Rock Physics

From mm. to Km. scale

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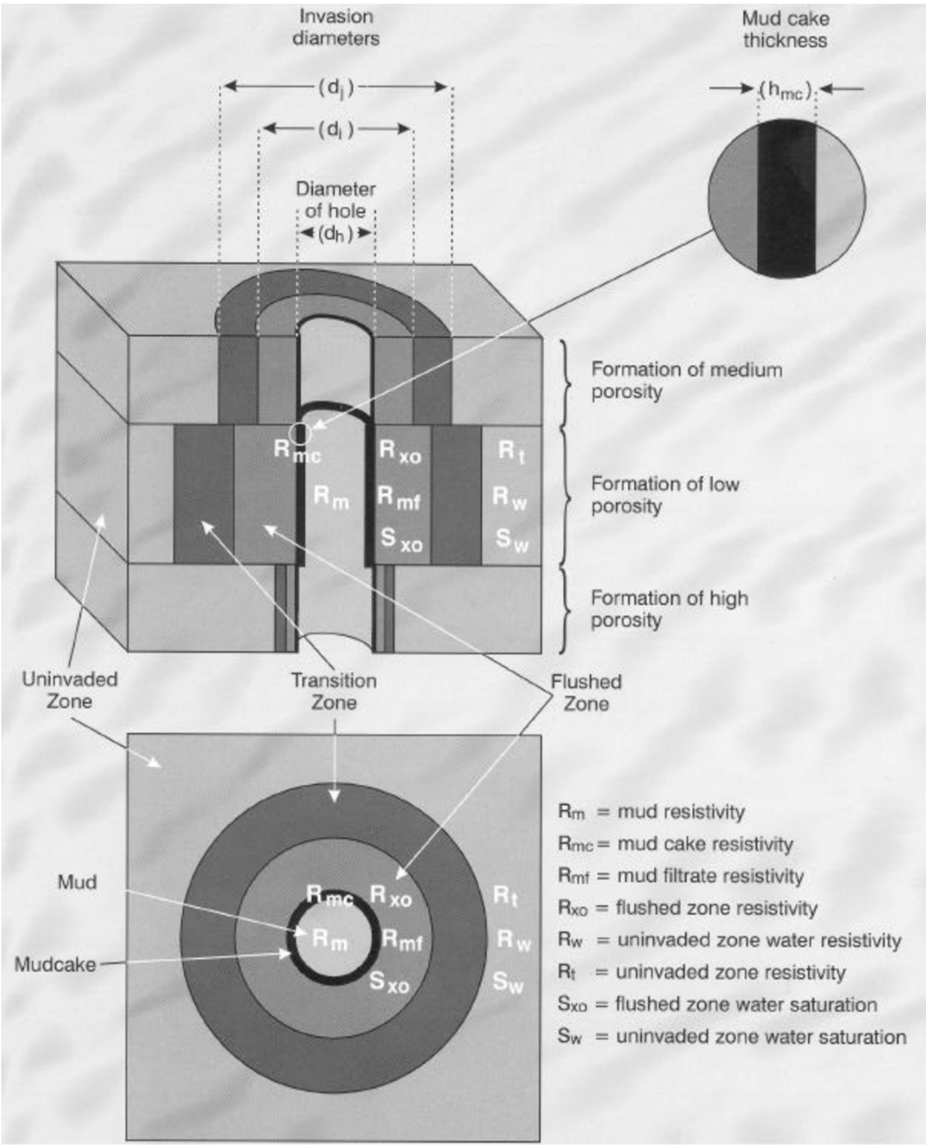
8-electrical logging

Some slides from P. Glover and S. Gautier.

Contents :

I. **Introduction**

➢ Invaded zone



The resistivity of the formation in the invaded zone depends upon :

-resistivity of the mud filtrate R_{mf}
-resistivity of any remaining formation water R_w
-saturation of the mud filtrate S_{xo},
-saturation of the remaining formation water S_w -porosity of the rock *f* (Formation factor)

I. **Introduction**

- Temperature and pressure

The resistivity of formation fluids and water-based drilling muds varies greatly with temperature, but little with pressure. The increase is approximately 4% per degree centigrade. This is automatically corrected, following this equation:

$$\boldsymbol{R_{wT2} = R_{wT1}\left(\frac{T_1 + X}{T_2 + X}\right)}$$

Where :

$$\mathbf{X} = \mathbf{10}^{-(\mathbf{0.340396}\cdot \boldsymbol{log_{10}}(\boldsymbol{R_{wT1}}) - \mathbf{0.641427})}$$

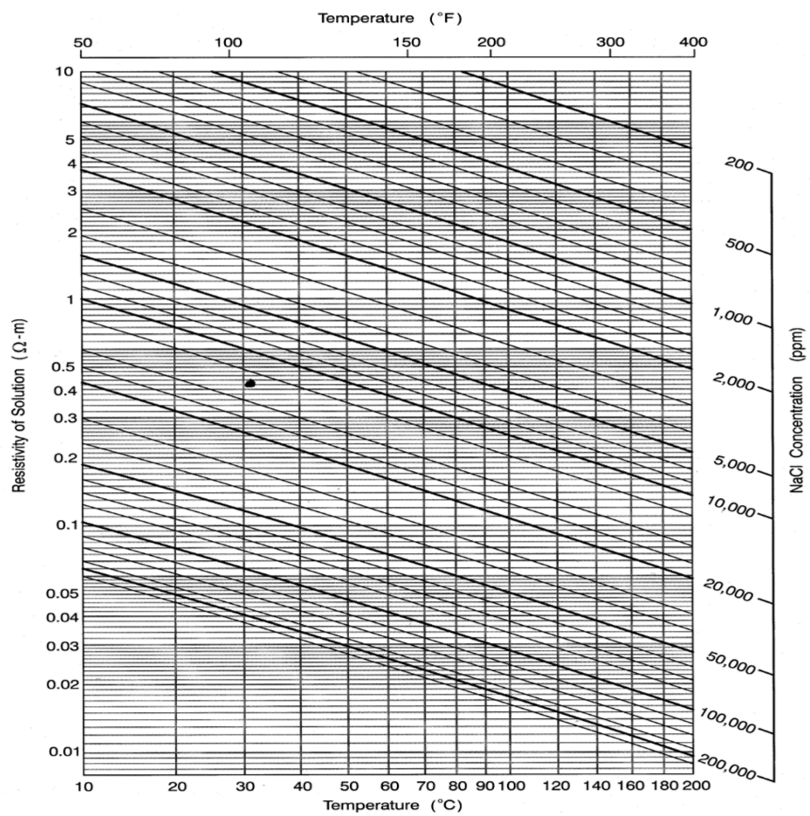
$\boldsymbol{R_{wT1}}$ → Resistivity of the fluid at temperature T_1

$\boldsymbol{R_{wT2}}$ → Resistivity of the fluid at temperature T_2

I. **Introduction**

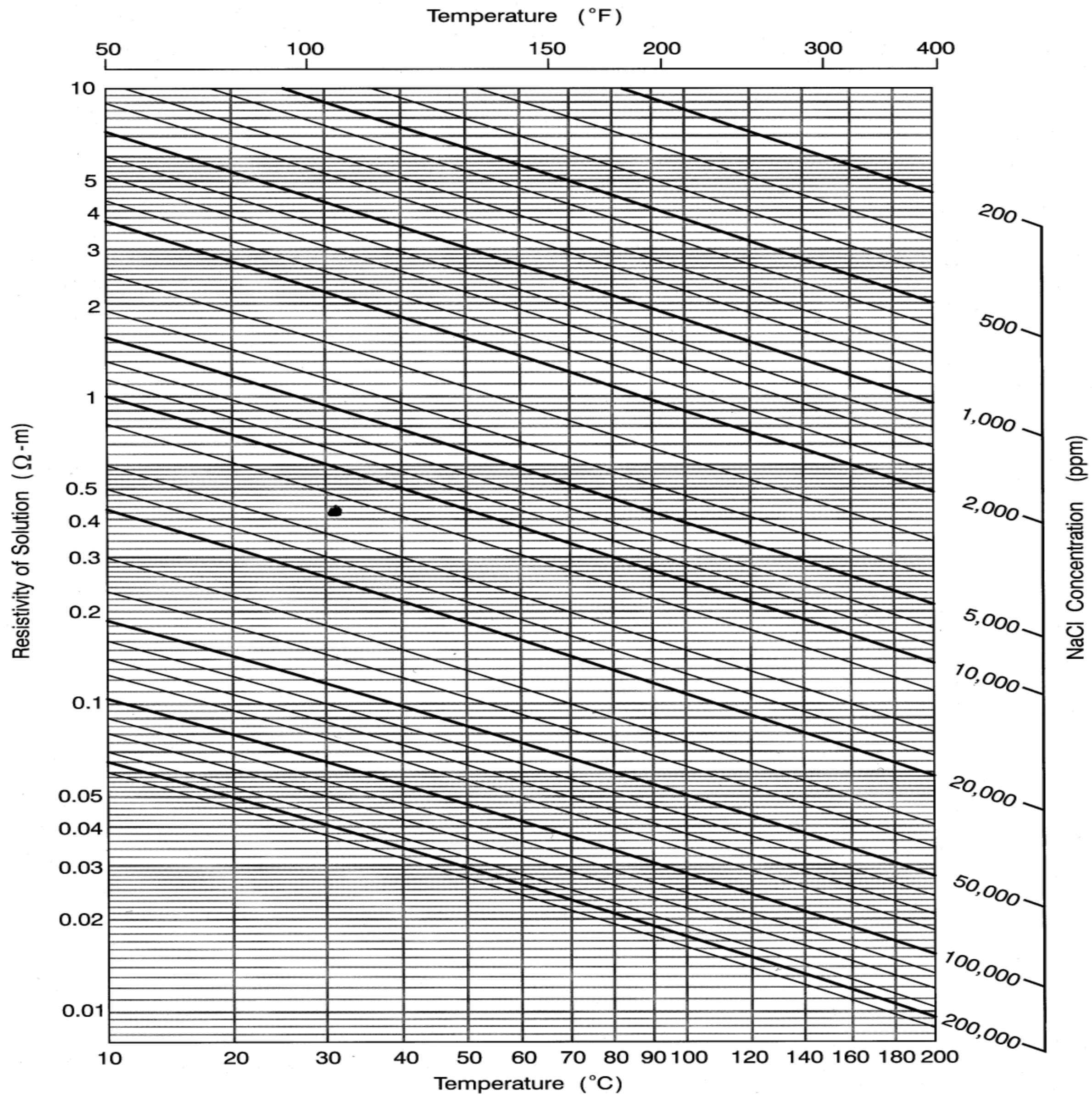
➢ Temperature and pressure

The resistivity of formation fluids and water-based drilling muds varies greatly with temperature, but little with pressure. The increase is approximately 4% per degree centigrade.



I. **Introduction**

- <u>Temperature and pressure</u>



I. **Introduction**

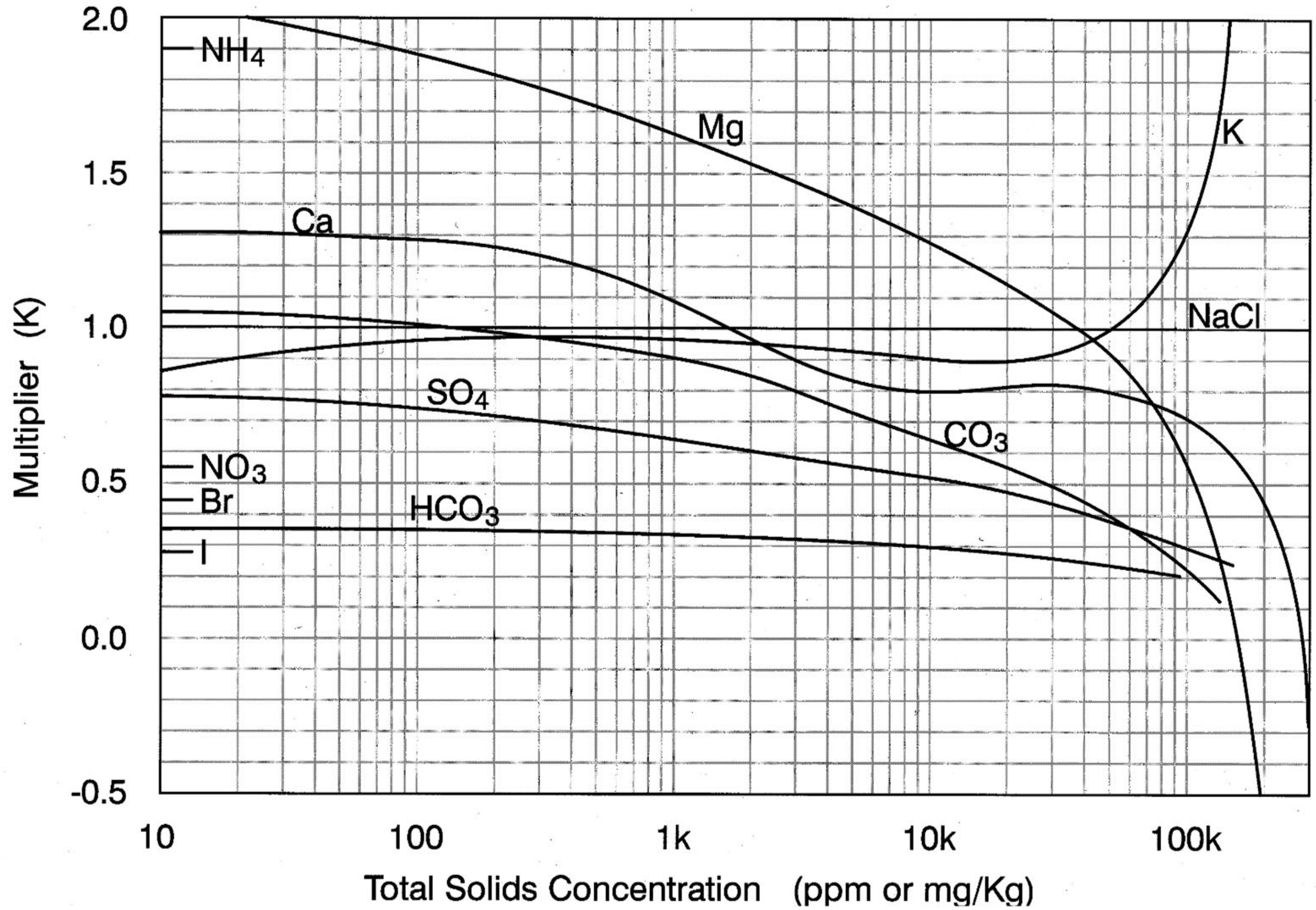
- Effect of salt composition

The resistivity of the formation fluids depends upon the concentration and type of salts dissolved in it. We know the concentration and type of dissolved solids in the formation water usually from chemical analysis of samples obtained from the borehole.

For simplicity, we express the dissolved salts in a solution as an NaCl equivalent.

I. **Introduction**

➢ Effect of salt composition



For example, a solution contains 20,000 ppm NaCl, 10,000 ppm KCl and 1000 ppm MgSO4. The multipliers are Na(1.00), Cl(1.00), K(0.9), Mg(1.63), SO4(0.64). The total NaCl equivalent is 20,000´1+20,000´1+10,000´0.9+10,000´1+1000´1.63+1000´0.64 = 30,635 ppm NaCl.

II. **Spontaneous potential**

- Spontaneous potential log

The *spontaneous potential* log (SP) measures the natural or *spontaneous potential difference* (sometimes called *self-potential*) that exists between the borehole and the surface in the absence of any artificially applied current.

It is a very simple log that requires only an electrode in the borehole and a reference electrode at the surface.

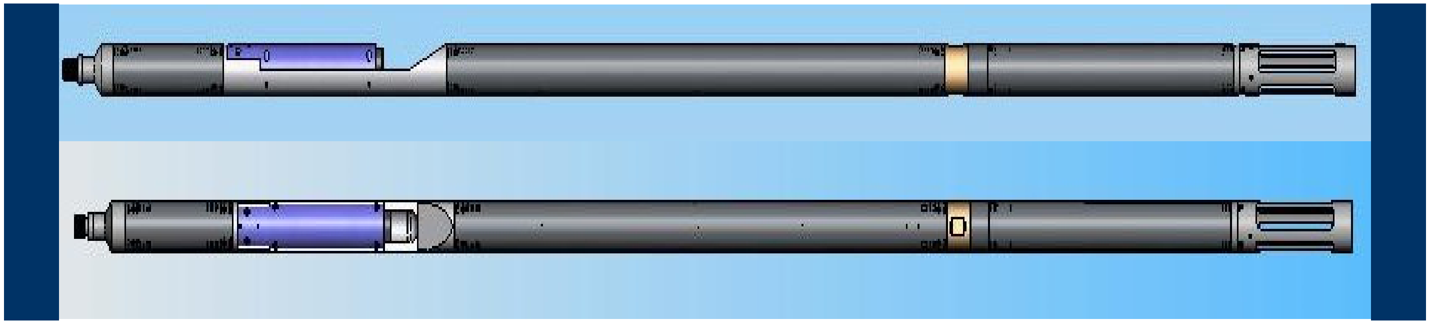
These spontaneous potentials arise from the different access that different formations provide for charge carriers in the borehole and formation fluids, which lead to a spontaneous current flow, and hence to a spontaneous potential difference.

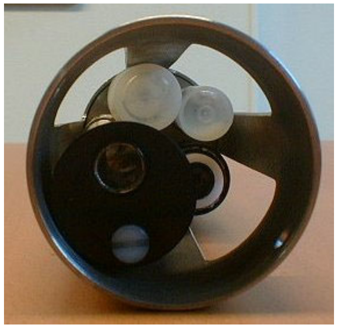
II. **Spantaneous potential**

➢ SP uses

The SP log has four main uses:

- The detection of permeable beds.
- The determination of Rw.
- The indication of the shaliness of a formation.
- Correlation.





