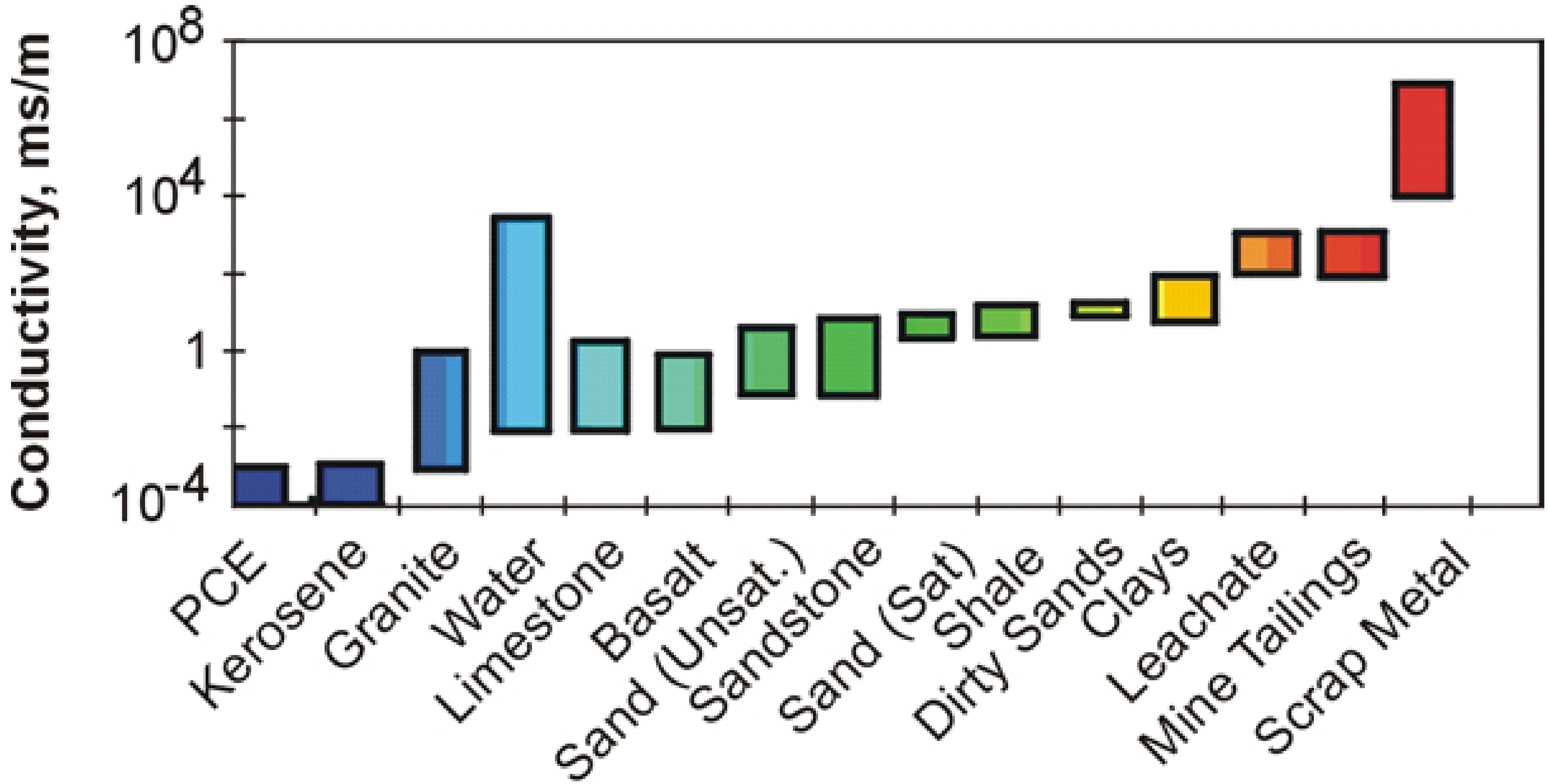
J = current density

$\frac{dV}{dh}$ = head or voltage gradient, respectively

Despite the similarity between Darcy’s and Ohm’s Laws, electric currents have zero viscosity so even a narrow crack can provide an effective electrical connection between pores that not contribute to hydraulic permeability.

3. **Mineralogical Conduction**

➢ Conductivity Ranges of Various Materials



3. **Mineralogical Conduction**

- Resistivity ranges of Various Materials

Table 17. 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

3. **<u>Mineralogical Conduction</u>**

- <u>Temperature effect</u>

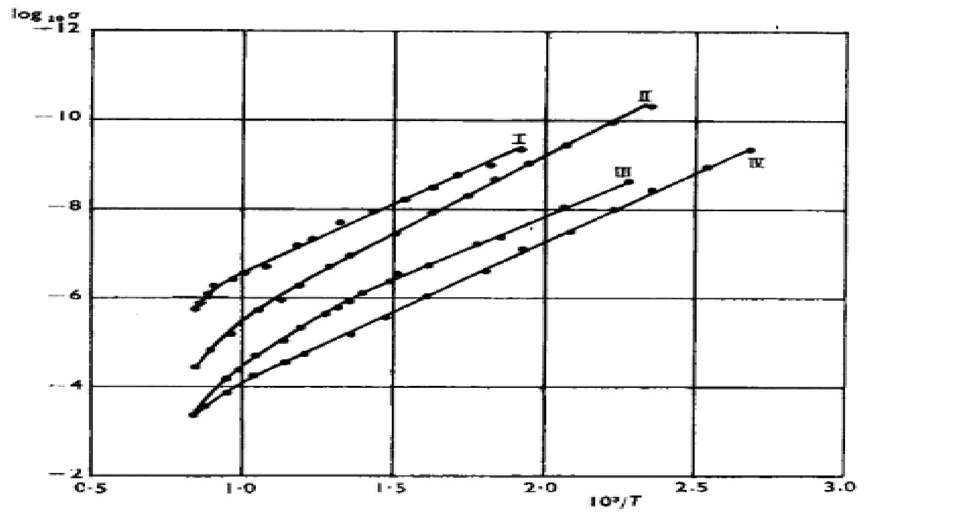


FIG. 1.—*The relation between the conductivity σ and the absolute temperature T of different rocks.* I—*granite*; II—*gabbro*; III—*crystalline basalt*; IV—*glassy basalt*.

