Water Saturation from Electric Logs

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(a subsidiary of Royal Dutch Shell plc)

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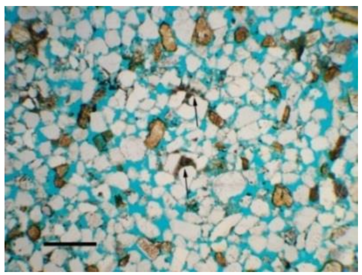
Water Saturation from Electric Logs

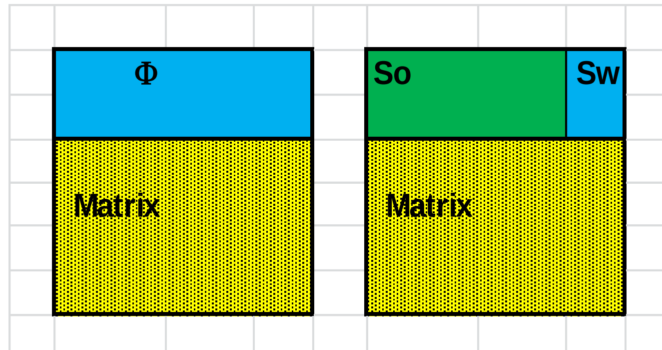
Outline

- What is Water Saturation and why do we care ?
- Fluid Levels within the Reservoir
- Formation water
  - what is it composed of?
- Resistivity logging
  - Rt = Ro, water-leg
  - Rt >> Ro , hydrocarbons
- Archie's equations
  - and using then to calculate Water Saturation
- When doesn't Archie work ?
  - thin beds, shaly sands, fresh water etc
- What else helps us quantify water saturation?
  - PNC, NMR, Dielectric, Core
- Summary

What is Water Saturation and why do we care?

- Water within the pore space
  - (*other fluids include Oil, Gas, Condensate, CO_2, H_2S*)
- Water Saturation is Water Volume / Pore Volume



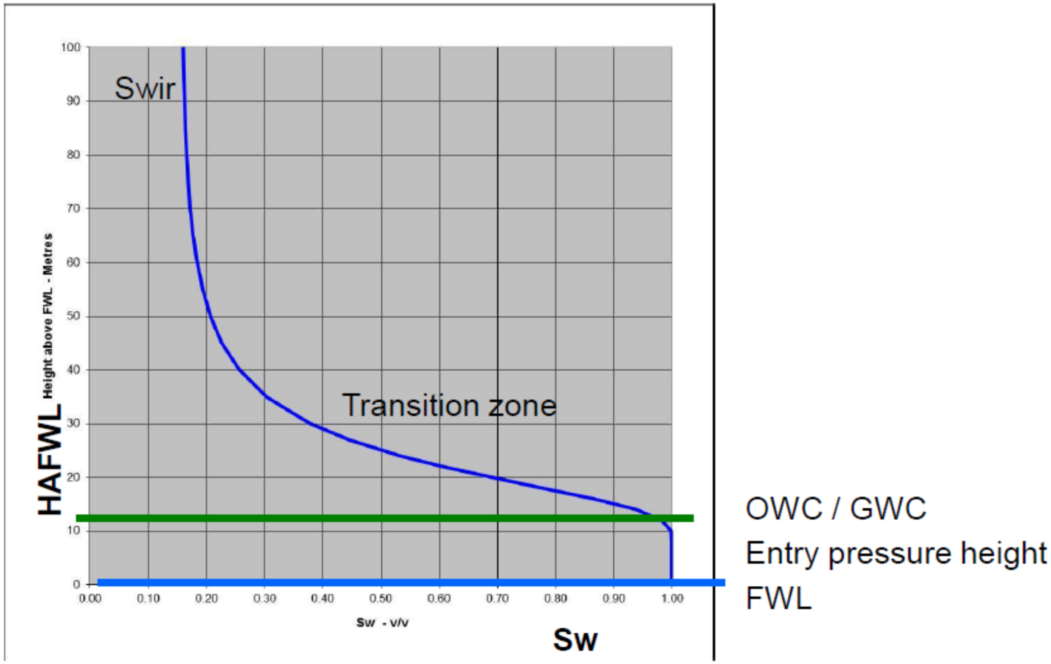


- Sw is a major input to Hydrocarbon Volumes Calculations
- STOOIP = (GRV * N:G * Φ * (1-Sw)) / Bo

where; *STOOIP = Stock Tank Oil Originally in Place*
GRV = Gross Rock Volume;
N:G = Net to Gross ratio
Φ = porosity;
<u>1 - Sw = pore space filled with hydrocarbon</u>
Bo = Formation Volume Factor
There is a similar equation for Gas in-place

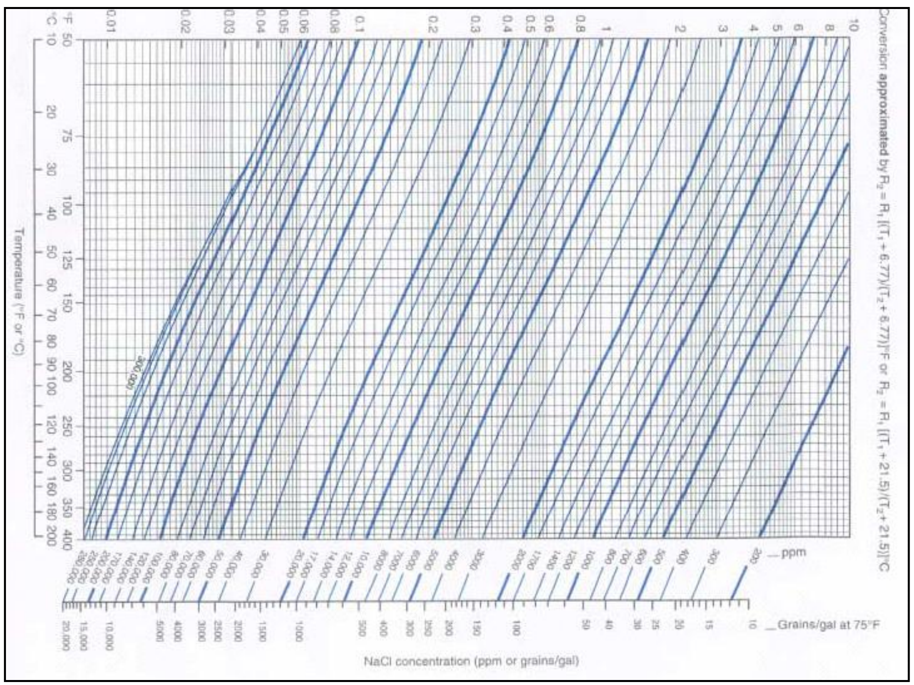
Fluid Distribution within the Reservoir

- Hydrocarbons are less dense than water, and migrate upwards until they are trapped, displacing the most of the formation water in the reservoir.
- Migrating gas or oil displaces the water from the bigger capillaries first so reservoir quality has a major impact on hydrocarbon saturation
- FWL, free water level, is where Pc, capillary pressure, is zero
- OWC/GWC, oil/gas water contact, first occurrence of hydrocarbons
- Difference between FWL and OWC is Entry Pressure Height
- Transition zone, interval between OWC and Irreducible Water Saturation
- Swir - Irreducible Water Saturation, when no more water can be displaced



What is Formation Water Composed of ?

- Generally water and dissolved salts in varying amounts,
  - dissolved salts are important for Sw calculations
- An example water analysis showing what salts can be in formation water, not just Sodium Chloride.
  - *API RP45 is the standard for water analysis in the Oil Patch*
- Rw is formation water resistivity
- Rw varies with temperature (Arps equation)



Rw vs. temperature graph

API Water Analysis		
Whole Sample Properties		
Appearance before filtration	Slightly hazy grey water	
Appearance after filtration	Clear colourless water	
Total dissolved solids (mg/l)	69,280	
Specific garvity at 60/60 deg.F	1.044	
Determined Resistivity (Ohmm at 60 deg.F)	0.143	
Hydrogen Sulphide	Not detected	
pH at 20 deg.C	7.03	
Components		
Cations	mg/litre	meq/litre
Sodium	25540	1110
Potassium	770	20
Calcium	455	23
Magnesium	135	11
Barium	205	3
Strontium	150	3.4
Total Iron	5.3	-
Dissolved Iron	0.15	0.01
Anions		
Chloride	40170	1130
Sulphate *	33	0.68
Bicarbonate	1800	30
Carbonate	nil	nil
Hydroxide	nil	nil
Additional Components		
Boron	22	
Aluminium	< 0.50	
Silicon	26	
Phosphorus	0.51	
Lithium	22	
Comments		
The analysis has shownm the sample to be predominantly formation water		
* Sulphate results calculated from total Sulphur determined by inductively coupled plasma emission spectrometry		

How do we quantify water saturation?

