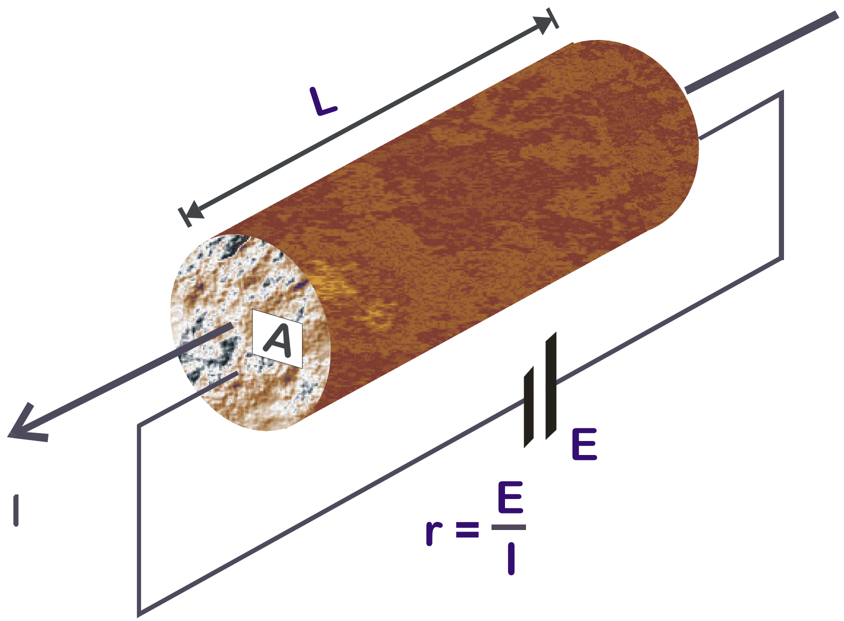
ELECTRICITY

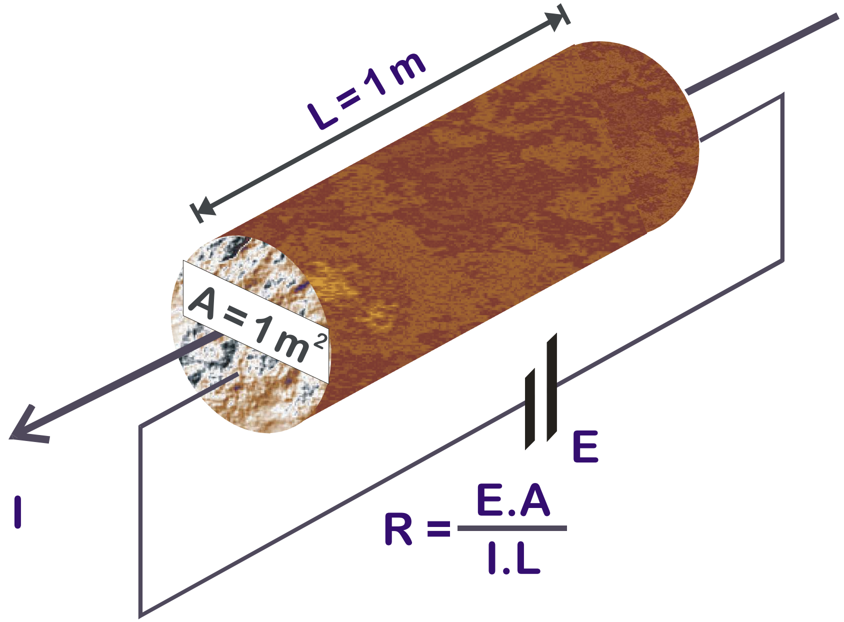
&

CONDUCTIVITY

Resistivity & conductivity



The resistance is defined as the ratio of the electric field strength and the electric current



The specific resistance "R" or Ro is defined as the resistance over a specific volume of matter

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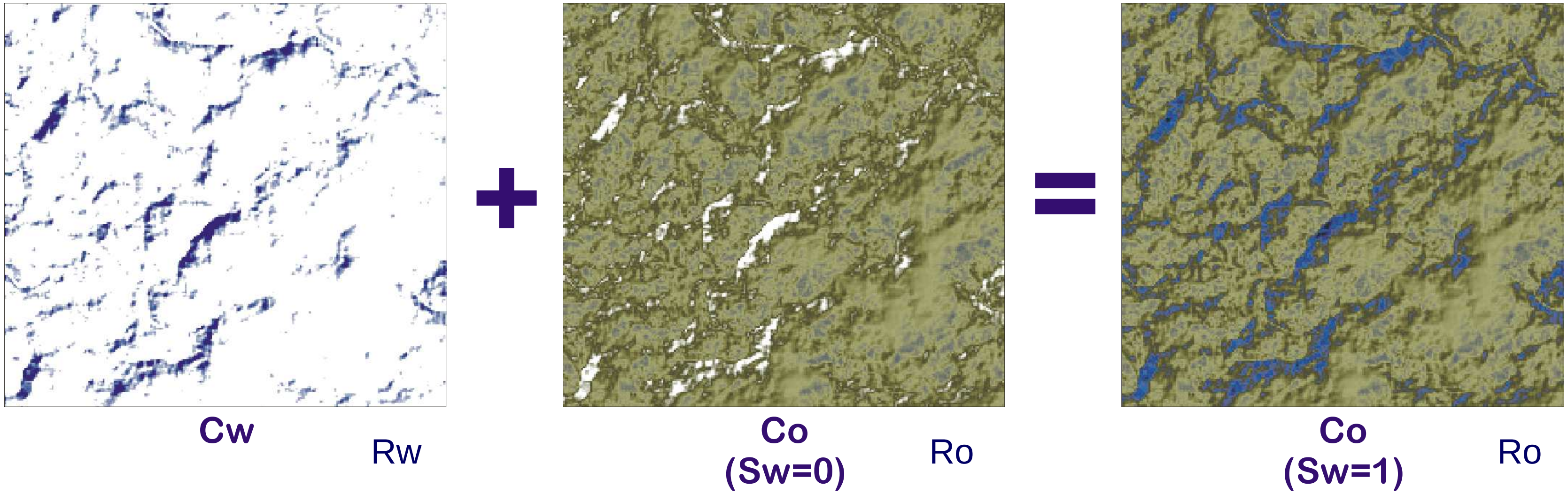
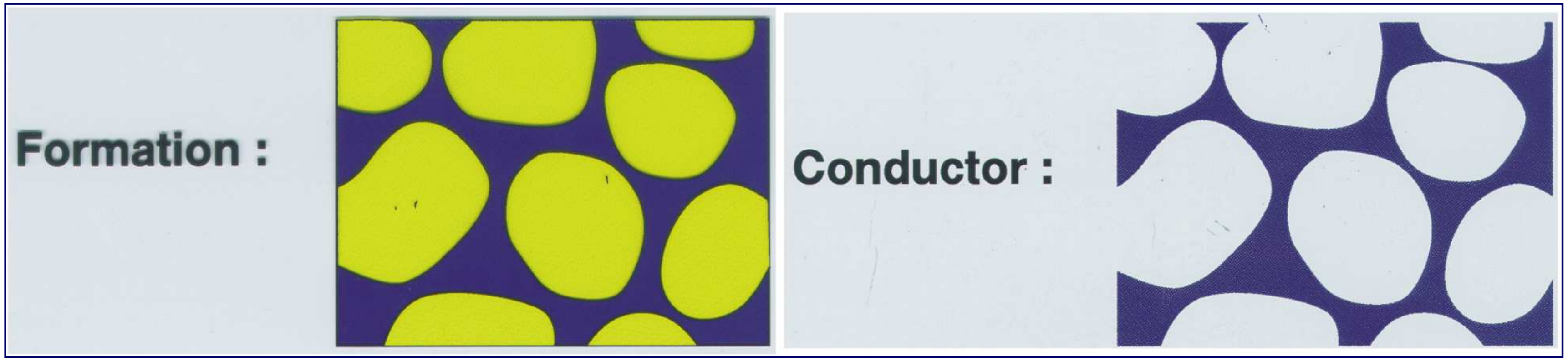
Resistivity & conductivity

Formation resistivity factor; defined by the matrix and pore content: F or $F_R = C_w/C_o$





Formation resistivity factor; defined by the matrix and pore content: F or $F_R = C_w/C_o$

Resistivity & conductivity

A rock sample or formation and its resistivity R or Ro consist of:

Non-conductive components:
- matrix minerals; water-poor silica minerals (quartz, feldspar), carbonates, carbonaceous matter, hydrocarbons
- fresh water

Conductive components:
- matrix ore minerals; magnetite, pyrite, galena as a semiconductor
- matrix water bearing silica; shales, clays
- brine

Resistivity "R" is often replaced by conductivity "C"

$$C = \frac{1}{R}$$

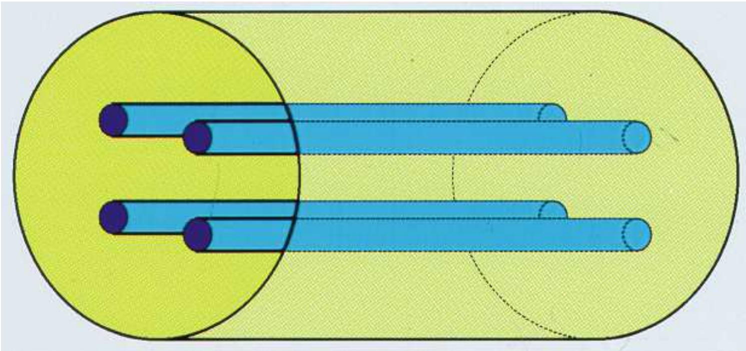
- C has the redefined unit of mho/m
- To avoid very small values, 1/(1 ohm) is valued as 1000 m.mho (millimho's).

Resistivity & conductivity

The relation between F_R and rock porosity for capillary pore space

$$A_n = \varphi A$$

- block with a length L
- n saturated straight capillary tubes
- total cross-sectional area ($A_n = n.\pi.r_c^3$)
- porosity ϕ



$$R_{w.cap} = \frac{E \cdot A_n}{I_{w.cap} \cdot L}$$

The resistivity of the brine in the capillary pore space

$$I_{w.cap} = I_o$$

assumed

$$F = F_R = \frac{R_o}{R_{w.cap}} = \frac{A}{A_n} \cdot \frac{I_{w.cap}}{I_o}$$

The formation resistivity factor F is the ratio of the resistivities of the matrix and fluid

$$F = F_R = \frac{1}{\varphi}$$

Resistivity & conductivity

Relation between FR and matrix cementation/compaction

Archie-1: $F = F_R = \frac{1}{\varphi^m} = \frac{R_o}{R_w} = \frac{C_w}{C_o} \longrightarrow \log F = -m \log \varphi$

"m": the cementation factor or lithology exponent

The total rock resistivity Ro decreases with increasing porosity for the samekind of pore geometry.