II. **Spontaneous potential**

- Origin of SP

The spontaneous potential has two origins:

- *electrochemical* (arise from electrical interactions between the various chemical constituents of the rocks and fluids)
- *Electrokinetic (*arise from the movement of electrically charged ions in the fluid relative to the fixed rock)

II. **Spontaneous potential**

➢ Conditions

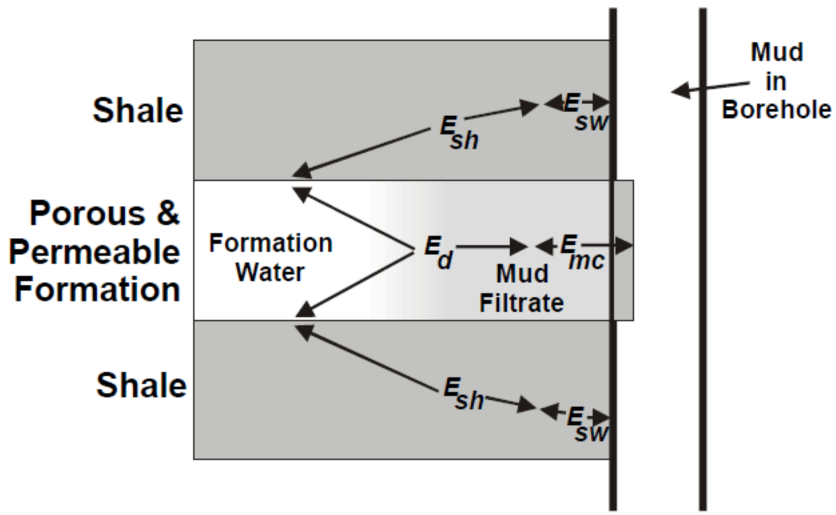
There are three requirements for the existence of an SP current:

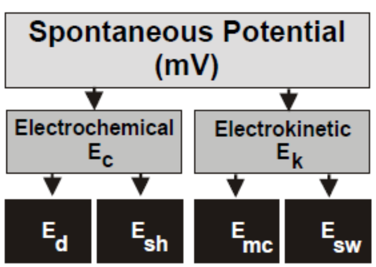
- A conductive borehole fluid (i.e., a water based mud).
- A sandwich of a porous and permeable bed between low porosity and impermeable formations.
- A difference in salinity between the borehole fluid and the formation fluid, which are the mud filtrate and the formation fluid in most cases.

Note, however, that in some special cases an SP current can be set-up when there is no difference in salinity, but where a difference in fluid pressures occur.

II. Spontaneous potential

➢ Electrochemical Components





The spontaneous potential has 4 Components:

Ed: The *diffusion potential* (sometimes called the *liquid-junction potential*). This potential exists at the junction between the invaded and the non invaded zone, and is the direct result of the difference in salinity between the mud filtrate and the formation fluid.

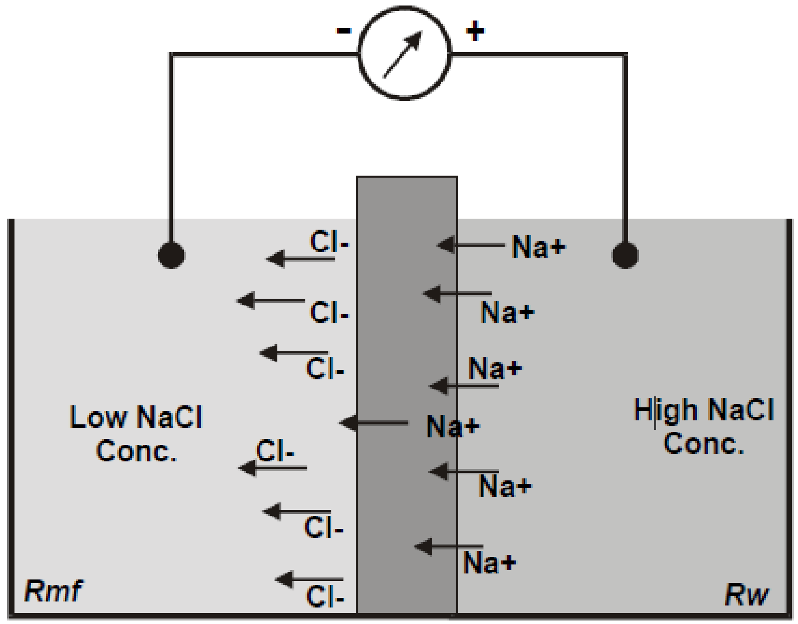
Esh: The *membrane potential* (*shale potential*). This potential exists at the junction between the non-invaded zone and the shale sandwiching the permeable bed. Shales have the property that they can preferentially retard the passage of anions.

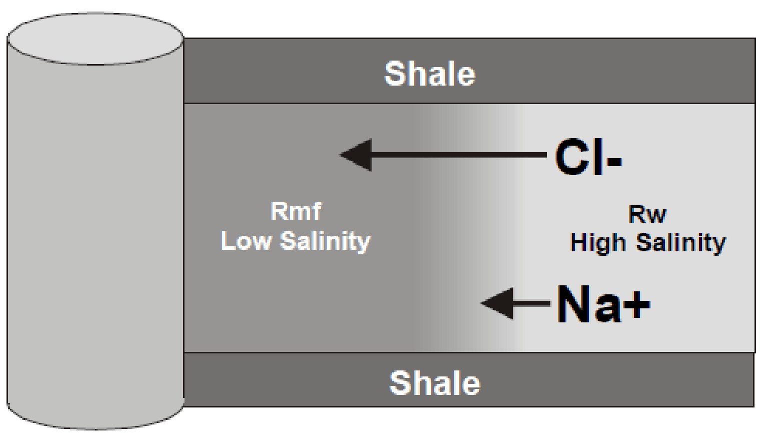
Emc: mudcake potential: This potential is produced by the movement of charged ions through the mudcake and invaded zone in a permeable formation.

Esw: The shale wall potential: This potential is the same in origin to the mudcake potential, but applies to the flow of fluids from the borehole into shale formations. It is usually very small because the flow into impermeable shales is small

II. **Spontaneous potential**

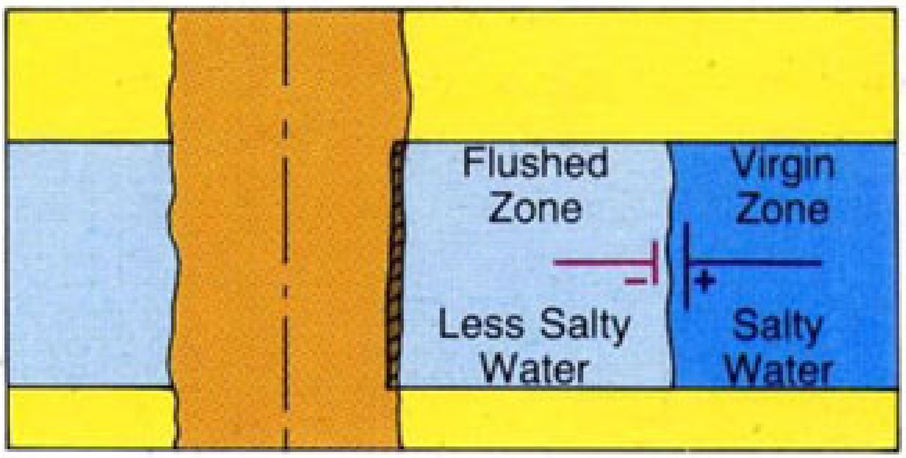
- Diffusion potential





II. **Spontaneous potential**

- Diffusion potential



diffusion of salt between two liquids that have different charges

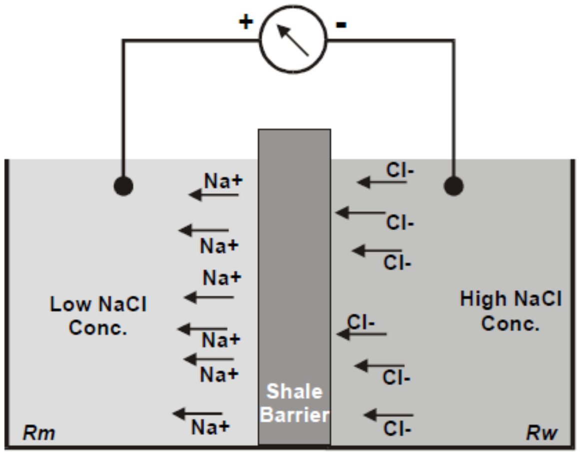
(Fick law : $\mathbf{j = -D}\ \frac{dC}{dx}$)

II. **Spontaneous potential**

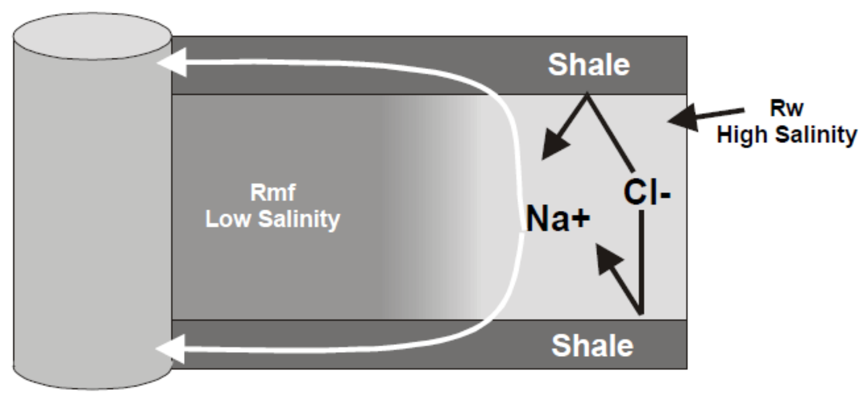
➢ Membrane potential

Shales have the property that they can preferentially retard the passage of anions➔ *permselectivity* or *electronegative permselectivity* and is a property of *membranes*.

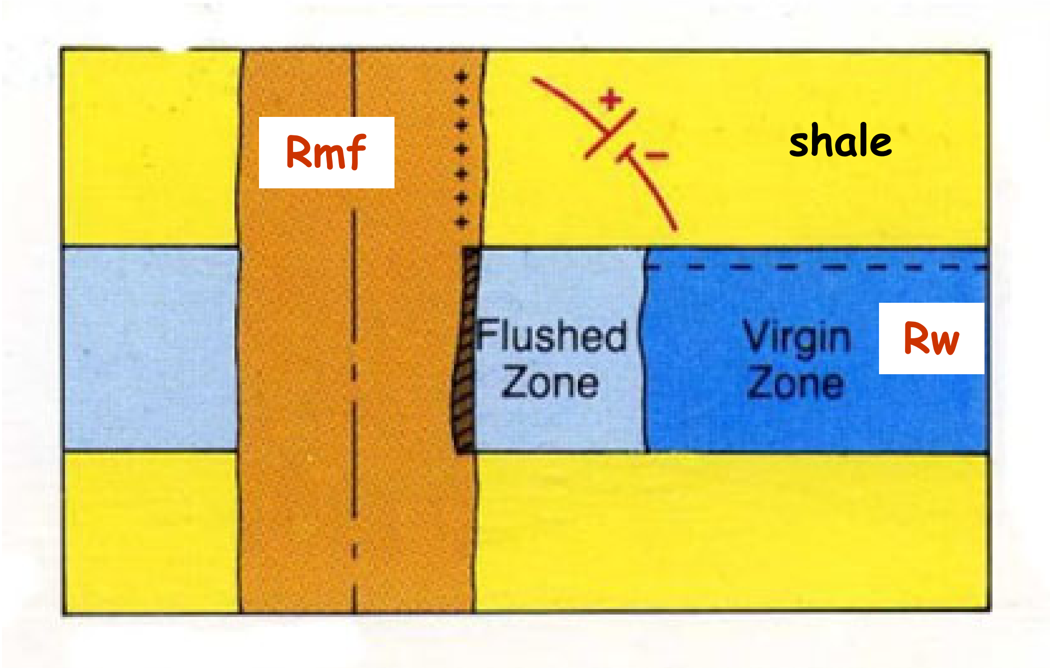
It is due to an electrical double layer that exists at the rock-fluid interface, and that has the ability to exclude anions from the smaller pores in the rock (sometimes called *anion exclusion*). The strength of this effect depends upon the shale mineralogy, the fluid concentration and the fluid pH. This results in the shale being more positive than the non-invaded zone, and hence there is an electrical membrane potential, which causes current to flow from the invaded zone into the shale (and hence borehole).



Anions excluded



II. **Spontaneous potential**



Clays = cationic membrane

cations are attracted

anions are blocked

Battery :

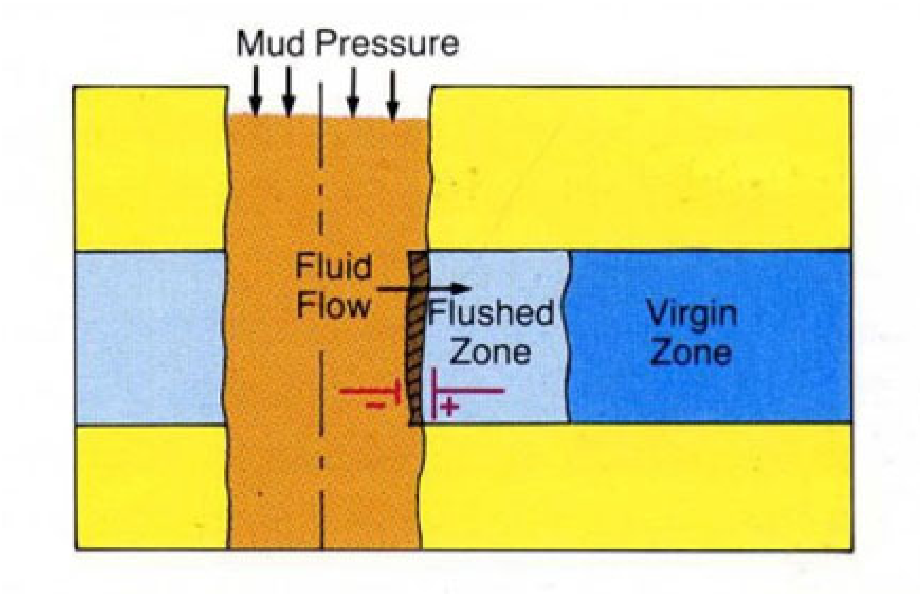
+ low salinity formation,

- High salinity formation

II. **Spontaneous potential**

➢ mudcake potential

The *mudcake potential*. This potential is produced by the movement of charged ions through the mudcake and invaded zone in a permeable formation. Its size depends upon the hydraulic pressure drop, and since most of this is across the low permeability mudcake, the great majority of electrokinetic potential is also generated across the mudcake, with an insignificant amount in the invaded zone.



II. **Spontaneous potential**

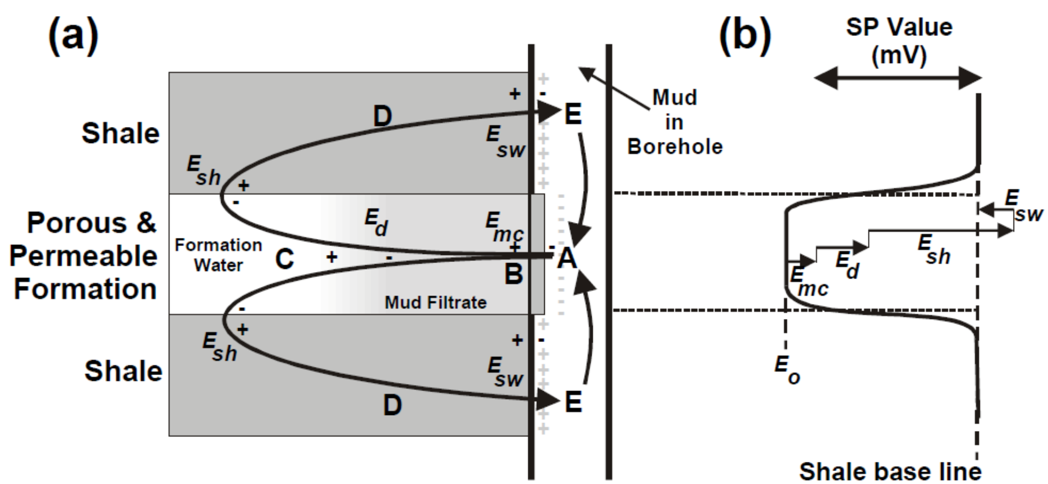
➢ Combined Spontaneous Potential Effect

if formation water more saline than the mud filtrate.

- First assume that point A in the borehole has some unknown potential relative to the surface *Eo*.

- The mudcake potential *Emc* induces a current flowing into the formation through the mudcake. Therefore at point B, the potential is *Eo* + *Emc* and current has flowed from A to B.

- The diffusion potential *Ed* across the interface between the invaded and non-invaded zones induces a current flowing from the invaded zone into the non-invaded zone. Therefore at point C, the potential is *Eo* + *Emc* + *Ed* and current has flowed from A through B to C.



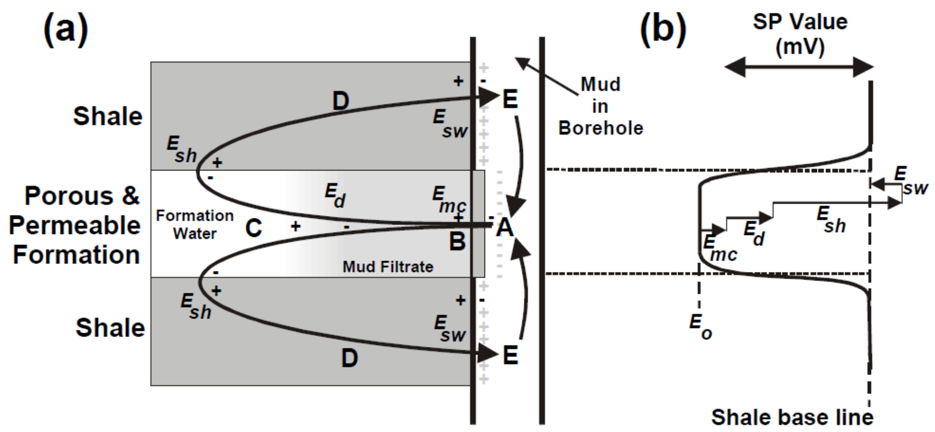
II. Spontaneous potential

➢ Combined Spontaneous Potential Effect

- The membrane potential E_m across the interface between the permeable formation and the shale above it induces a current flowing into the shale from the non-invaded zone. Therefore at point D, the potential is $E_0 + E_{mc} + E_d + E_m$ and current has flowed from A through B and C to D.

- The shale wall potential E_{sw} induces a current flowing into the shale from the borehole. This current counteracts the current flow set-up in the previous steps. Therefore at point E, the potential is $E_0 + E_{mc} + E_d + E_m - E_{sw}$ and the current has flowed from A through B and C to D, and has been slightly reduced there by the small countercurrent due to the shale wall potential. The overall effect is for a net current to flow from A through B, C and D to E.