From logs

- Resistivity measurements using Archie based equations

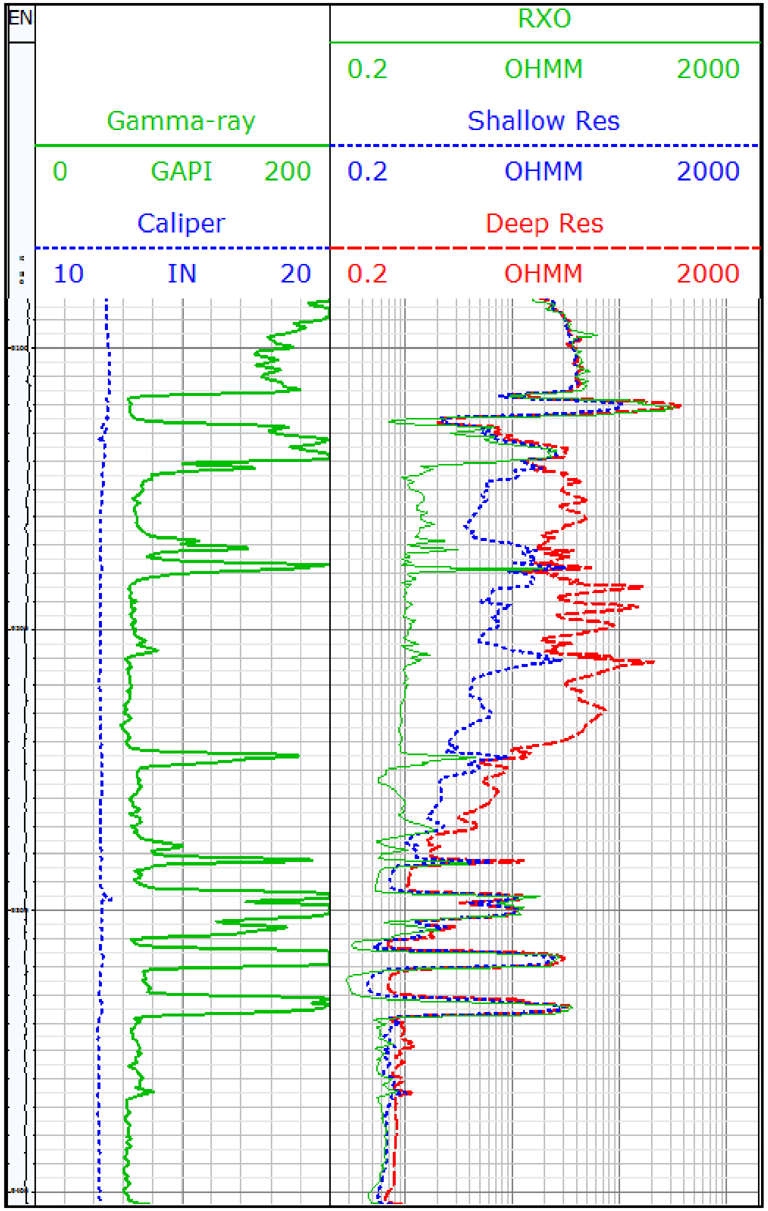
The Electrical Resistivity Log as an Aid in Determining Some Reservoir Characteristics. G. E. Archie, 1942.
paper presented at Dallas meeting of AIME October 1941 and published in SPE-AIME Transactions 1942

- *Other logs (all shallow reading tools)*
  - *Pulsed Neutron Capture (still salinity dependant)*
  - *Magnetic Resonance (sort of)*
  - *Dielectric permittivity (just the flushed zone really)*

- Also from core

Resistivity Logs

- **Measures electrical conductivity due to:-**
  - Brine in the pore space
  - Capillary bound water
  - Water in shales
- Hydrocarbons and Matrix are mostly non-conducting, but there are some conductive minerals
- Resistivity is the inverse of Conductivity
- **Laterolog**
  - Lower frequency (35Hz)
  - Needs a conductive path to the formation.
  - Slightly better Vertical Resolution
  - Can read up to 20,000 Ohmm.
  - 6ft+ depth of investigation.
- **Induction**
  - Higher Frequency(20+KHz)
  - Works in OBM and air filled holes
  - Vertical Resolution poor, but Array tools are comparable to laterolog.
  - Accurate up to 100 - 200 Ohmms
  - 4-8+ ft depth of investigation
- **A Plethora of Options**
  - Current tools generally Array type
  - LWD multi-frequency

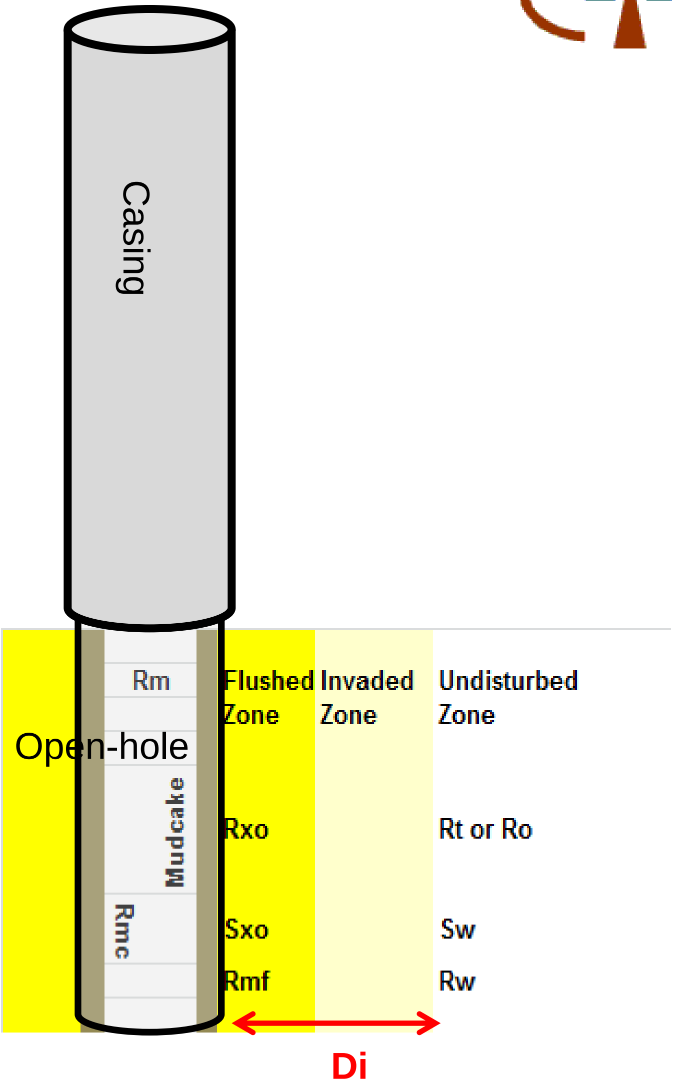


Resistivity Logging - operational considerations

Drilling fluid (mud) effects.

- Mud filtrate invades the rock pores near the well, displacing the natural fluids
- Changes the fluid and formation resistivity
- Solids in the invading mud may leave a mud cake on the borehole wall 0.5+" thick

- Flushed Zone:
  - Rxo - flushed zone resistivity
  - Sxo - flushed zone water saturation
  - Rmf - mud filtrate resistivity
- Undisturbed zone
  - Rt - true formation resistivity
  - Sw - water saturation
  - Rw - formation water resistivity



Mud invasion schematic.
Diameter of invasion (Di) is highly variable, difficult to estimate, but of the order of a few inches to a few feet. Assumed to be symmetrical around the borehole.

Archie Equations for Water Saturation

$$S_w^n = R_o/R_t \text{ and } R_o = F * R_w$$

where

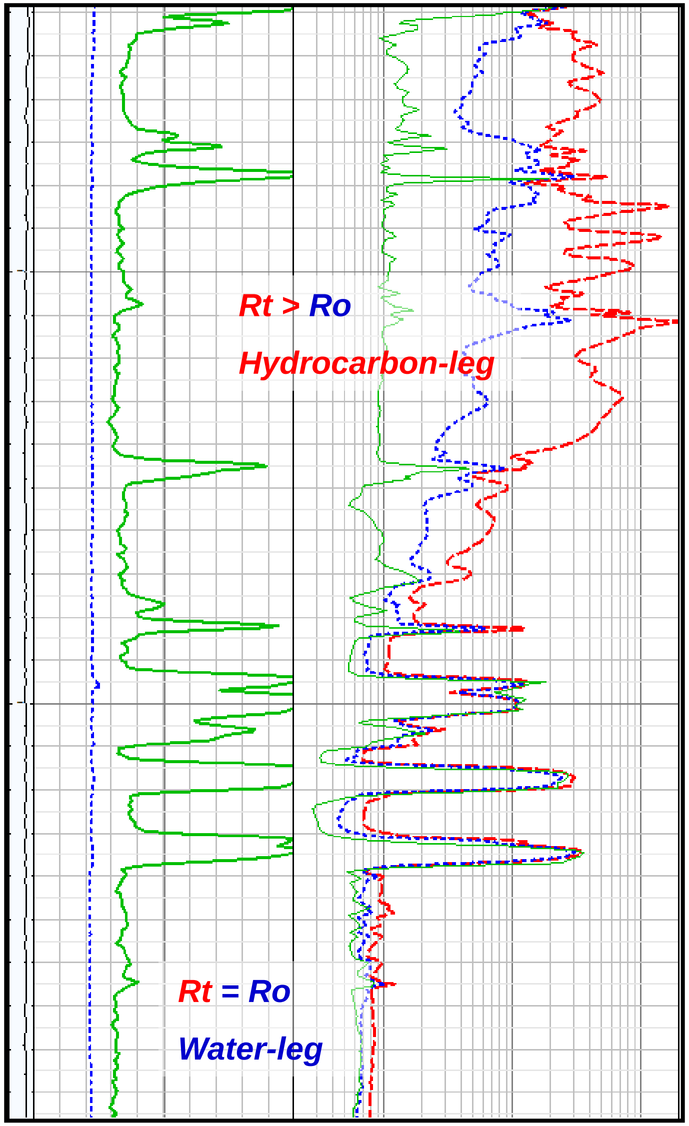
$$F = 1 / \Phi^m \quad (\text{also } F = a / \Phi^m)$$