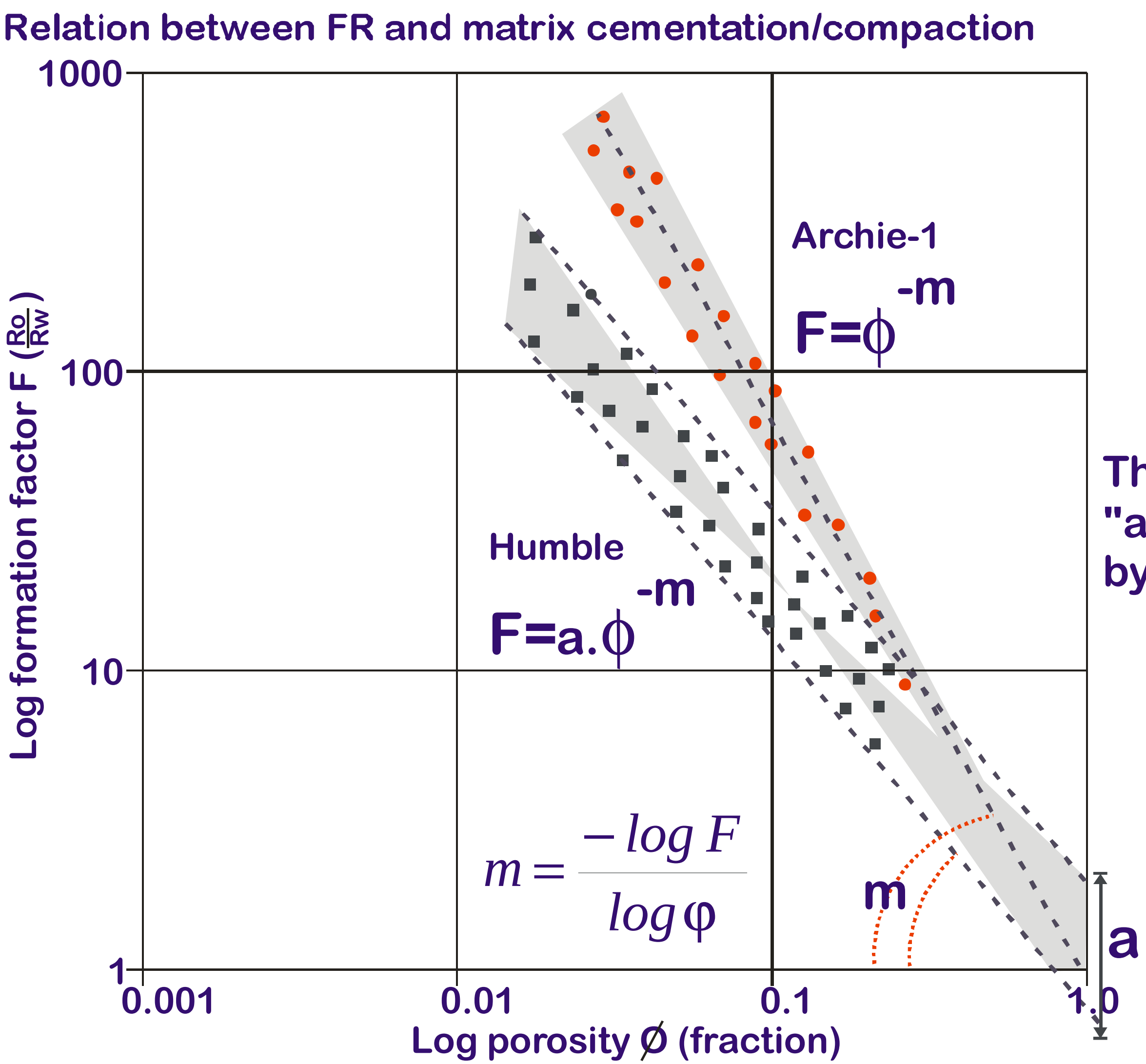
The pore geometry considered as a function of the lithology and the texture: Very tortuous or poorly connected pores have a higher resistivities

Humble general formula: $F = F_R = \frac{a}{\varphi^m}$

"a" depends on varieties, such as rock type, variation in pore type, quality of the measurement,

Often used standard fot the Humble relation: $F = F_R = \frac{0.62}{\varphi^{2.15}}$

Resistivity & conductivity



The best values for both, "a" and "m" are determined by laboratory evaluations

Resistivity & conductivity

Relation between FR and matrix cementation/compaction

Sands and sandstone relation of cementation factor (m) and sand consolidation		
Consolidation	Atmospheric	in-situ
very unconsolidated sand shallow potable water reservoirs	1.2	1.2
unconsolidated sand	1.4	1.6
unconsolidated to friable sand	1.5	1.7
friable sandstone	1.6	1.8
hard to friable sandstone	1.7	1.9
hard sandstone	1.8	2.0
very hard sandstone	2.0	2.2

Carbonates Relation of cementation factor (m) and Archie classification.		
Consolidation	atmospheric	in-situ
I BCD, interconnected	2.2	2.4
I BCD, moderate to abundant, poorly interconnected	2.6	2.8
I/II-II, no vugular porosity I/ III-III,	2.0	2.2
I/II-II BC, interconnected I/III-III BCD, moderate, poorer interconnection	2.2	2.4
LIII-II BCD abundant, , poorer interconnection I/III-III	2.6	2.8

Resistivity & conductivity

Relation between F_R and the water content (S_w)

The resistivity factor F_R of a formation partially saturated with brine

Archie-1: $\varphi^m \cdot C_w = C_o$

Relation between F_R and the water content (S)

Archie-2: $I_R = \frac{R_t}{R_o} = \frac{C_o}{C_t}$

I:resistivity index

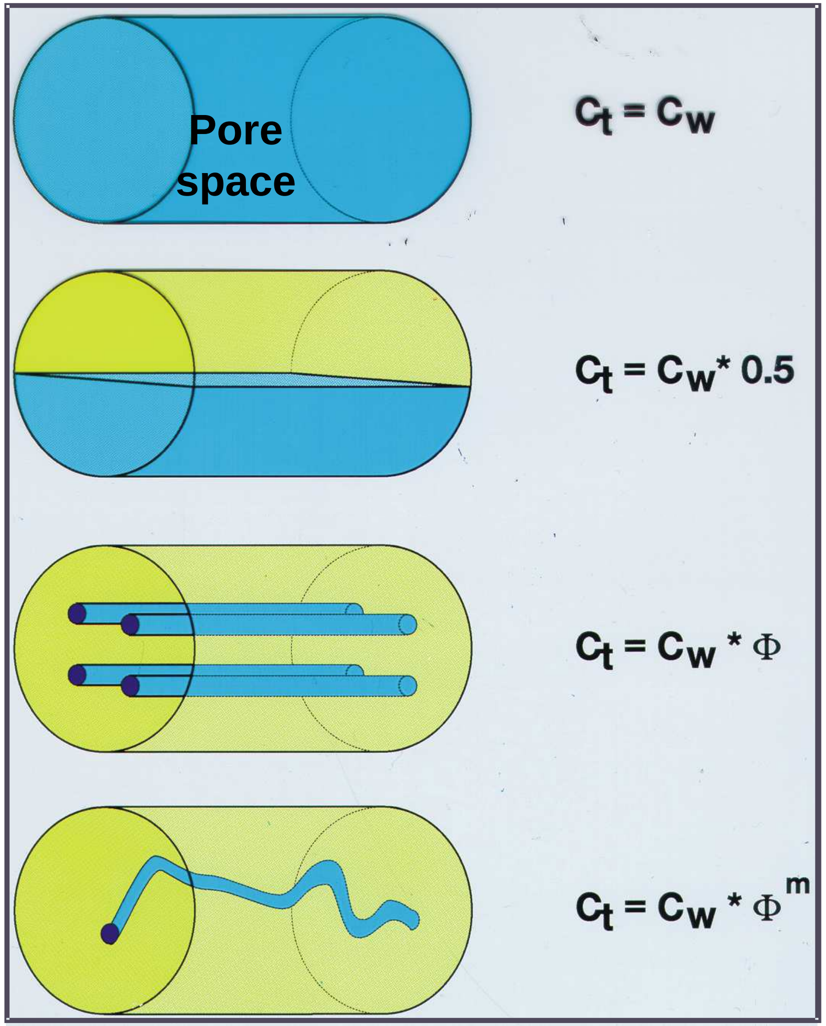
$$S_w = \left(\frac{R_o}{R_w}\right)^{\frac{1}{n}} = \left(\frac{F_r \cdot R_w}{R_t}\right)^{\frac{1}{n}}$$