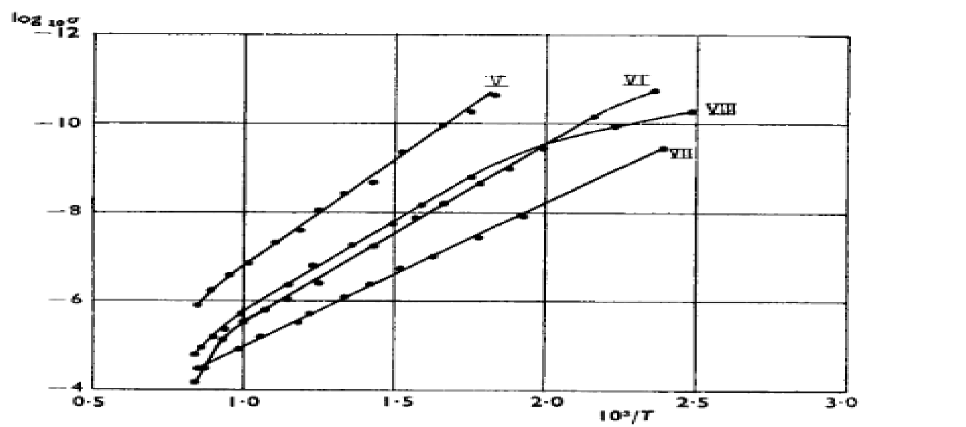


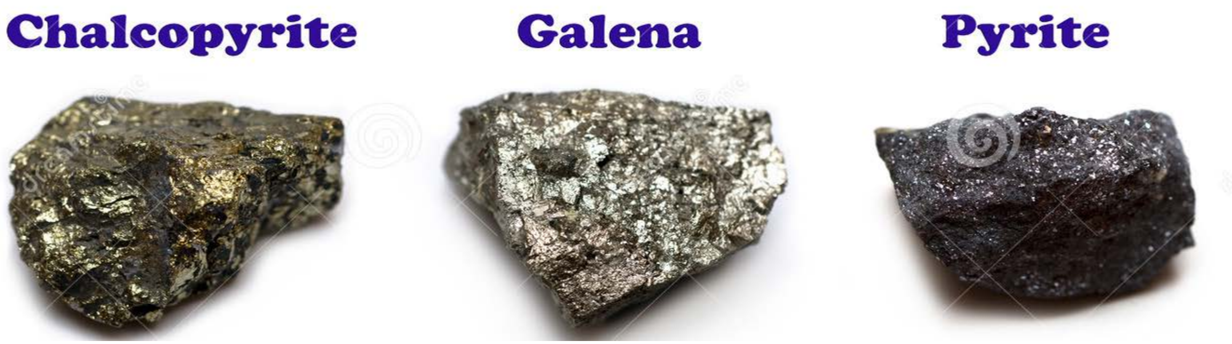
FIG. 2.—*The relation between the conductivity σ and the absolute temperature T of different rocks.* V—*gneiss*; VI—*peridotite*; VII *and* VIII—*eclogite*.

Coster, 1940

4. **Sulfide Conduction**

➢ Influence of sulfide, graphite

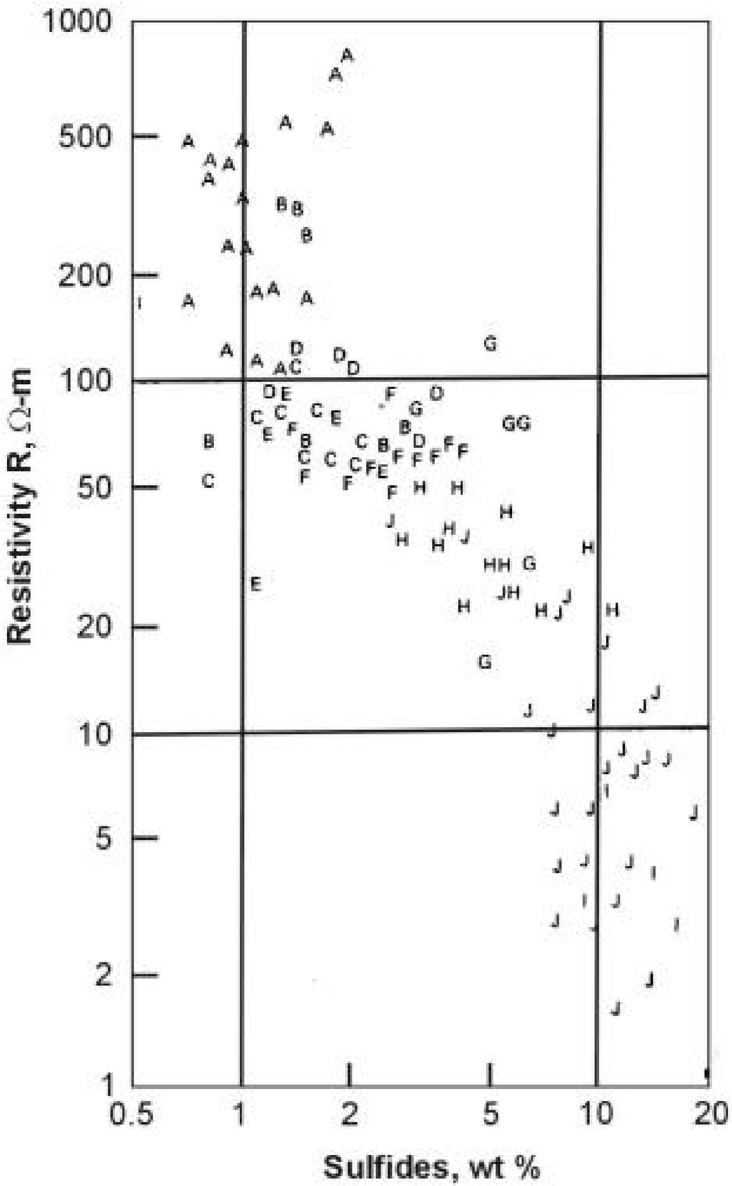
- Many important metal ores are sulfides.[4] Significant examples include: argentite (silver sulfide), cinnabar (mercury), galena (lead sulfide), molybdenite (molybdenum sulfide), pentlandite (nickel sulfide]), realgar (arsenic sulfide), and stibnite (antimony), sphalerite (zinc sulfide), and pyrite (iron disulfide), and chalcopyrite (iron-copper sulfide).



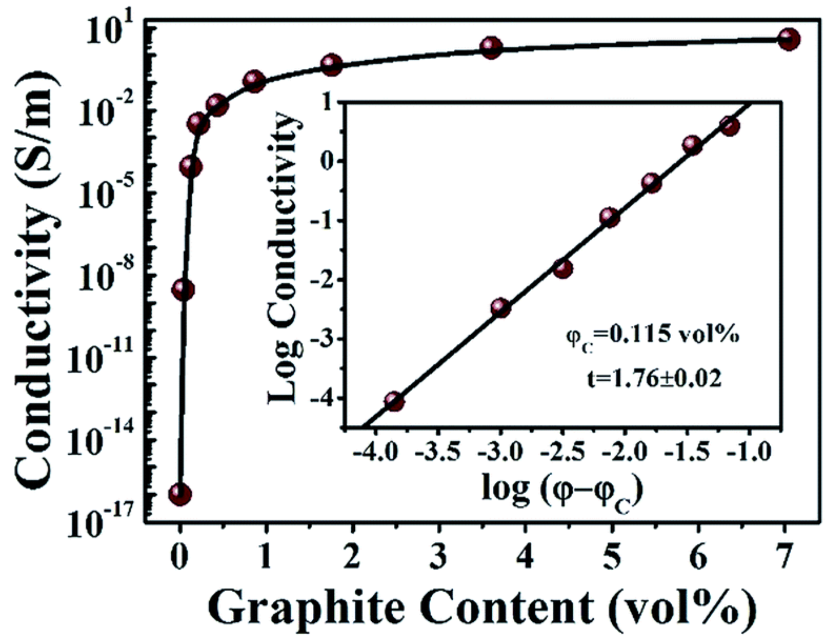
- Graphite

4. **Sulfide Conduction**

- Influence of sulfide, graphite



Electrical resistivity of rocks with various wt % of sulfide.