so

$$S_w^n = F.R_w / R_t \text{ and } S_{hc} = 1 - S_w$$

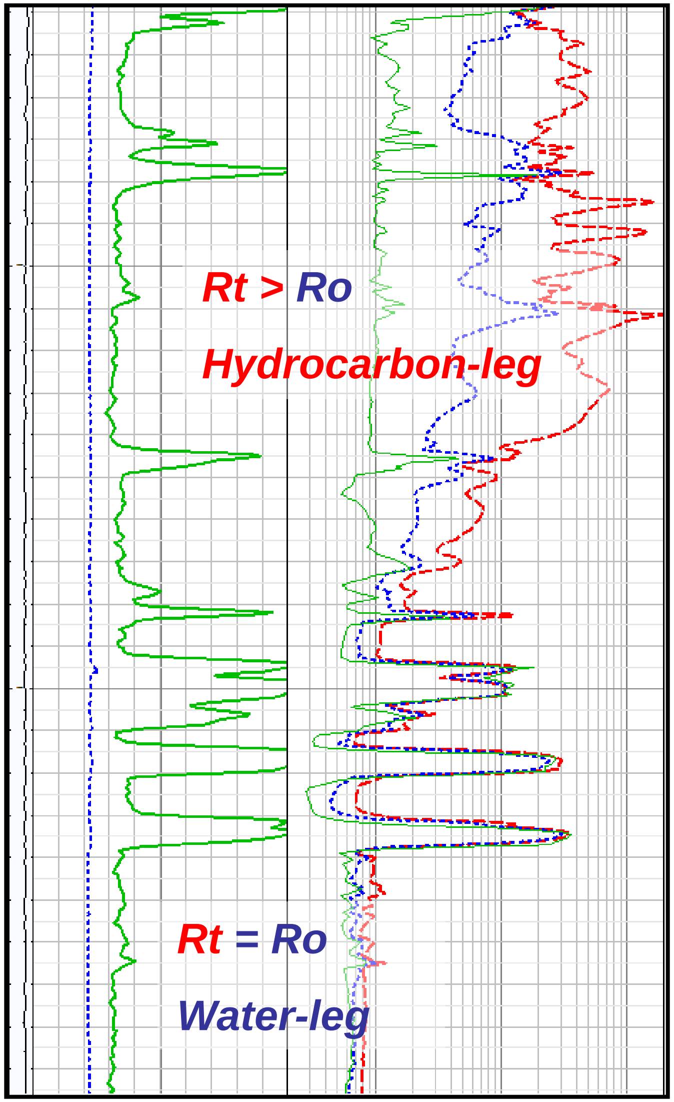
- m is the Formation Factor exponent
- n is the Saturation exponent
- Archie found a=1.0, m=2.00 and n=2.00

- Rw is formation water resistivity
- Ro and Rt are resistivity of the formation (including rock and fluids)
- Ro is rock <u>fully</u> saturated with water of Rw
- Rt is rock <u>partially</u> saturated with water of Rw
- the ratio, Rt/Ro, is proportional to the water saturation
- the ratio Ro/Rw is Formation Factor - F



The Archie Equations - Some Important Assumptions

- Rt is the true formation resistivity.
- Rt = Ro when all the pores are filled with water.
- The current travels through the water
    - the water has some dissolved salts.
- The matrix is non-conductive.
- Formation water salinity is constant.
- Rw varies with temperature only
- Porosity is the void space available for fluids.



The Archie Formation Factor

- **what is it?**

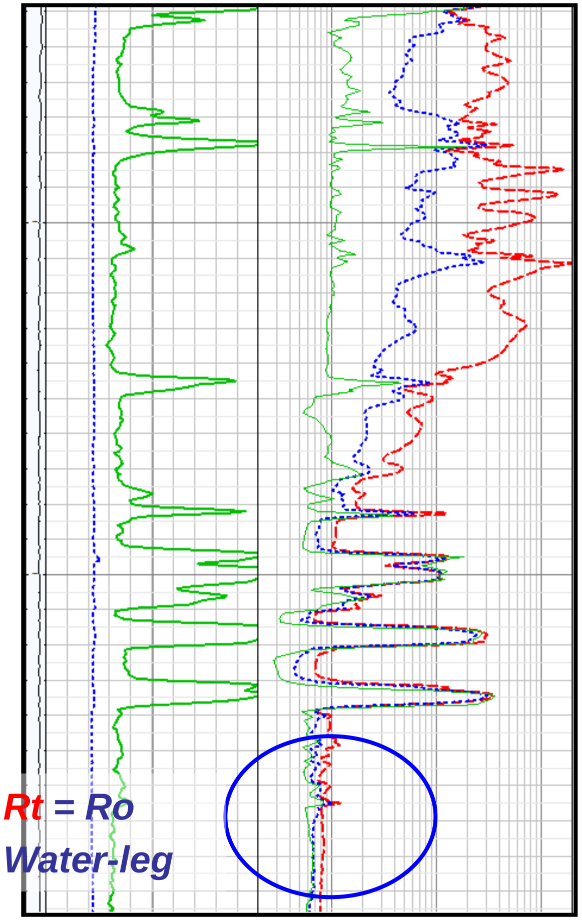
"A study of the resistivity of formations when all the pores are filled with water is of basic importance in the detection of oil or gas by the use of an electrical log. Unless this value is known, the added resistivity due to oil or gas in a formation cannot be determined."

- This really relates to the **water-leg**

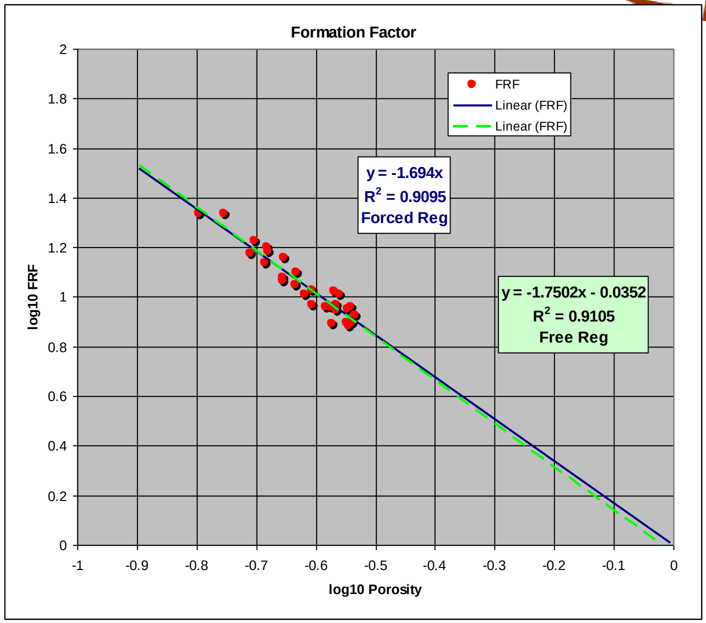
- Formation Factor, F, is the ratio of Ro to Rw
- and it is also a function of Porosity
- so F = Ro/Rw and $F = 1 / \Phi^m$

- m is the Formation Factor exponent
- It is related to pore geometry
  - *aka porosity exponent*
  - *aka cementation exponent*

- F = Ro/Rw and $F = 1 / \Phi^m$
- and $Ro = Rw/ \Phi^m$
- later $F = a / \Phi^m$ where a is the Tortuosity factor
- Archie; a=1 and m=2
- Humble; a=0.62 and m=2.15



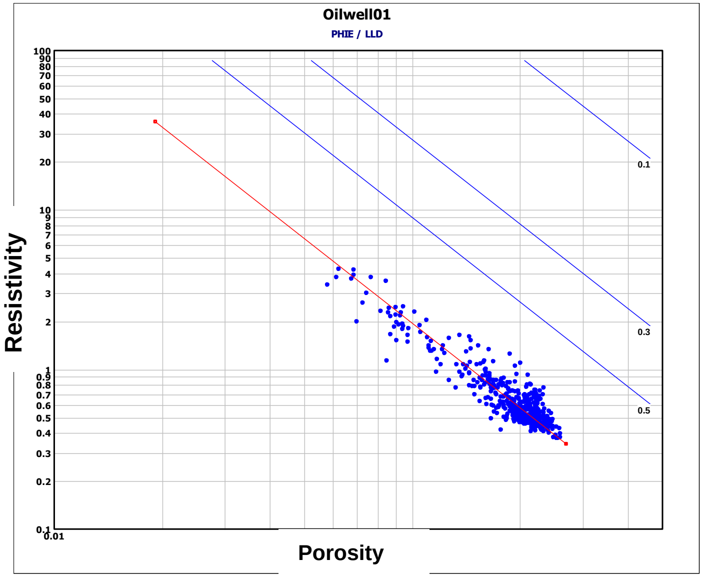
The Archie Formation Factor Exponent
- how is it determined?