n: saturation exponent

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

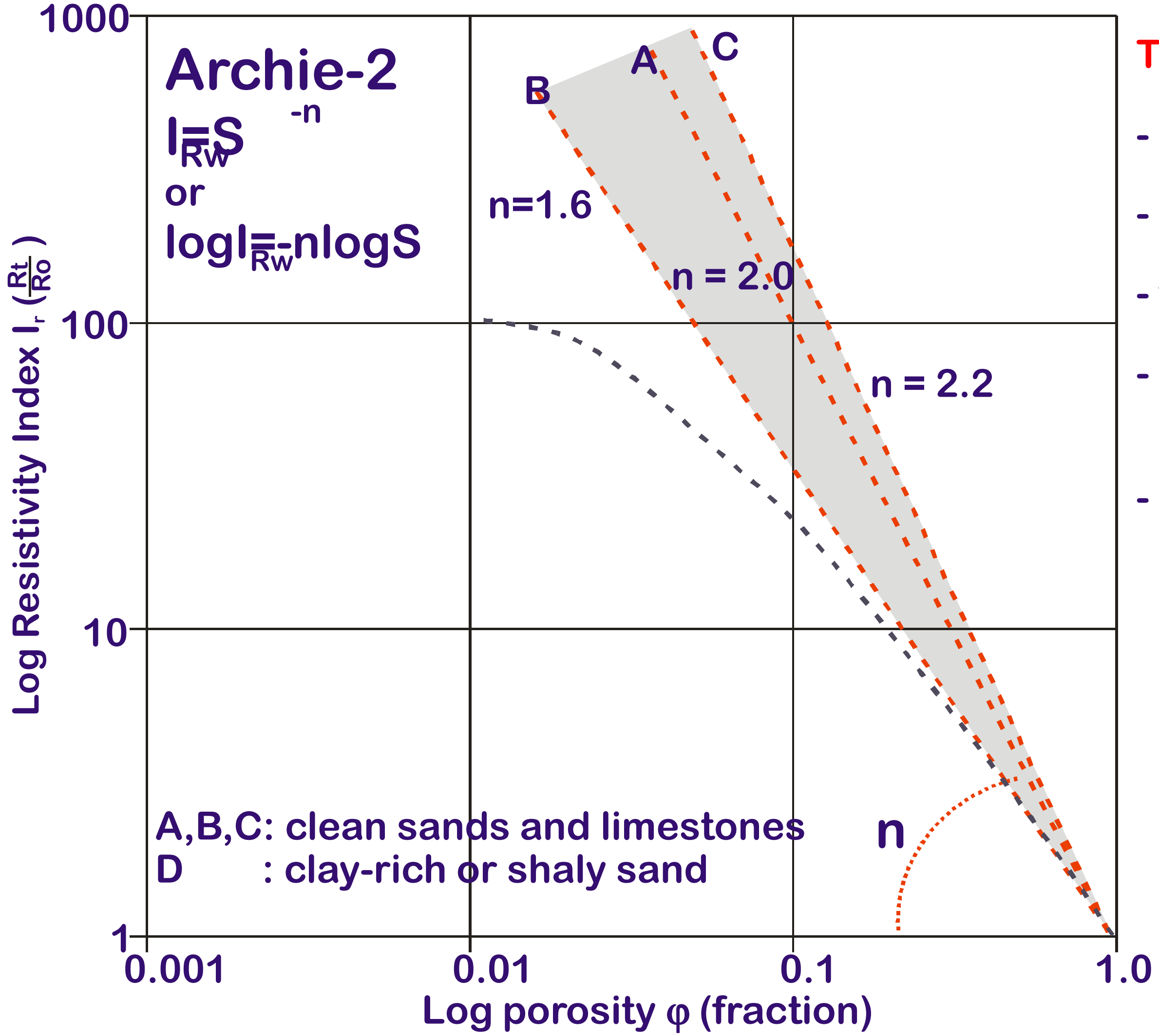
Humble:

$$S_w = \left(\frac{a \cdot R_w}{\varphi^m \cdot R_t}\right)^{\frac{1}{n}}$$



Resistivity & conductivity

Relation between F_R and the water content (S_w)



The value of n is influenced by:

- wettability,
- overburden pressure,
- fluid type; brine, oil, fresh water
- heterogeneity of fluid distribution, like tortuosity, and,
- the types and amounts of conductive clays

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Resistivity & conductivity

Relation between F_R and the water content (S_w)

LABORATORY AND WILD LIFE

From porosity tools		ϕ
Determined in the laboratory or guesed or estimated	m →	ϕ^{-m}
From a SP-reading, or water bearing zone, or lab test	R_w →	Ro
From resistivity tool(s)	R_t →	S_w^{-n}
Determined in the laboratory or guesed or estimated	n →	S_w

$$C_t = \varphi^{m} \cdot S_w^{n} \cdot C_w$$

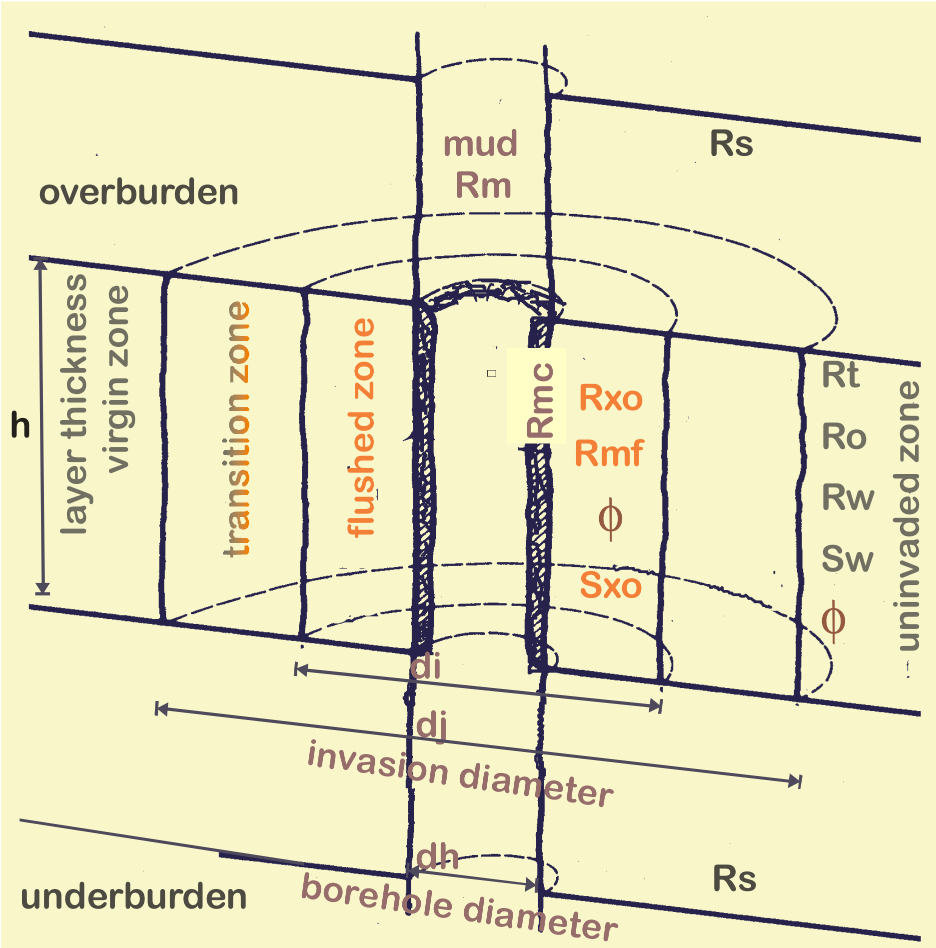
or

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

Resistivity & conductivity

Relation between F_R and the water content (S_w)

LABORATORY AND WILD LIFE



di : diameter of the flushed zone, i.e. the zone through which several pore volumes of filtrate circulated, containing a residual hydrocarbon saturation.
Dj : diameter to the virgin or uninvaded zone.
dh : diameter of the borehole
hmc: thickness of the mud cake
h : thickness of the layer
R_w : resistivity of the formation water in the uninvaded pores
R_{mf} : resistivity of the mud filtrate
R_{mc} : resistivity of the mud cake
R_m : resistivity of the mud

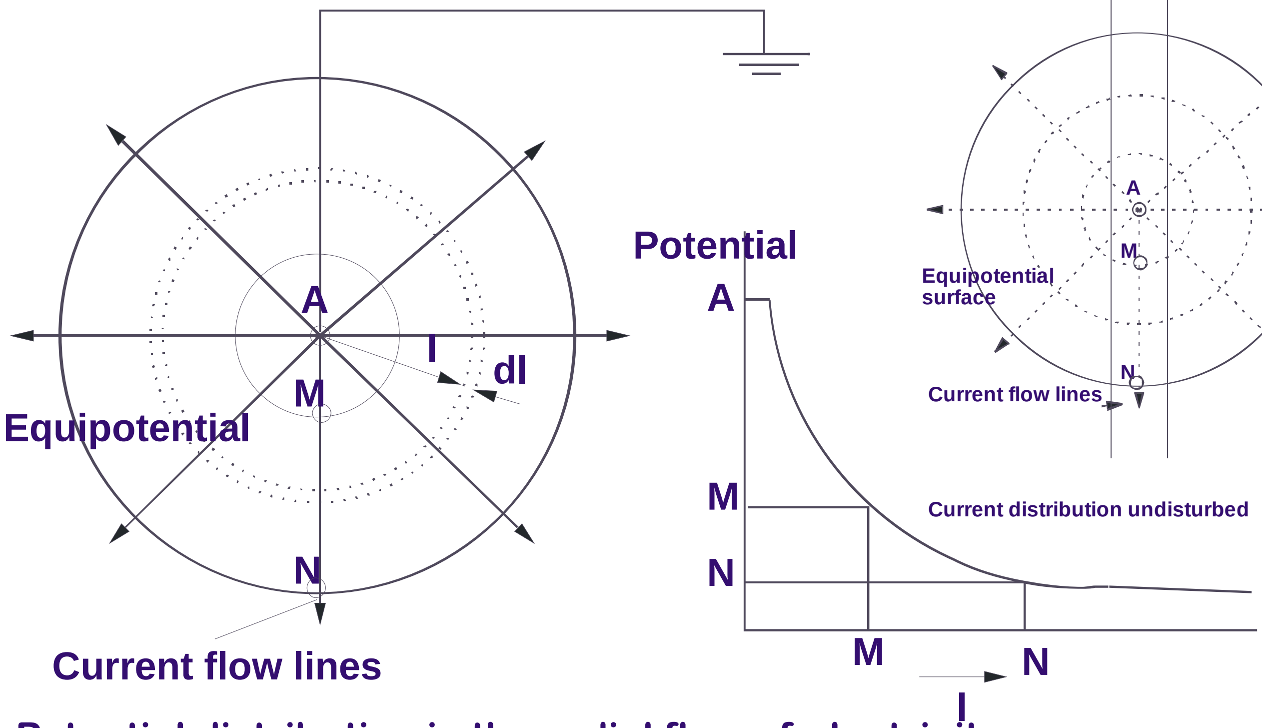
IMPORTANT:
WELL TERMINOLOGY

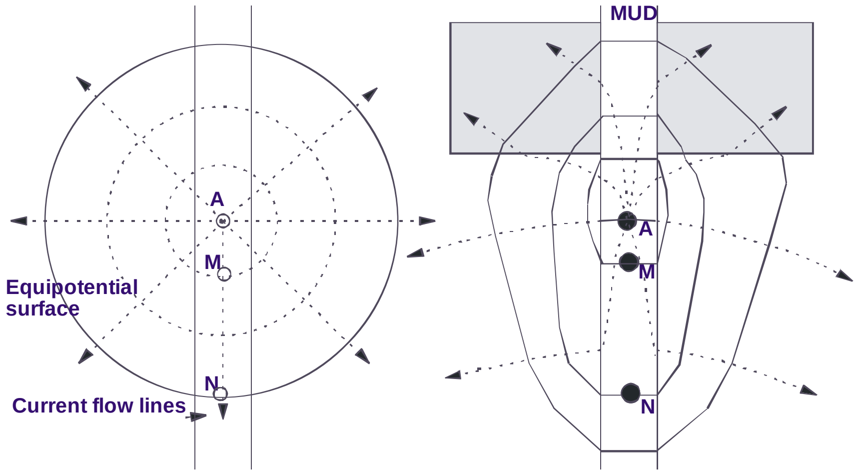
Resistivity & conductivity

Resistivity tools

Short normal (SN), Long normal (LN), and Lateral tool

ELECTRICAL SURVEYS (ES)





Current distribution undisturbed

Current distribution disturbed by borehole and beds

Potential distribution in the radial flow of electricity.