- The overall effect is for point E in the borehole opposite the shale wall to have a more positive potential than that at point A opposite the permeable formation. Hence there will also be a current flow in the borehole between the borehole opposite the shale beds and the borehole opposite the permeable bed to close the loop.



Note, since the value of *Eo* is arbitrary, there is no absolute value of spontaneous potential – what matters is the relative change in spontaneous potential.

II. **Spontaneous potential**

➢ Permeability

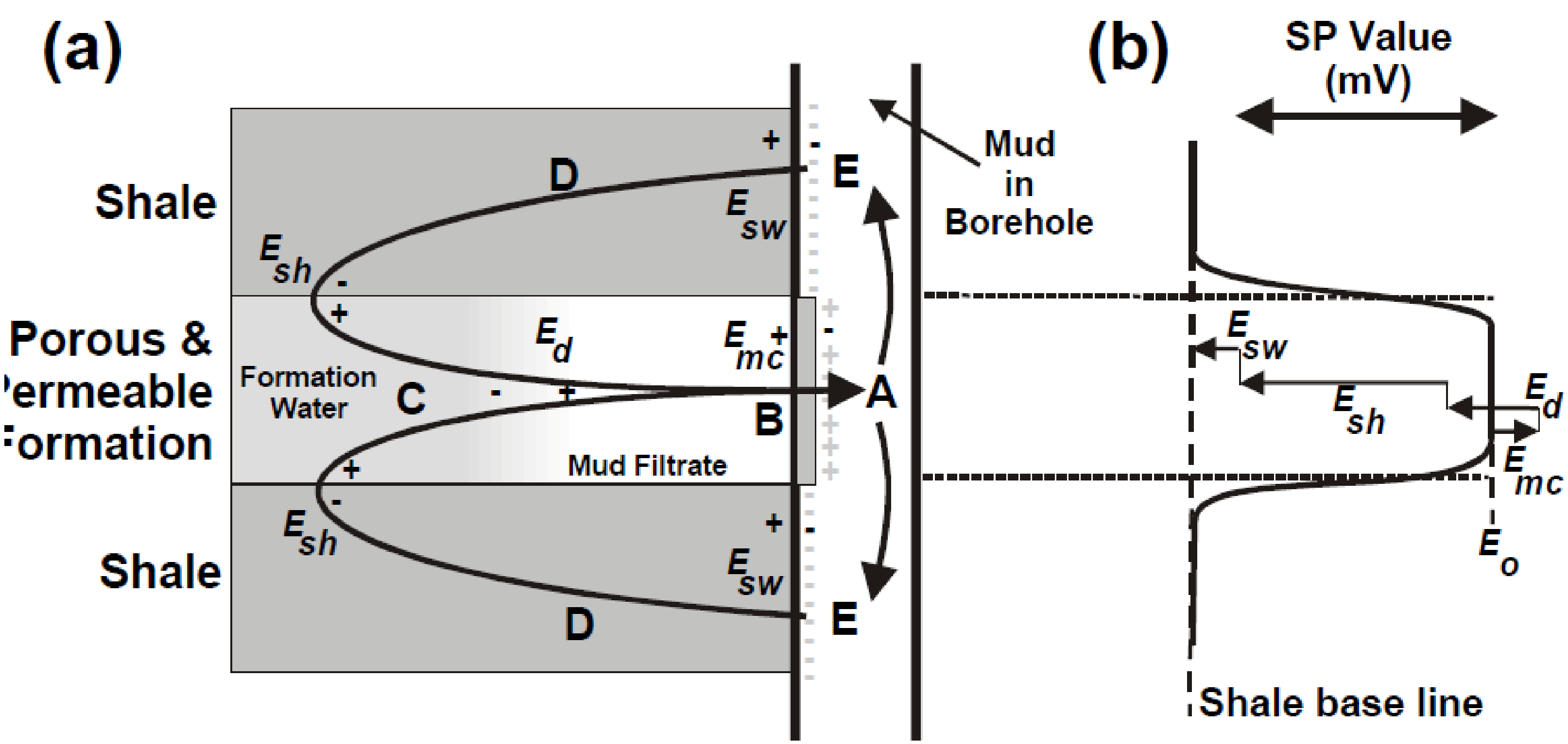
- So, is the SP opposite a permeable formation always less than that opposite the shale above (or below) it? ***NO***. This is for the particular case where the formation fluid is more saline than the mud filtrate.

- If the formation fluid is less saline than the mud filtrate, the opposite applies, and the SP opposite the permeable formation is *GREATER*.

II. **Spantaneous potential**

- Combined Spontaneous Potential Effect

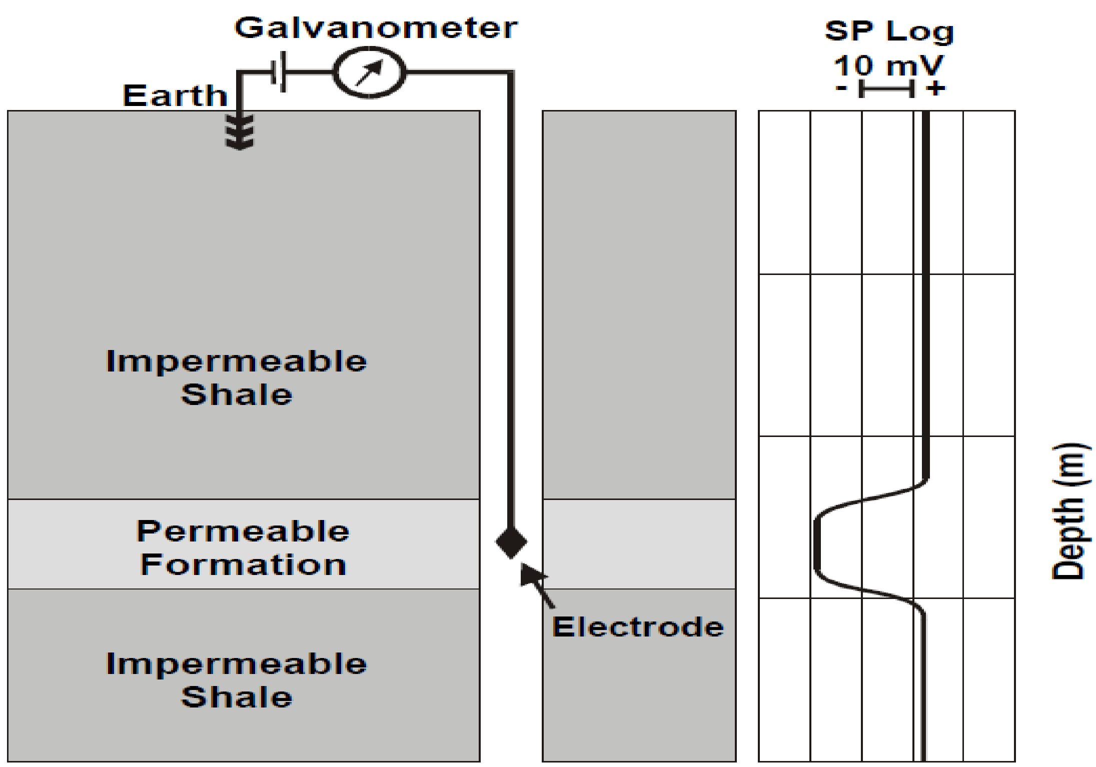
If mud filtrate more saline than formation water



II. **Spontaneous potential**

➢ Measurement Tools

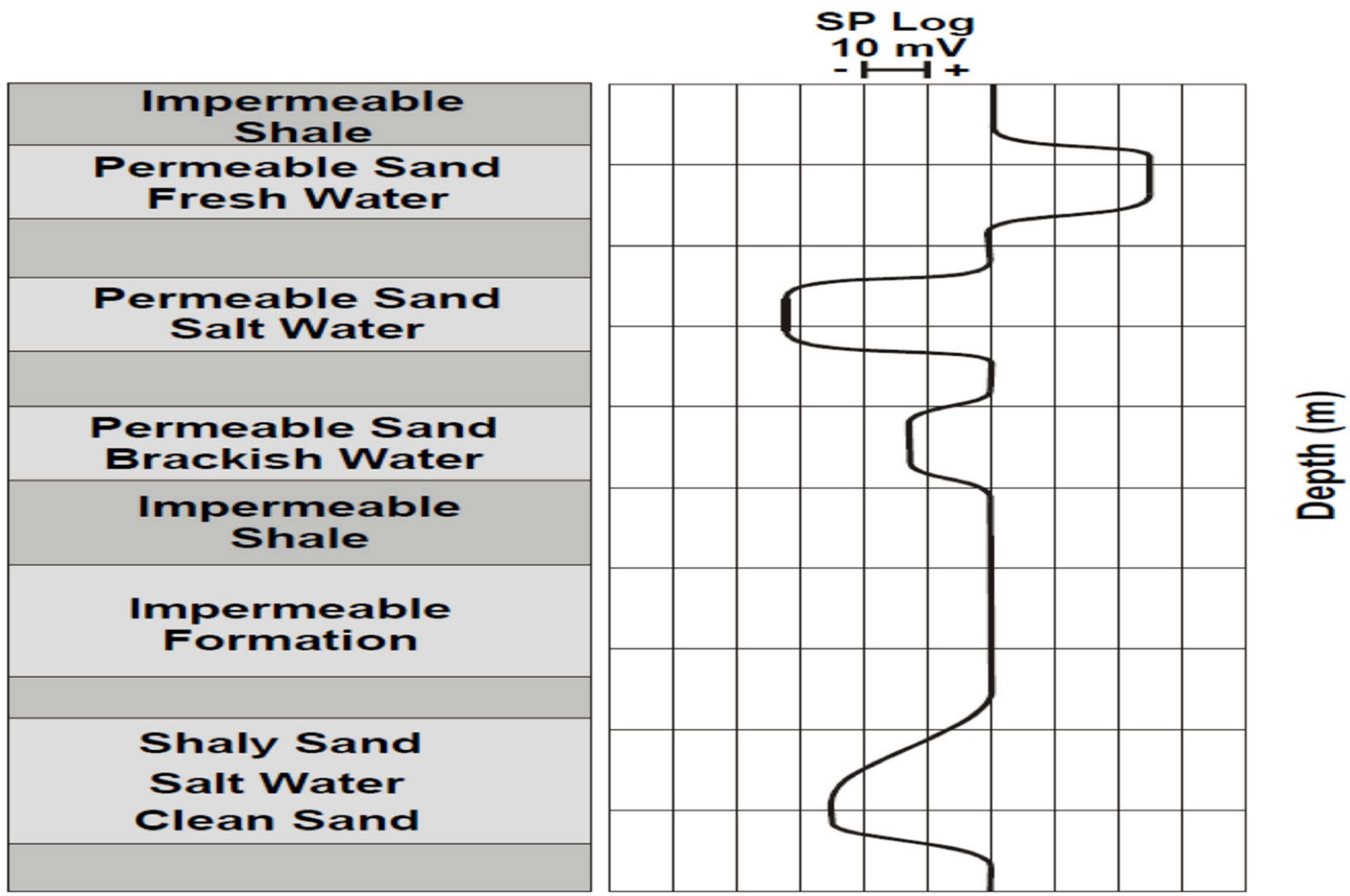
The tool is extremely simple, consisting of a single electrode that is connected to a good surface earthing point *via* a galvanometer for the measurement of DC potential.



II. **Spontaneous potential**

- Log presentation

SP is shown in millivolts, with negative deflections to the left and positive ones to the right.



II. **Spontaneous potential**

- Uses of Spontaneous potential

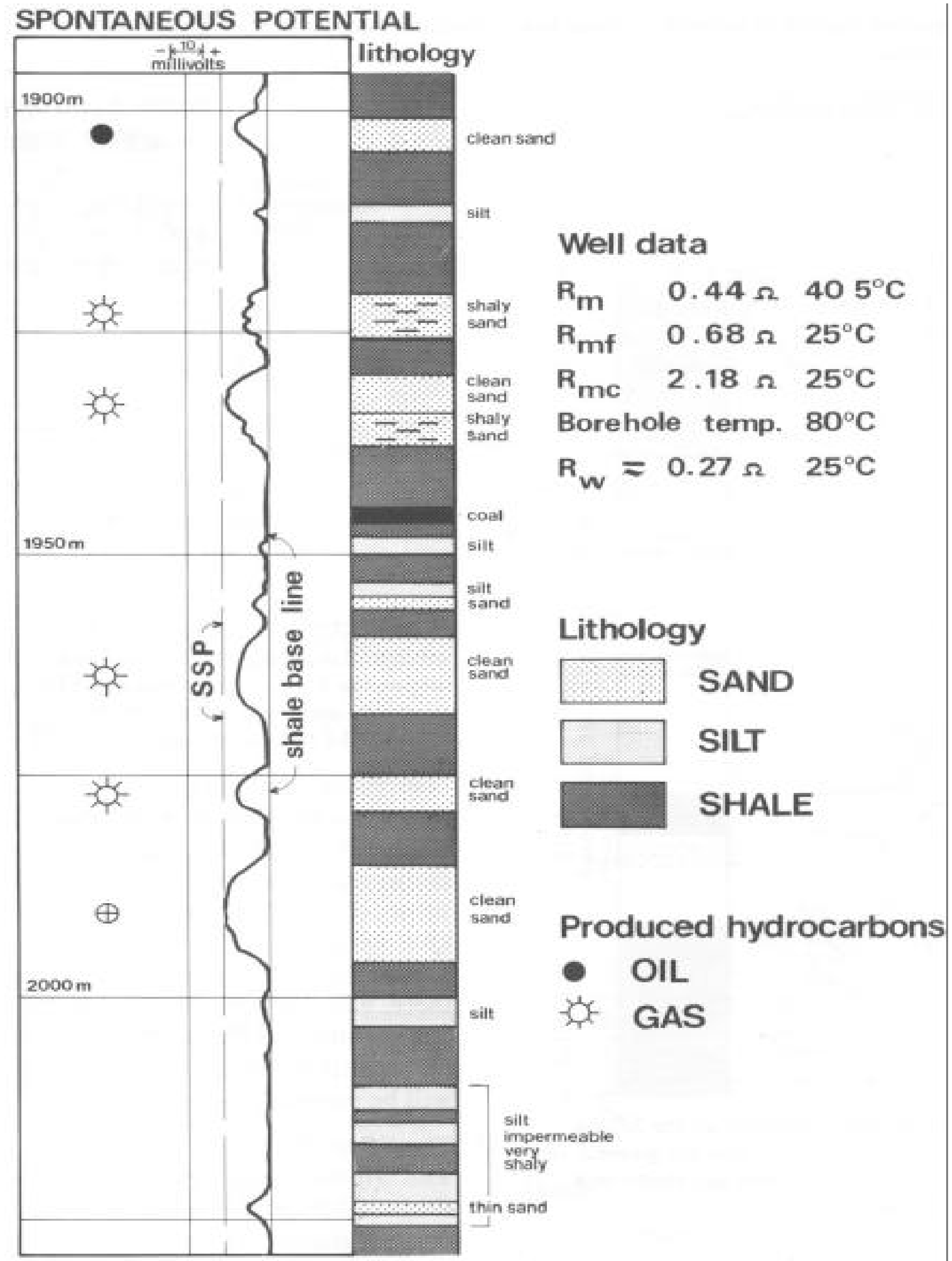
The main uses of this log are:

- The detection of permeable beds.
- The determination of R_w
- The indication of the shaliness of a formation.
- Correlation.

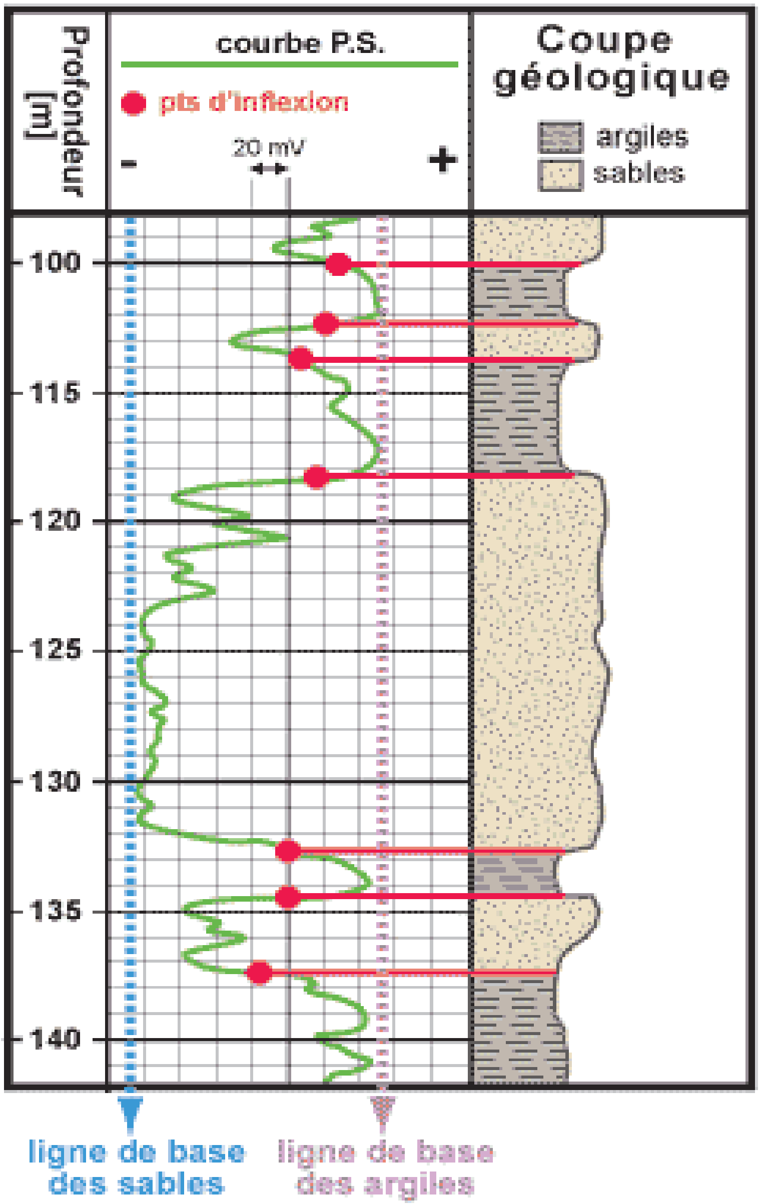
II. **Spontaneous potential**

- Permeable beds

- Use deflection!