- F = Ro/Rw and
- F = 1 / Φ^m
- later F = a / Φ^m

- Laboratory measurements of; Ro, Rw and Φ
- F determined from Ro/Rw
- and cross-plotted against Φ
- slope is -m
- forced regression gives a =1
- free regression generally a is not 1

- Not just core, but from logs in a water-leg
- Pickett Plot to derive aRw and m
- In the water-leg Ro = Rt and as
- F = Ro/Rw and F = 1 / Φ^m
- Ro = Rw/ Φ^m
- *Ro is cross-plotted against Φ (log-log x-plot)*
- slope is -m
- intercept with 100% porosity is aRw



The Archie Saturation Exponent

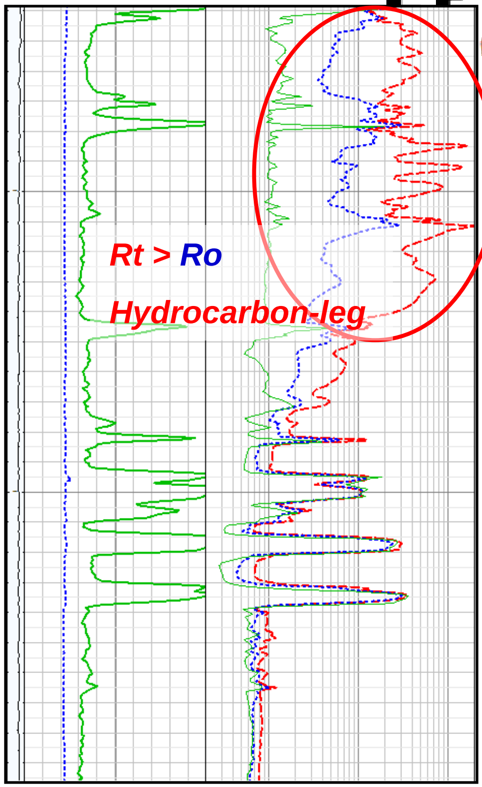
- **what is it and how is it determined?**

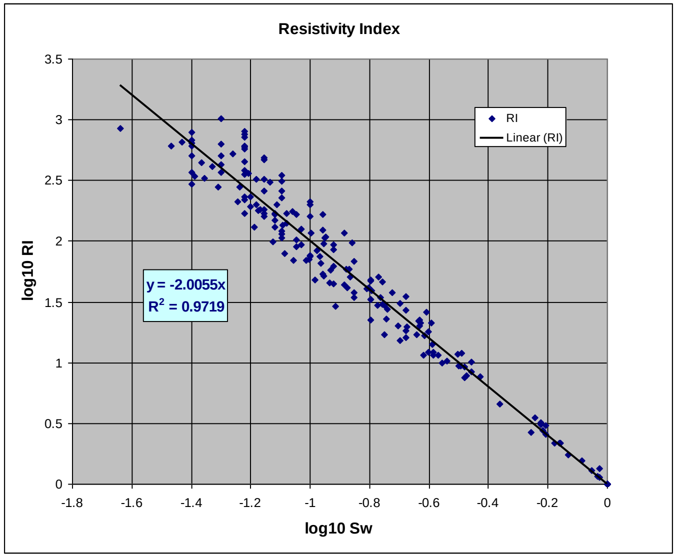
"Various investigators have studied the variations in the resistivity of sands due to the percentage of water contained in the pores....the following approximate equation applies..."

- Now up into the **Hydrocarbon-leg**.......
- $S_w^n = R_o / R_t$
- and $Ro = Rw / \Phi^m$

- Resistivity Index, RI is the ratio of Rt to Ro
- Archie showed that $Sw^n = Ro / Rt$
- and as $Ro = F.Rw$ then $Sw^n = F.Rw / Rt$

- Laboratory measurements of Ro, Rt and Sw
- RI cross-plotted against Sw, the slope is -n
- n is the Saturation Exponent

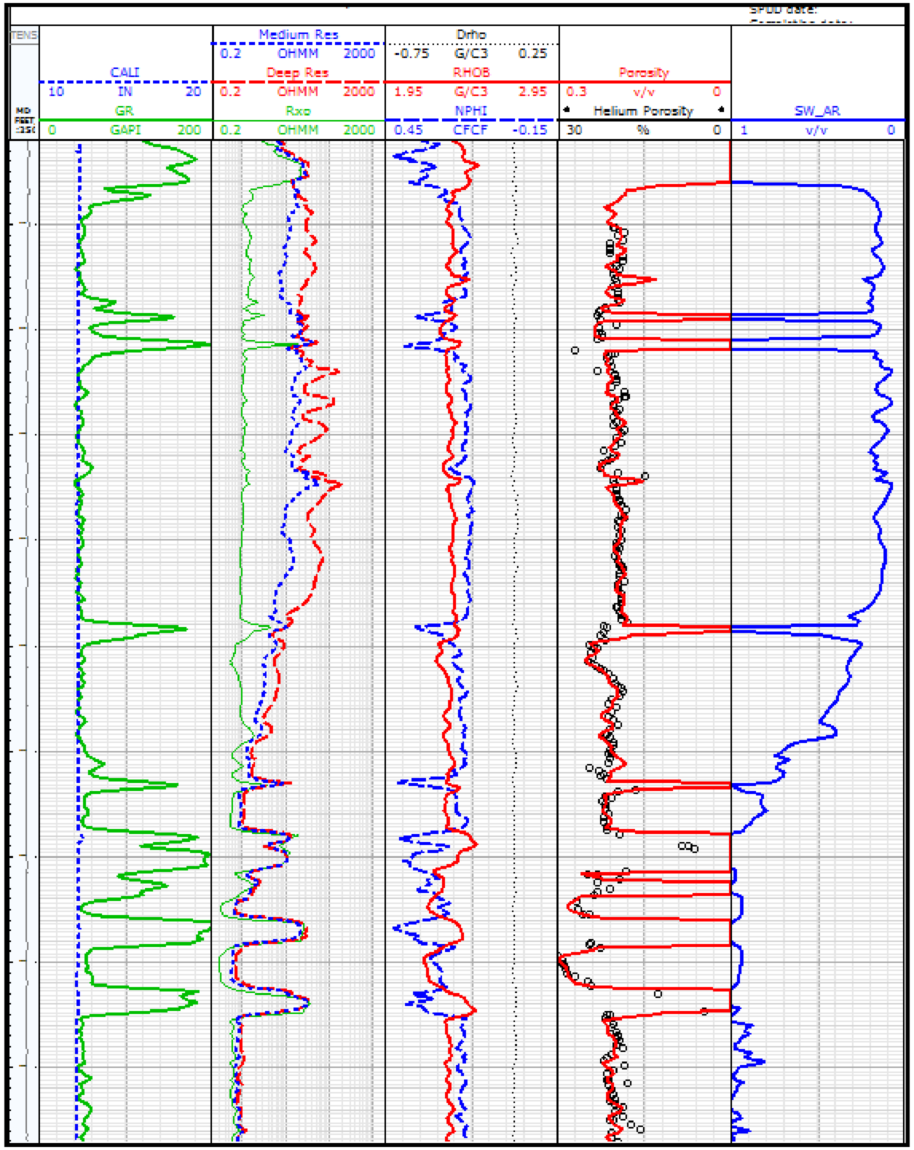




Archie Saturation Equations for Water Saturation

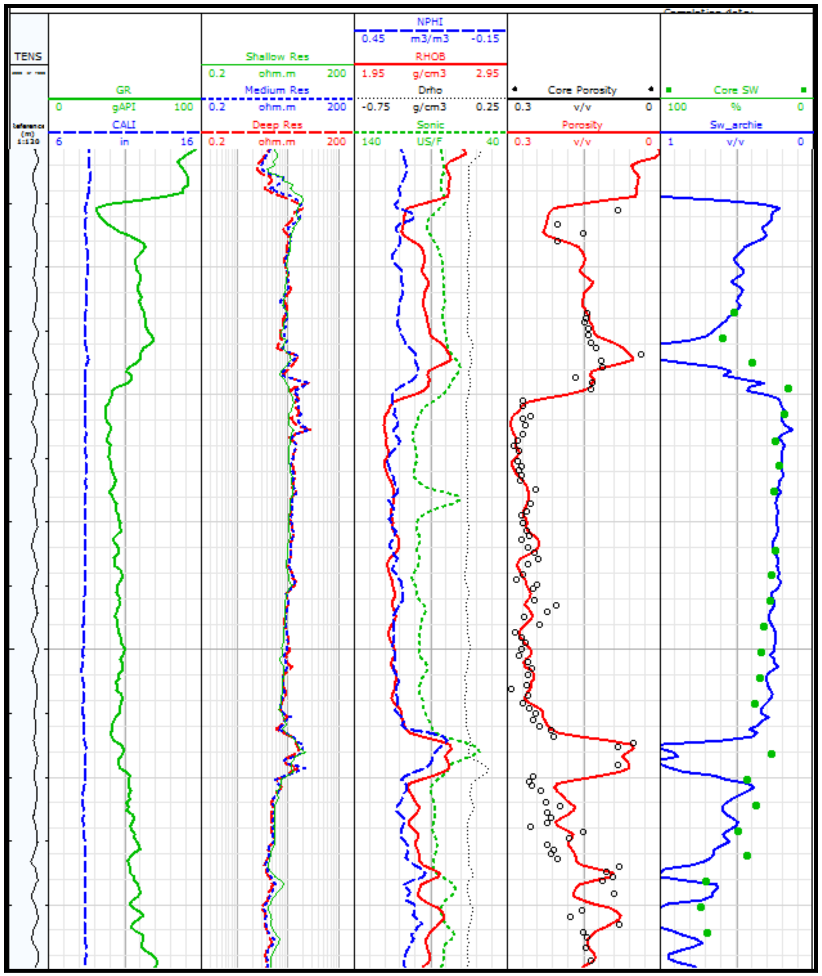
- So for Archie Saturation we need;
- Rt and Porosity (from logs)
- Rw - *at the right temperature*
- a, m and n