For a sphere the potential difference between electrode M and electrode N is as follows :

$$E_m - E_n = \sum_{AM}^{AN} \frac{I.R}{4.\pi.L^2}.dL = \frac{I.R}{4.\pi.AM}$$

Simplified to:

$$R = \frac{K_n.\Delta E}{I}$$

K_n is a proportionality factor depending on the electrode spacings

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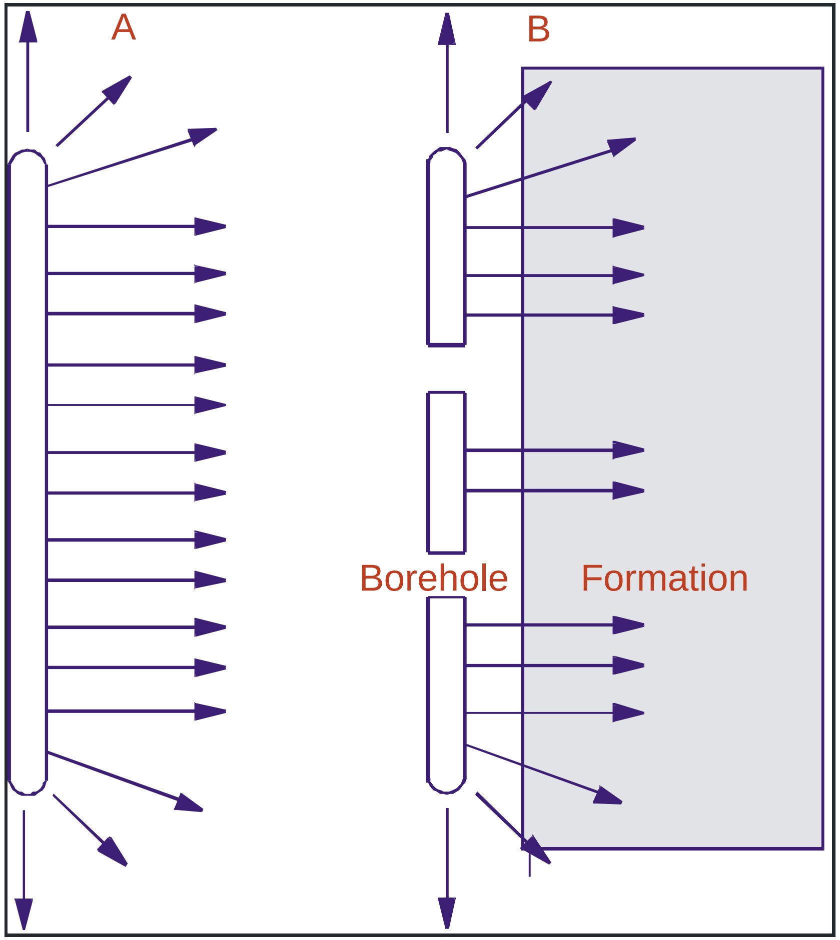
Resistivity & conductivity

Resistivity tools

Laterolog tools



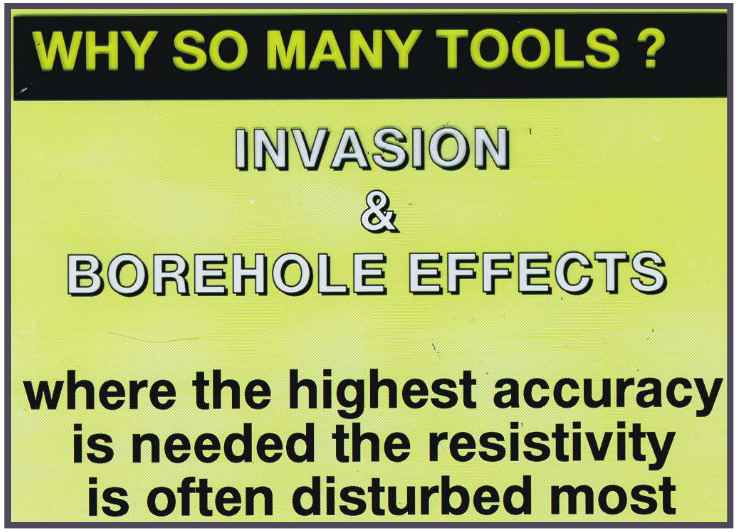
Pattern of current flow from a long cylindrical electrode located in a homogeneous medium

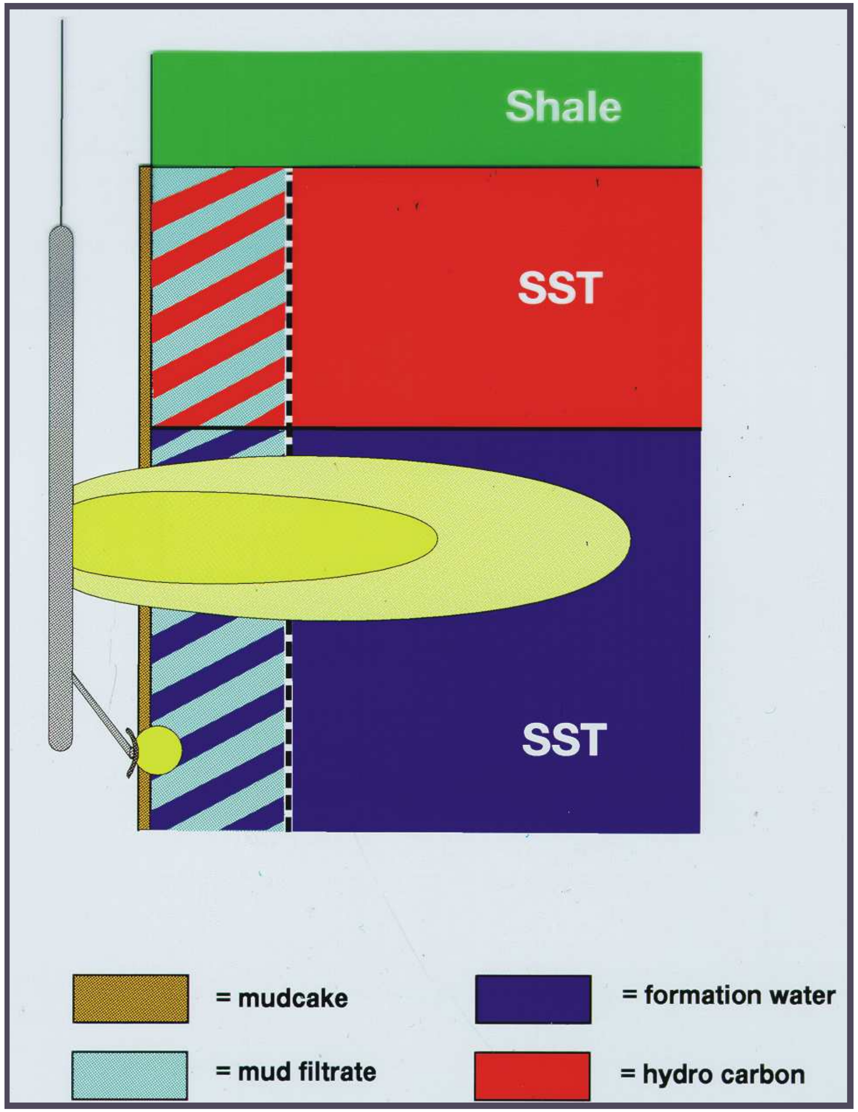
Logging with laterologs was introduced to cope with salty mud. These muds have a very high conductivity, and consequently the effect of the borehole on resistivity measurements is also very high. The Laterolog technique is therefore complementary to the induction logging method, designed for oil-base mud which has hardly any conductivity at all.

Resistivity & conductivity

RESISTIVITY LOGGING TOOLS

- Electric sonde
- Induction log
- Laterolog
- Micro-resistivity tool





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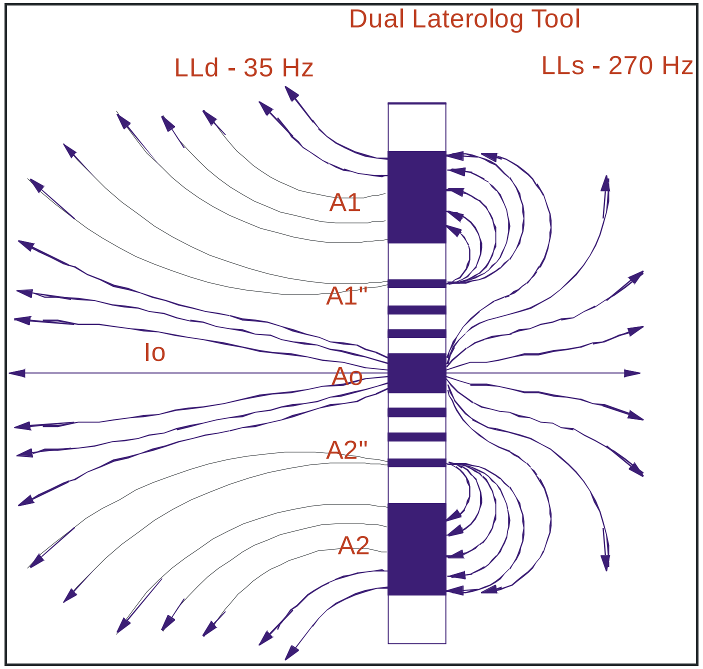
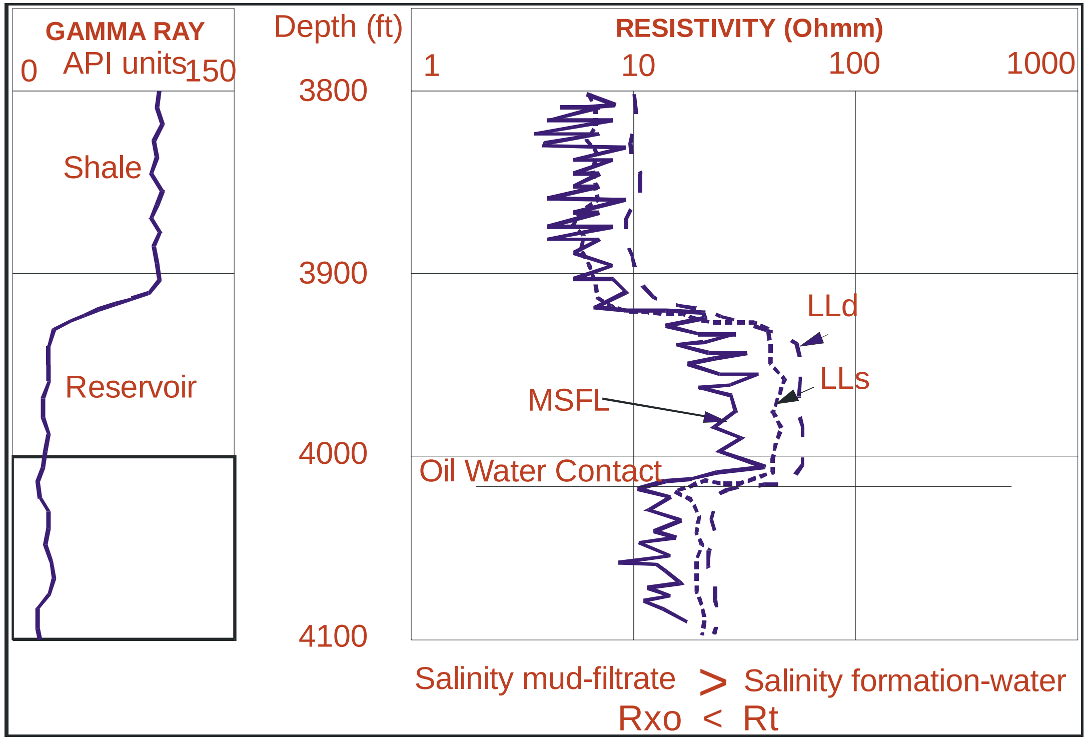
Resistivity & conductivity