5. **<u>Surface Conduction</u>**

- <u>Clay's conductivity</u>

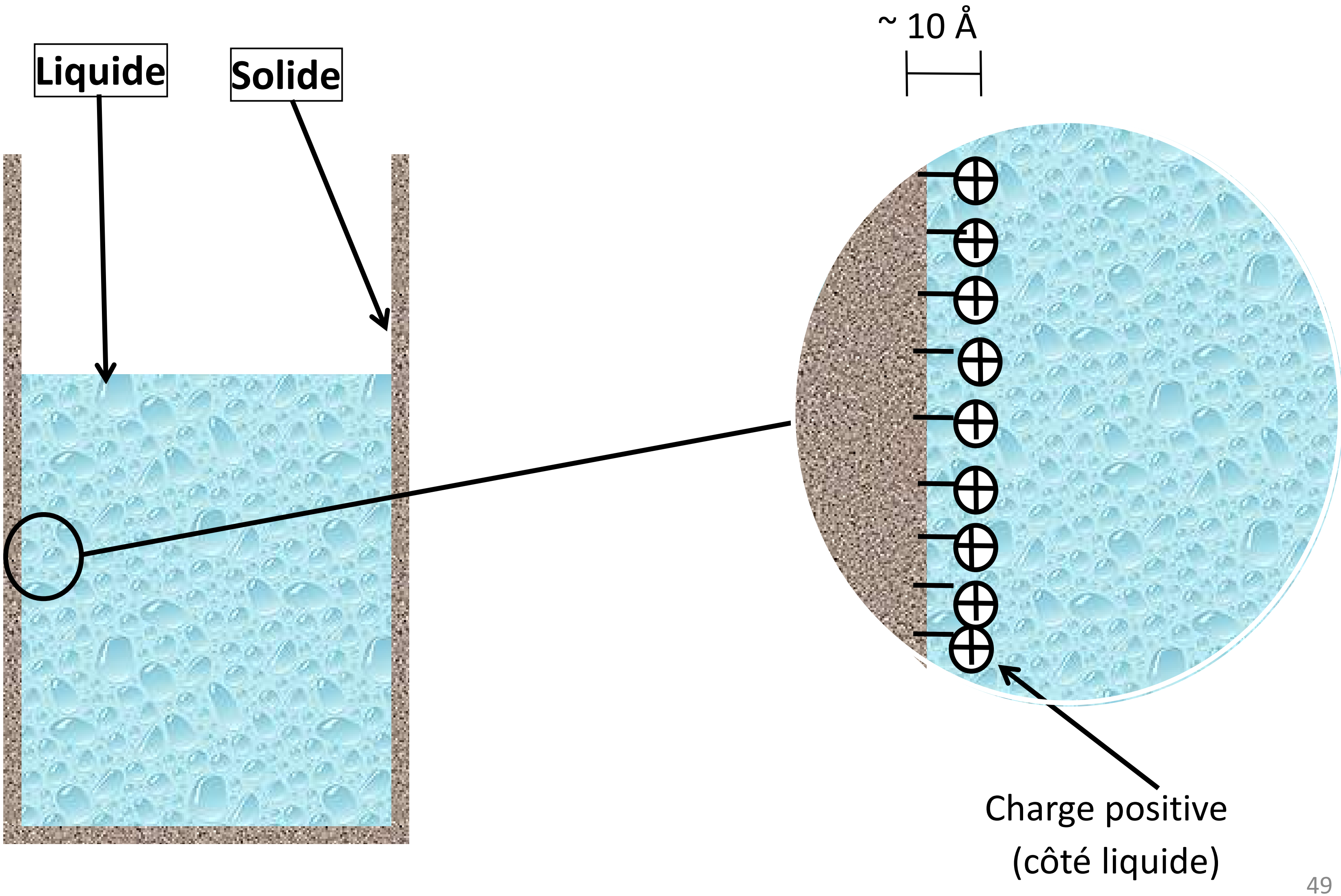
Table 8. Cation Exchange Capacities (CEC) of common clay types.

Clay type	Cation Exchange Capacity
Kaolinite	3 - 15
Chlorite	10 - 40
Illite	10 - 40
Montmorillonite	80 - 150
Vermiculite	100 - 150

This table shows that kaolinite has the least influence on conductivity, and vermiculite has the greatest influence. However, other factors influence conductivity values, including the degree of saturation and the salinity of the saturating fluid.

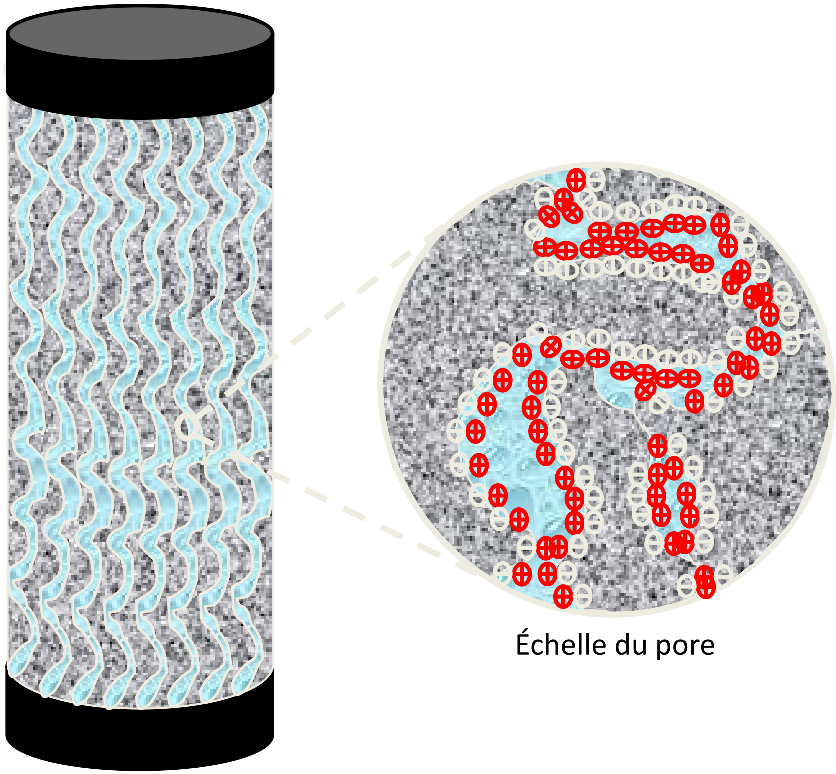
5. **Surface Conduction**

- Double electrical layer



5. **Surface Conduction**

➢ Electrical conductivity of saturated rocks



Échelle du pore

$$\sigma_{roche} = f_{[?]}\ ?$$

$$\sigma_{roche} \quad \alpha\ \boldsymbol{\sigma_{fluide}}$$
$$\alpha\ \phi$$
$$\alpha\ \frac{\mathbf{1}}{\boldsymbol{\tau}}$$
$$+\ \boldsymbol{\sigma_{surface}}$$

