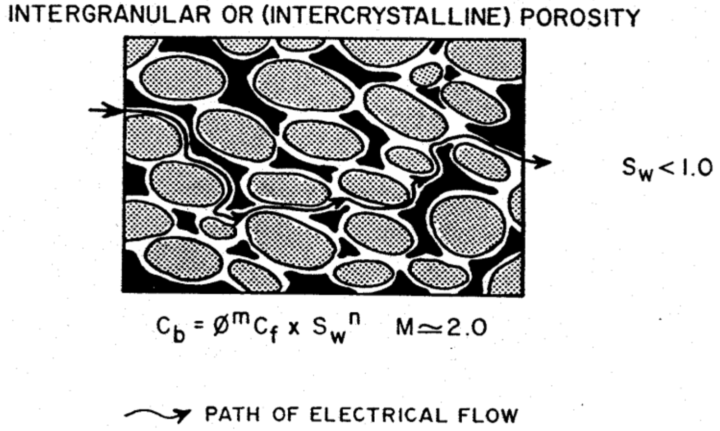
Chapter 2
Electrical Properties of Rocks



Lecture notes for PET 370

Spring 2012

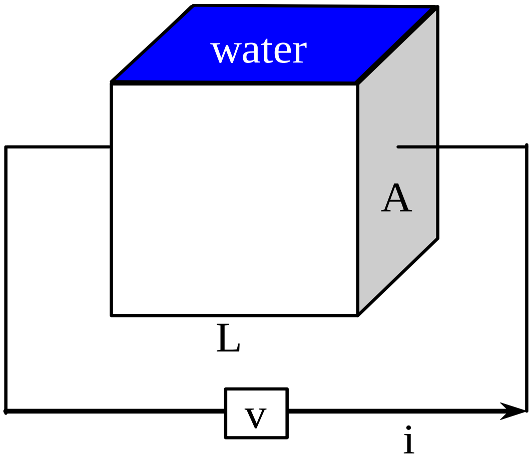
Prepared by: Thomas W. Engler, Ph.D., P.E.

Electrical Properties of Rocks	Definitions

- Electrical properties of a rock depend on the pore geometry and fluid distribution

- Electric current by “ionic conduction”

- Consider the following tank completely filled with brine water,



→ apply a voltage, v

→ measure a current, i

→ calculate a resistance by **Ohms Law:**

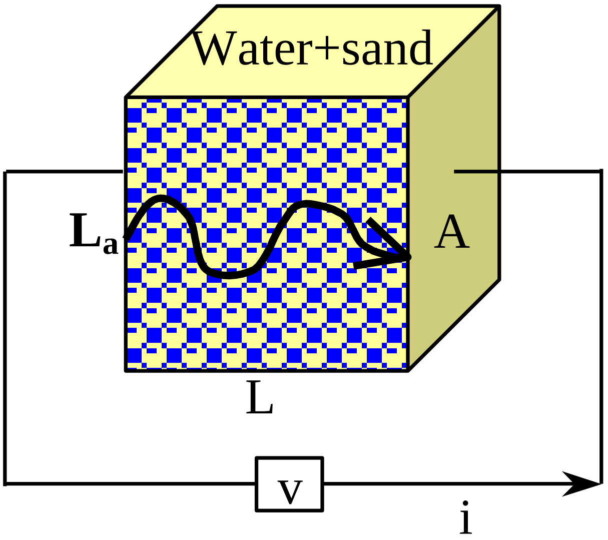
$$v = i\,r$$

→ Define water resistivity, R_w, as:

$$R_w = r_w \frac{A}{L}$$

Electrical Properties of Rocks Definitions

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



- Resistance with respect to the water phase

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

- Resistance with respect to fluid-filled, porous rock

$$r_o = R_o \frac{L}{A}$$

- Since $r_o \approx r_w$,

$$\frac{R_o}{R_w} = \left(\frac{A}{A_p}\right)\left(\frac{L_a}{L}\right)$$

Electrical Properties of Rocks | Definitions

- Define the Formation Resistivity Factor, F, as:

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

- Define tortuosity;

$$\tau = \left(\frac{L_a}{L}\right)^2$$

- Define porosity,

$$\phi = \left(\frac{A_p}{A}\right)$$

- Thus

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

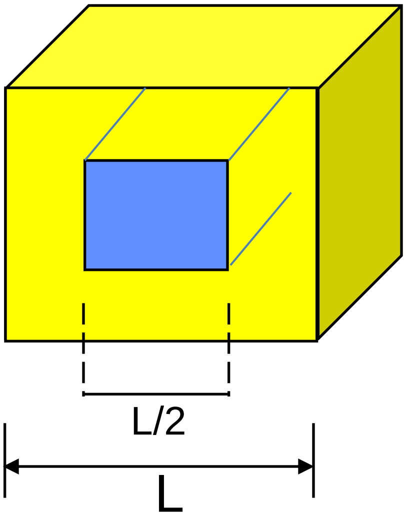
Simplified theoretical relationship between F and ϕ does not account for heterogeneity.

Applications of Formation Factor

1. To determine R_o and subsequently compare with the true formation resistivity, R_T, to identify hydrocarbon zones.
2. To determine F and subsequently use to estimate porosity.
3. To determine R_w for water saturation calculations.

Consider a synthetic rock sample made of an insulator material and shaped as a cube of length *L*. There is a square tube of dimension *L/2* through the cube. Assume the inner square tube is filled with brine of resistivity R_w and that the current will flow perpendicular to the front face.