Resistivity tools

Laterolog tools



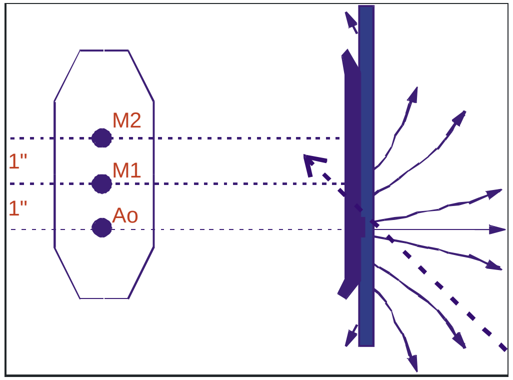
The Dual Laterolog configuration: Transmission on two frequencies for different detection depths.



Example of investigation depth of the Dual Laterolog

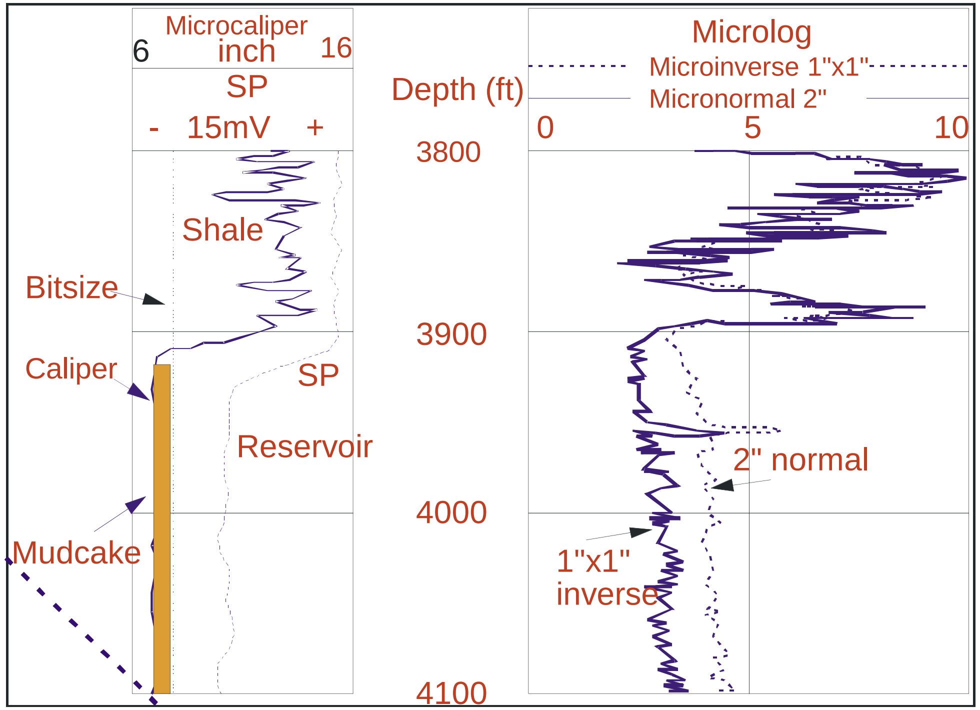
Resistivity & conductivity

Resistivity tools

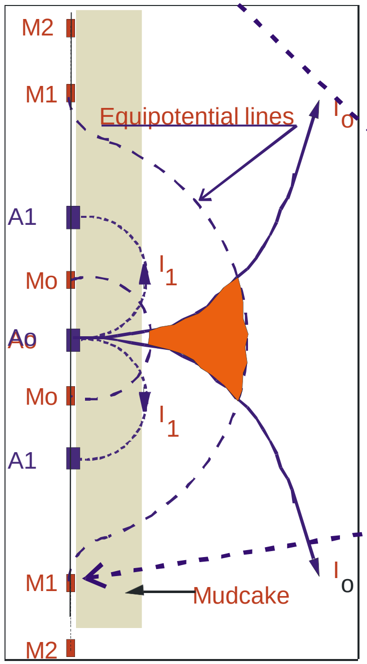


The microlog principle

Micro-resistivity devices



A MLC or Microlog Calliper example



Micro-SFL principle (After Schlumberger)

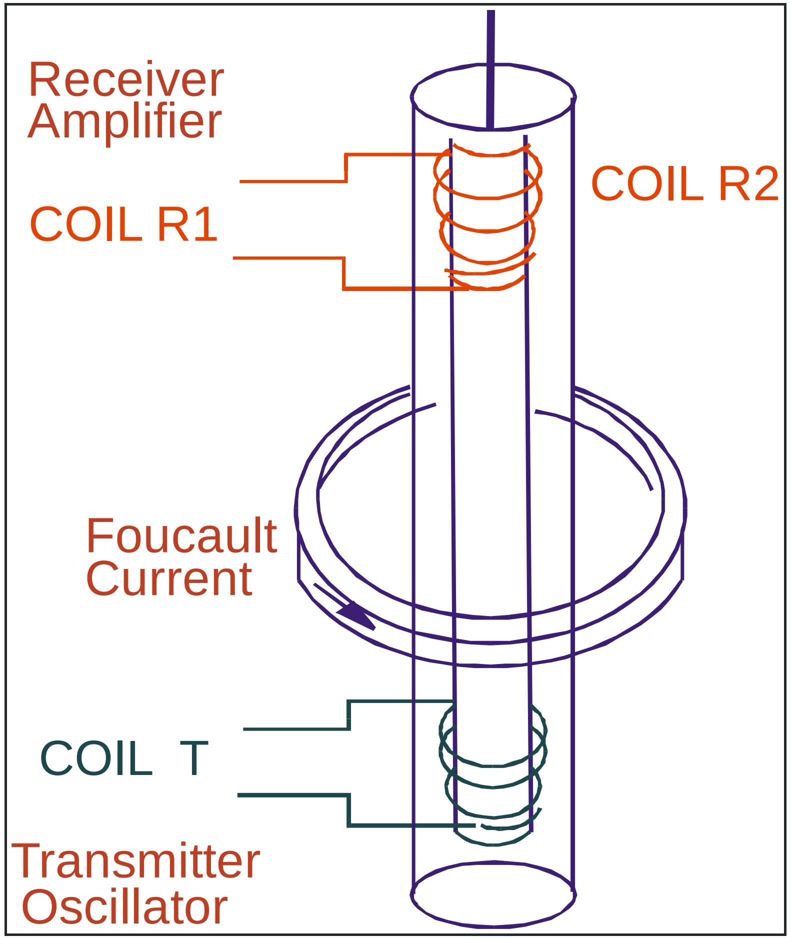
Measurements on the mudcake

$$R_{xo} = \frac{E_{Mo} - E_{M1}}{I_O}$$

Resistivity & conductivity

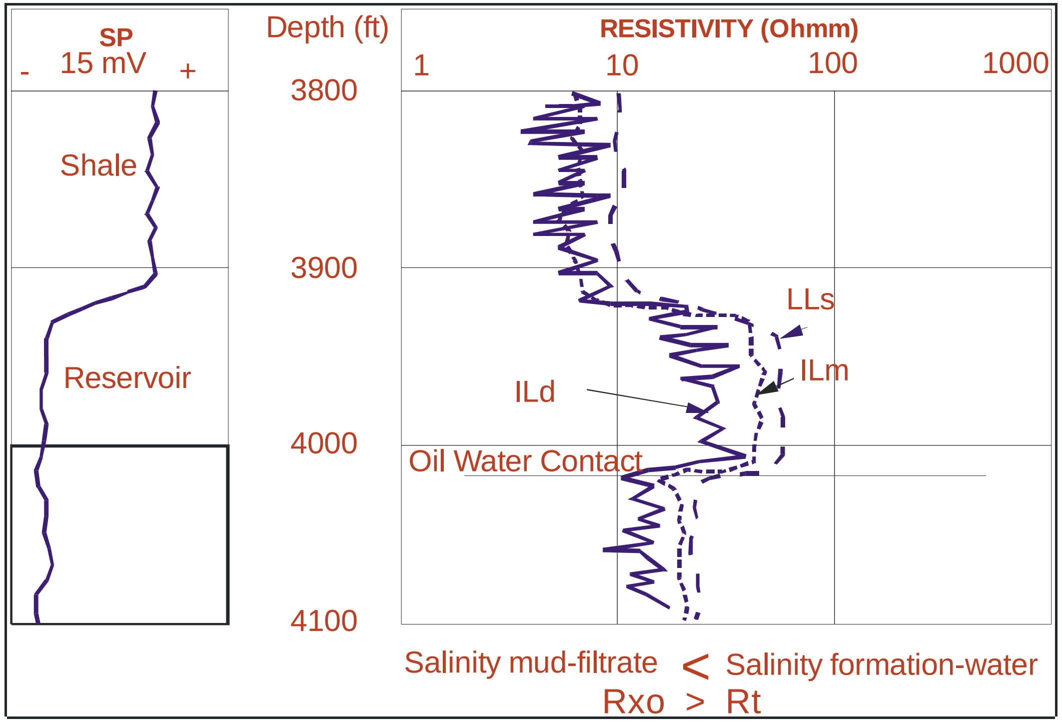
Resistivity tools

Induction logging



Principle of the Induction Tool

The induction log, originally designed for resistivity recording in wells drilled with non-conductive fluids, has found its widest application in holes drilled with fresh and oil based muds.