$$\sigma_{roche} = \frac{\sigma_{fluide}}{\tau} \times \phi + \sigma_{surface}$$

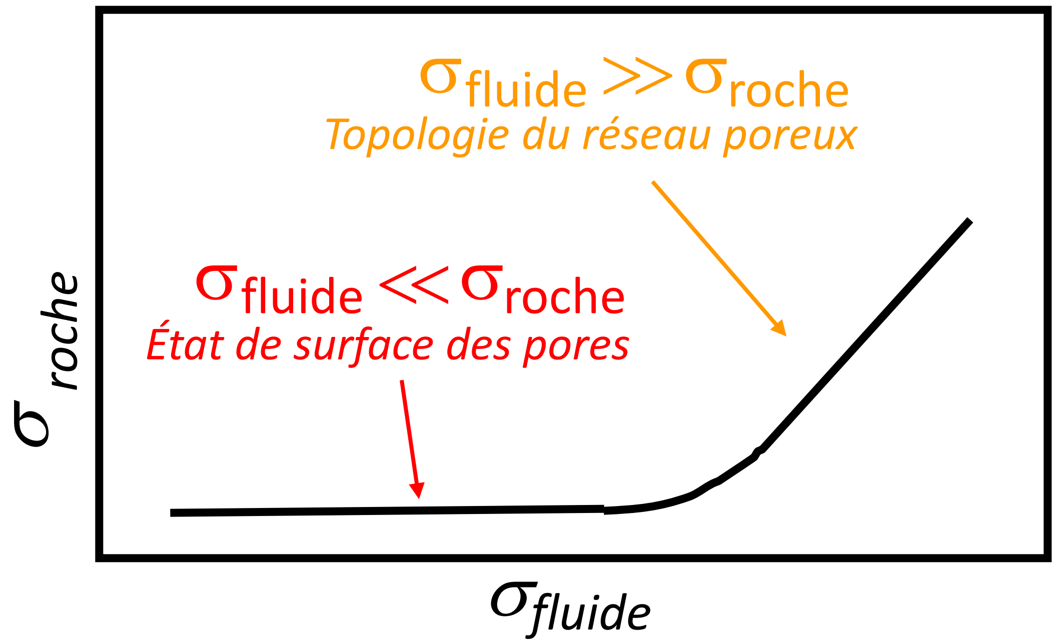
Tortuosité

Porosité

Conductivité de surface

5. **Surface Conduction**

- Electrical conductivity of saturated rocks



$$\sigma_{roche} = \frac{\sigma_{fluide}}{\tau} \times \phi + \sigma_{surface}$$

Tortuosité

Porosité

Conductivité de surface

5. **Surface Conduction**

➢ Electrical conductivity of saturated rocks

$$\boxed{C_0 = \frac{C_w}{F}}$$

$$\boxed{C_0 = \frac{C_w}{F} + C_s}$$

Waxman & Smith (1968)

C_0 → Rock conductivity (logged)
C_w → Pore fluid conductivity
F → Formation factor
C_s → Surface conductivity

5. **Surface Conduction**

- Formation factor

Dominant if **Cs <<Cw**

$$\boxed{F = \frac{1}{\phi^m}}$$

Archie (1942)

$$\boxed{F = \frac{\tau}{\phi}}$$

Walsh & Brace (1984)
Katsube & Hume (1987)
Pezard (1990)

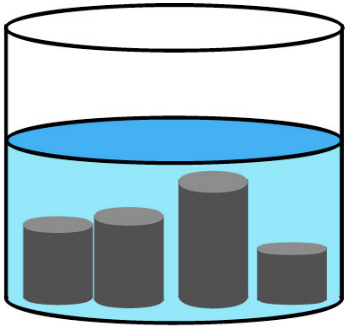
ϕ	Porosity
m	Cementation factor
F	Formation factor
τ	Electrical tortuosity