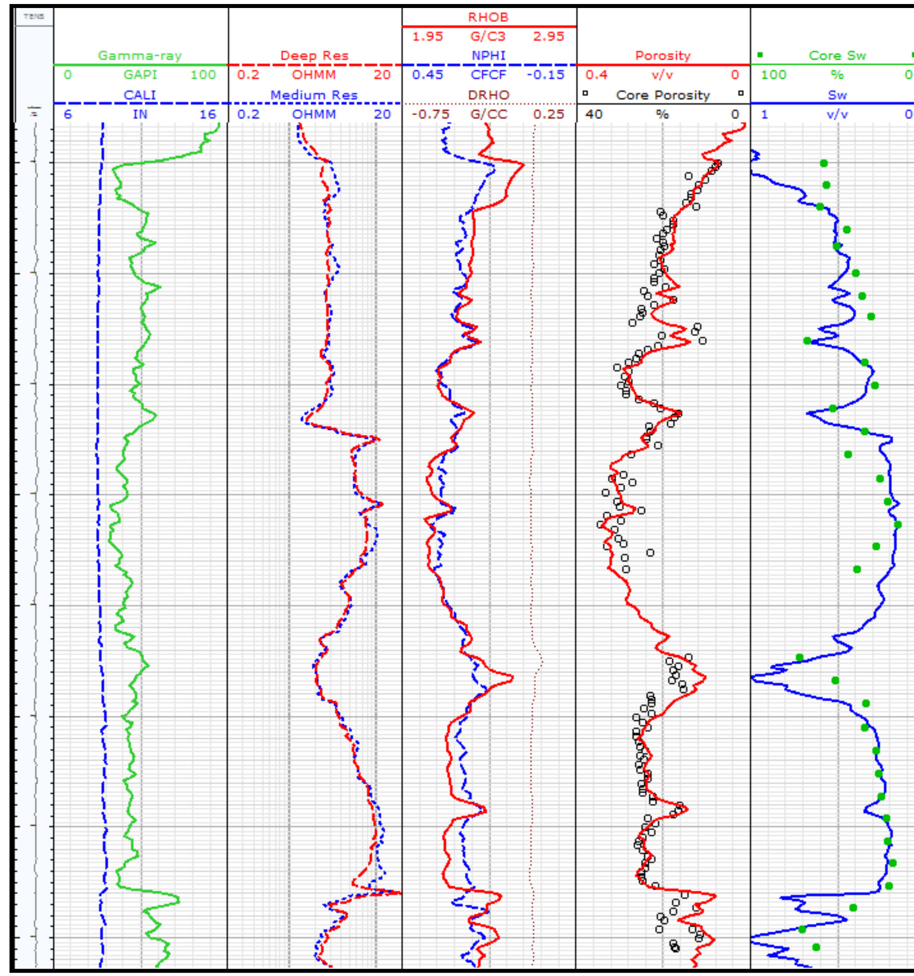
- $F = 1 / \Phi^{m}$
- *also* $F = a / \Phi^{m}$
- $S_w^{\,n} = F.R_w / R_t$



Does Archie Really Work?

Water Saturation from Dean-Stark extracted core compared to Archie derived Sw suggests that yes it does in many cases

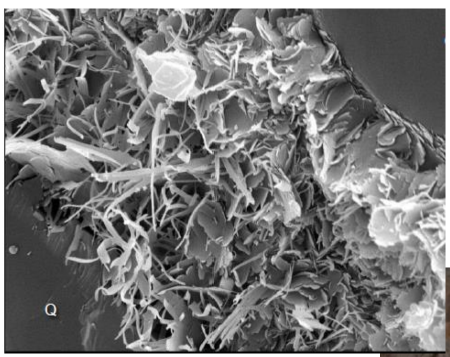




"It should be remembered that the equations given are not precise and represent only approximate relationships."

So what makes Archie stop working?

- conductive "matrix" - clays, pyrite
  - Excess Conductivity or Shaly sands
- beds thinner than the resolution of the Resistivity logs
- fresh formation water (or other non-conductive fluids)
- large variability in pore size - vugs, fractures
- variable formation water salinity
- variably rock wettability

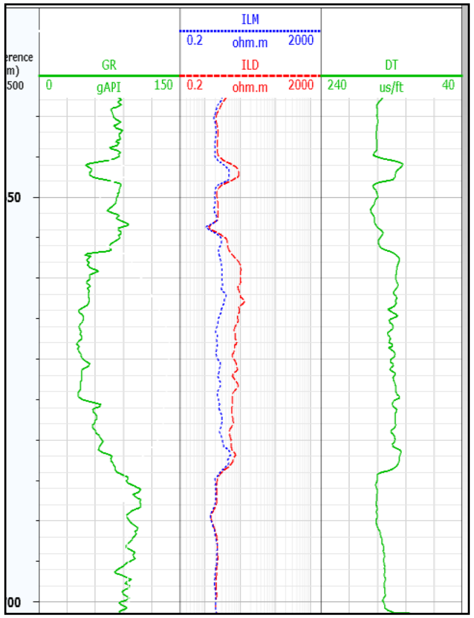


Pore filling Illite.

Laminated sand and shale

Vugs

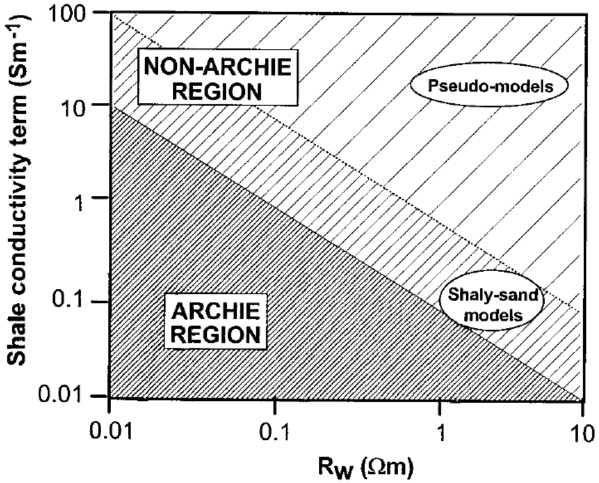
Fresh water



Excess Conductivity or Shaly sands

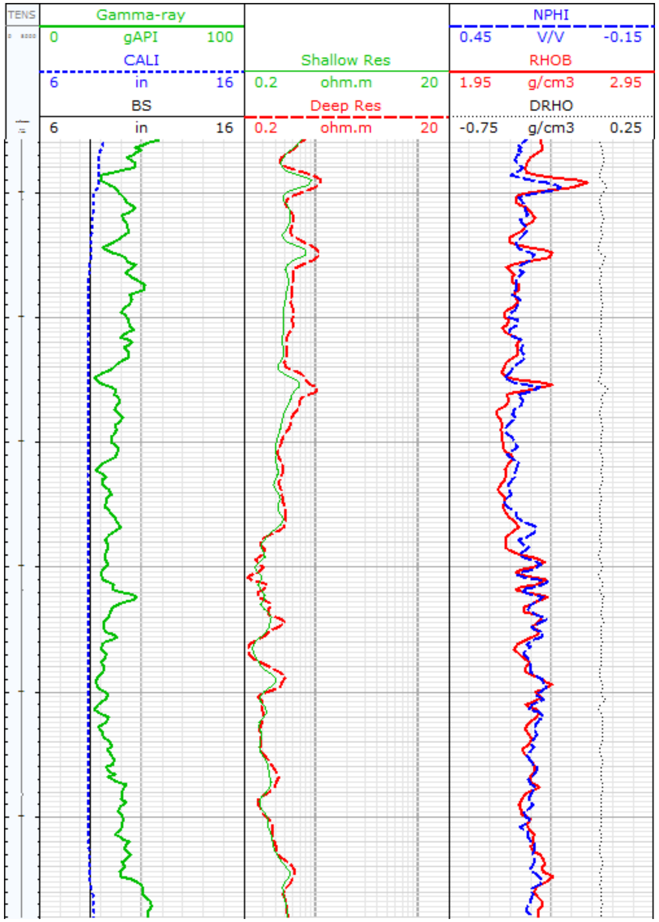
- Archie Clean Sand Equation: $S_w^n = F.R_w / R_t$
- An example of a Shaly Sand Equation:
- Simandoux - $S_w^n = F.R_w * (1/R_t - (V_{sh} * S_w)/R_{sh})$

- Shaly Sand Equations (using Effective Porosity):
- Requires additional parameters;
  - Shale Volume - Vsh
  - Shale Resistivity - Rsh
  - Shale Porosity - Φsh
- How can these be determined?
- Is that Clay or is that Shale ?
- How is the Shale/Clay distributed ?