A section recorded by the Dual Induction (DIL) Shallow Laterolog

Resistivity & conductivity

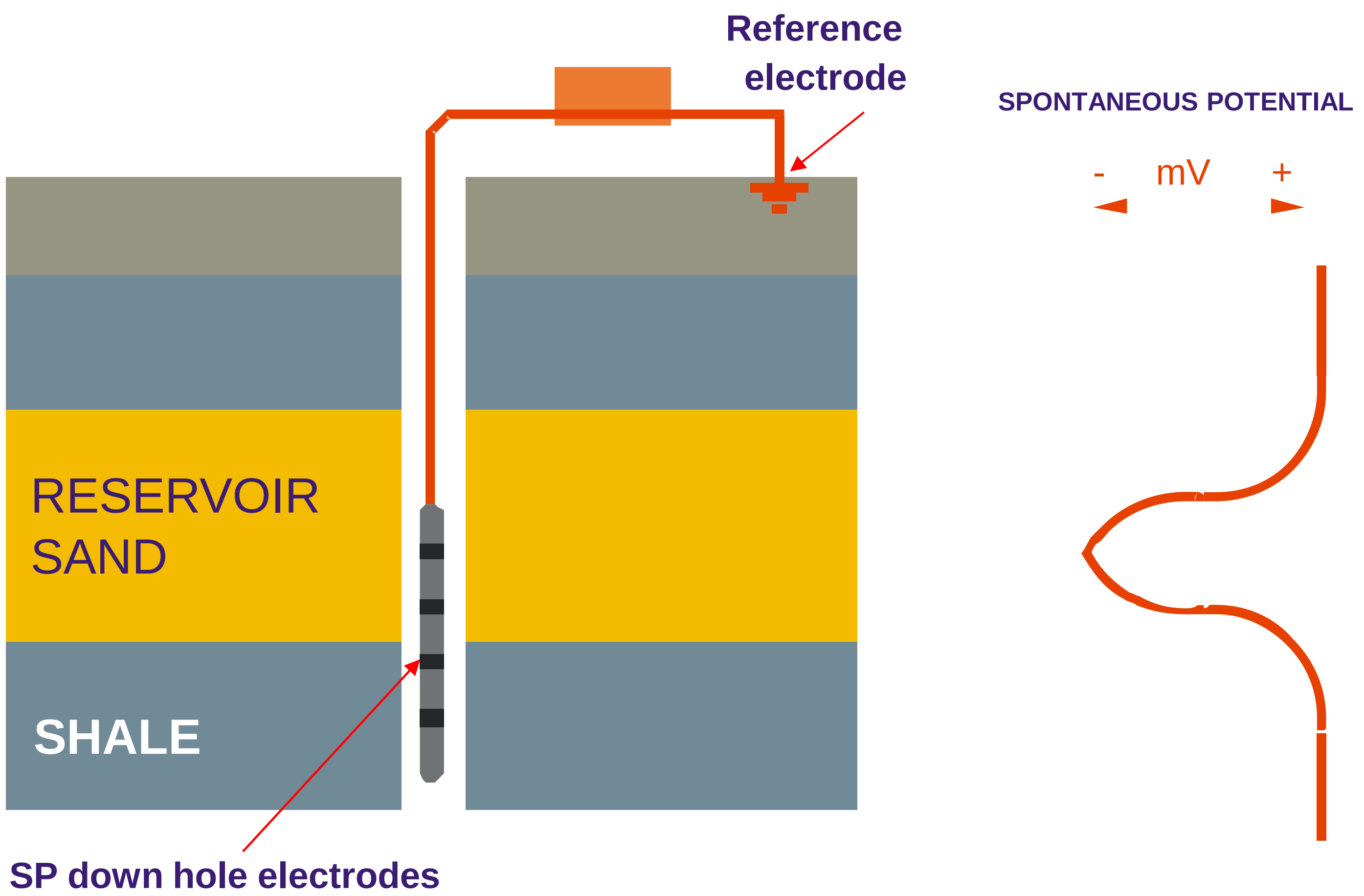
Resistivity tools — **Vertical & Horizontal Resolution**

Summary of the depth of investigation of the resistivity tools		
Depth of investigation resistivity tools	**Vertical**	**Horizontal**
(Figures are rounded off in feet)	**(ft)**	**(ft)**
SN (Short Normal)	1.5	1.5
LN (Long Normal)	5	5
Lateral	20	20
ILD Induction deep (6FF40)	6	10
ILD Induction (6FF27)	4	4
ILM Induction medium	5	6
LLD (Laterolog Deep)	2	10
LLS (Laterolog Shallow)	2	2
LL3 (Laterolog 3)	3	4
LL7 (Laterolog 7)	3	4
MLI (Microlog Inverse 1 x 1")	0.2	0.2
MLN (Microlog Normal 2")	0.3	0.3
MLL (Micro-Laterolog)	0.5	0.5
MSFL (Micro-SFL)	1	0.5

Resistivity & conductivity: Self Potential

Sketch of a spontaneous potential measurement in a drill hole

Potentiometer circuit



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Resistivity & conductivity: Self Potential

ORIGIN OF ELECTRICAL POTENTIALS

Electrokinetic potential or streaming potential:
Effect when a solution of electrical resistivity and viscosity is forced through a capillary or porous medium.

Liquid-junction (or diffusion) potential:
Due to the difference in mobility of various ions in solutions of different concentrations.

Shale (or Nernst) potential:
Two identical metal electrodes are immersed in different solution. then there will be a potential difference. Also known as the electrochemical, or staticself-potential

Resistivity & conductivity: Self Potential

ORIGIN OF ELECTRICAL POTENTIALS (continue)

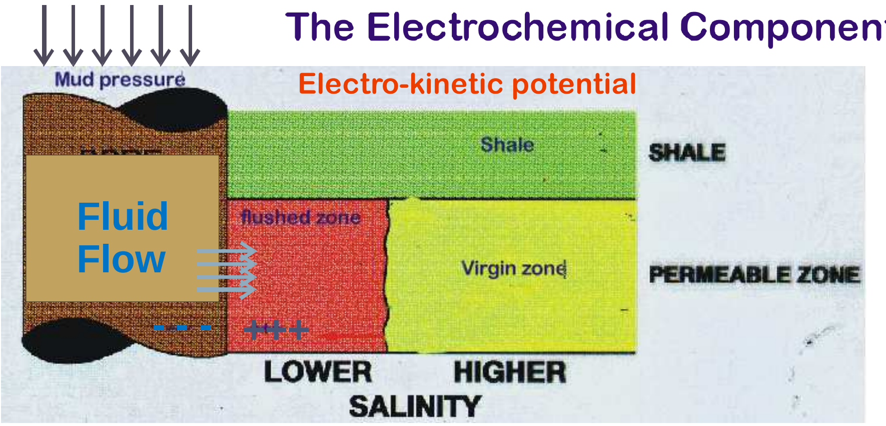
Mineralization potential:
Two different metal electrodes dipped in an aqueous concentration give a potential difference. This electrolytic contact potential and the staticself-potentialare associated with layers and mineral zones.

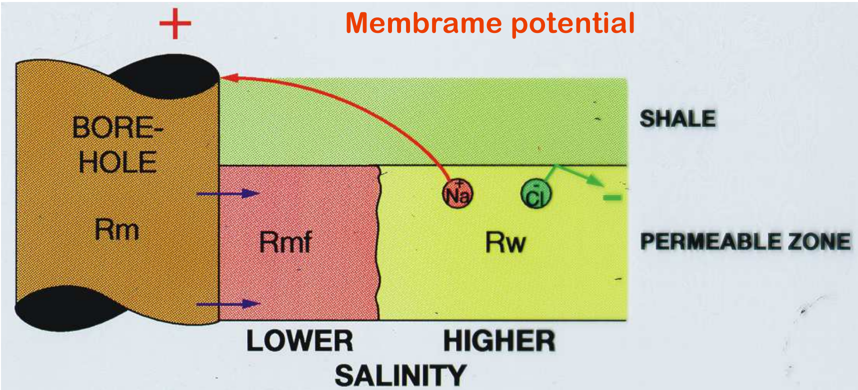
Erratic potentials:
- Metal corrosion (underground pipes, cables, etc.)
- Large-scale earth currents induced from the ionosphere, nuclear blasts, thunderstorms
- Currents of bio-electric origin, like plant roots

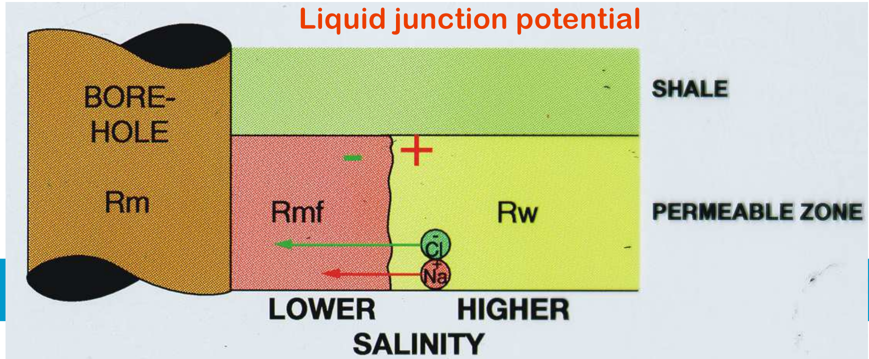
Static self-potential is temperature dependent

Resistivity & conductivity: Self Potential

The Electrochemical Component







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Resistivity & conductivity: Self Potential