Calculate F and the relationship of F with porosity.



General relationship based on both theoretical and experimental studies is given by:

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

where *a* and *m* are functions of pore geometry.

<u>Methods:</u>

a. Simple theoretical models

simple models designed with uniform pore geometry do ***not*** capture variation in porous media.

b. Direct measurement in lab

accurate but requires rock sample

c. Empirical correlations based on lab data

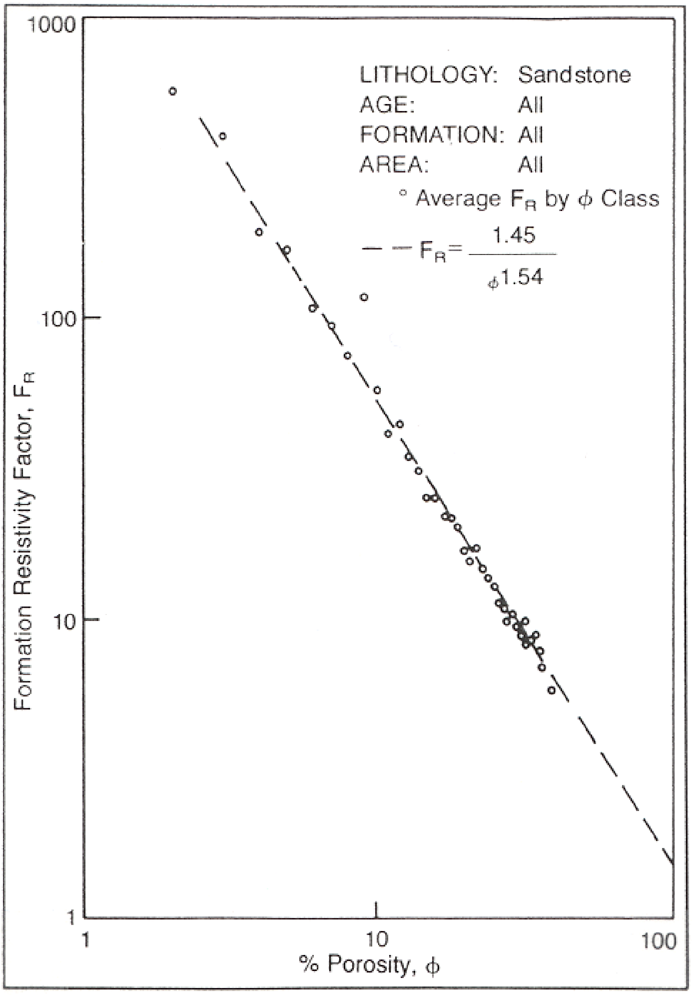
most convenient and popular, however may not be appropriate for given rock type

Electrical Properties of Rocks | ϕ – F relationship

b. Direct measurement in lab

“The practical application of $F = f(\phi)$ for a particular rock type is best accomplished by evaluating the cementation factor using lab-measured values of F and ϕ.”

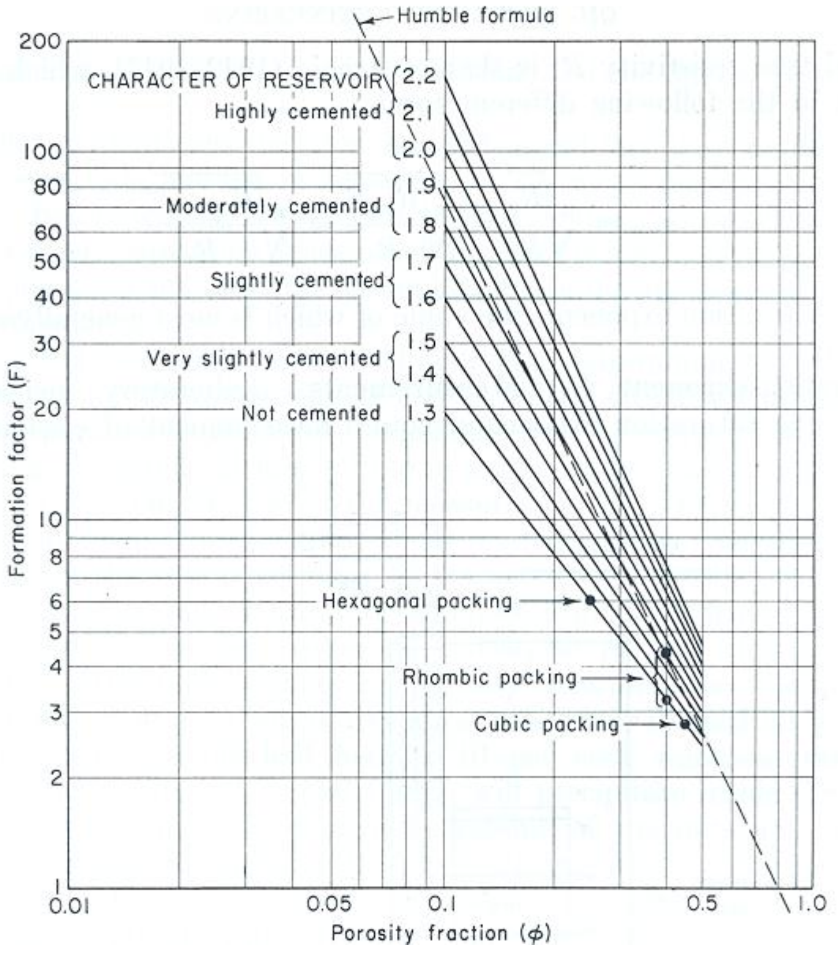
....Helander (1983)



c. Empirical Correlations

Archie (1942) suggested the following empirical equation based on lab measurements:

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



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

Electrical Properties of Rocks | ϕ – F relationship

Empirical Correlations

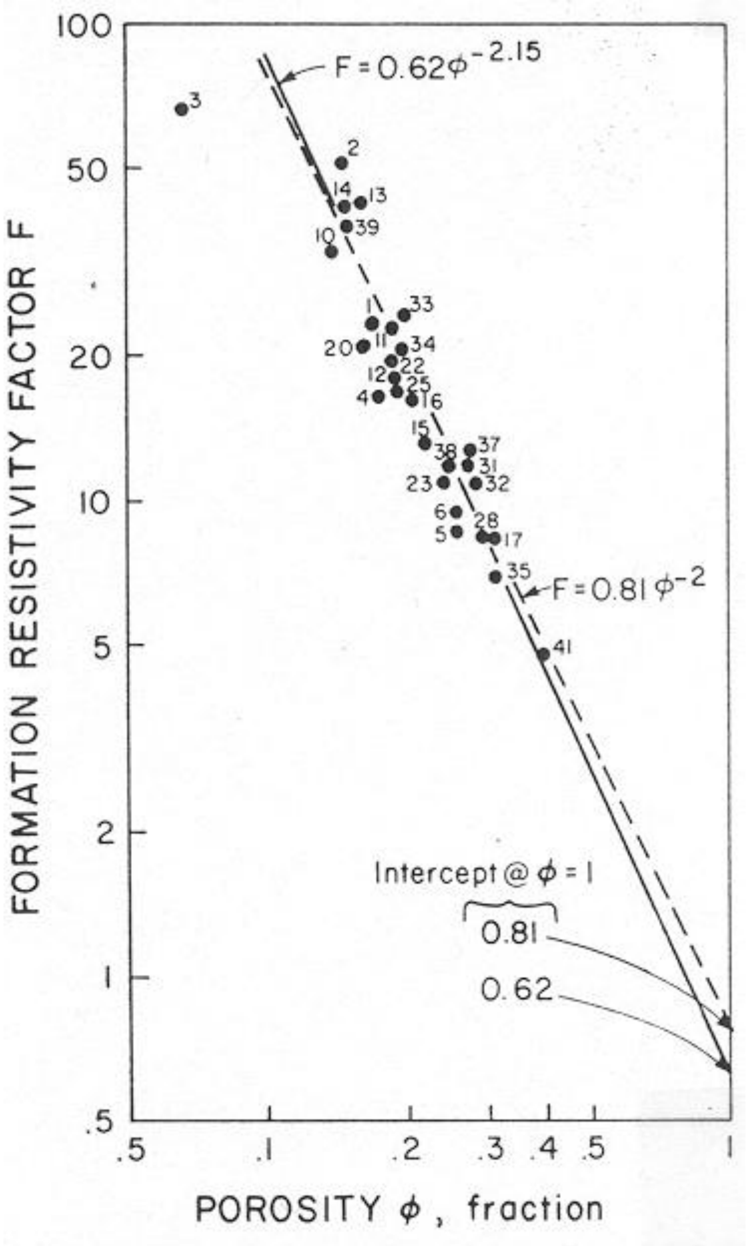
Winsauer, et al (1952) - analyzed data from 30 samples (28 ss, 1 lms, 1 unconsolidated ss)

Developed correlation known as “Humble Eq.”