Worthington, P. F. (2000), Recognition and evaluation of low-resistivity pay, Petroleum Geoscience, 6, 77-92.

Low Resistivity Pay



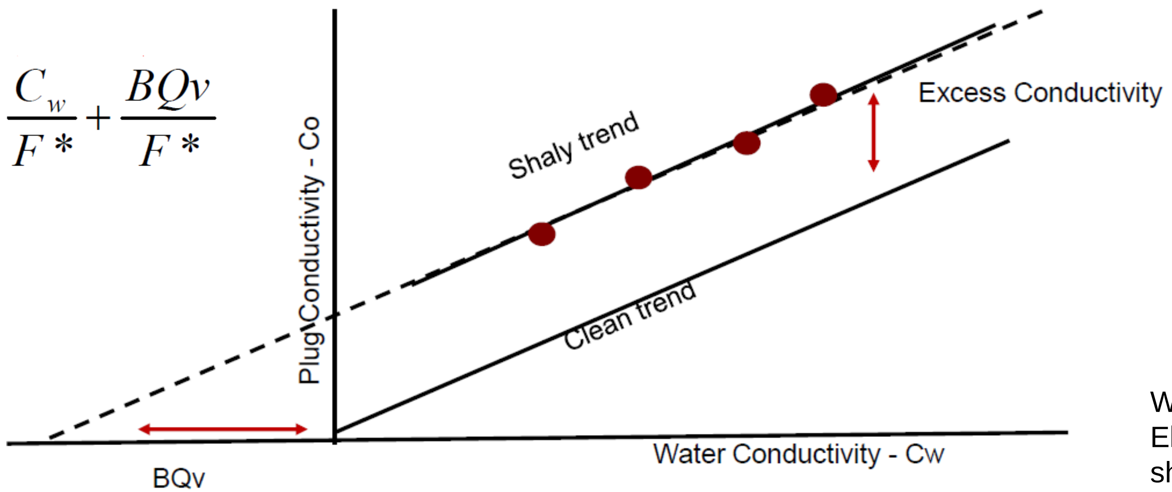
Excess Conductivity or Shaly sands

- Waxman-Smits Shaly Sand Equation:
- $Sw^n = Rt/F.Rw * (1 + Rw*B*Qv/Sw)/(1 + Rw*B*Qv)$
- Using Total Porosity and based on core data
- B related to Rw

$$B = \frac{-1.28 + 0.225 \times T - 0.0004059 \times T^2}{1 + Rw^{1.23}\left(0.045 \times T - 0.27\right)}$$

- Qv related to clay conductivity, can be measured from core
  - Derive Qv from Co/Cw plot
  - Core plug fully saturated with water with known Cw
  - Measure plug conductivity Co, repeat with changing Cw

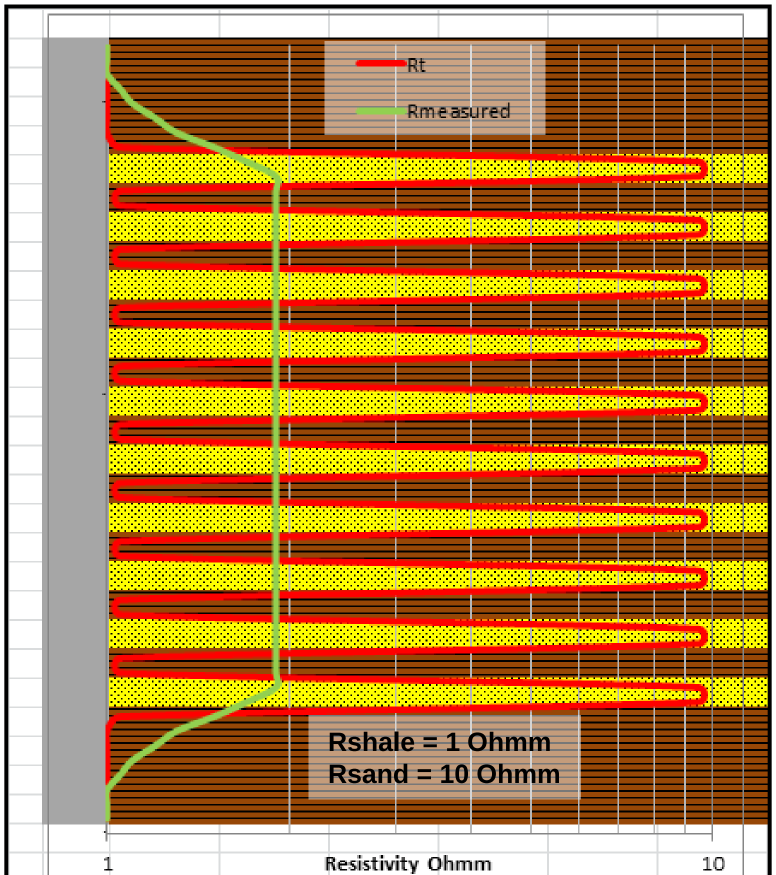
$$C_o = \frac{C_w}{F*} + \frac{BQv}{F*}$$

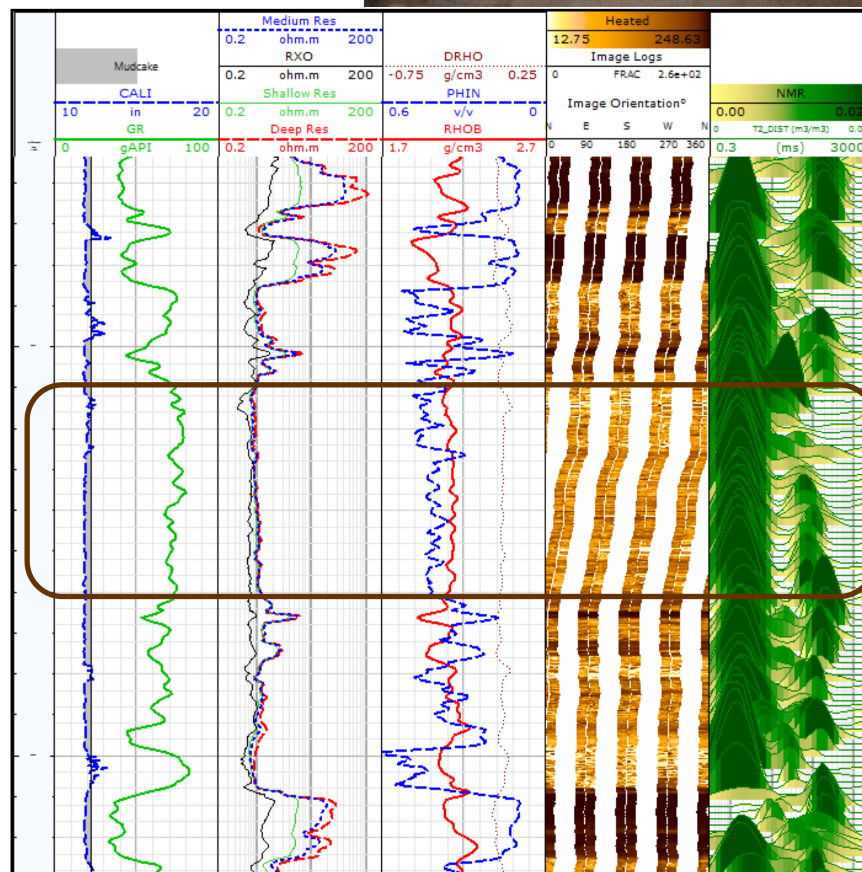


Waxman, M.H., and Smits, L.J.M.,1968, Electrical conductivities in oil-bearing shaly sands: Society of Petroleum Engineers Journal, v. 8, p. 107-122.