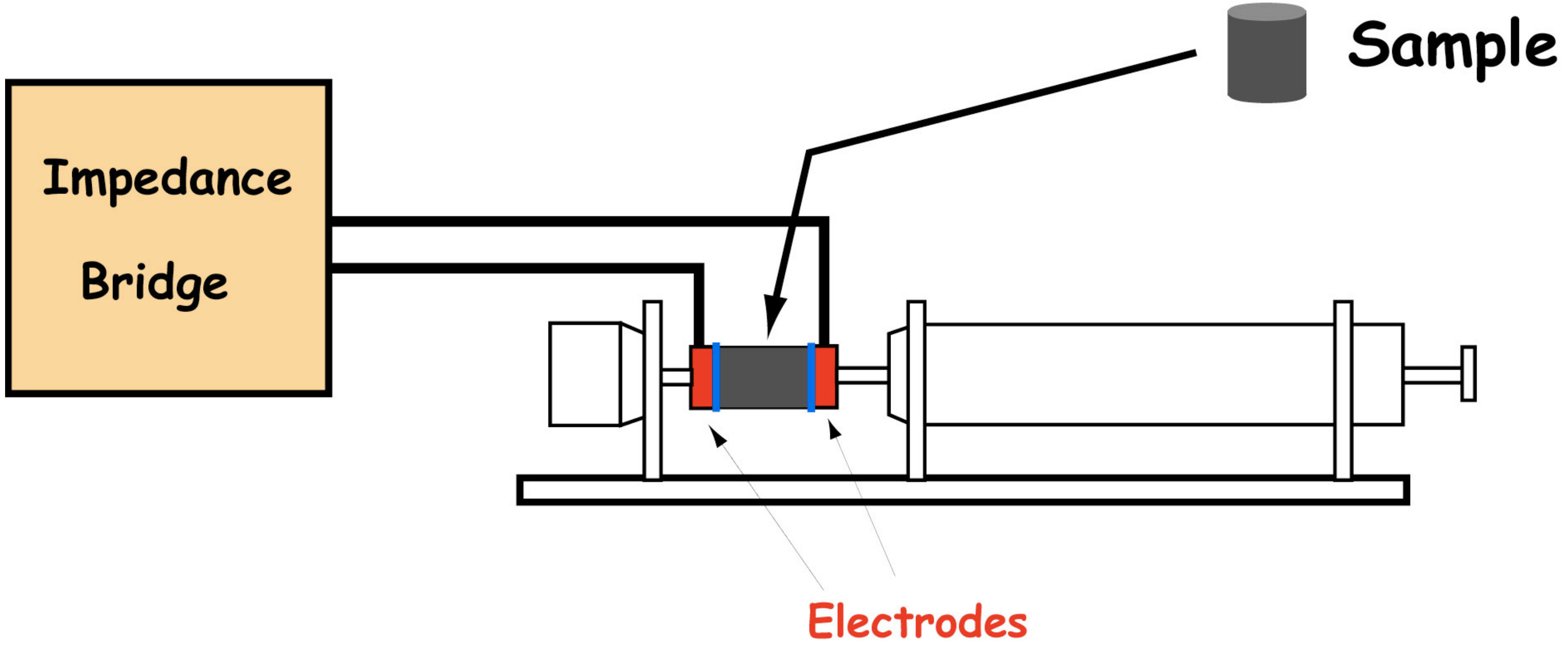
5. **Surface Conduction**

Samples saturated &

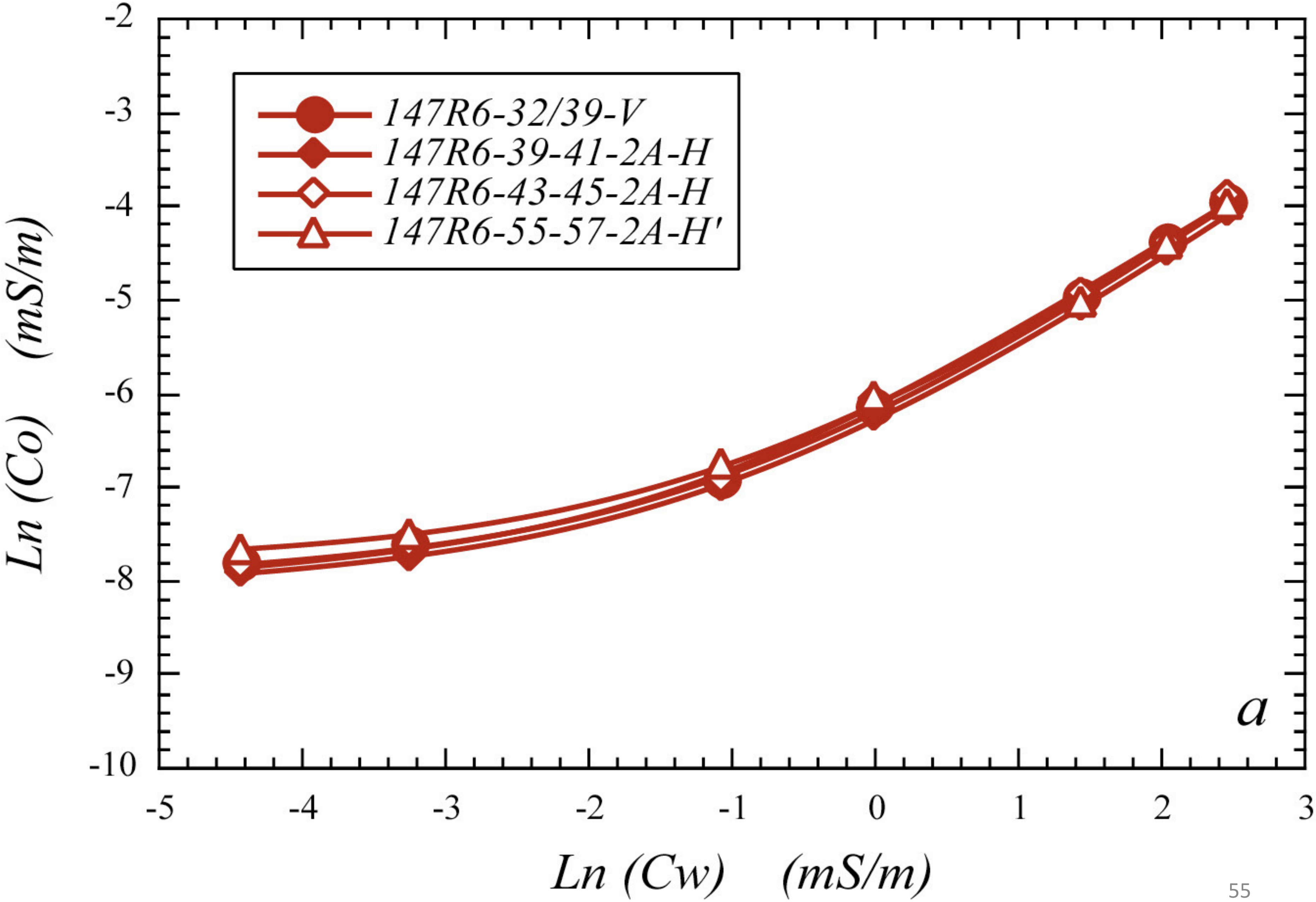
measurements at 7 salinities (from 0.05 to 100g/l)

and 5-7 frequencies (from 20 Hz to 100 kHz)

