The University of Texas at Austin

WHAT STARTS HERE CHANGES THE WORLD

# Advanced Petrophysics:
# Fluid Saturation in Porous Media, Part 1 of 3


**Instructor: Zoya Heidari, Ph.D.**

Associate Professor
The University of Texas at Austin




## PGE381L Outline

- Introduction to petrophysics, geology, and formation data
- Porosity
- **Fluid saturations**
- Permeability
- Quantification of heterogeneity, spatial data analysis, and geostatistics
- Interfacial phenomena and wettability
- Capillary pressure
- Relative permeability
- Dispersion in porous media
- Introduction to petrophysics of unconventional reservoirs

## What Do We Learn in This Lecture?

- **What is fluid saturation?**
- **How to estimate fluid saturation in the laboratory?**
- How to estimate fluid saturation in-situ condition?
- How does presence of clay minerals affect water/hydrocarbon saturation estimates?
- How to quantitatively take into account the effect of clay minerals in fluid saturation assessment
- Laboratory vs. in-situ estimates of fluid saturations
- How to calculate total hydrocarbon reserves?



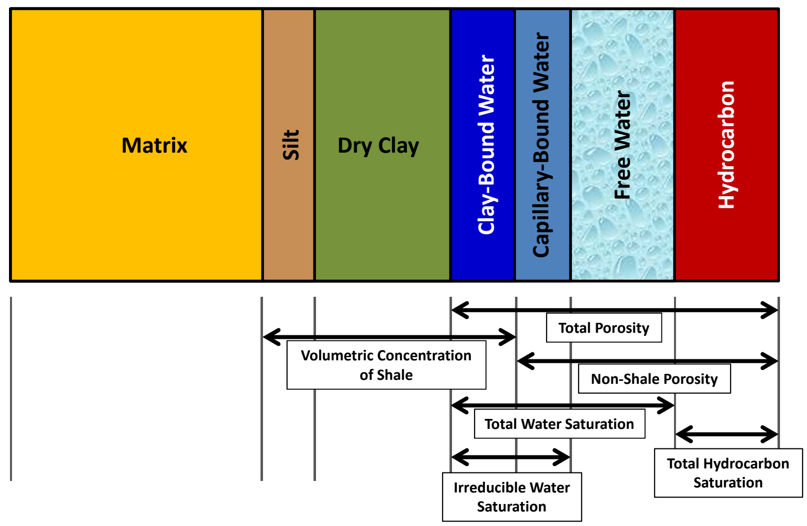
## What is Water/Hydrocarbon Saturation?

$$Fluid\ Saturation = \frac{Fluid\ Volume}{Rock\ Pore\ Volume}$$

$$S_w = \frac{V_w}{V_p} \qquad S_o = \frac{V_o}{V_p} \qquad S_g = \frac{V_g}{V_p}$$

$V_p$: Void space or pore volume
$V_w$: Volume of water
$V_o$: Volume of oil
$V_g$: Volume of gas

## Fluid Saturation and Fluid Mobility






## How to Estimate Fluid Saturations

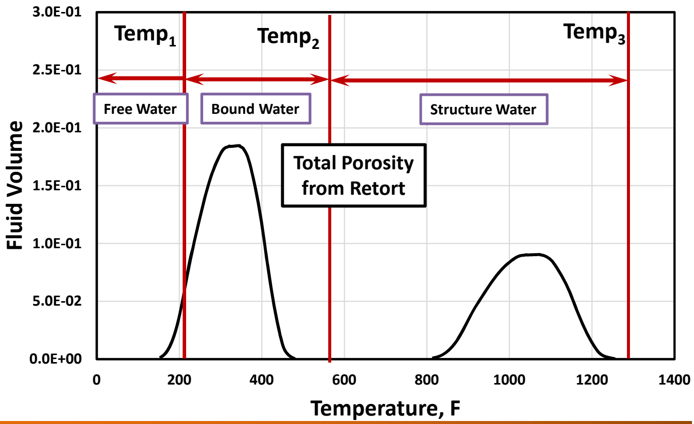
**Water/hydrocarbon saturation is <u>not</u> measured!**