II. Spontaneous potential



Ps = constant = clays

Deflection = limit of a Lithology

II. **Spontaneous potential**

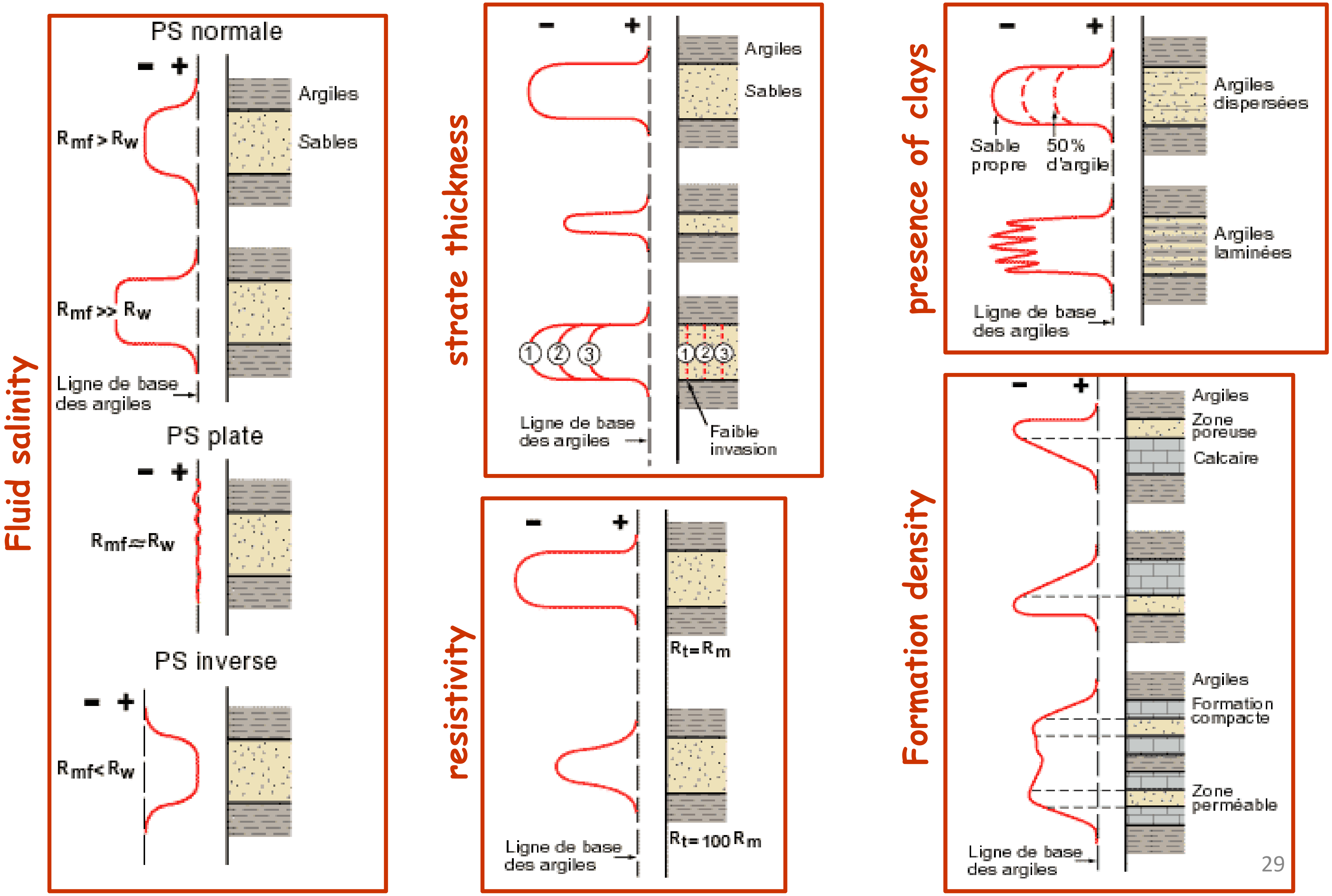
- Resolution/ Amplitude

SP tool has a poor resolution.
Amplitude is affected by:

- The thickness of the permeable bed, *h*.
- The true resistivity of the permeable bed, R_t.
- The diameter of the invaded zone, d_i
- The resistivity of the invaded zone, R_{XO}
- The resistivity of the bounding formations.
- The resistivity of the mud, R_m
- The diameter of the borehole, *dh*.
- The relative salinities of the mud filtrate and the formation fluids.

II. **Spontaneous potential**

➢ Factor influencing PS

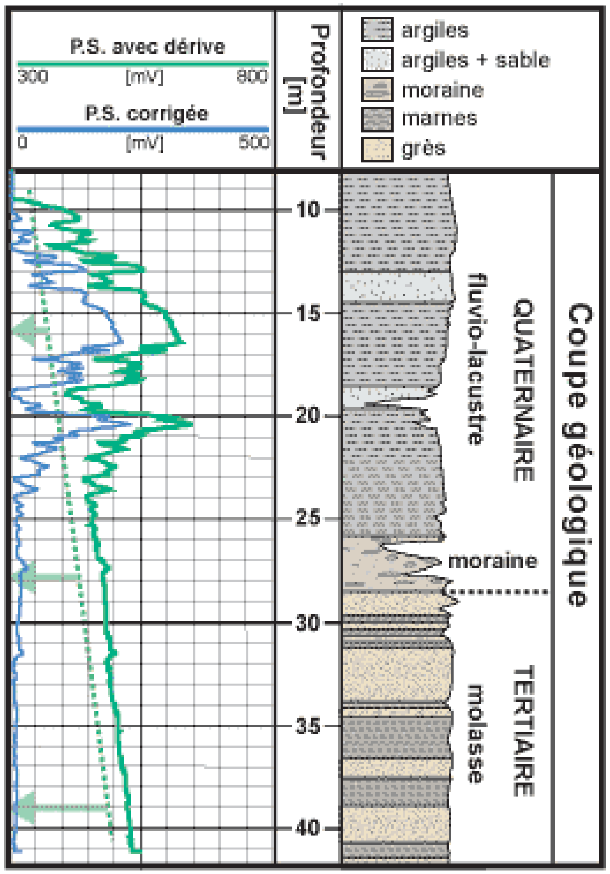


II. **Spontaneous potential**

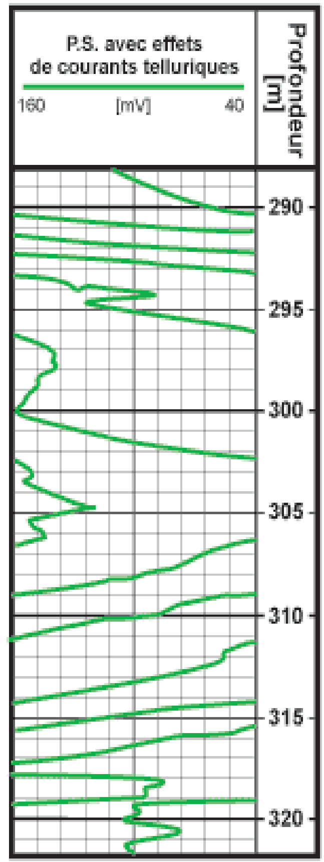
➢ Factor influencing PS

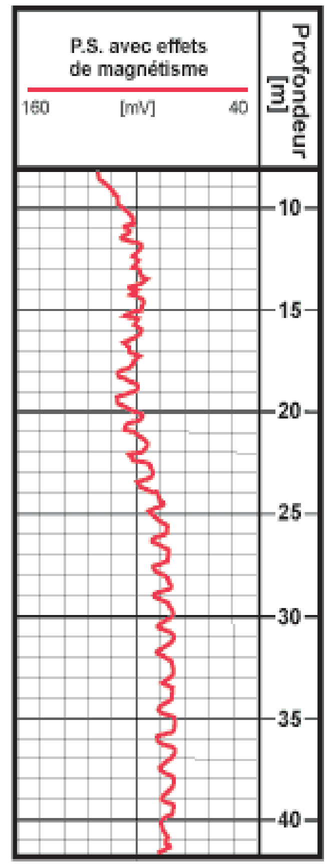
Drift

Bad reference:
Drift of the measurement



parasite voltage and currents





II. **Spontaneous potential**

➢ Calculation of R_w

3 methods:

- **The Quick-Look Method – Procedure** (ignore presence of clays)

- **The Single Chart Method – Procedure**

- **The Smits Method – Procedure** (very accurate)

II. **Spontaneous potential**

➢ Calculation of shale volume

The shale volume is sometimes calculated from the SP log using the relationship:

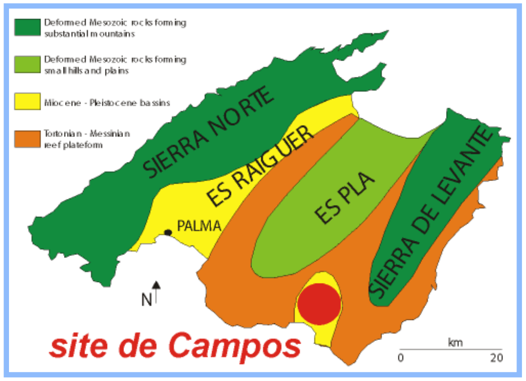
$$Vsh= \left(1 - \frac{PSP}{SSP}\right)$$

PSP = SP log read in a thick homogeneous shaly sand zone,

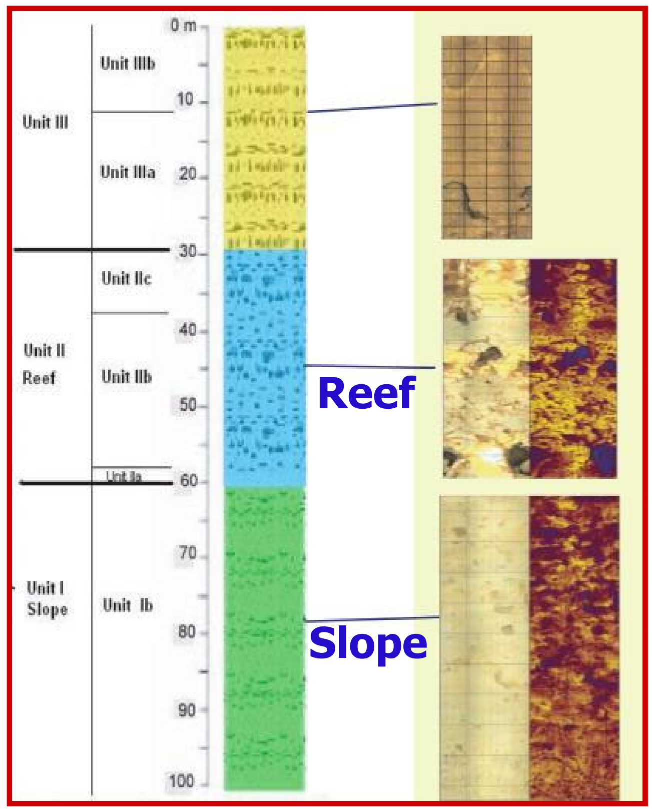
SSP = SP log read in the thick clean sand zone.

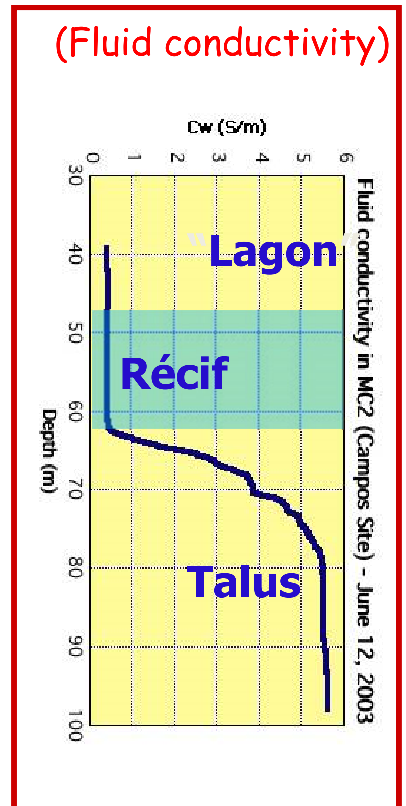
II. **Spontaneous potential**

- <u>Example: water pollution</u>

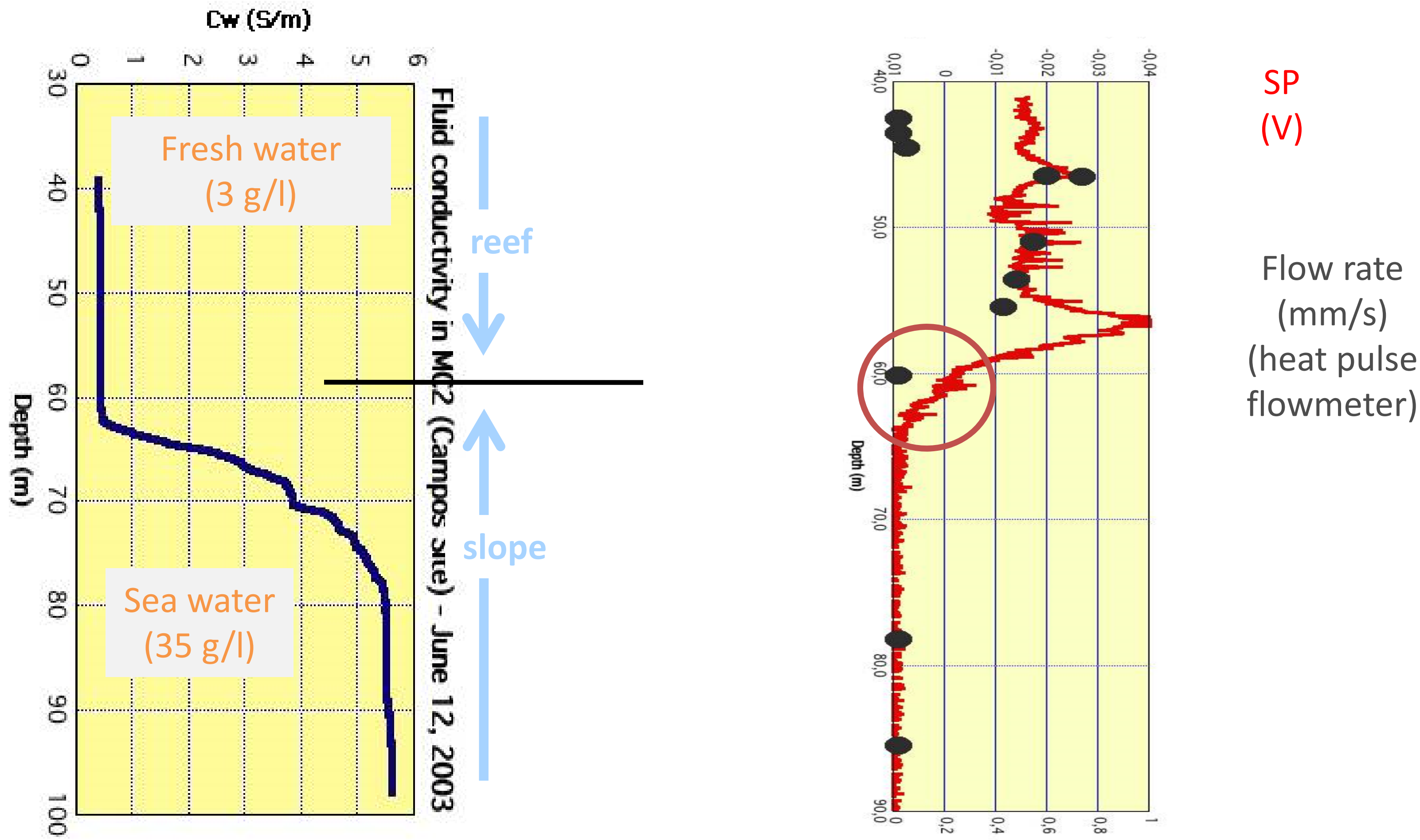


Campos





II. Spontaneous potential



→ **hydro-electrical coupling**

III. **Resitivity Log – Galvanic methods**

➢ Electrical logging

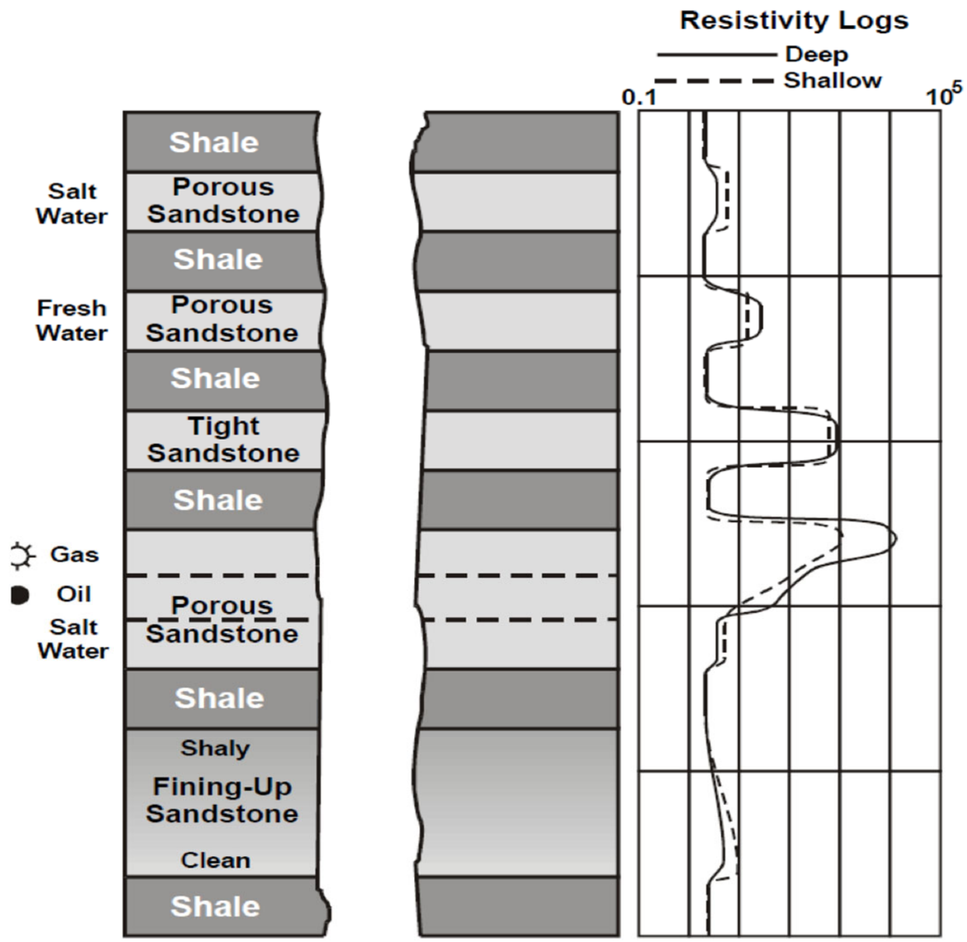
Electrical logs are perhaps the most important tools available to a petro-physicist. This is because they provide a method for calculating the water saturation.