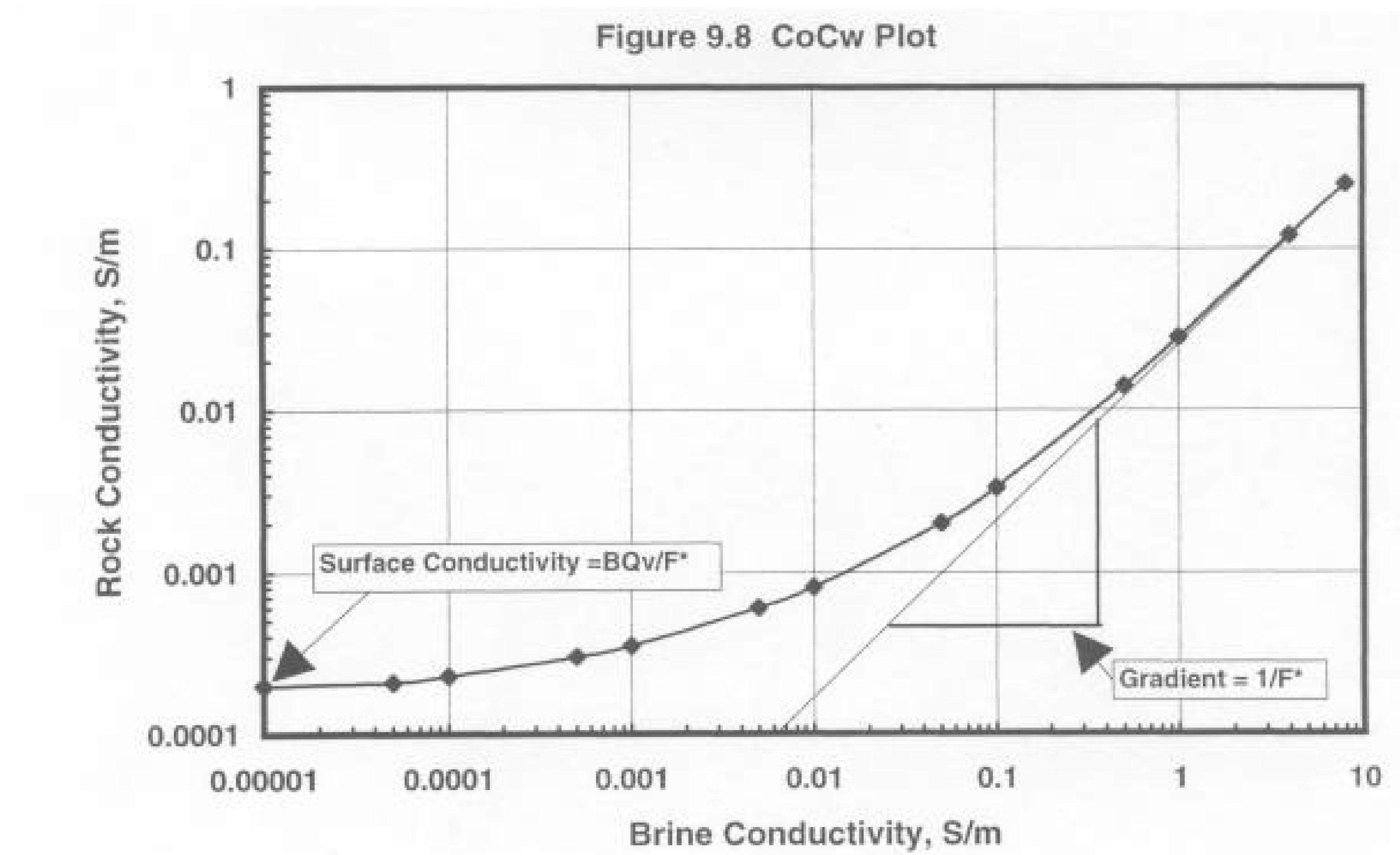




5. **Surface Conduction**

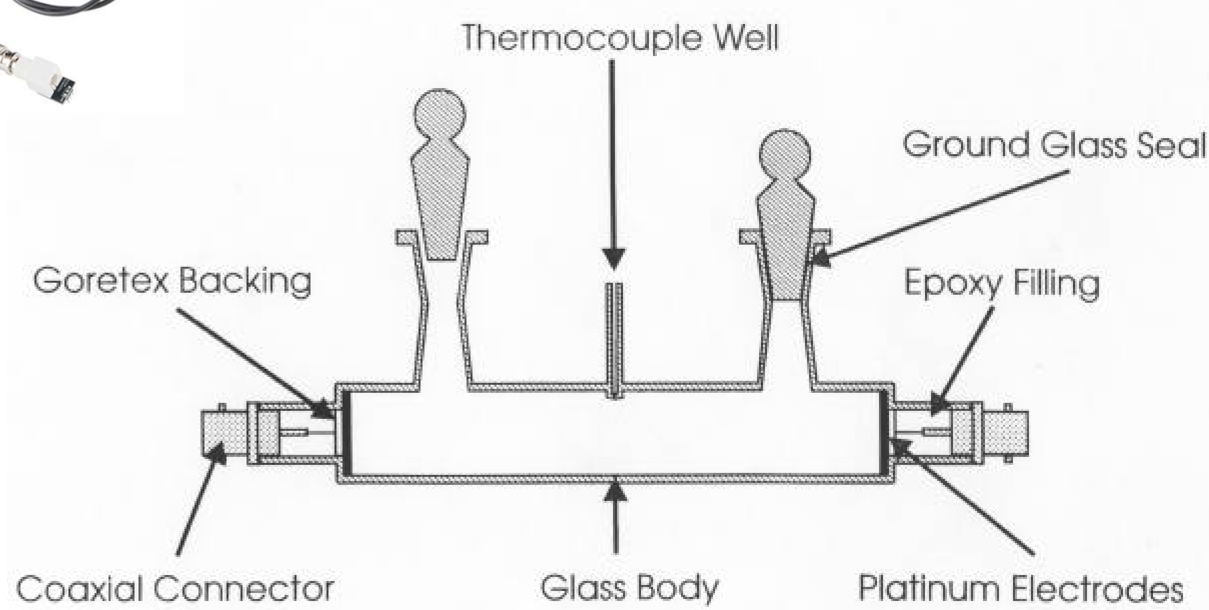


5. **Surface Conduction**



- Fluid conductivity

Figure 9.4 Fluid Resistivity Cells

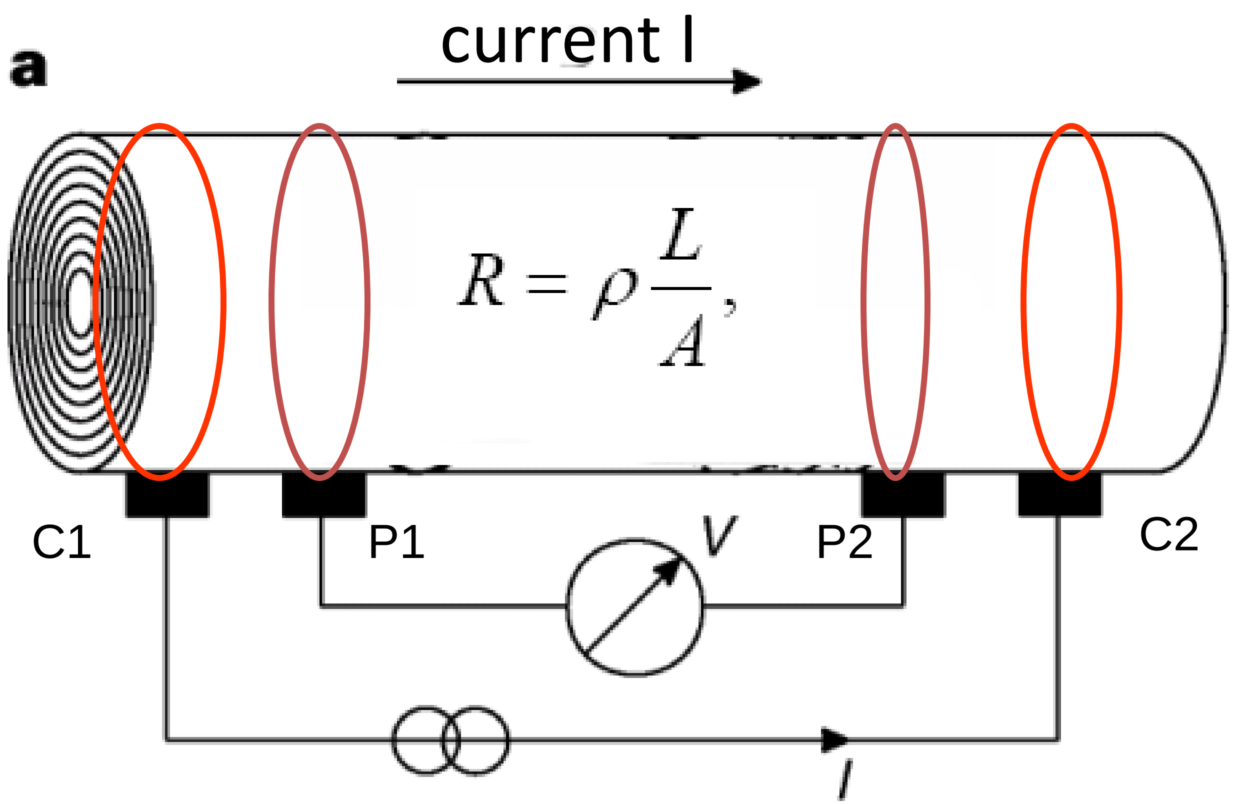


Paul Glover

6. **Methods to measure electrical conductivity**

- Four Electrode Resistivity Measurement on rock sample

… are used to avoid electrode contact resistance effects seen in two electrode measurements.