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

Tixier (1979) – simplified equation using same data

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

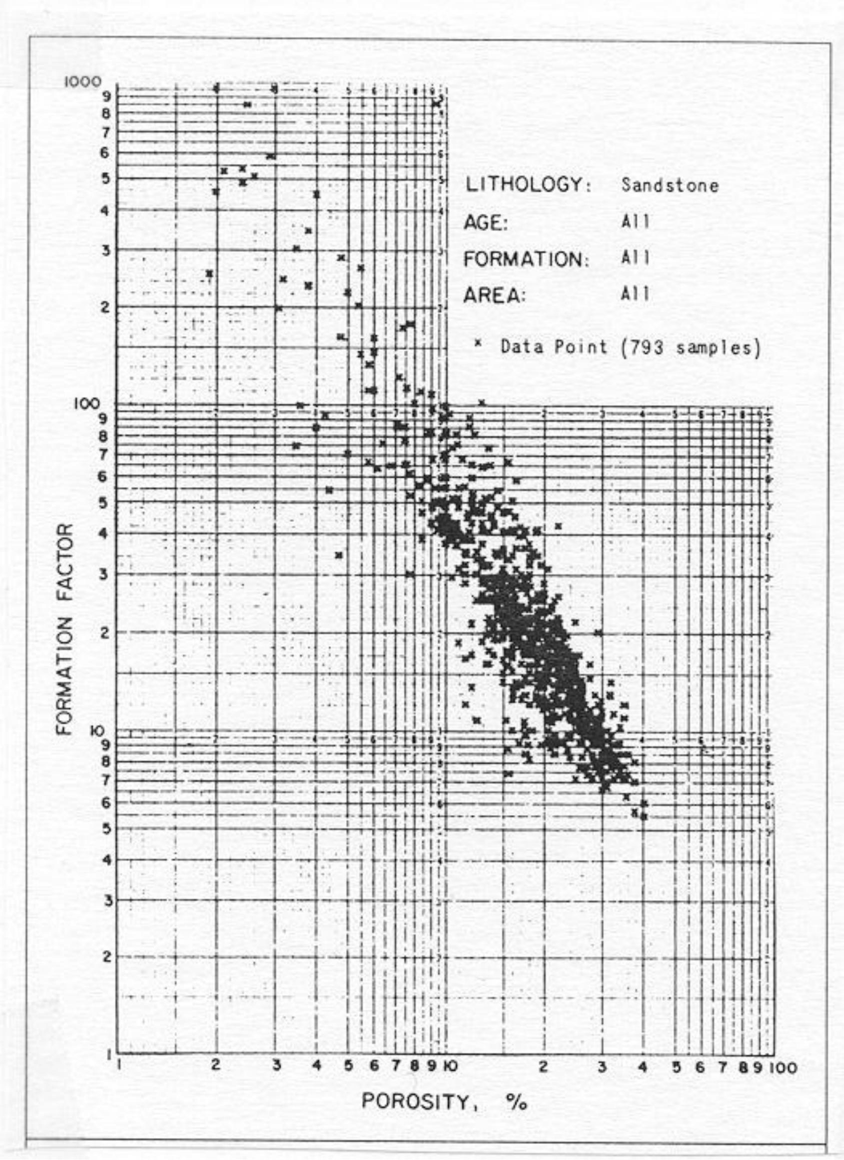


Electrical Properties of Rocks | ϕ – F relationship

Empirical Correlations

Carothers (1968) - analyzed 793 sandstone data points. Generalized correlation:

$$F = 1.45\ \phi^{-1.54}$$



Electrical Properties of Rocks

ϕ – F relationship

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

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

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

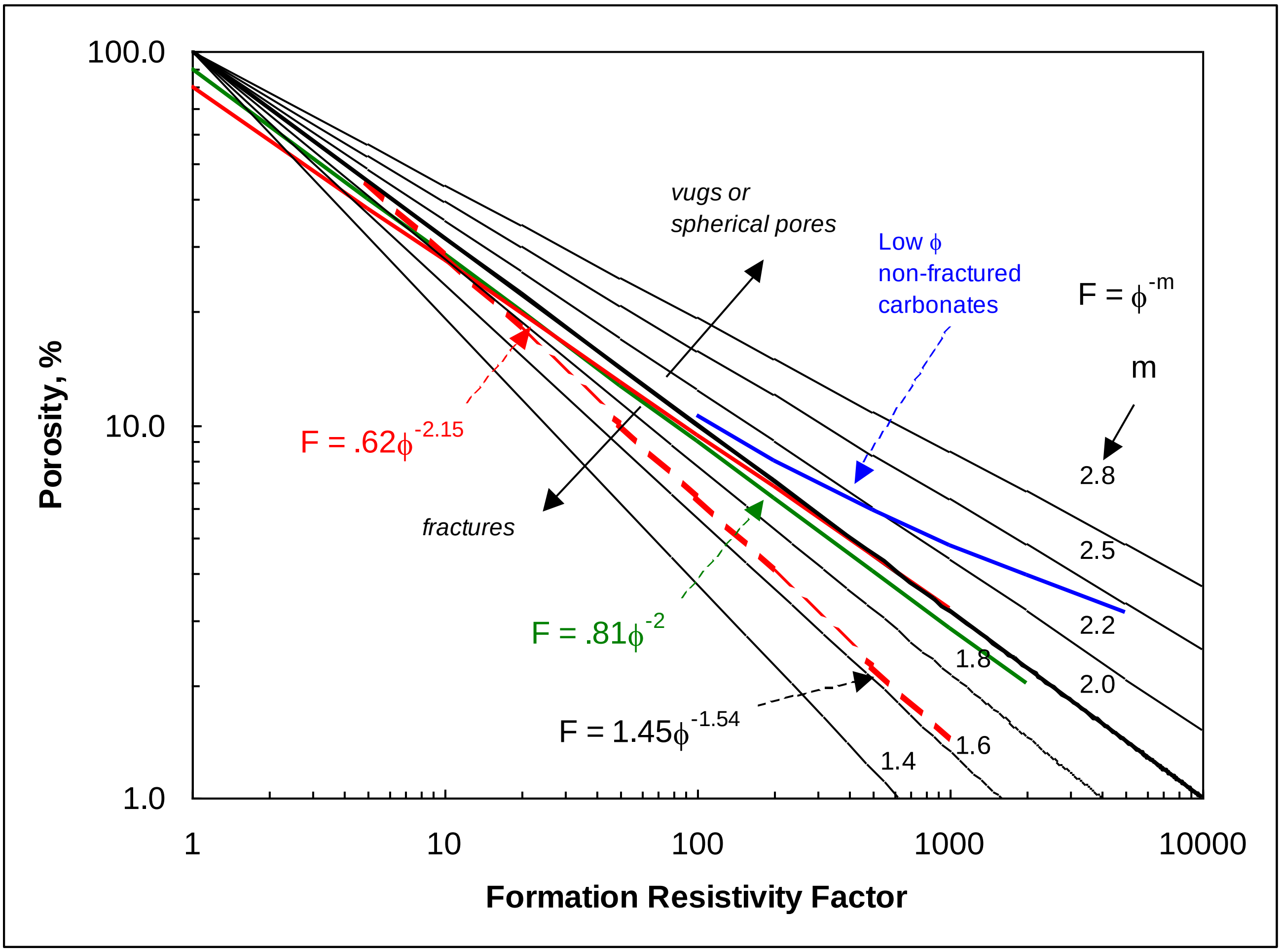
$F = 0.81\ \phi^{-2}$

Archie- most types of carbonates

$F = \phi^{-2}$

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

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



ϕ – F relationship

Define:

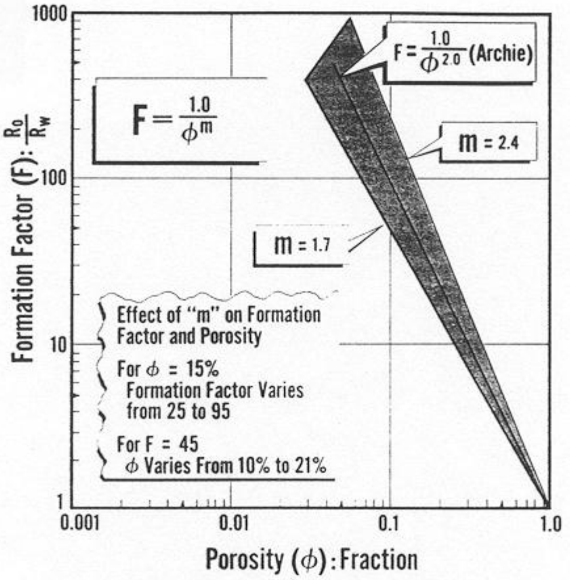
m – pore geometry exponent
a – pore geometry (tortuosity) factor

Characteristics:

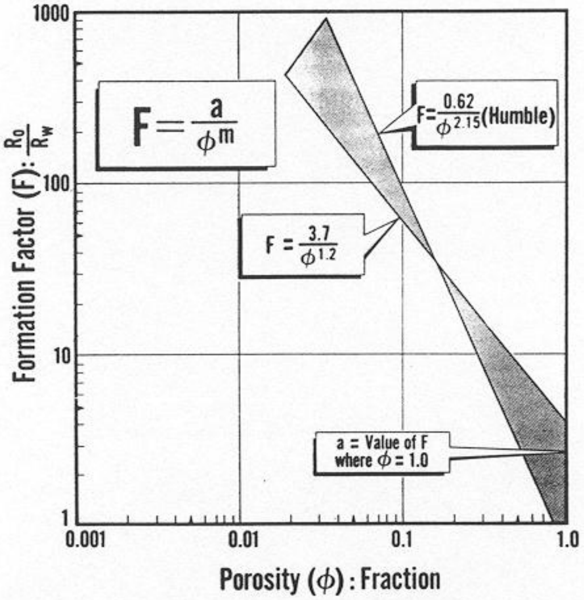
- Coefficient *a* varies from 0.35 to 4.78 and *m* from 1.14 to 2.9 (higher in carbonates)
- Observed variation in m-exponent, attributed to:
  - Degree of cementation
    - an increase in cementation increases *m*
  - Shape, sorting and packing of grains
  - Types of pores: intergranular, vuggy, fractures
    - fractures m ~ 1.0, vugs m > 2.0
  - tortuosity
  - constriction in porous network
  - presence of conductive solids
  - compaction due to overburden pressure
  - thermal expansion

Electrical Properties of Rocks | ϕ – F relationship

Influence of a and m (Corelab)



Formation Factor vs Porosity
For Range of Measured Cementation Factor



Formation Factor vs Porosity
Illustrating Variation In Intercept "a"

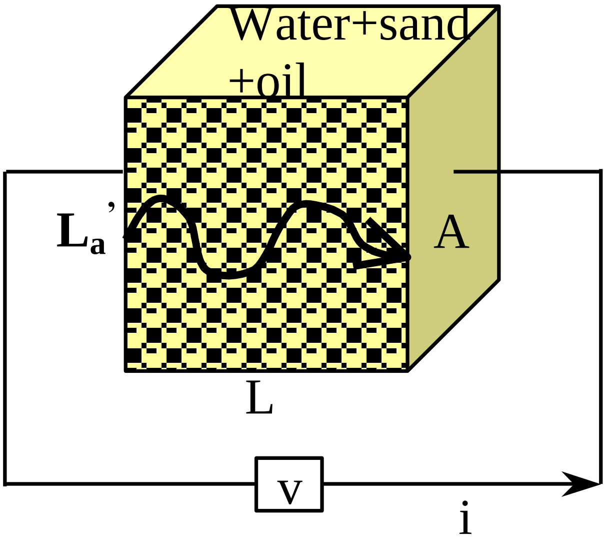
Electrical Properties of Rocks

Resistivity-Saturation Relationship

Consider the tank filled with a porous sand saturated with both water and hydrocarbons.

