Petrophysics

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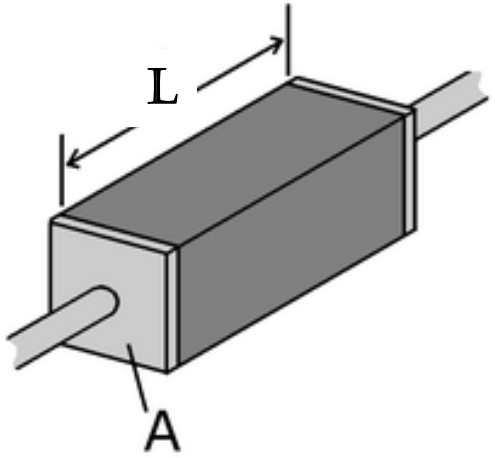
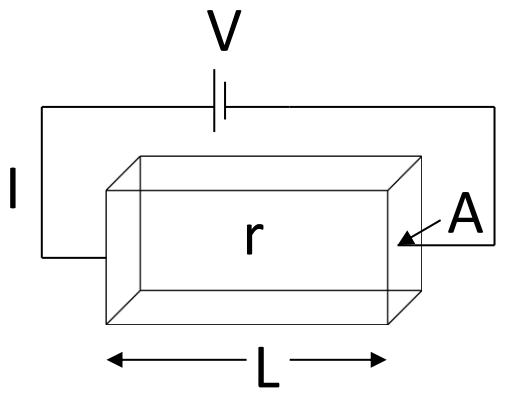
Electrical Properties

- Resistivity (R) is one of the most useful physical properties that can be measured directly in the borehole, and it is reciprocal of conductivity (σ).
- Resistivity (R) is an intensive property of the material which is independent of size and shape and shows the degree to which a substance resists or impedes the flow of electrical current. Resistance (r), however, is an extensive property of the material, and its relationship to resistivity is defined as shown on the right figure.
- It is possible to infer saturations from formation resistivity measurements if the porosity and water resistivity are known. In conjunction with lithology logs, they can also identify hydrocarbon bearing intervals and to estimate net-pay thickness.



r	resistance (ohms)
A	Cross sectional area (meters²)
L	Length (meters)
R	resistivity (ohm-meters)
V	Voltage (Volt)
I	current (Amp)



$R \uparrow \rightsquigarrow r \uparrow$
$L \uparrow \rightsquigarrow r \uparrow$
$A \uparrow \rightsquigarrow r \downarrow$

$$r = \frac{RL}{A}$$

* The unit of resistivity is ohm-meter
* The unit of conductivity is Siemens per meter

Formation Resistivity

- In reservoir rocks, the sedimentary minerals that make up the formation matrix are nonconductors.
- Hydrocarbons such as gas and oil are nonconductors.
- Current flow in sedimentary rocks is associated with the water in the pore space. They current is carried by the ions of the salt dissolved in the water.
- Hence, formation resistivity is affected by water saturation, water salinity, and reservoir temperature.

Factors Influencing Resistivity of Natural Porous Media

Salinity of water
Porosity
Stress
Temperature
Pore Geometry
Rock Composition
Wettability

Nomenclature

- R_w is the resistivity of the formation water.
- R_o is the resistivity of the formation saturated 100% by the formation water of resistivity R_w.
- R_t is the true resistivity of the formation partially saturated with water of resistivity R_w and hydrocarbon.
- R_{mf} is the resistivity of the mud filtrate in the flushed zone.
- R_{xo} is the resistivity of the flushed zone formation.

* Mud filtrate is the liquid that passes through the medium, leaving the cake on the medium.

$$F = \frac{R_o}{R_w} \qquad I = \frac{R_t}{R_o}$$

Formation Resistivity Factor

- Formation resistivity factor F is defined as:

$$\boldsymbol{F = \frac{R_o}{R_w}}$$

- where $R_o \geq R_w$. Archie found that the formation resistivity factor could be related to the porosity of the core by an equation of the form:

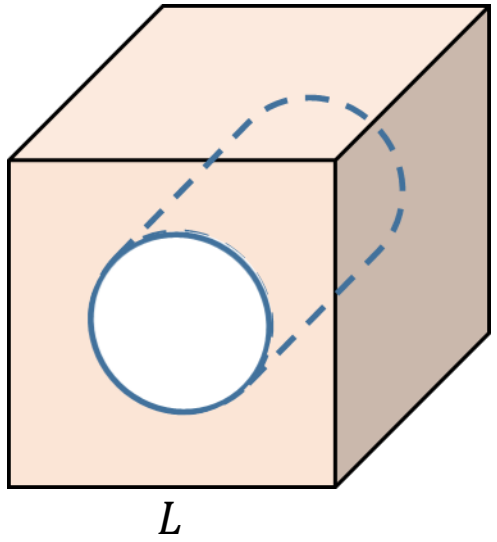
$$F = \frac{a}{\phi^m}$$

where a is an empirical constant and m is a cementation factor that varies from 1.3 for unconsolidated sands to 2.5 for consolidated sandstones.