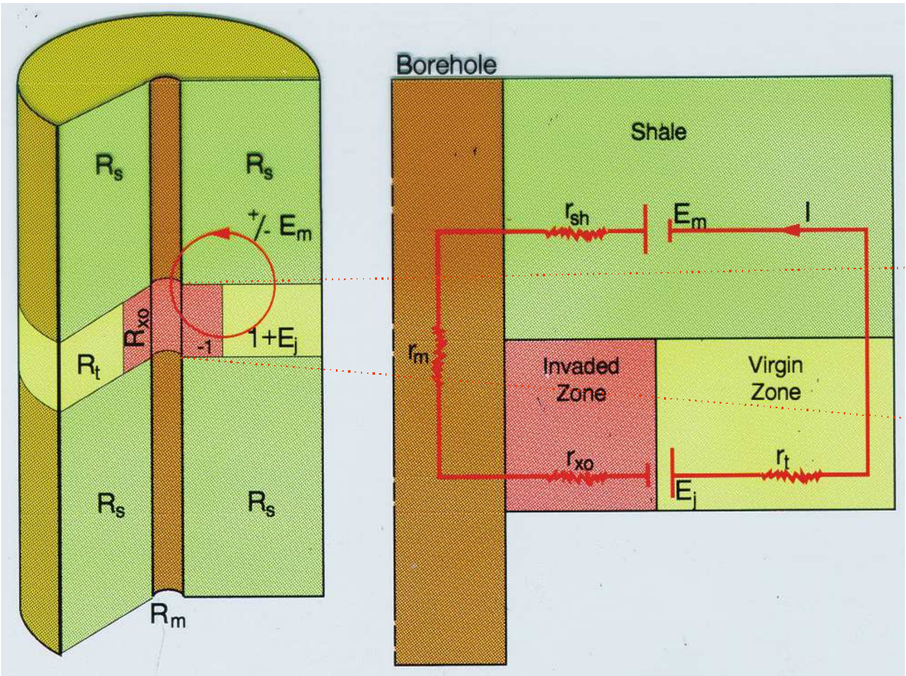
Combination of SP Components: Resistivities and Borehole Potential

$$E_{total} = I \cdot R_m + I \cdot R_{mc} + I \cdot R_{xo} + I \cdot R_t + I \cdot R_{sh}$$

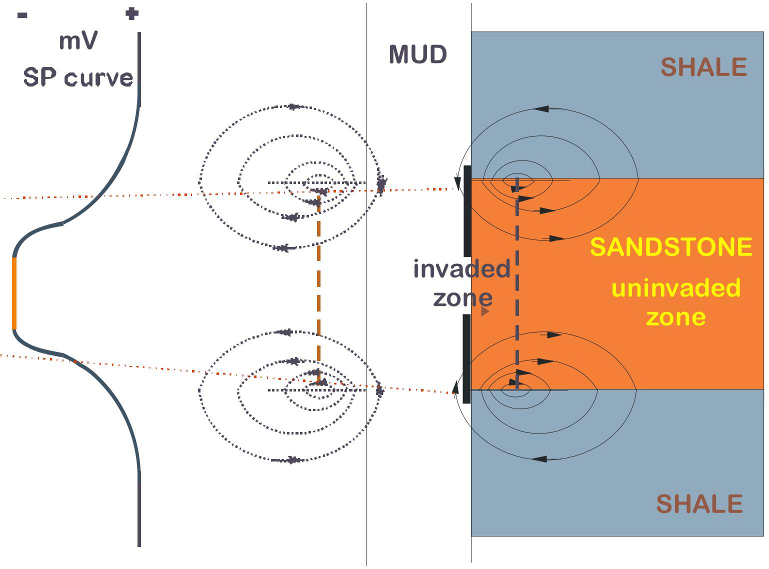
1. the borehole filled with mud (Rm),
2. the mudcake (Rmc),
3. the invaded zone filled with mudfiltrate (Rxo),
4. virgin zone filled with uncontaminated fluids (Rt),
5. the surrounding shales (Rsh).

or

$$E_{total} = E_m + E_j + E_{kmc} + E_{ksh}$$



Currents created in the mud, invaded zone, shale and sandstone, by the Ej, Em and Ek



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Resistivity & conductivity: Self Potential

Borehole information on groundwater, formation water and minerals:

Electric currents; Propagated in rocks & minerals in three ways:

Electronic:
The normal type of current flow in materials containing free electrons, like metals

Electrolytic:
In an electrolyte the current is carried by ions at a comparatively slow rate

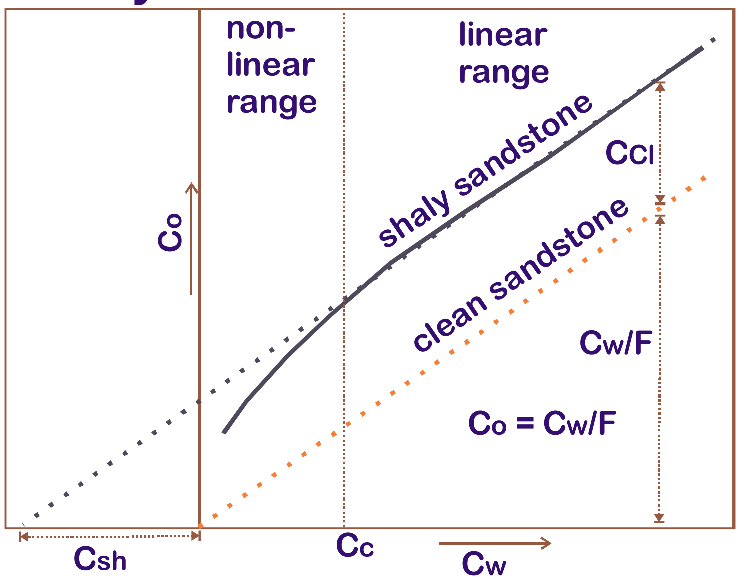
Dielectric:
Dielectric conduction takes place in poor conductors or insulators, which have very few or no free carriers.

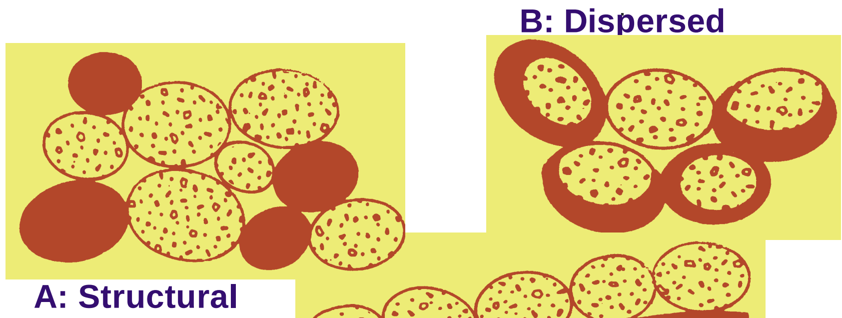
The main applications for SP-measurements are:

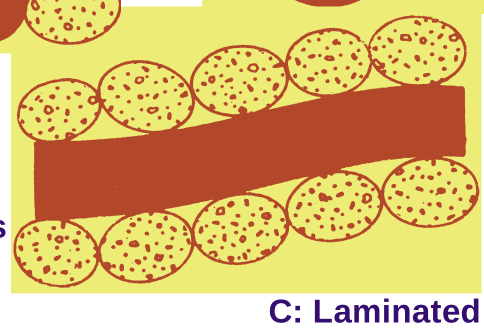
- Groundwater control
- Determination of formation water resistivity
- Evaluation of lithology, such as shale and coal
- Detection of permeable beds and their boundaries
- Determination of the shale content of a layer
- Well to well correlation
- Determination of the environment of deposition

Resistivity & conductivity: Self Potential

Clay determination







Three types of clay distribution in a permeous sand aggregate.

Clay	Density (g/cm^3)	Hydrogen (%)	Average Q_{CEC} (meq/g)
Kaolinite $Al_4(Si_4O_{10})(OH)_8$	2.69	1.5	0.03
Illite $K_{1-1.5}Al_4(Si_{6.5-7.0}\ Al_{1-1.5}O_{20})(OH)_4$	2.76	0.5	0.20
Montmorillonite $(\frac{1}{2}Ca,Na)_{0.7}(Al,Mg,Fe)_4(Si,Al_8O_{20})(OH)_4$	2.33	0.5	1.0
Chlorite $(Mg,Al,Fe)_{12}(Si,Al)_8O_{20}(OH)_{16}$	2.77	1.2	0.0

CEC by Waxman-Smits

$$C_0 = \frac{1}{F^*}\left(C_w + C_e\right)$$

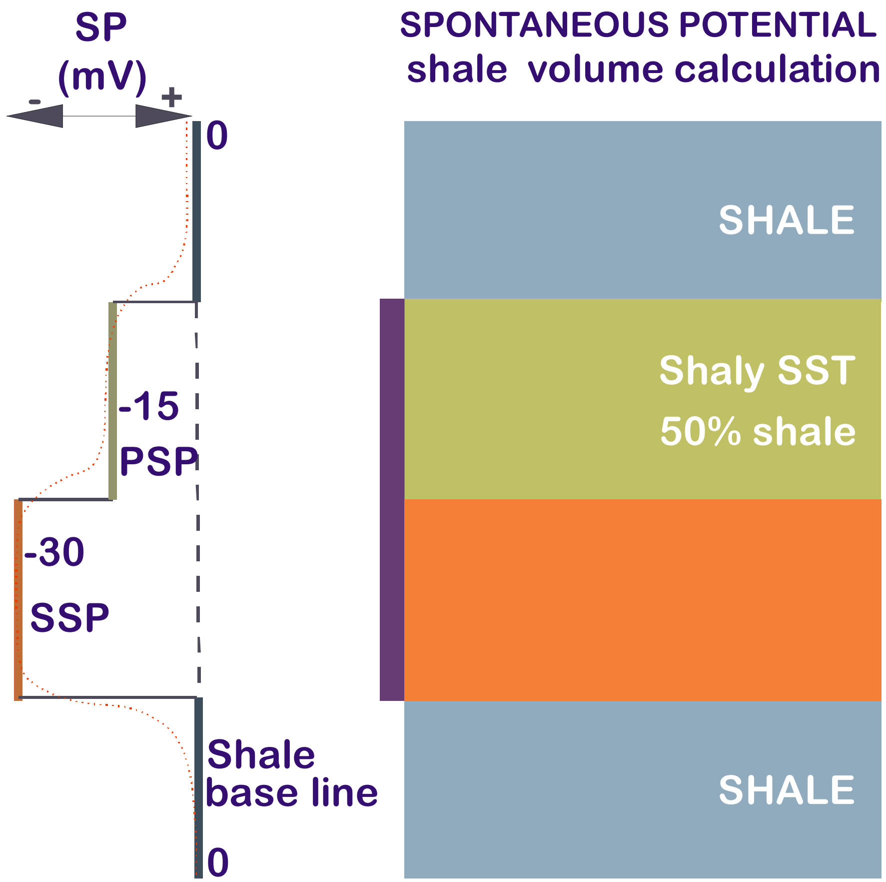
If *Co* and *Cw* are measured in the laboratory, then *F** and *Ce* can be obtained through:

$$Ce = B \times Qv$$

*F**	: formation factor corrected for shale
Co	: conductivity of 100% water-bearing reservoir, mmho/m
Cw	: conductivity of the formation water, mmho/m
Ce	: conductivity of the clay fraction, mmho/m
B	: the equivalent conductance of the counter-ions as a function of the solution conductivity

Resistivity & conductivity: Self Potential

Shale volume calculation



The SP electrode only measures a potential deflection while travelling uphole: SP=I x Rm

The shale volume calculated from the SP:

$$V_{sh} = \frac{PSP - SSP}{SSP}$$

V_{sh} : the shale volume as fraction of the bul k volume in %

PSP : the SP log reading of a shaly reservoir as a deflection from the shale base line corrected for environmental effects such as mud resistivity Rm.