Resistance with respect to the water phase only,

$$r_w = R_w \frac{L'_a}{A'_p}$$



Resistance with respect to the porous, hydrocarbon bearing rock,

$$r_t = R_T \frac{L}{A}$$

Since $r_t \approx r_w$,

$$\frac{R_T}{R_o} = \left(\frac{A_p}{A'_p}\right)\left(\frac{L'_a}{L_a}\right)$$

Electrical Properties of Rocks

Resistivity-Saturation Relationship

Define resistivity index, I as: $I = \frac{R_T}{R_o}$

Archie correlated experimental data
and suggested: $I \propto \frac{c}{S_w^n}$

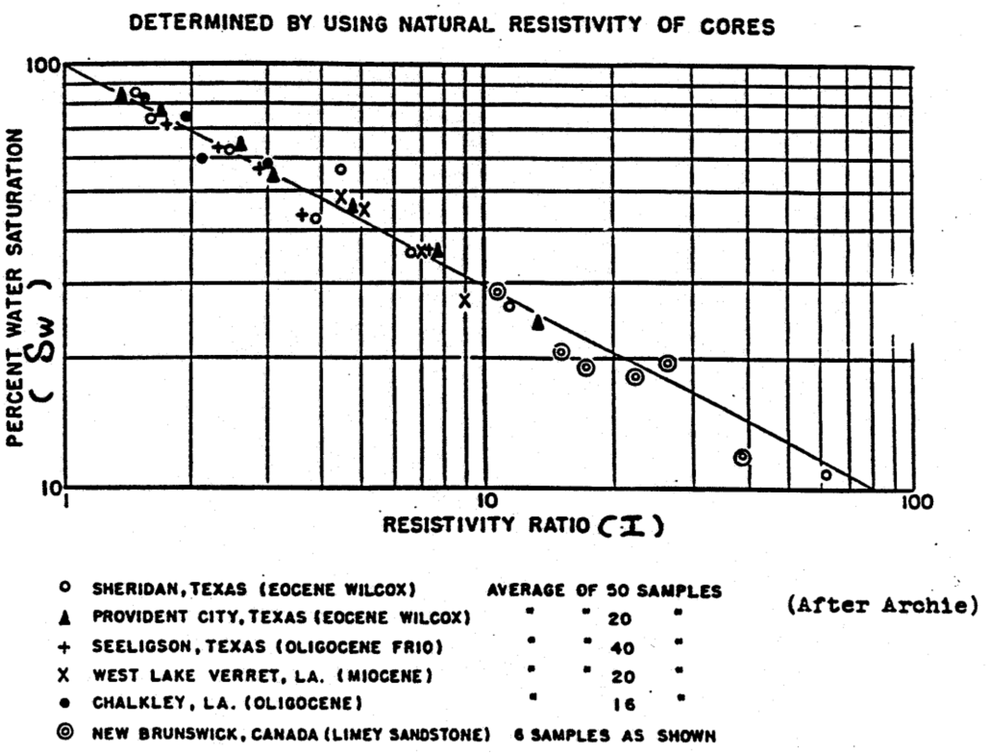
Combine, $\frac{R_T}{R_o} = \frac{c}{S_w^n}$

Plot,

$$\log(S_w) = \frac{1}{n}\log(c) - \frac{1}{n}\log\left(\frac{R_T}{R_o}\right)$$

Electrical Properties of Rocks

Resistivity-Saturation Relationship



(After Archie)

$$\log(S_w) = \frac{1}{n}\log(c) - \frac{1}{n}\log\left(\frac{R_T}{R_o}\right)$$

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

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

Electrical Properties of Rocks

Resistivity-Saturation Relationship

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

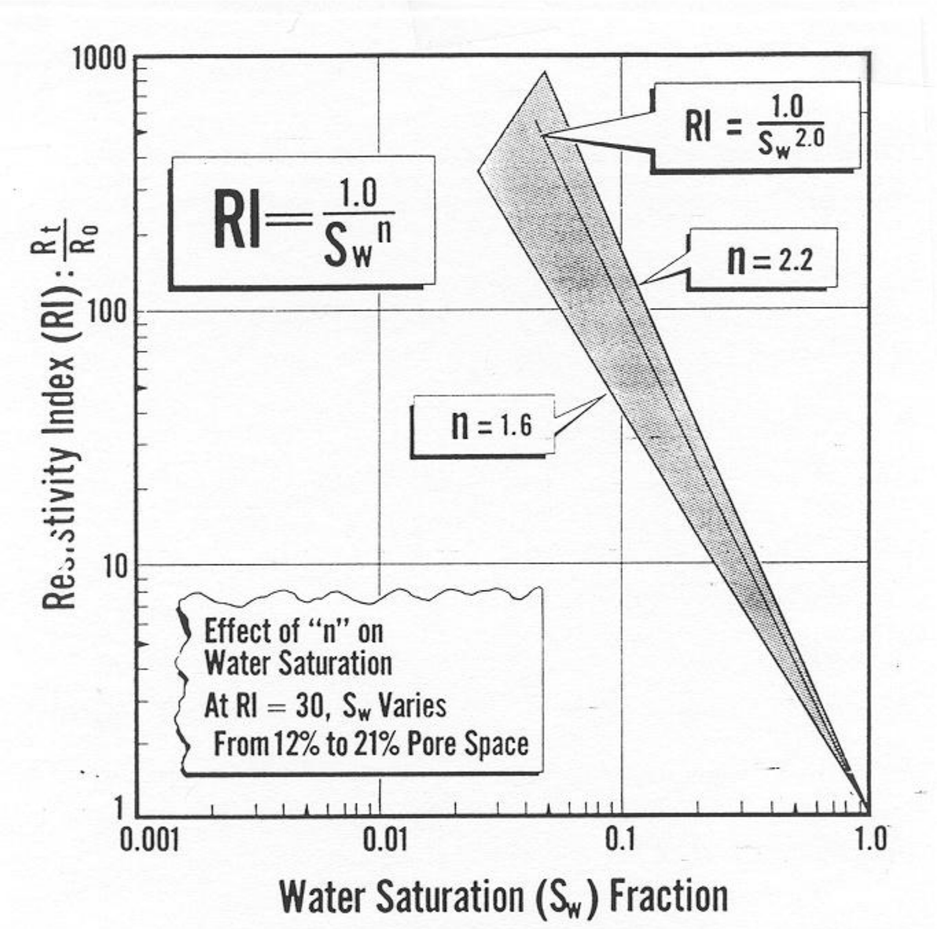
* Only valid when hydrocarbon and water zones are of the same porosity and salinity