The electrical tools also have a number of qualitative uses, principle of which are :

- indications of lithology
- facies and electro-facies analysis
- Correlation
- determination of overpressure
- determination of shale porosity
- indications of compaction
- investigation of source rocks.

III. Resitivity Log – Galvanic methods

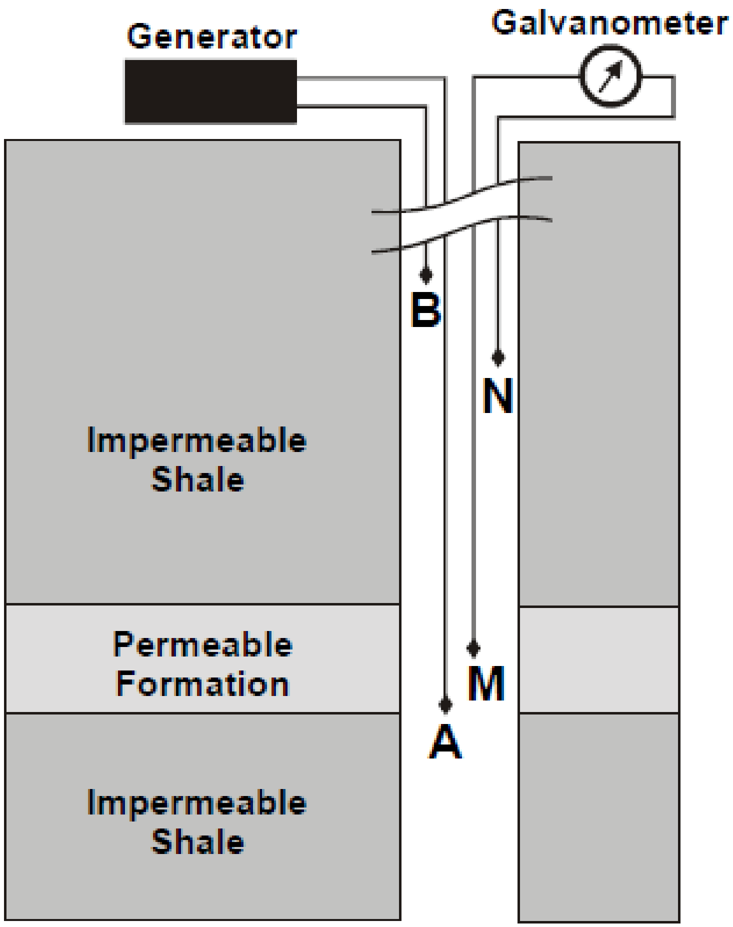
➢ Example



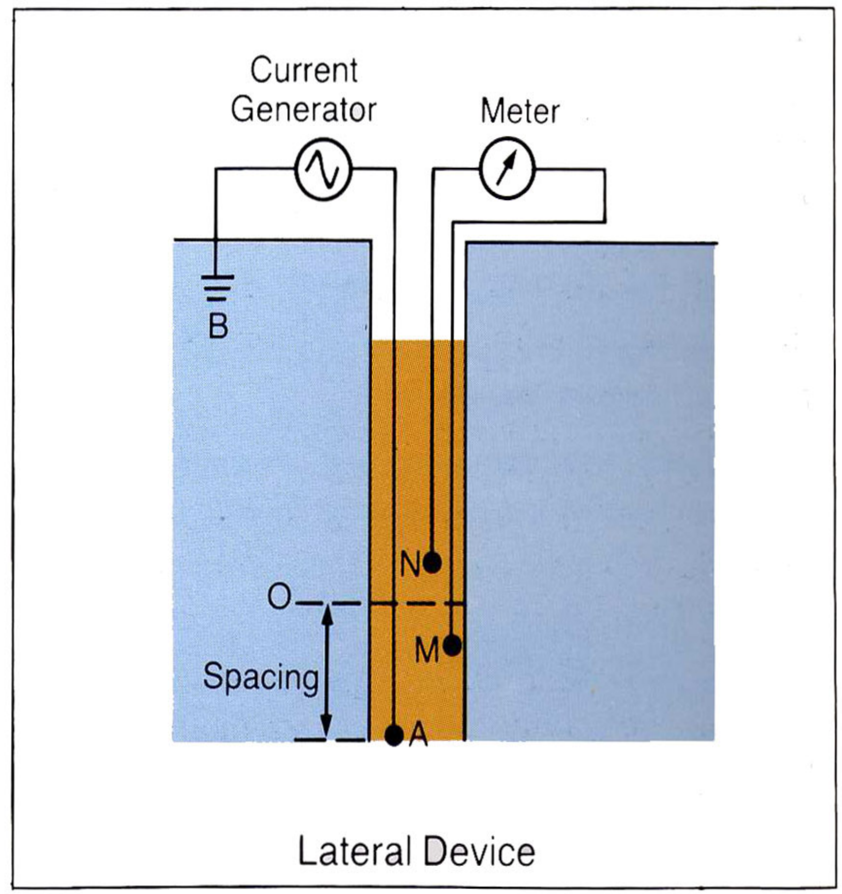
Note the lower resistivity in shales, which is due to the presence of bound water in clays that undergo surface conduction. The degree to which the sandstones have higher resistivities depends upon (i) their porosity, (ii) their pore geometries, (iii) the resistivity of the formation water, (iv) the water, oil and gas saturations (oil and gas are taken to have infinite resistivity).

III. Resitivity Log – Galvanic methods

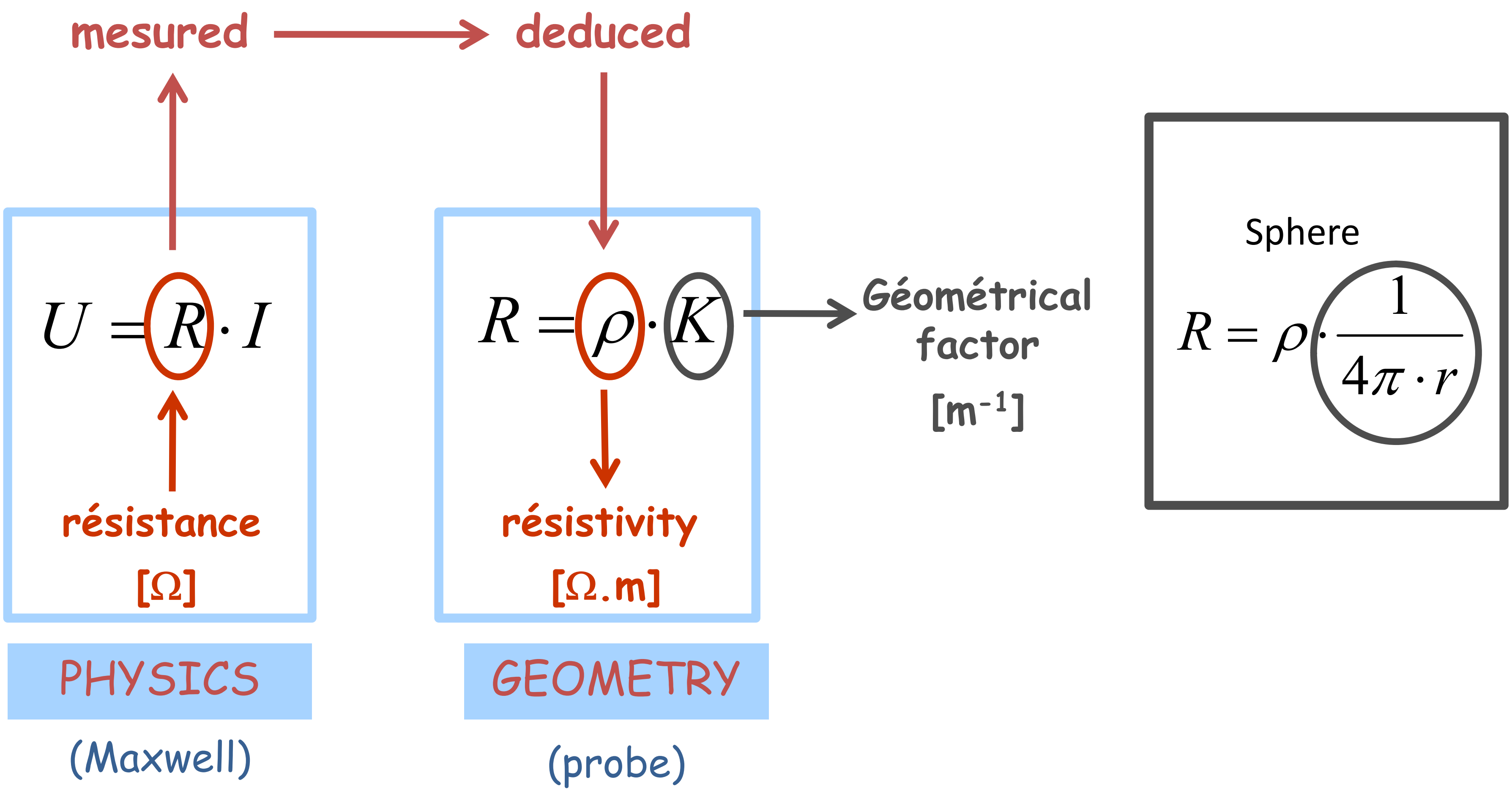
➢ Methods



Lateral Device



III. Resitivity Log – Galvanic methods



III. Resitivity Log – Galvanic methods

Sundberg, 1932

resistivity

$$R_O = R_W \cdot F$$

Water résistivity (pf)

Formation factor

conductivity

$$C_O = \frac{1}{R_O} = \frac{C_W}{F}$$

Waxman & Smits, 1968

$$C_O = \frac{C_W}{F} + C_S$$

volume — surface

Archie, 1942

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

porosity

Imentation index

→ Topology of the porous media

III. Resitivity Log – Galvanic methods

Salinity (Na^{+}, Mg^{2+}, Cl^{-},…)

T

$$C_O = \frac{C_W}{\phi^{-m}} + C_S$$

Clay(s)

porosity

Cimentation index

III. Resitivity Log – Galvanic methods

- Methods

single point | *differential* | *normal* | *lateral*

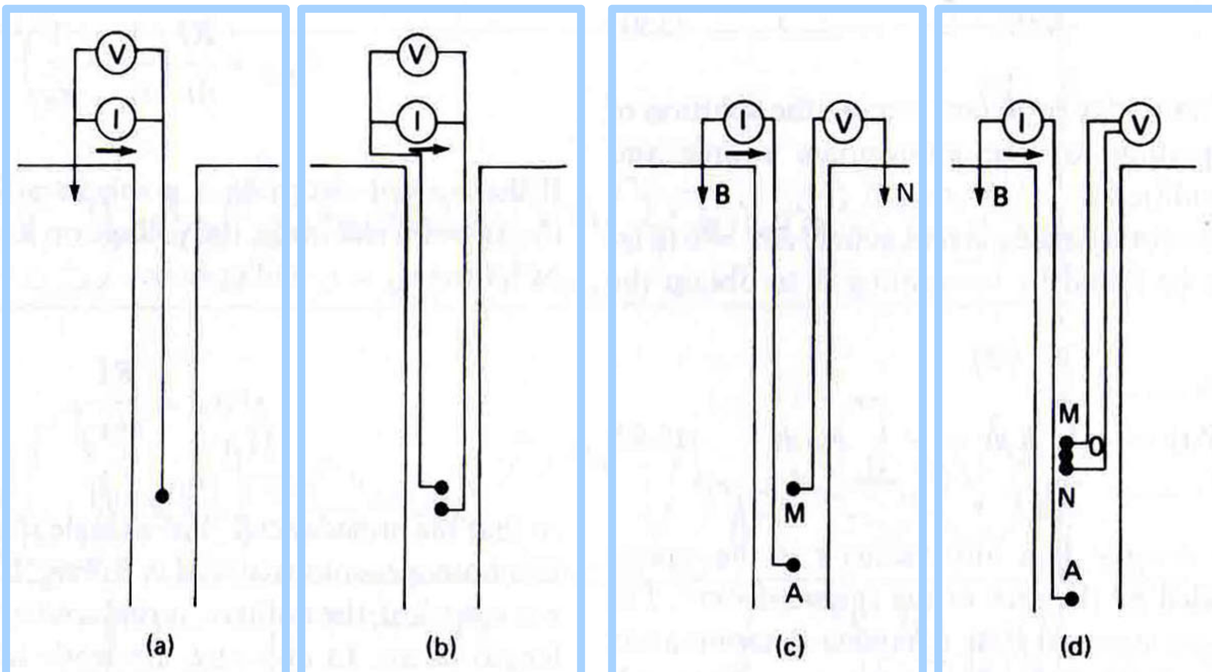
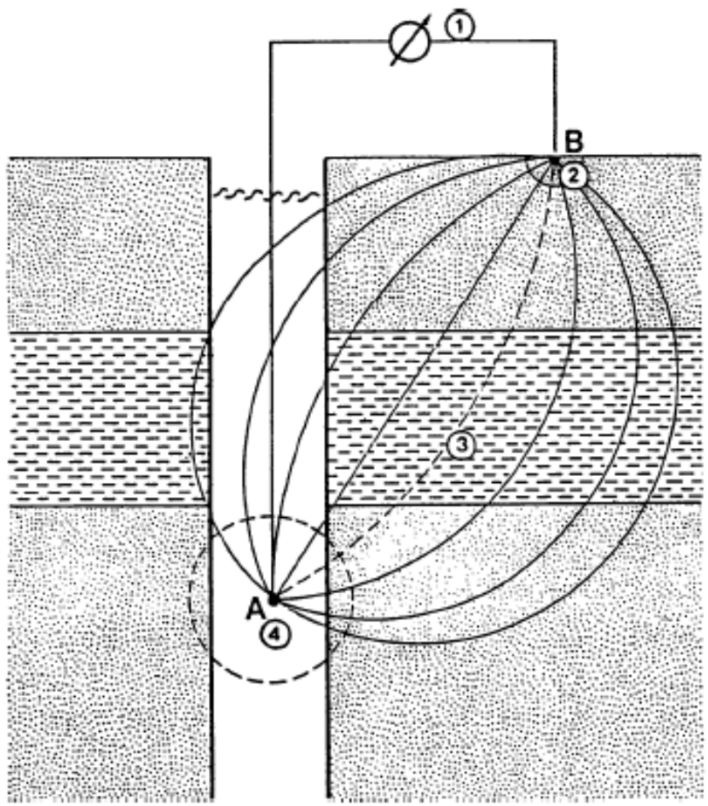


Figure 5.30 *Electrode arrangements of four common arrays with current source* I *and voltage measurement* V*: (a) single-point resistance; (b) differential resistance; (c) normal array; (d) lateral array*

III. **Resitivity Log – Galvanic methods**

- Methods: single point

Résistivity measured between 1 electrode in surface and 1 electrode in borehole



Volume : 10 time the electrode diameter

Influence by the fluid in the well

Good quatitative tools

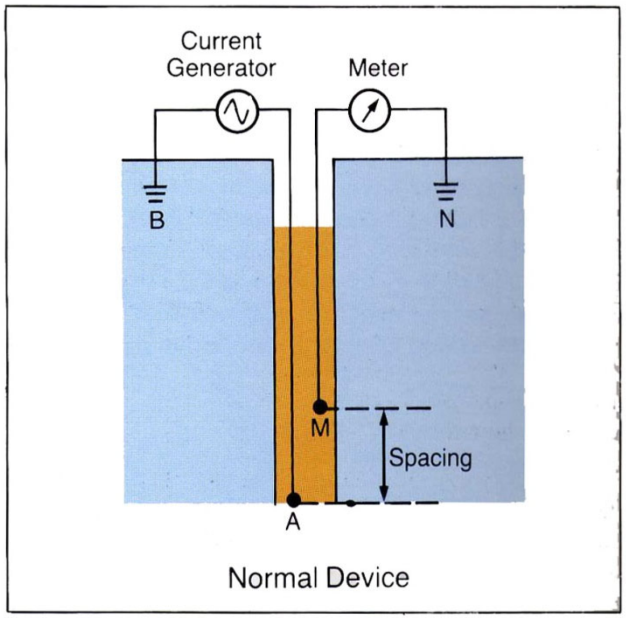
Good resolution

III. Resitivity Log – Galvanic methods

➢ Methods: normal

Resistivity of rocks around the well

Normal Device



potential MN from A (with B,N→ ∞)

$$V = R \cdot I \frac{1}{4\pi \cdot AM}$$

rayon d'investigation = 2AM

résolution verticale = 2AM

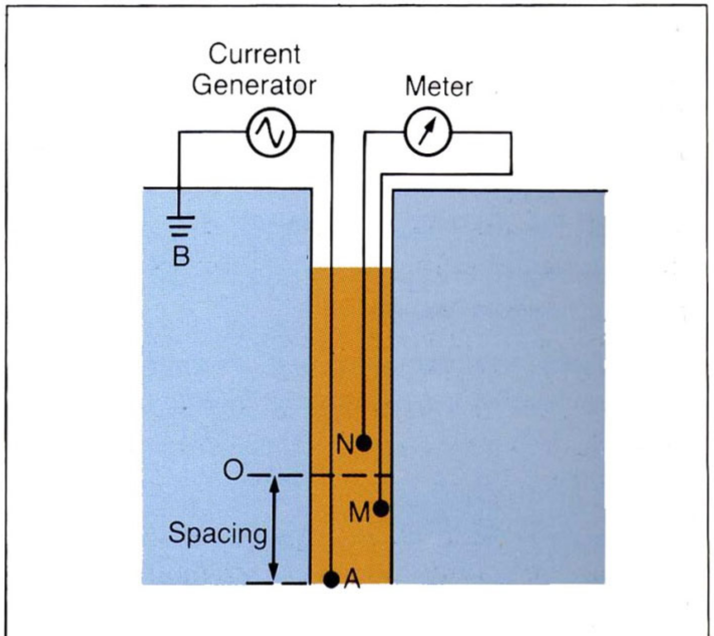
→ short normal 16'' (AM=40 cm)