SSP : the SP log reading in a clean reservoir as the deflection from the shale base line corrected for environmental effects. Thus the SP reading in the thickest and cleanest sand.

$$V_{sh} = \frac{PSP - SSP}{SSP} = \left| \frac{-30 - (-15)}{-30} \right| = 0.5 \text{fr.b.v.}$$

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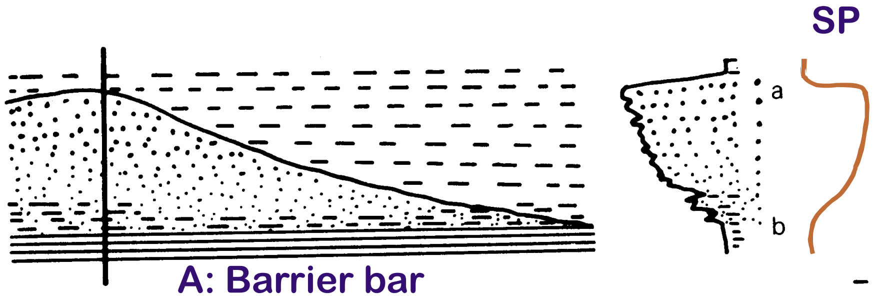
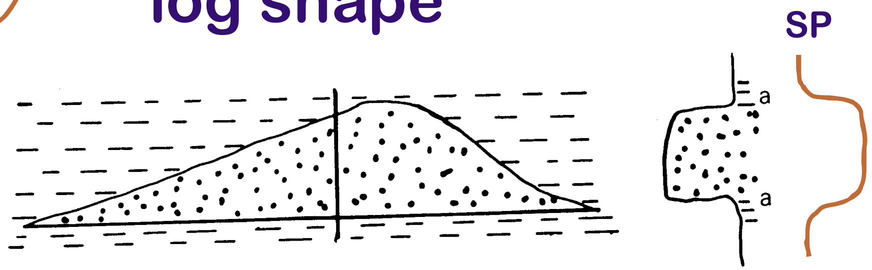
Resistivity & conductivity: Self Potential

Geological Information

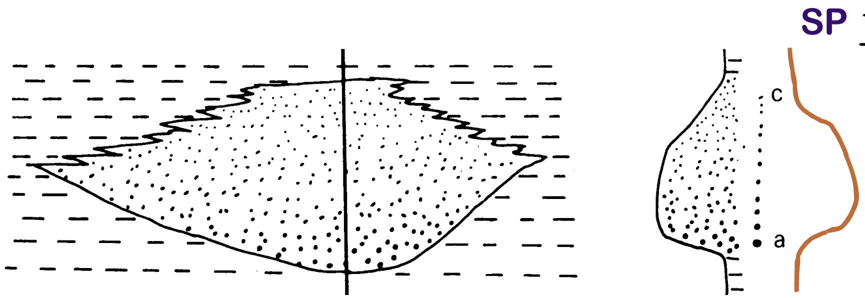
The environment of deposition is often indicated by the log shape



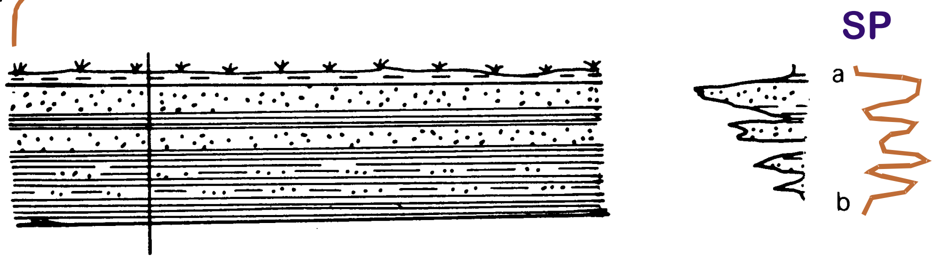
A: Barrier bar
Coarsening upward (a/b or a/c)



B: Chenier beach
Well sorted sands (a/a)



C: Channel fill
Fining upward (c/a)



D: Deltaic sequence
Interbedded fine sand/shale sequences (b/a)

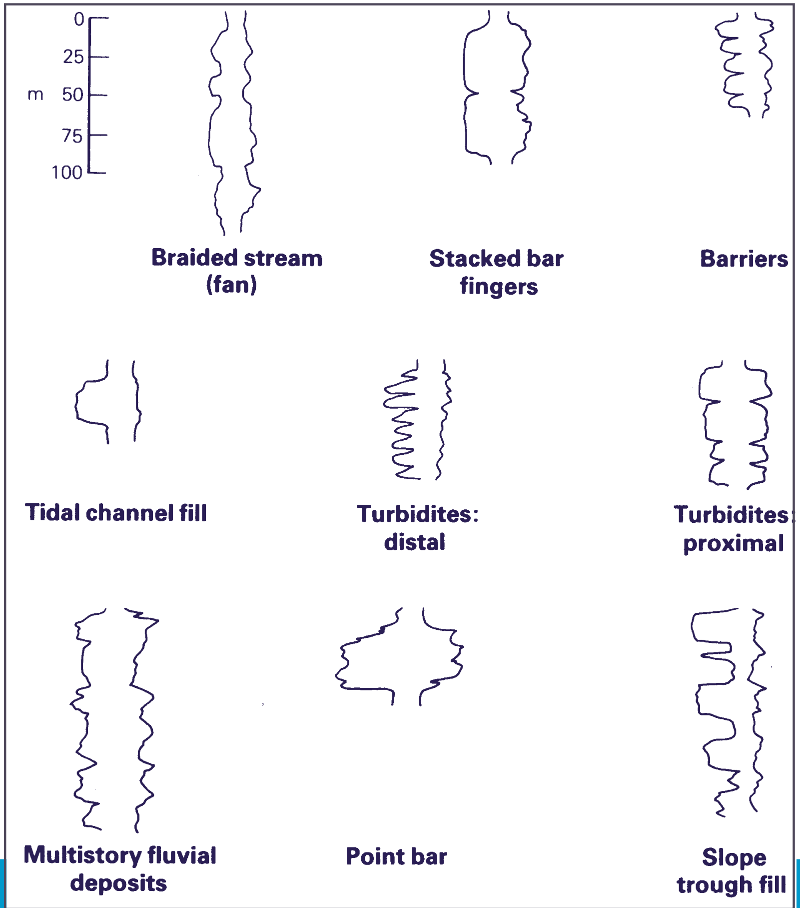
Typical geometries of SP-curves for sandstone environments

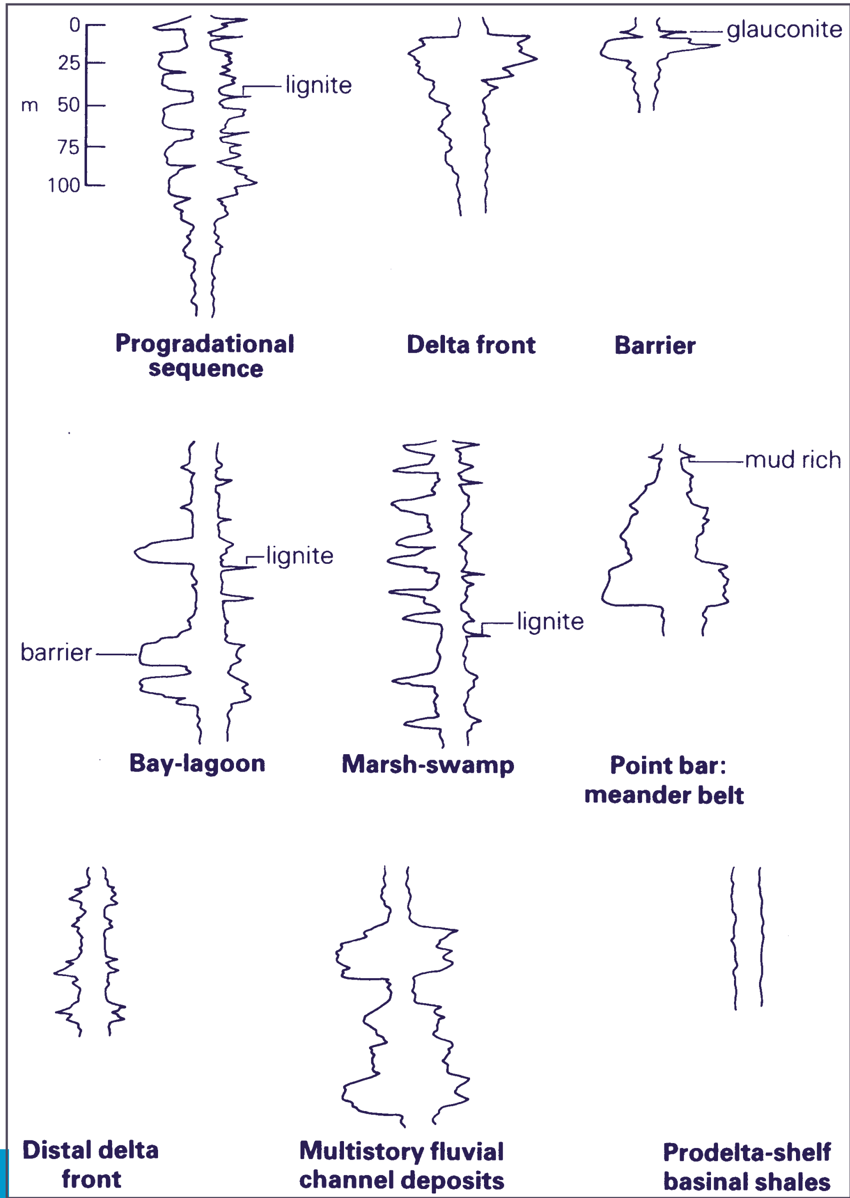
Resistivity & conductivity: Self Potential

Geological Information

SP/Resistivity log patterns:

- Below: sand rich depositions. Note the blocky appearance.
- Right the variety of sand/shale depositional environments





Resistivity & conductivity