What stops Archie working ?
Resistivity in Thin Beds

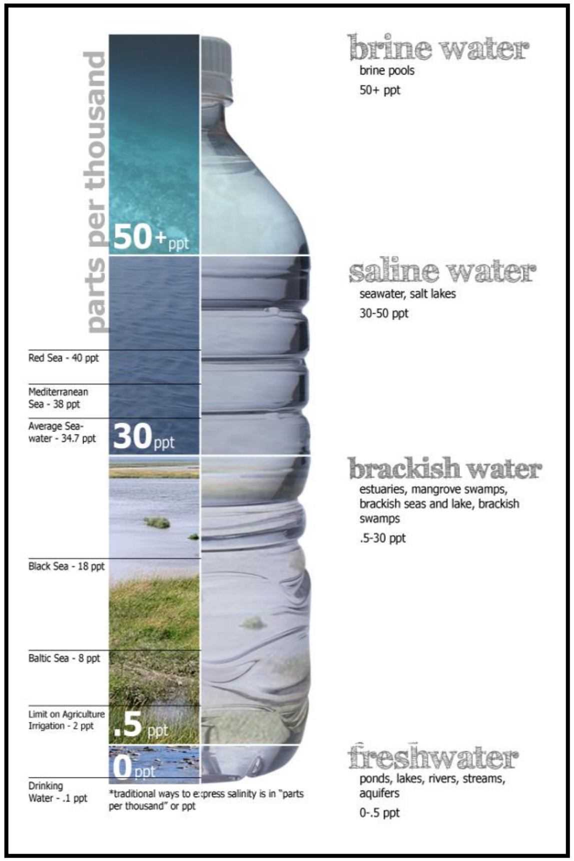
- The scale of the Geology is below the ability of the logging tool to resolve significant details.
- Deep Resistivity tools have poor vertical resolution
- Often considered as a Shaly Sand problem

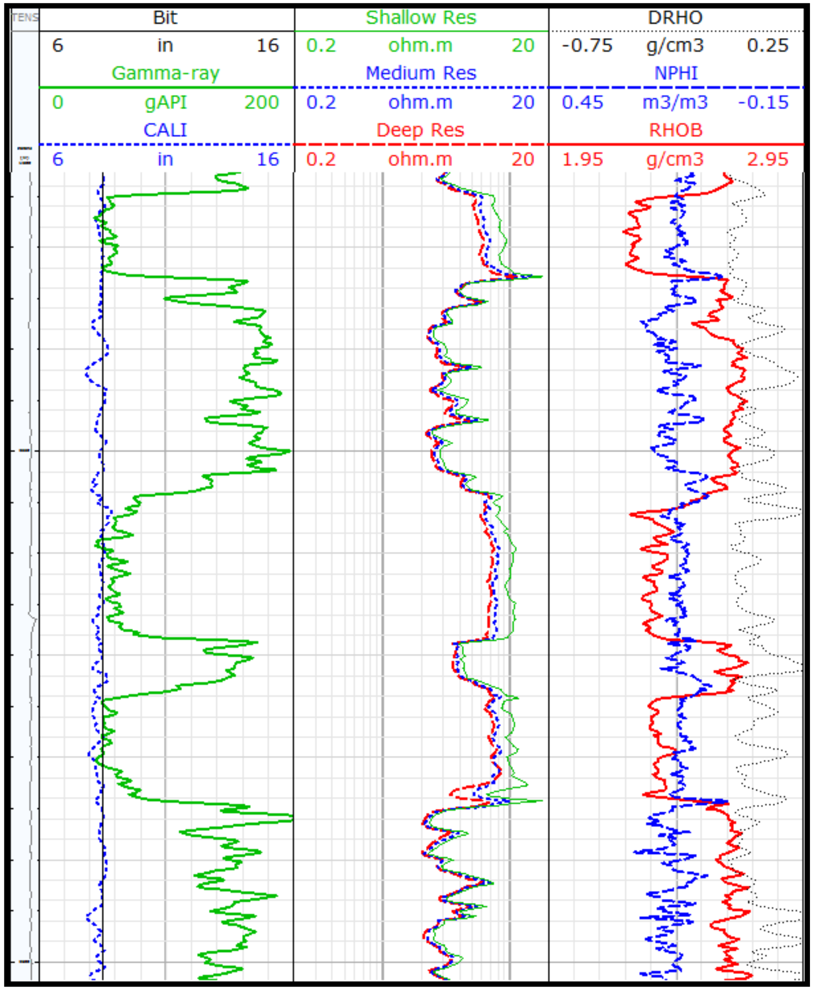




What makes Archie stop working?

- 'fresh' formation water
- little or no dissolved salts
- little or no contrast between Ro and Rt



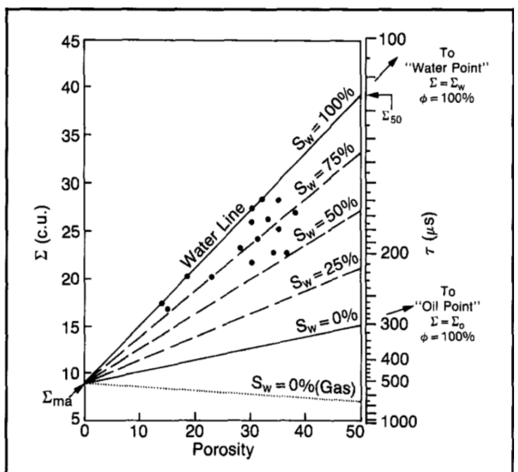


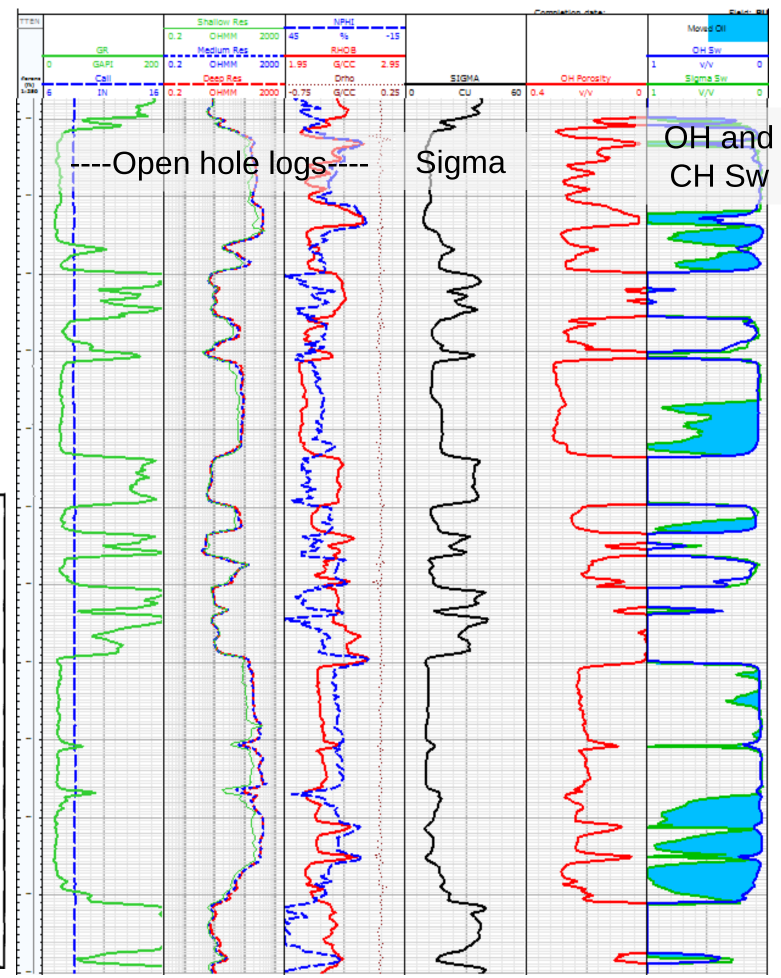
What else helps us quantify water saturation?
Cased-hole Pulsed Neutron Capture (Sigma) Logs

- PNC tools emits regular pulses of neutrons and measures the rate at which thermal neutrons are captured, by detection of GR emitted during the capture.

- Interpreting Sigma Curve (Σ)
- Σ log = (1- Φ) Σ matrix +Sw Φ Σ water + (1 -Sw) Φ Σ hc
- Input Parameters
  - Sigma Water
    - varies with salinity *(as Chlorine does most of the capturing)*
    - but which water - formation or injection?
  - Sigma Oil
  - Sigma Matrix

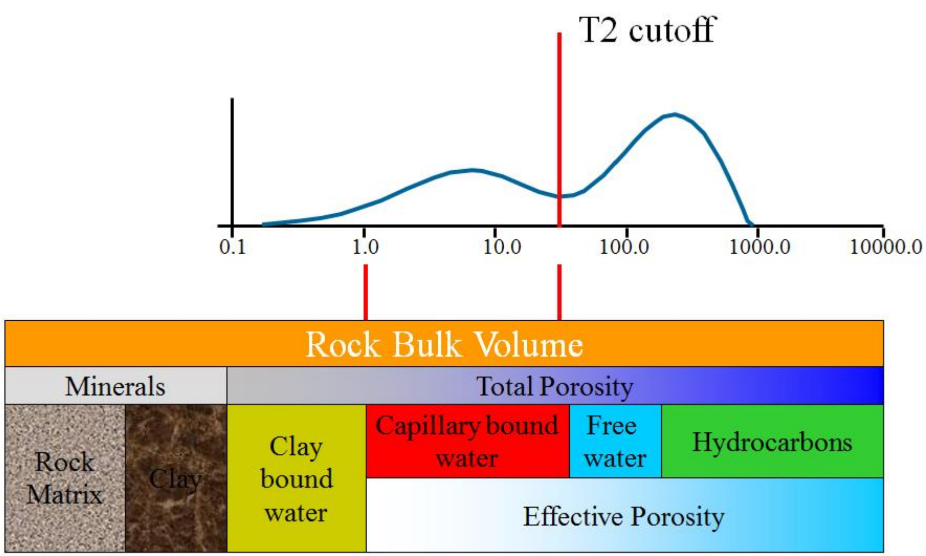
Material	Tau (msec)	Computed Sigma @ 20°C (cu)
Fresh Water (H_2O)	205	22.2
Salt Water	152-35	30-130
Oil	228	20
Gas	910	5
		Apparent Sigma
Sandstone		8.0-10.0
Limestone		12.0
Dolomite		8.0