Formation Resistivity Factor – **Ex 1**

An idealized porous medium is made of an impermeable insulator material shaped as a cube of length L. A cylindrical hole of radius $L/4$ is drilled through the middle. The hole is filled with brine of resistivity R_w. Electric current and fluid will flow through the porous medium in the direction parallel to the cylindrical hole.

- Calculate the porosity of the porous medium.
- Calculate the formation resistivity factor for the porous medium.
- Show that the formation resistivity factor and the porosity of this idealized porous medium obey Archie's equation. What are the values for a and m?



Formation Resistivity Factor – Ex 2

- A series of cores from a well gave the resistivity factor versus porosity data shown to the right.
- A thick saltwater-bearing layer of the reservoir is encountered in an offset well with a resistivity of 1.29 ohm-meter. If the resistivity of the salt water is 0.056 ohm-meter, predict the porosity of the water-bearing layer.

Formation Resistivity Factor	Porosity
30.0	0.092
19.3	0.120
12.5	0.165
8.4	0.205
6.0	0.268

Formation Resistivity Factor – **Ex 3**

- Table to the right presents the original experimental data used by Winsauer et al. (1952) to derive the Humble Formula.
- They plotted the resistivity factor versus porosity on a log-log graph paper. They left out the datum from core 3 as it did not quite fit the trend of the other data.
- After manually drawing a line through the remaining data, they measured the slope and the intercept, and from them derived Humble Formula:

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

- Perform a linear regression on the same data and derive a new and improved Humble formula.

Core ID	Porosity (%)	Formation Resistivity Factor
1	17.0	23.3
2	14.7	51.0
3	6.7	67.0
4	17.6	16.6
5	26.3	8.6
6	25.6	9.4
7	13.9	33.0
8	18.6	22.9
9	18.8	18.6
10	16.1	42.0
11	15.0	41.0
12	22.1	13.1
13	20.6	16.6
14	30.7	8.4
15	16.4	21.1
16	18.8	19.3
17	24.8	10.8
18	19.1	17.2
19	29.8	8.4
20	27.1	11.7
21	28.2	10.9
22	19.4	24.0
23	19.7	20.8
24	31.5	6.9
25	19.3	24.4
26	27.3	12.4
27	25.1	11.6
28	15.0	37.3
29	18.4	19.0
31	39.5	4.7

Formation Resistivity Index

- Formation resistivity index I is defined as:

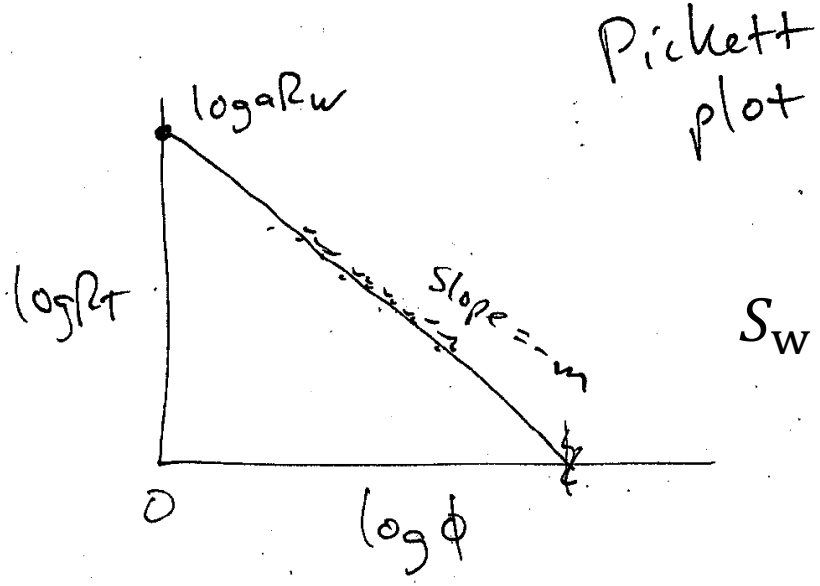
$$I = \frac{R_t}{R_o}$$

- Archie found that the formation resistivity index is related to the water saturation by an equation of the form:

$$I = \frac{1}{S_w^n}$$

where n is the water saturation exponent.

- For the sections where the formation is fully saturated with water:



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

Formation Resistivity Index – **Ex 1**

Calculate F, R_o and R_t for different porosity values.
Assume:

- $a = 1$
- $m = 2$
- $n = 2$
- $R_w = 0.025\ \text{ohm} \cdot \text{m}$
- $S_w = 25\%$

ϕ [%]	F [-]	R_o [ohm · m]	R_t [ohm · m]
5			
10			
15			
20			
25			
30			

Lab-Derived Evaluation of Shaly Reservoir Rocks

Wettability Effect

- Different values of resistivity can be obtained at the same water saturation in rocks if the wettability is changed.
- Oil-wet rocks have a high resistivity because water is discontinuous phase in this case, the electric path is interrupted by the insulating oil.
- Archie's saturation exponent n is considerably greater than two for oil-wet rocks.