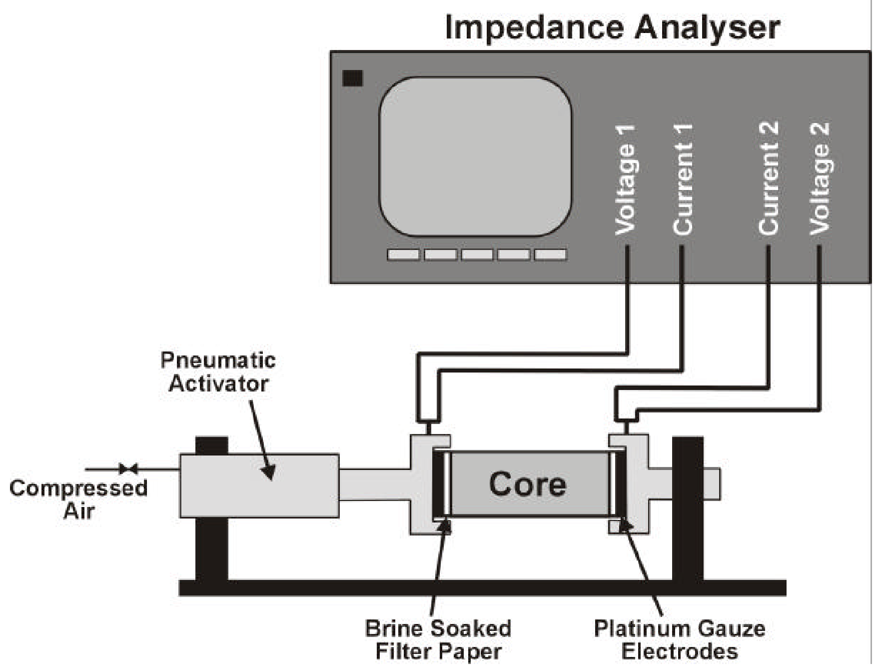


6. **Methods to measure electrical conductivity**

➢ Four Electrode Resistivity Measurement on rock sample

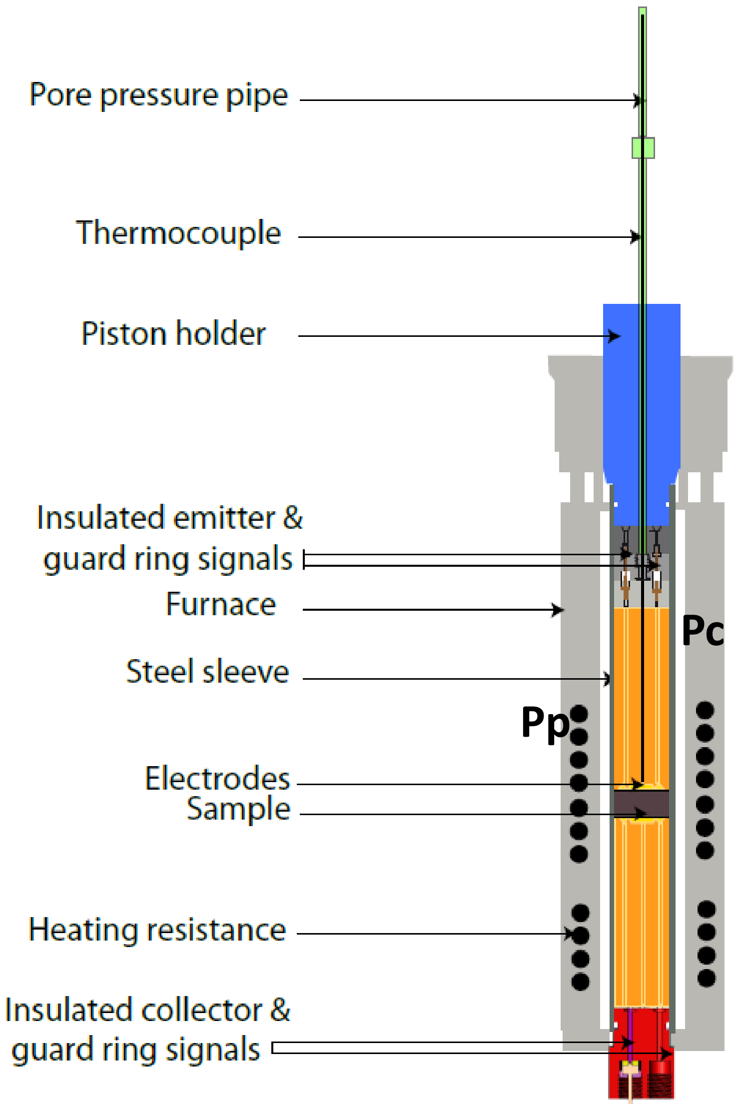
… are used to avoid electrode contact resistance effects seen in two electrode measurements.

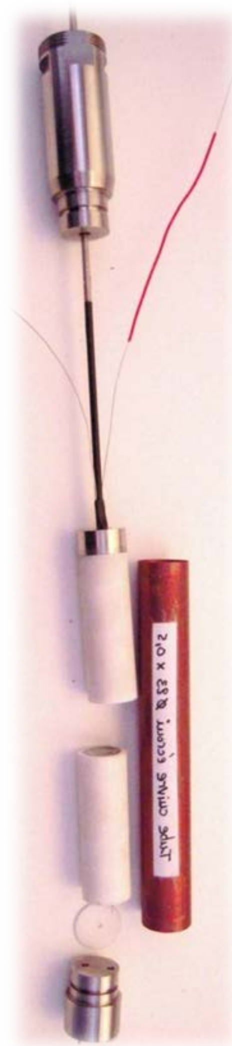
Figure 9.2 Ambient Condition Electrical Rig



6. **Methods to measure electrical conductivity**

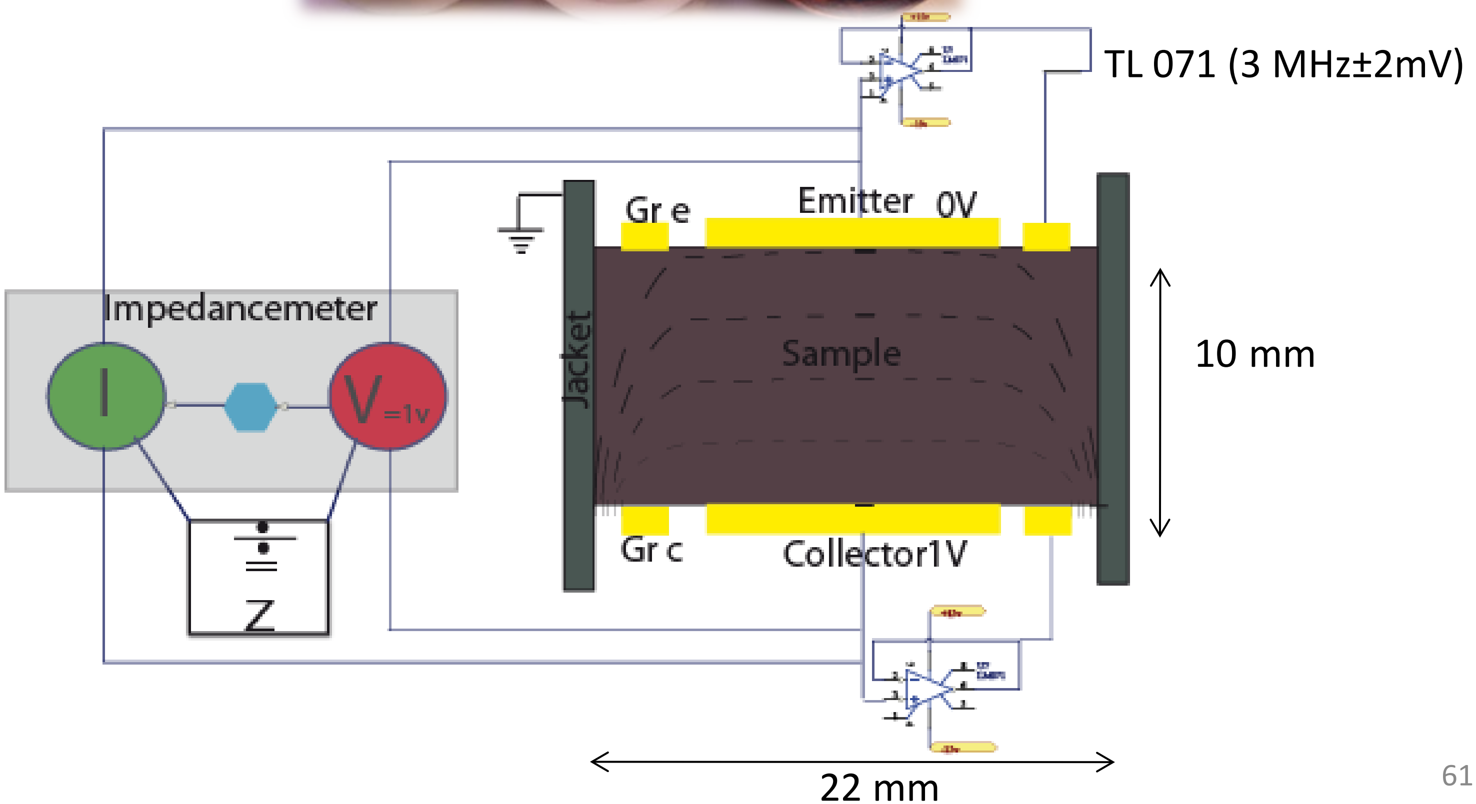
➢ High temperature resistivity mesurements