→ long normal 64'' (AM=160 cm)

III. Resitivity Log – Galvanic methods

- Methods: lateral

Lateral Device



Lateral Device

potential MN coming from A (B→ ∞)

$$V = R \cdot I \frac{MN}{4\pi \cdot AM \cdot AN}$$

Radius of investigation = AO

Vertical resolution = AO

AO : 18'8'' (5m70)

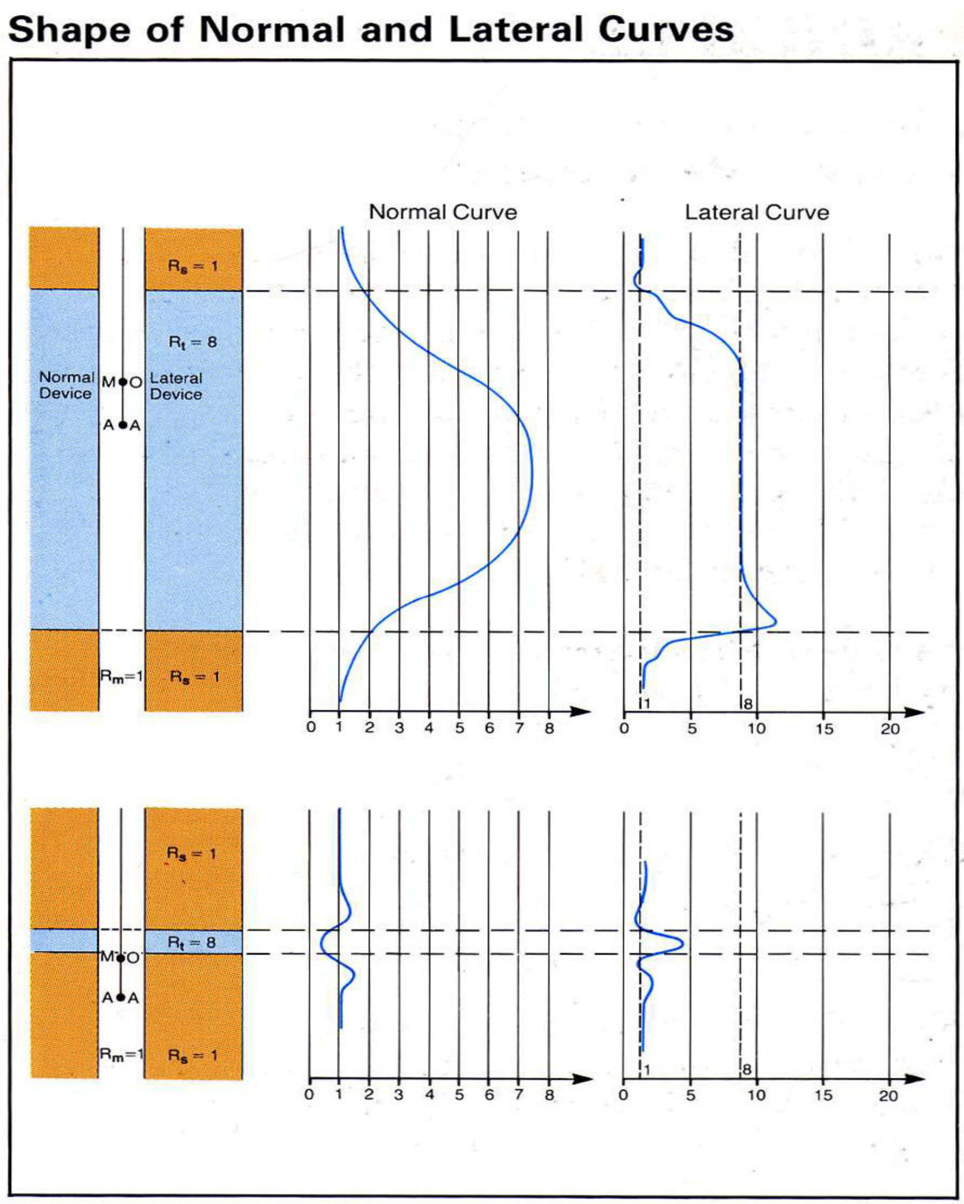
→ **Rt** (if formation thickness enougth)

III. **Resitivity Log – Galvanic methods**

- Methods: lateral

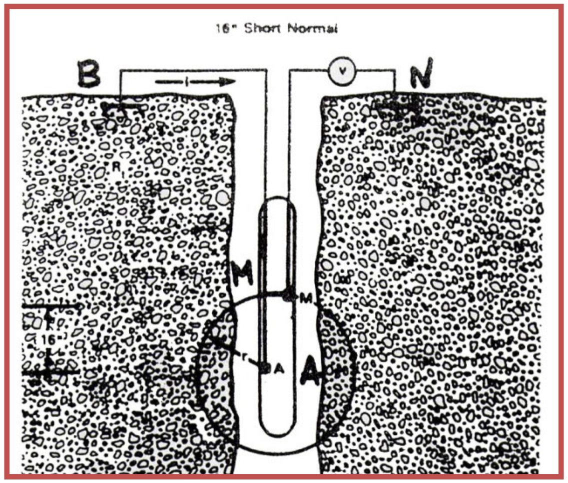
Thick rock strata

Thin rock strata



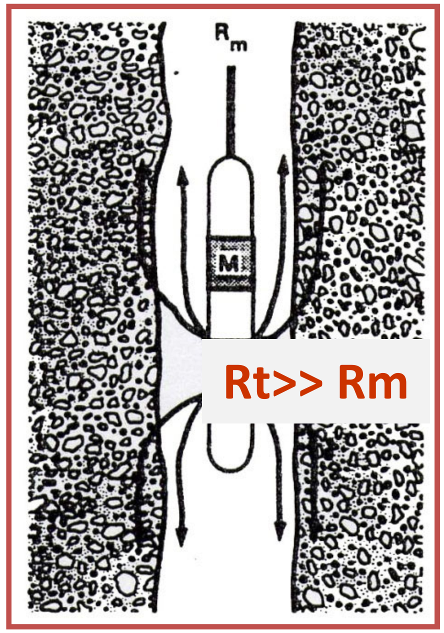
III. Resitivity Log – Galvanic methods

Ideal case



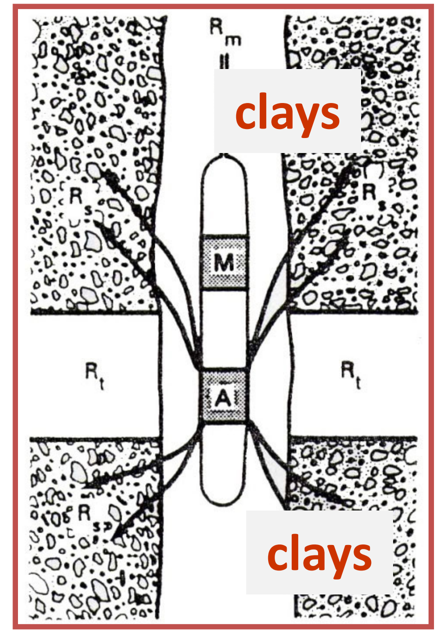
… never !

Hole effect



Formation = high resistivity
→ Measure mud and hole resitivity!

Clays effect

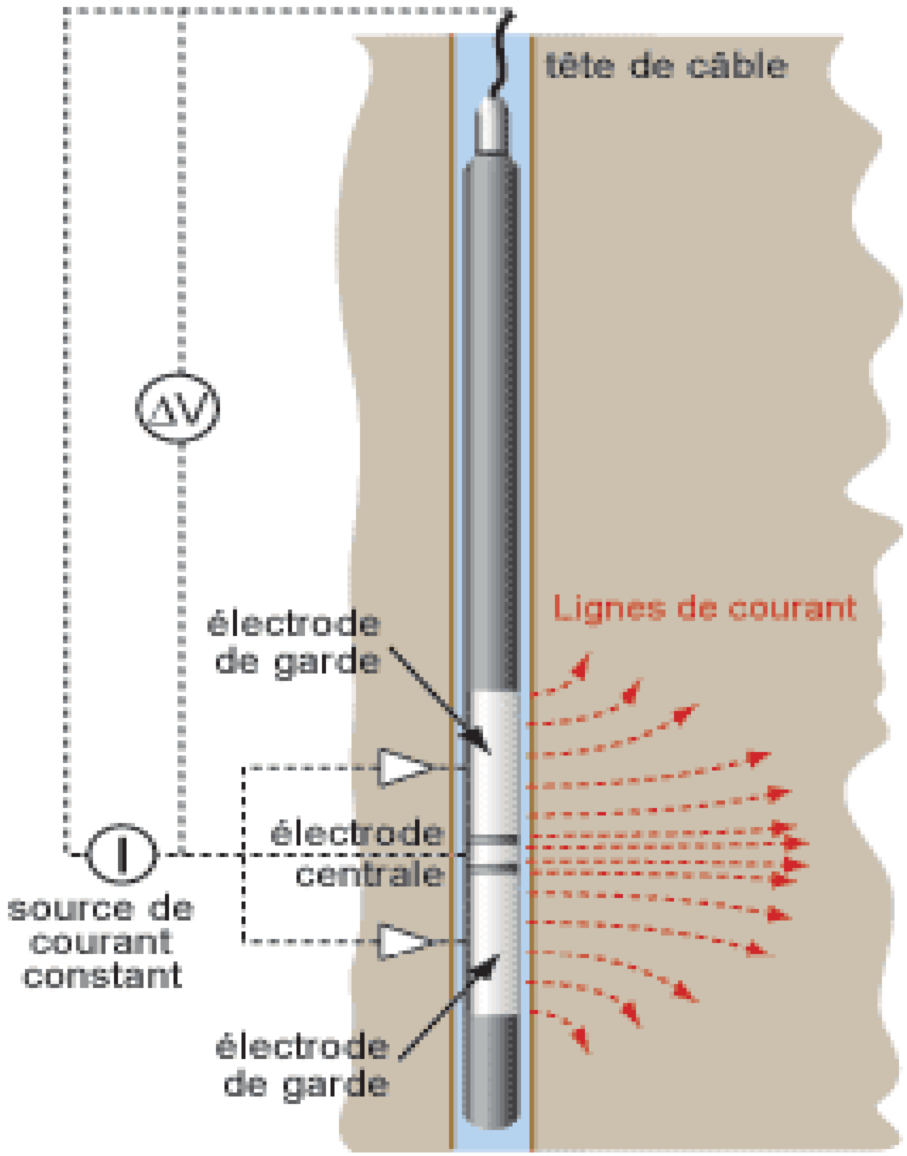


courant goes in clays formation

→ Need to focalise the courant

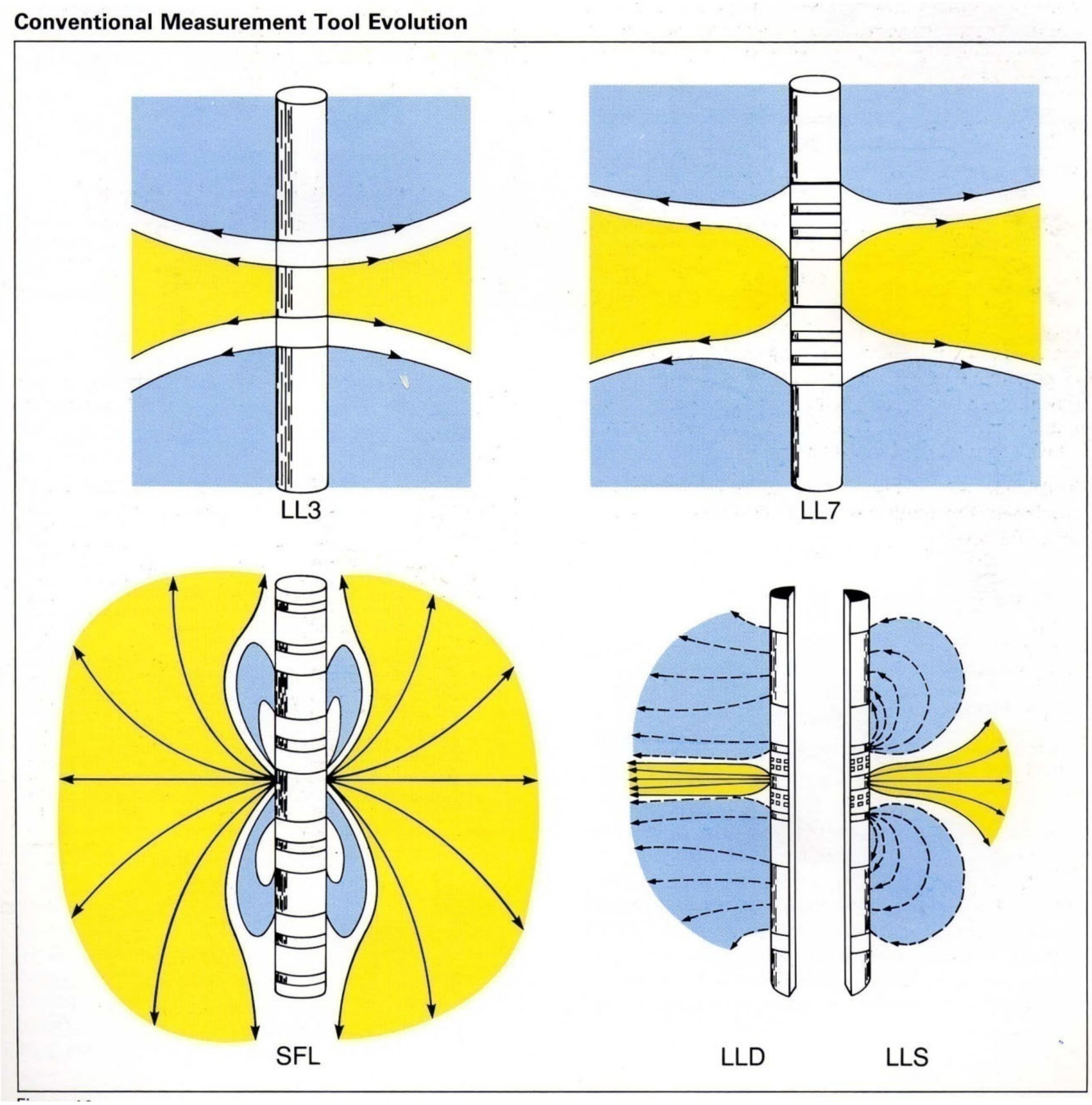
III. **Resitivity Log – Galvanic methods**

- Guard ring electrods



III. Resitivity Log – Galvanic methods

- LL3, LL7



LL7 : 1 m

LL3 : 30 cm

2,5 cm

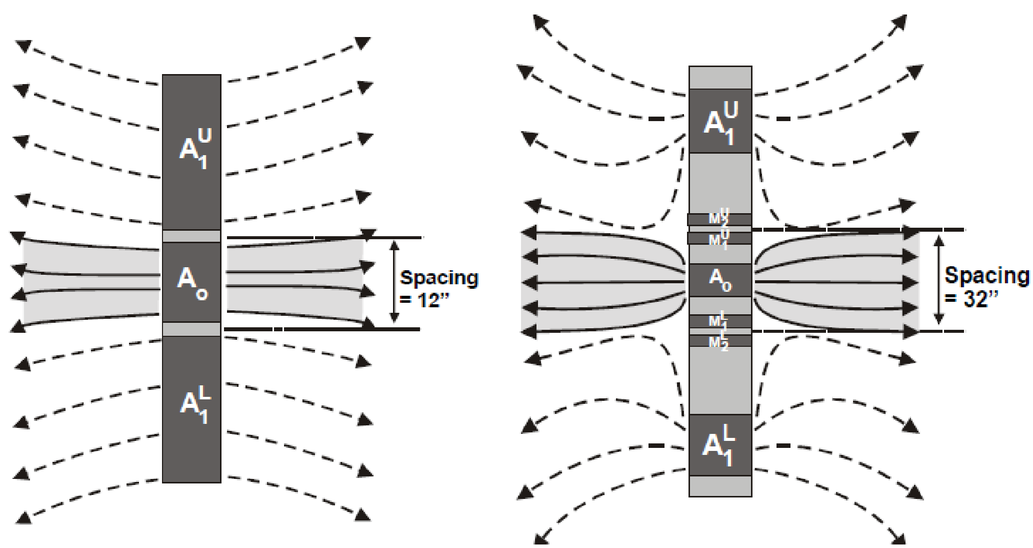
Rt

III. **Resitivity Log – Galvanic methods**

- LL3, and LL7

- LL3 and LL 7 (three and 7 electrodes)

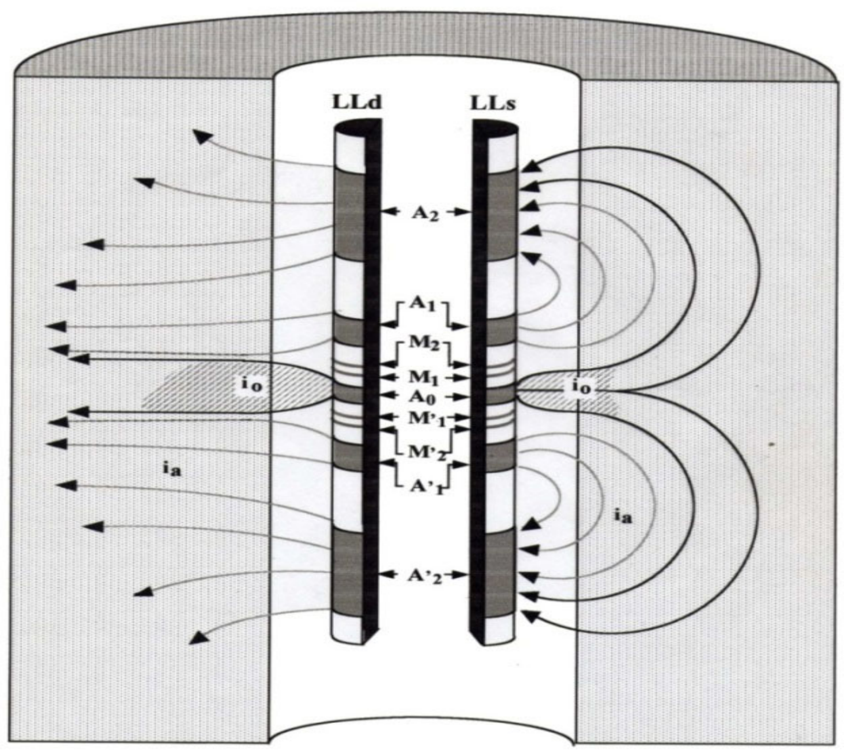
Electrode in the middle which is 1 foot long emits the main current, while the 5 foot long electrodes either side of it emit a current that is designed to help keep the central current more focussed. This is called a ***bucking current*** and the electrodes are called ***guard electrodes***.