General form known as Archie's Law.

$$S_w = \sqrt{\frac{FR_w}{R_t}}$$

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

Significance of saturation exponent (after Corelab)



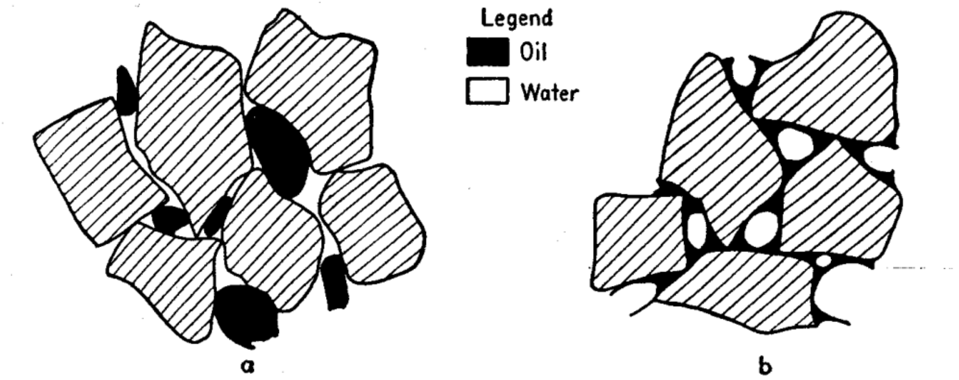
Resistivity Index vs Water Saturation For Range of Measured Saturation Exponents

Electrical Properties of Rocks

Resistivity-Saturation Relationship

- Observed variation in saturation exponent, *n* attributed to:

1. **wettability of rock surface**
2. rock texture
3. presence of clays
4. measurement techniques; i.e., static vs dynamic
5. nature of displacing fluid

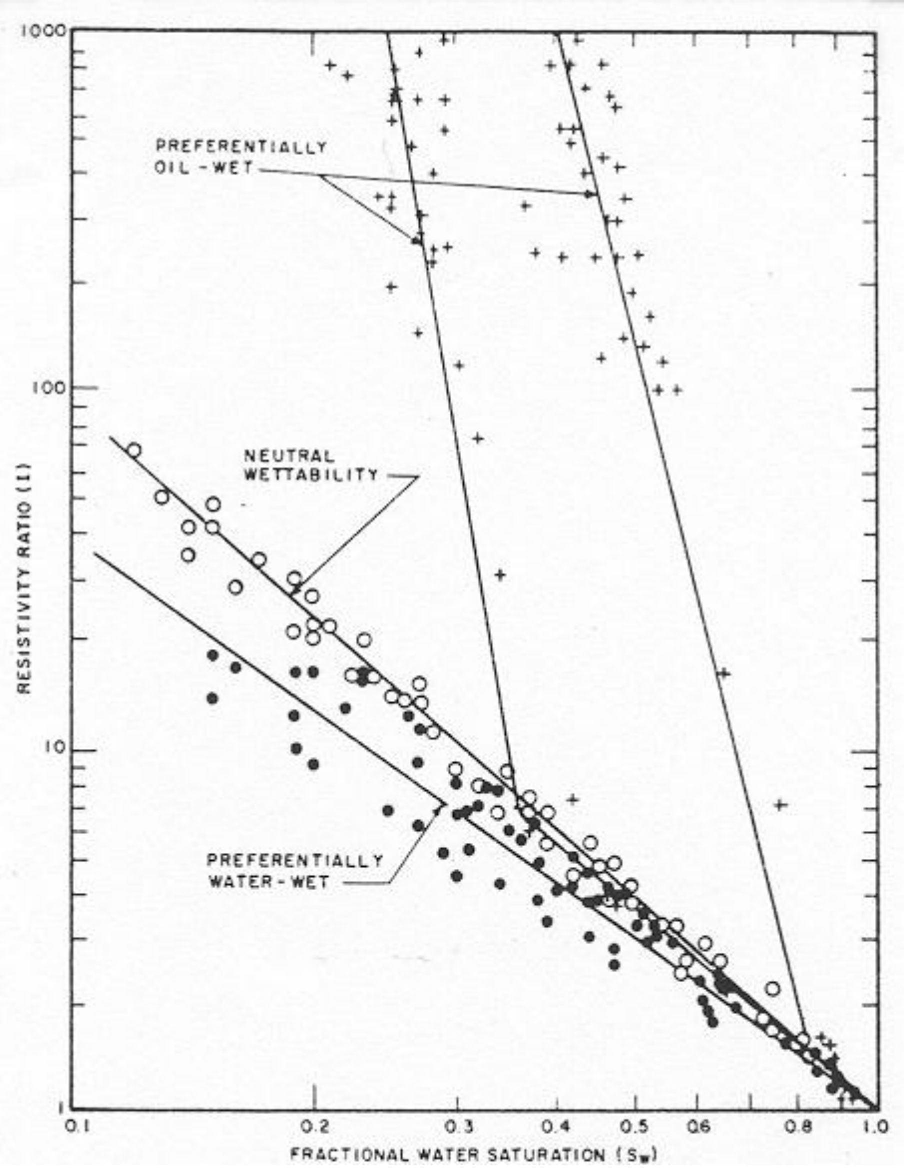


Fluid distribution in the pore spaces as a function of fluid wettability. Water and oil saturations in (a) a water-wet sand and (b) an oil-wet sand. Pirson (1958)