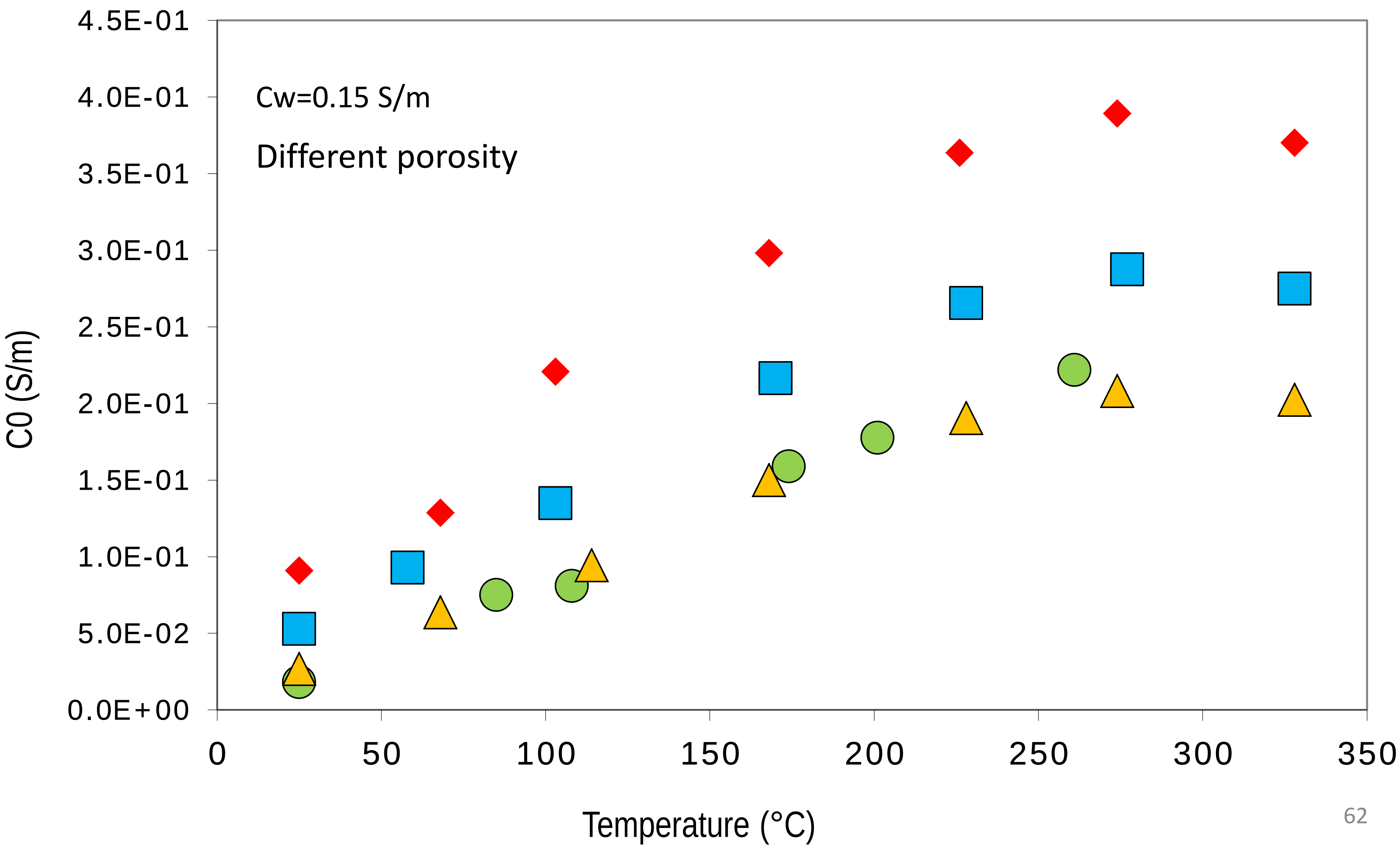
6. **Methods to measure electrical conductivity**

➢ High temperature resistivity mesurements



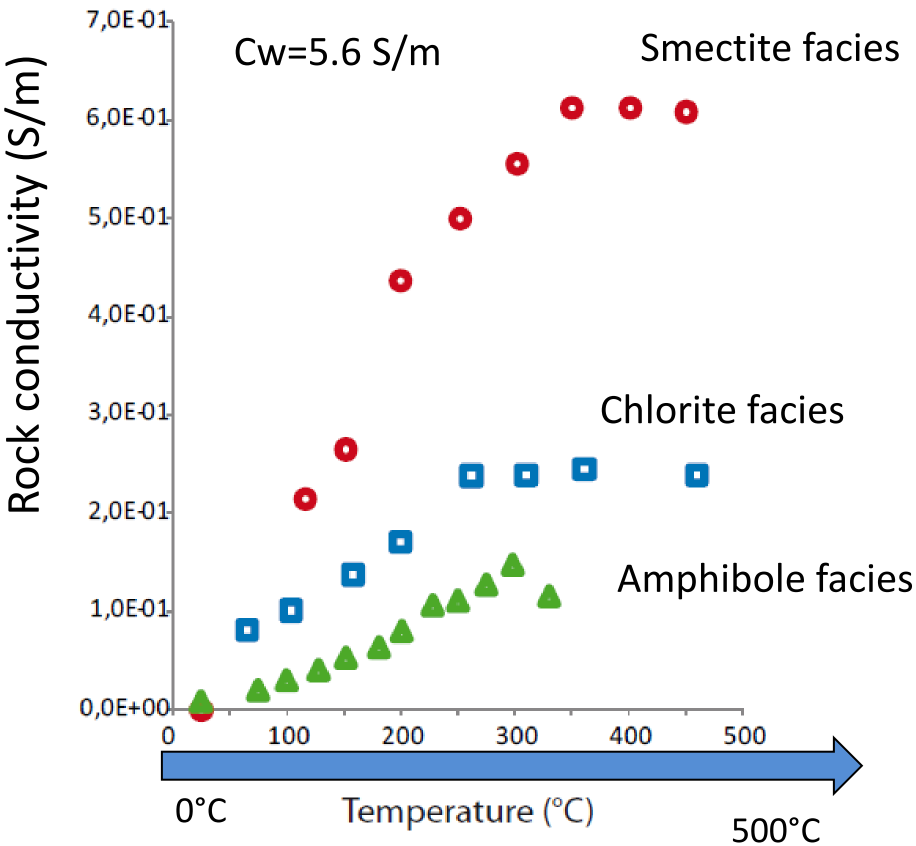
6. **Methods to measure electrical conductivity**

➢ High temperature resistivity mesurements (Sandstones)

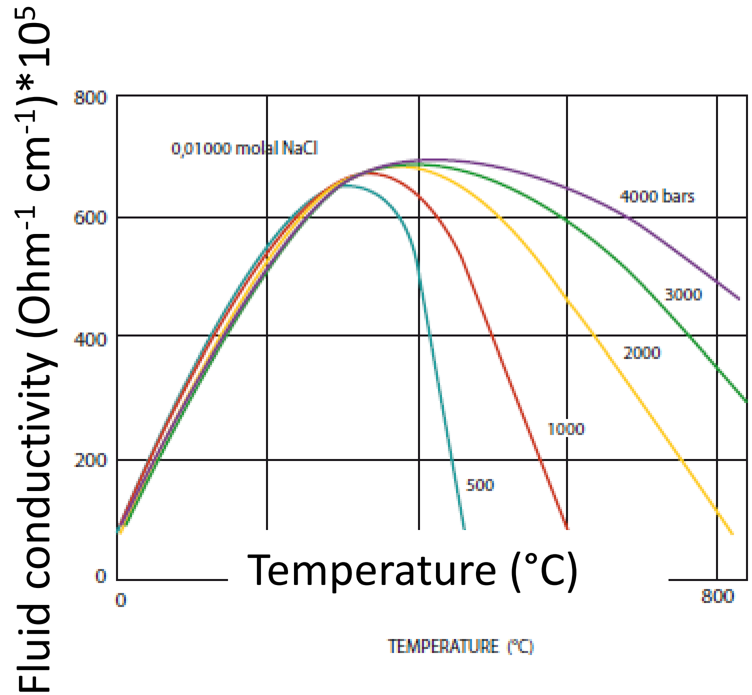


6. **Methods to measure electrical conductivity**

➢ High temperature resistivity mesurements (Basalts)



Temperature (°C)



Quist and Marshall, (1968)