III. **Resitivity Log – Galvanic methods**

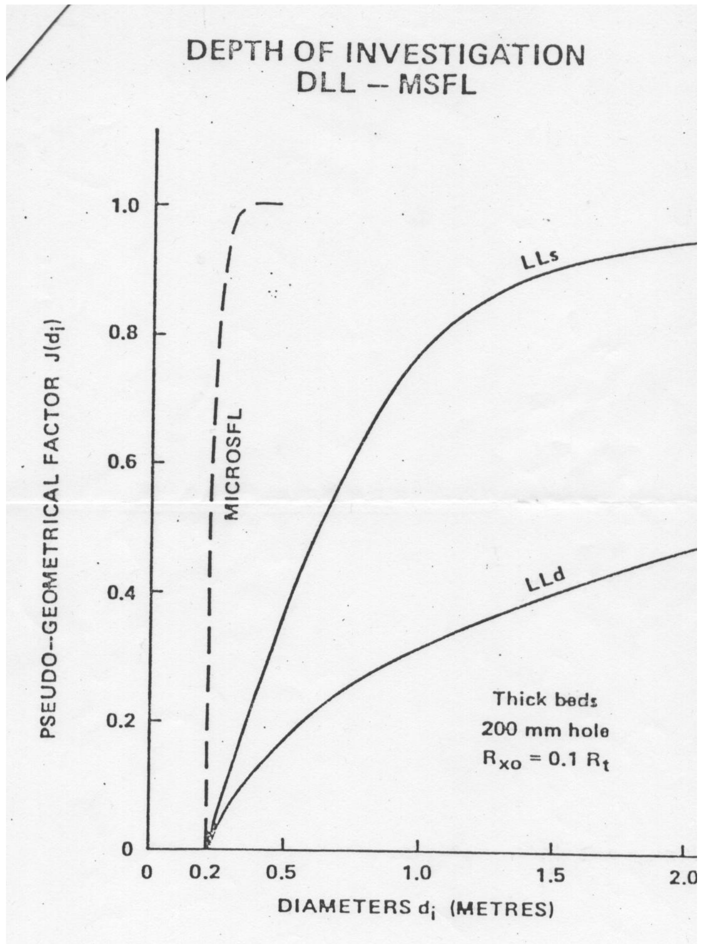
➢ Dual laterolog

- Dual laterolog (9 electrodes)
- Deep penetration LLd (35 Hz)➔ R_T
- Shallow penetration Lss (280 Hz) ➔ R_{XO}



III. **Resitivity Log – Galvanic methods**

- Resolutions



III. **Resitivity Log – Galvanic methods**

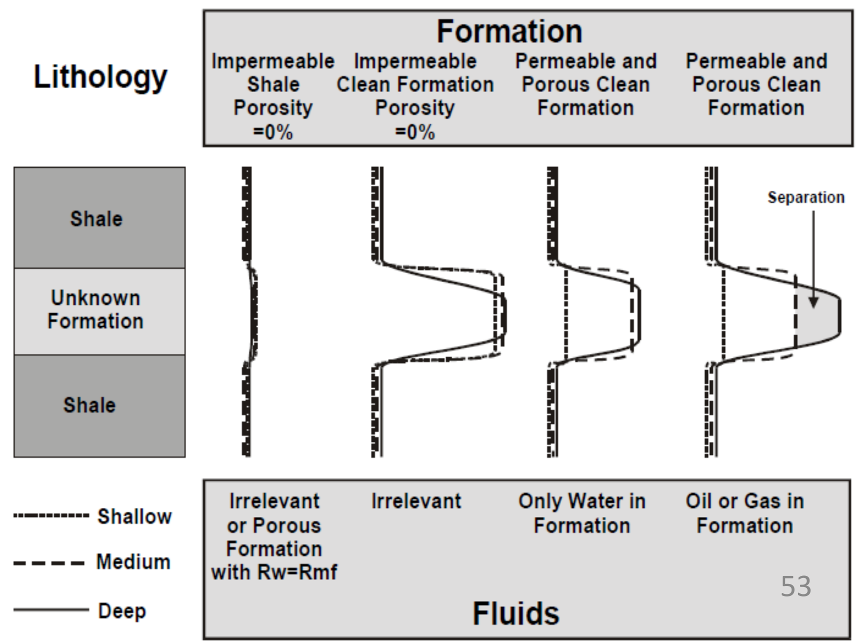
➢ Uses of Electrical logs

- Recognition of Hydrocarbon Zones
- Calculation of Water Saturation
- Textures and Facies Recognition
- Lithologies recognition

III. **Resitivity Log – Galvanic methods**

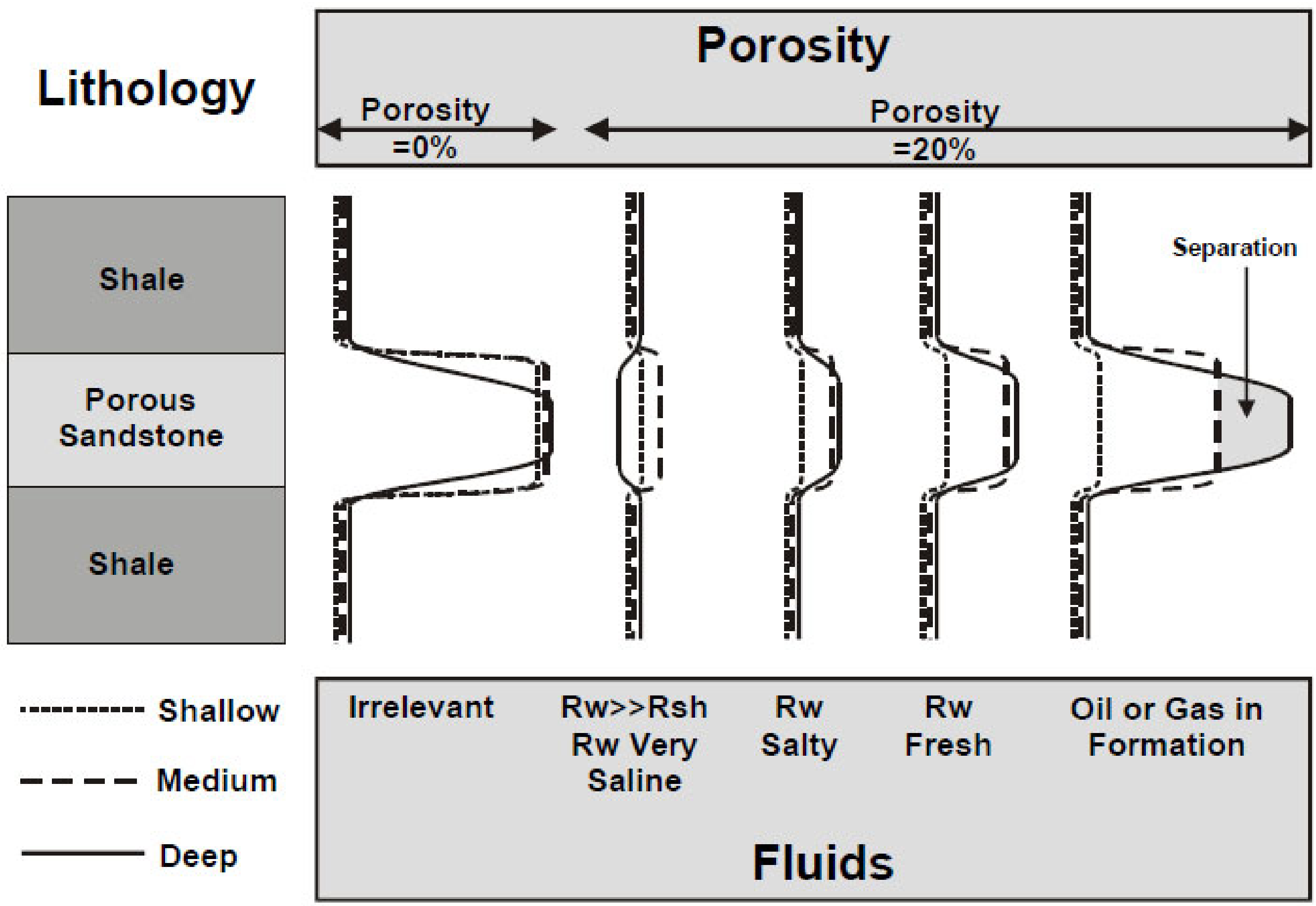
➢ Recognition of Hydrocarbon Zones

- If all three curves are low resistivity, and overlie each other, the formation is an impermeable shale, or, rarely, the formation is permeable and water-bearing but the mud filtrate has the same resistivity as the formation water.
- If all three curves are higher resistivity than the surrounding shales, and overlie each other, the formation is an impermeable cleaner formation (sandstone, limestone).
- If the shallow curve has low resistivity, but the medium and deep penetrating tools have a higher resistivity that is the same (they overlie each other), the formation is permeable and contains only formation water.
- if the shallow curve has low resistivity, the medium as a higher resistivity, and the deep one has an even higher resistivity (i.e., there is separation of the of the medium and deep tool responses), the formation is permeable and contains hydrocarbons



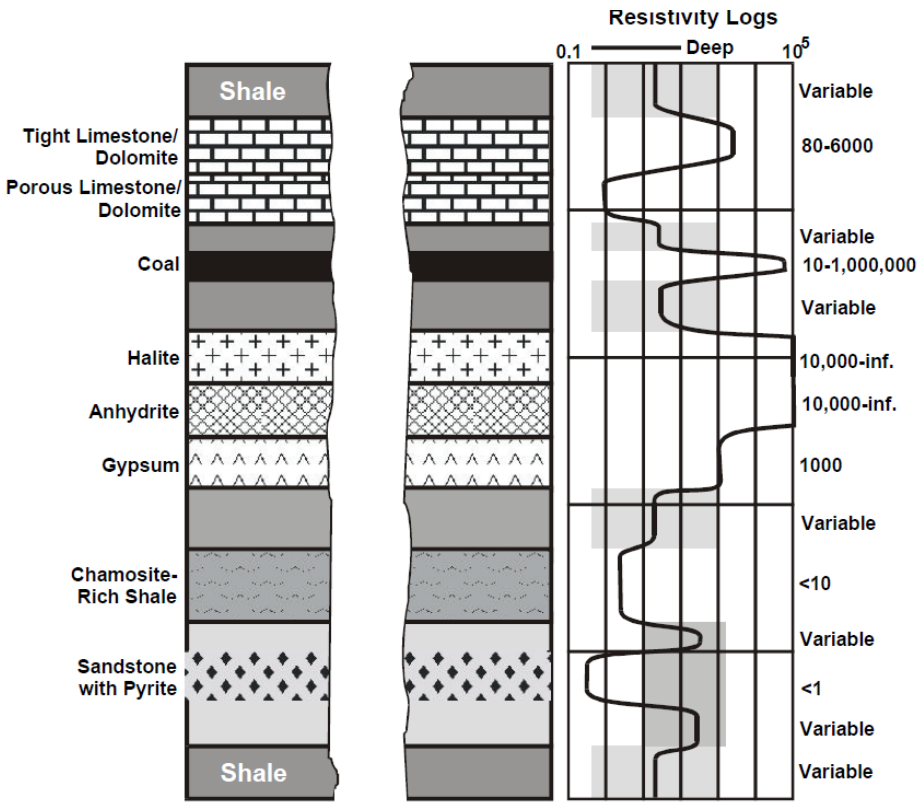
III. **Resitivity Log – Galvanic methods**

➢ Recognition of Hydrocarbon Zones



III. **Resitivity Log – Galvanic methods**

➢ Facies and lithologies recognition



most common are:

· Gypsum – 1000 Ωm.

· Anhydrite – 10,000 - ∞ Ω m.

· Halite - 10,000 - ∞ Ω m.

· Coals – 10 –106 Wm.

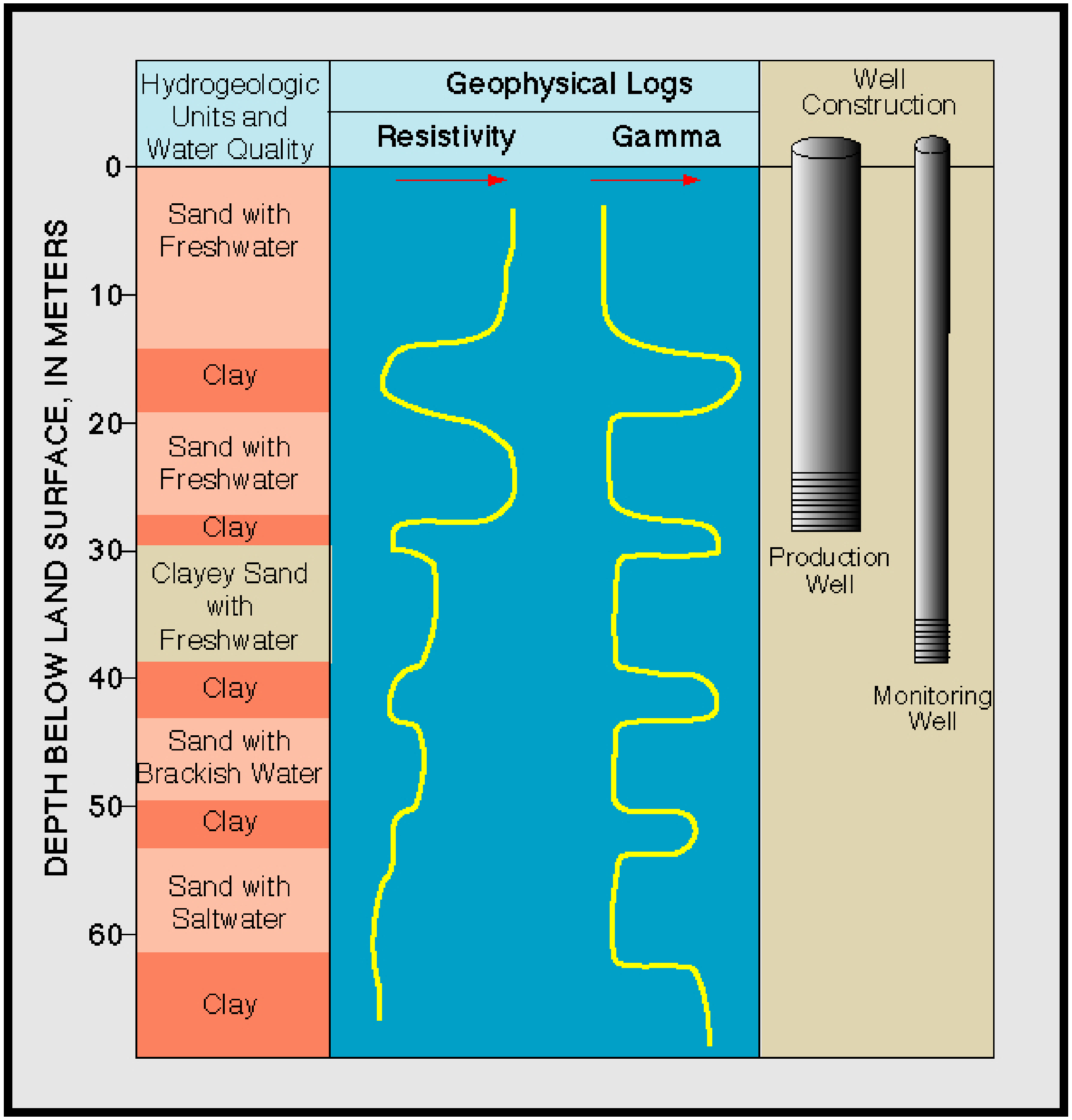
· Tight limestones and dolomites – 80 – 6000 Ω m.

· Disseminated pyrite - <1 Ω m (pyrite has a resistivity of 0.0001 – 0.1 Ω m.

· Chamosite - <10 Ω m.