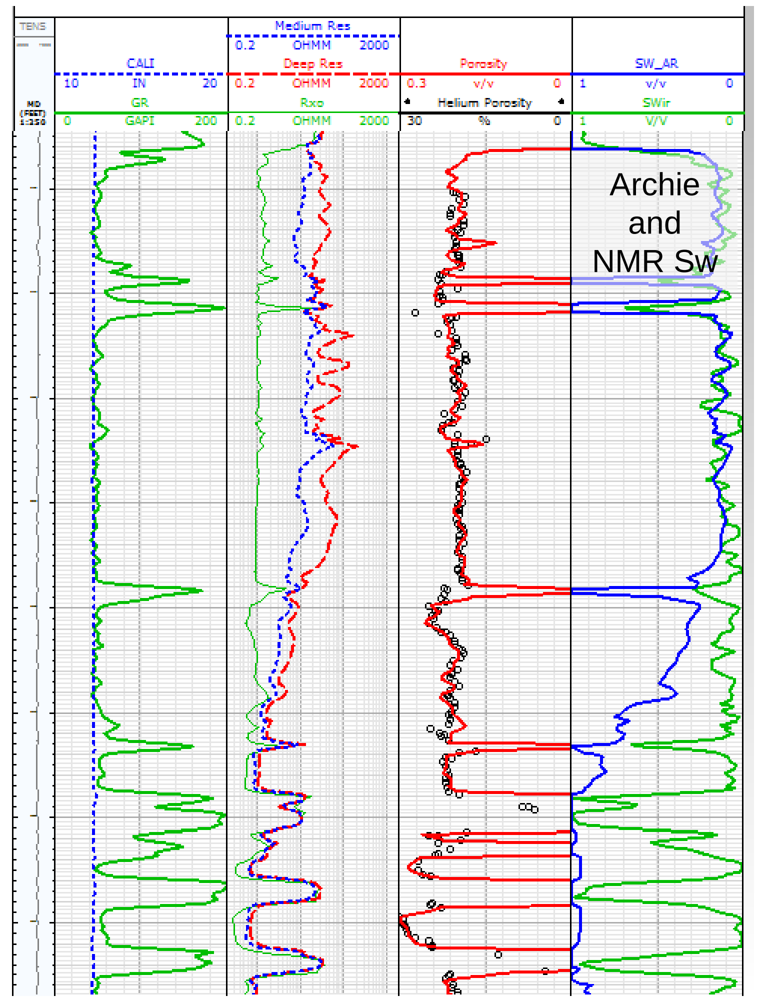




What else helps us quantify water saturation? Magnetic Resonance Tools

- we can use Free Fluid and Capillary Bound Water to calculate Swir
  - Swir = CBW / (CBW + FF)
- But assumes that FF is all hydrocarbons, so doesn't work in the transition zone nor water-leg without other logs.
- NMR tools are also generally shallow reading and can be effected by Gas





What else helps us quantify water saturation?
Dielectric Tools

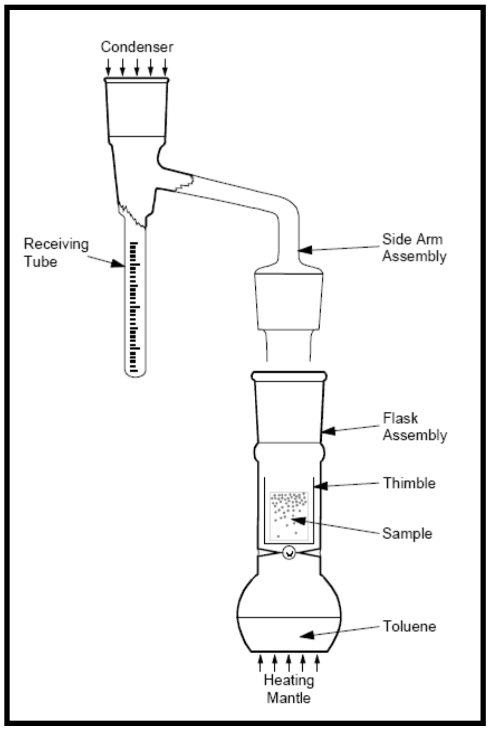
- Dielectric permittivity, ε, is:
  - A physical quantity that describes how an electric field affects, and is affected by a dielectric medium,
  - Is determined by the ability of a material to polarize in response to the field, thereby reduce the total electric field inside the material.
  - Thus, permittivity relates to a material's ability to transmit (or "permit") an electric field.
- Big contrast between water and oil
  - Oil : ε ~ 2
  - Rock : ε ~ 5-9
  - Water : ε ~ 50-80

- Water ε varies with salinity and frequency
- Good resolution, but shallow reading, (new tools 1in to 4in); therefore Sxo and not Sw

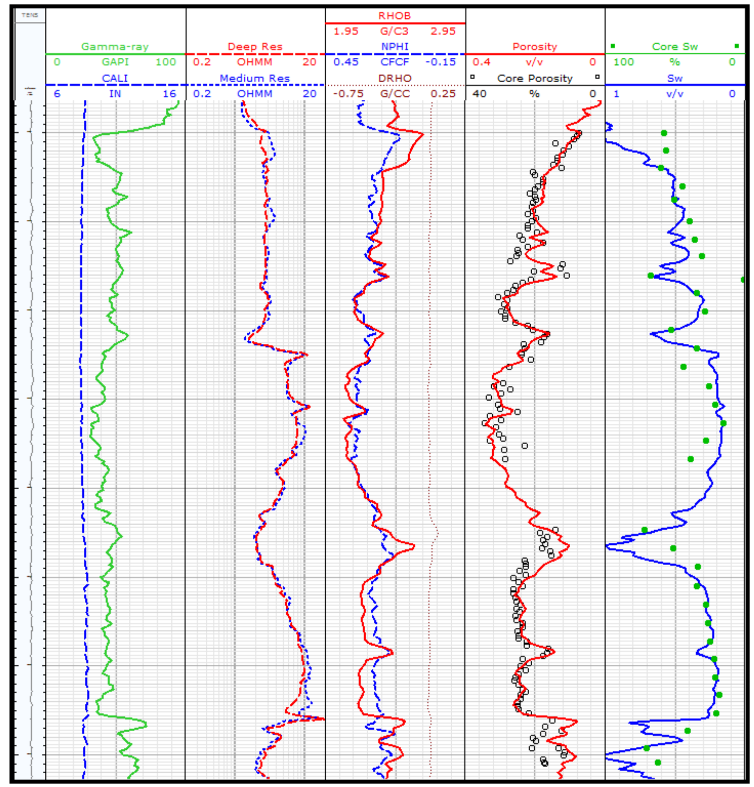
What else helps us quantify water saturation?

- **Directly from core - Dean-Stark extraction**
  - Core with Oil Base Mud
  - Works Best in Oil-leg

Dean-Stark Apparatus



comparison to Archie



E. W. Dean and D. D. Stark (1920). "A Convenient Method for the Determination of Water in Petroleum and Other Organic Emulsions.". *Industrial & Engineering Chemistry* 12 (5): 486–490.

with thanks to Dr Colin McPhee.

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- Resistivity logging
  - Rt = Ro, water-leg
  - Rt >> Ro , hydrocarbons
- Archie's equations
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- When doesn't Archie work ?
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Water Saturation from Electric Logs - some useful stuff

http://petrowiki.org/PetroWiki
http://imis.spwla.org/ *- then Technical - Glossary*
http://www.glossary.oilfield.slb.com/

Term	Units	Explanation
a	unitless	Archie 'tortuosity' factor
B	(1/ohmm)/(meq/ml)	specific cation conductance
Φ	fraction/%age	Porosity
F	unitless	Formation factor
FWL	metres/feet	Free water level, is where Pc is zero
GWC	metres/feet	Gas water contact, first occurrence of hydrocarbons
HAFWL	metres/feet	Height above free water level
m	unitless	Formation Factor exponent
n	unitless	Saturation exponent
OWC	metres/feet	Oil water contact, first occurrence of hydrocarbons
Pc	psi/bar	Capillary pressure
Qv	meq/ml	Cation exchange capacity per unit of pore volume
RI	unitless	Resistivity index
Rm	Ohmm	Mud resistivity
Rmc	Ohmm	Mud cake resistivity
Rmf	Ohmm	Mud filtrate resistivity
Ro	Ohmm	Resistivity of rock fully saturated with water
Rsh	Ohmm	Shale Resistivity
Rt	Ohmm	True formation resistivity
Rw	Ohmm	Formation water resistivity
Rxo	Ohmm	Flushed zone resistivity
Sw	fraction/%age	Water saturation
Sxo	fraction/%age	Flushed zone water saturation
Vsh	fraction/%age	Shale Volume