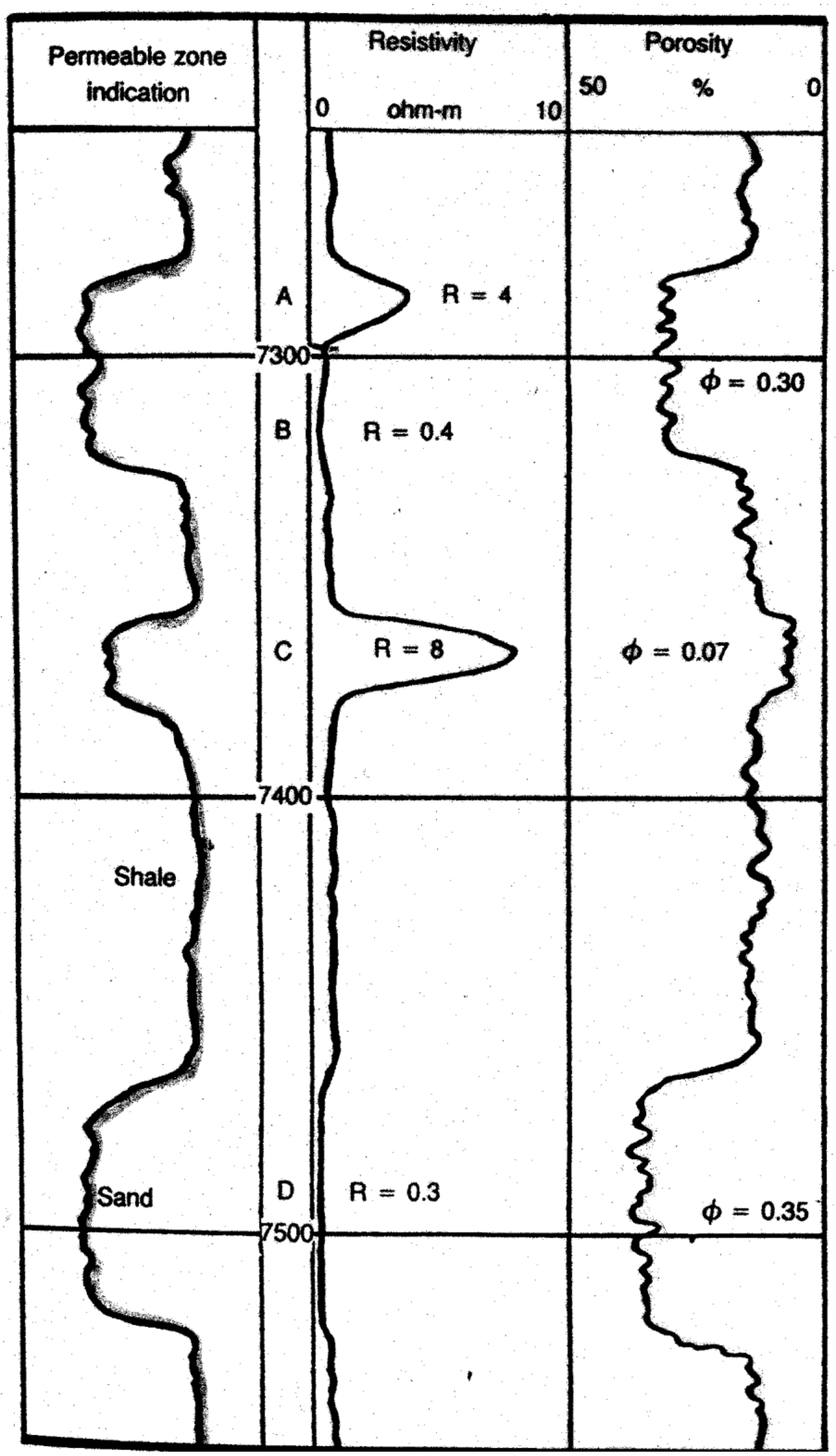
Electrical Properties of Rocks

Resistivity-Saturation Relationship

Wettability influence on rock surface



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


Permeable zone indication
Resistivity
0 ohm-m 10
Porosity
50 % 0
A
R = 4
7300
ϕ = 0.30
B
R = 0.4
C
R = 8
ϕ = 0.07
7400
Shale
Sand
D
R = 0.3
ϕ = 0.35
7500

References

Chapter 1, Sec 1.1-1.4, 1.6,1.8, Bassiouni, Z: Theory, Measurement, and Interpretation of Well Logs, SPE Textbook Series, Vol. 4, (1994)

Corelab, Fundamentals of Core Analysis, Houston, TX (1983)

Helander, D.P.: Fundamentals of Formation Evaluation, OGCI Publications,Tulsa, OK (1983)

Archie, G.E.:"Electrical Resistivity Log as an Aid in Determining Some Reservoir Characteristics", *Trans*., AIME (1942) **146,** 54-61.

Pirson, S.J.: Oil Reservoir Engineering, McGraw-Hill Publishing, NY, 2nd Ed (1958)