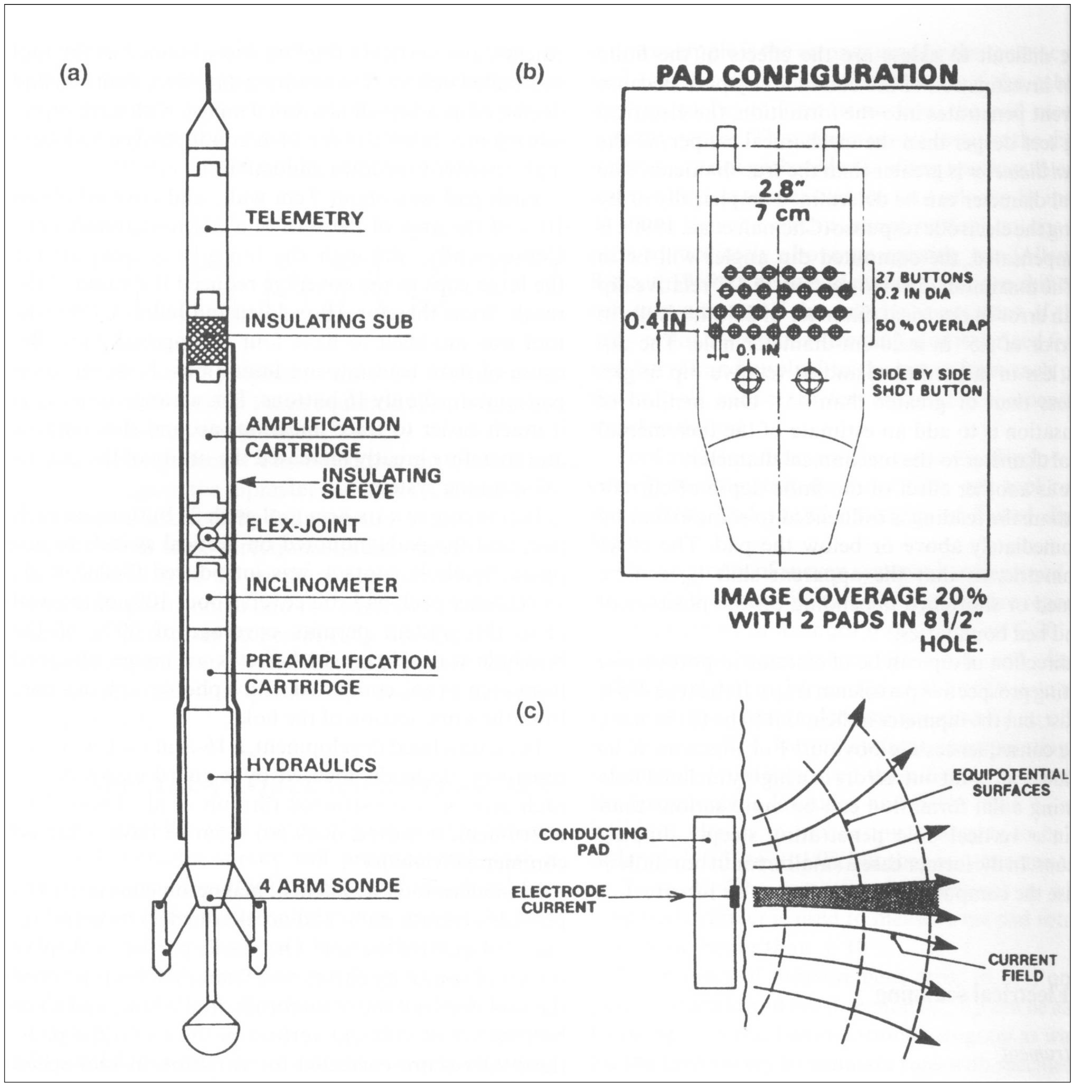
III. Resitivity Log – Galvanic methods

- Shale recognitions



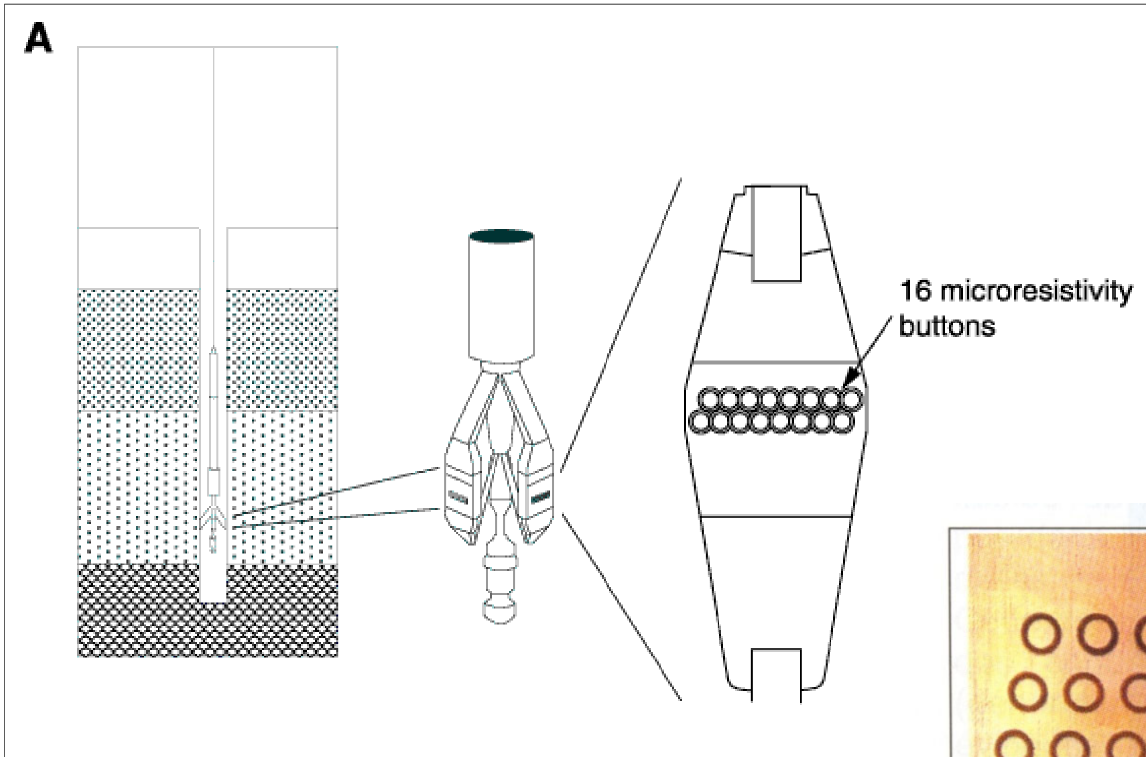
IV. **Borehole images**

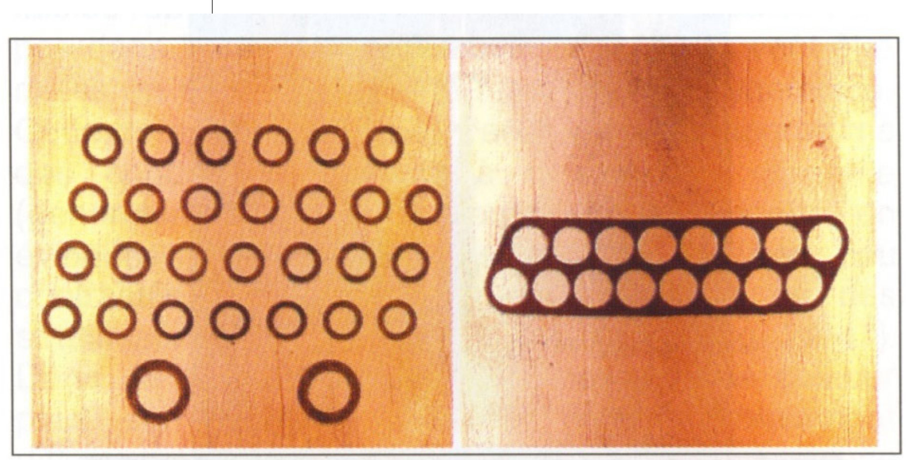
- FMS: formation micro scanner



IV. **Borehole images**

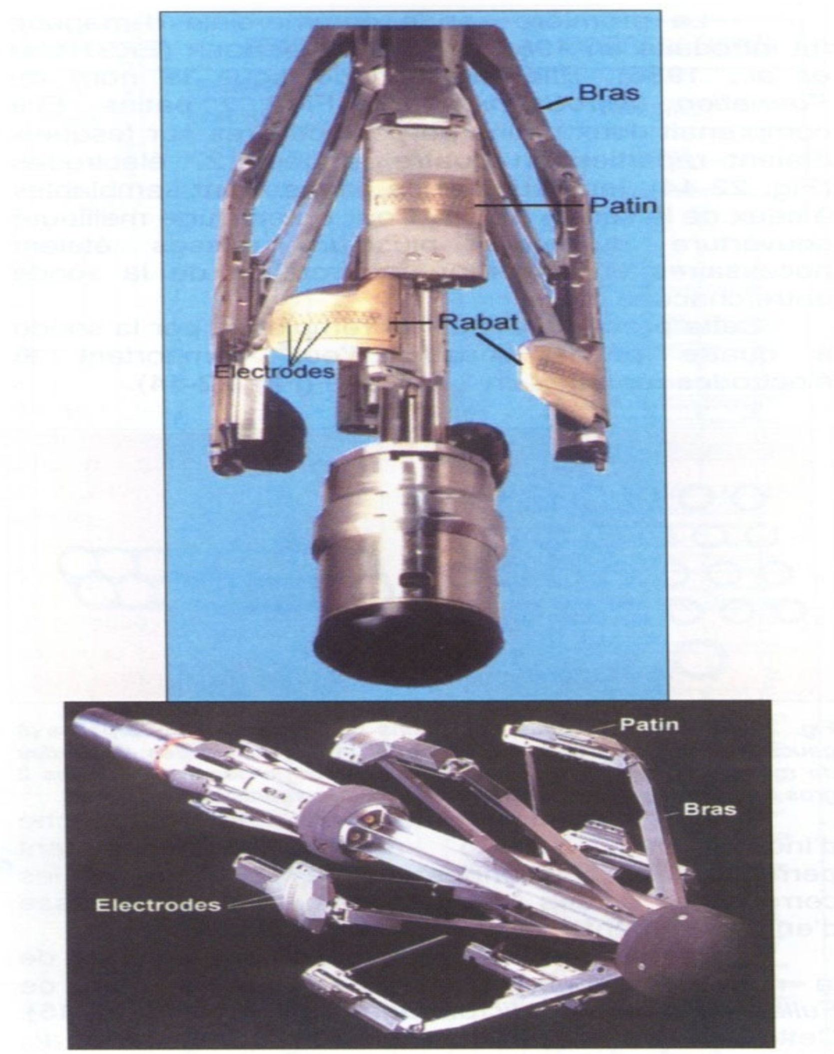
- FMS: formation micro scanner





IV. **Borehole images**

➢ Fullbore Formation microImager



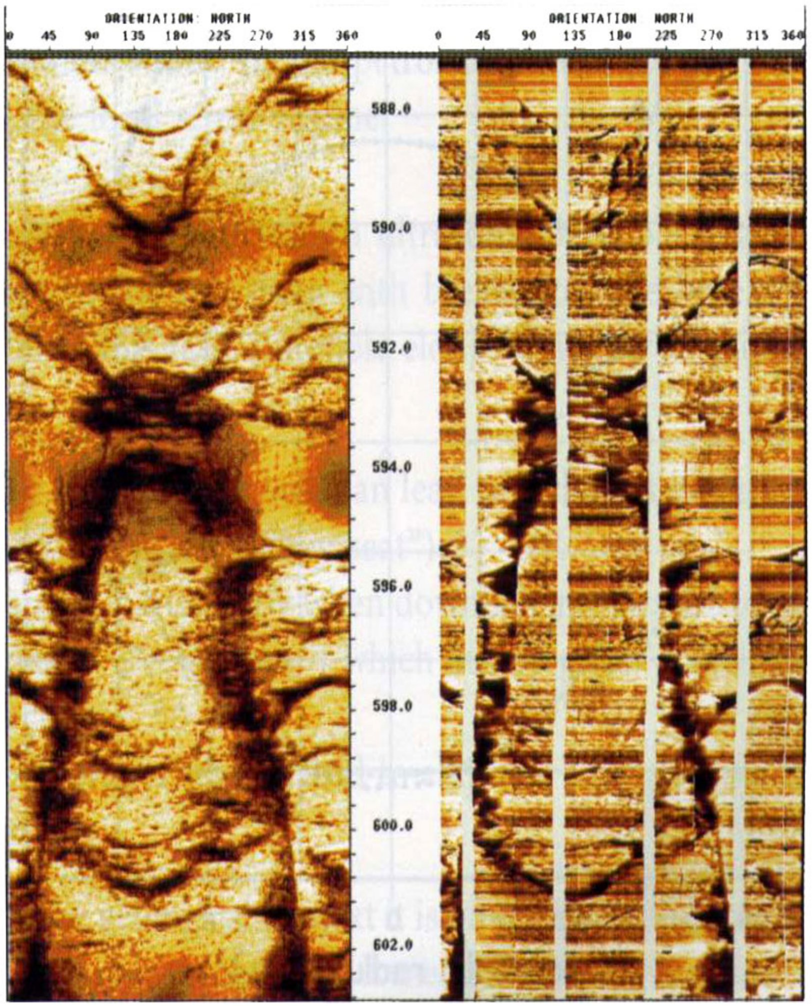
4 arms + 4 rabats

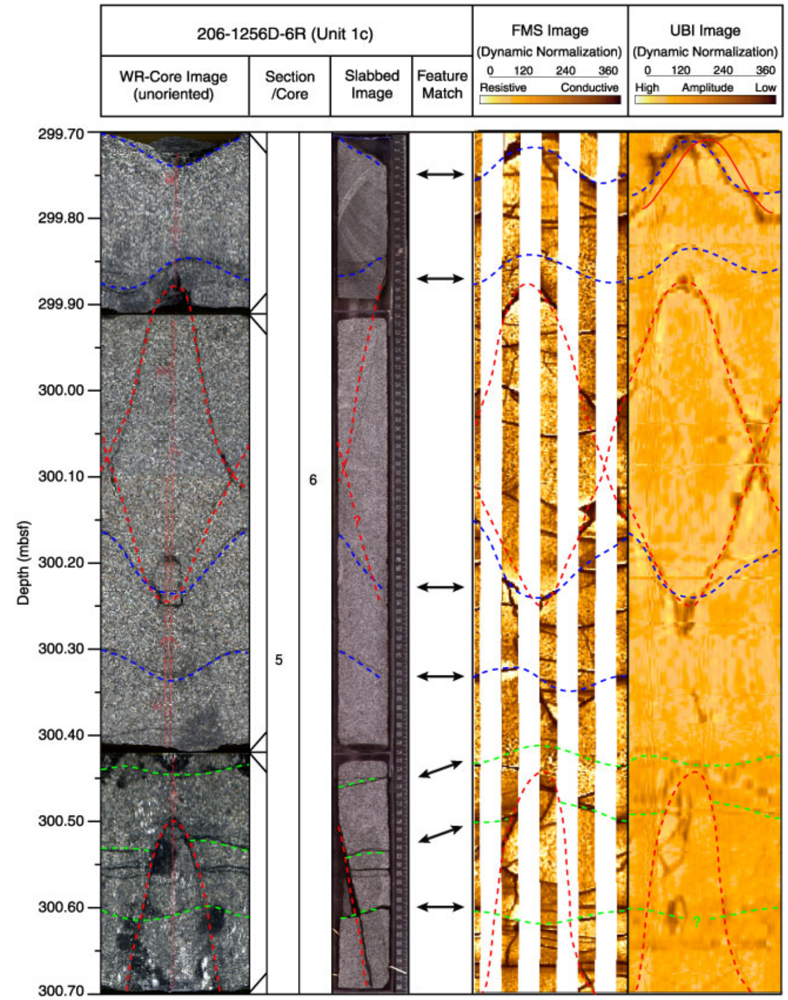
24 resistivity bouttons

Resolution: 5 mm

IV. **Borehole images**

- Comparison between acoustic and electrical images





High resolution compare to acoustic images but discontinuous

IV. **Borehole images**

- Uses

- Fractures
- Veins
- Dip and dip direction
- Facies

IV. **Borehole images**

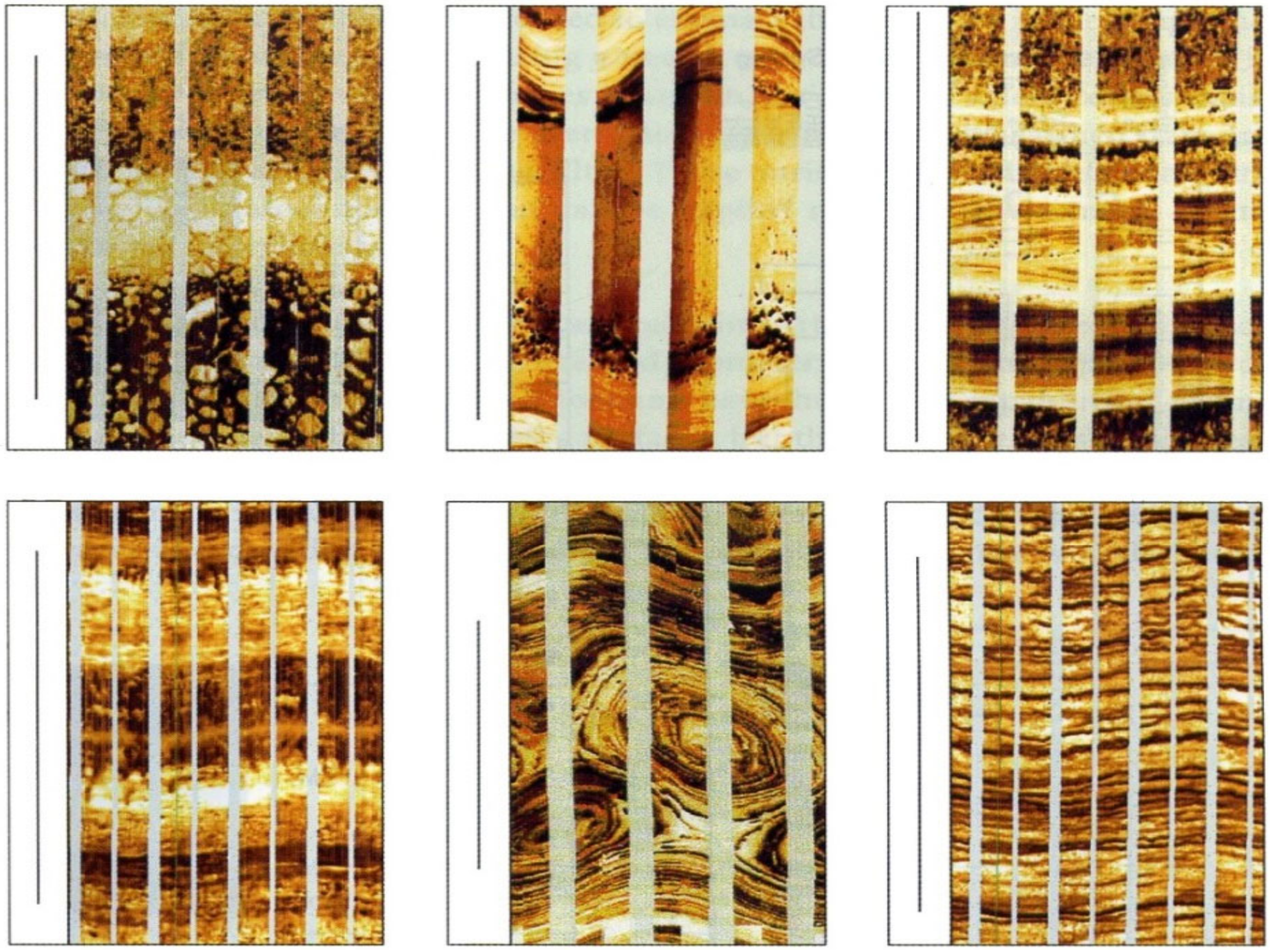


Figure 2.2.18. Various examples of bedding types on electrical borehole images (all FMI). From upper left to lower right: A conglomerate in a debris flow; rip-up clasts in a fluvial channel fill; thin cross-beds in a tidal sandstone; burrowing in a carbonate/clastic mixed shelf deposit; overturned sand layers in a slump; stylolites in a limestone. Bar on left of images corresponds to one meter.