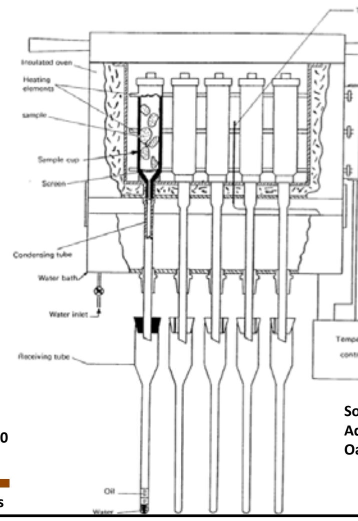
**Water/hydrocarbon saturation is estimated!**

- How to Estimate Fluid Saturations?
  - Laboratory-based fluid saturation assessment:
    - Routine core analysis: Retort and Dean-Stark methods
    - Unconventional fluid saturation assessment methods: 2D NMR measurements
    - Imaging of core samples
  - In-situ assessment of fluid saturation using well logs

# Retort Method

The **retort** method is performed by **heating** the sample **in air** to extract the fluid. As done commercially, the heating is incremented to three pre-defined temperature steps: 230 °F (110 °C), 600 °F (315 °C), and 1300 °F (700 °C).



Retort oven

Source: Peters, E. J., 2012, Advanced Petrophysics. Live Oak Book Company.



# Assumptions/Limitations: Retort

- Do we measure weight or volume of the fluids?
- Assumptions (Volume measurement):
  - All fluid is recovered
  - The volumes can be measured accurately with low uncertainty.
- Assumptions/Uncertainties (Weight measurement):
  - The weight difference between the before extraction (or retort) sample weight and the sample weight after the extraction (or retort) can be measured accurately
  - Conversion of weight to volume

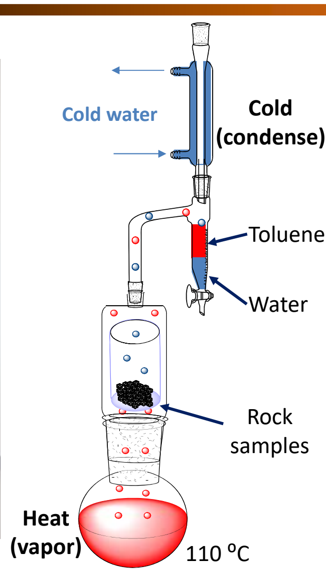
# Assumptions/Limitations: Retort

- What is the impact of high temperatures on the results?
  - Water of crystallization (hydration) of the rock is driven off
    - How does it impact estimates of water saturation?
  - The heated oil has a tendency to crack and coke
    - How does it impact estimates of oil saturation?



# Dean-Stark (DS) Method

**Dean Stark Apparatus**




The **Dean Stark** method involves **bathing** the rock sample in **toluene**. This is done in an assumed closed environment, where the **toluene vapor extracts water** from the sample.

- **Water Volume**
- **Oil Volume**

## Assumptions/Limitations: Dean-Stark Method

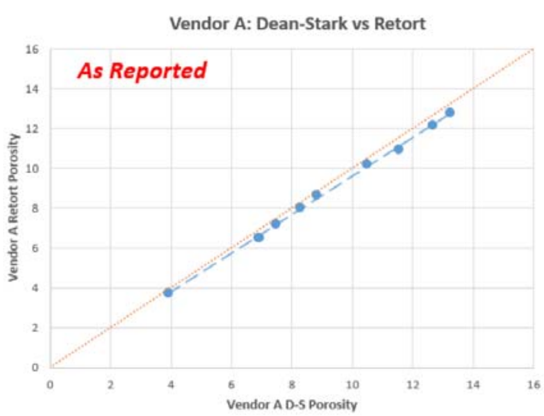
- Do we measure $\boxed{\text{weight}}$ or volume of the recovered water?

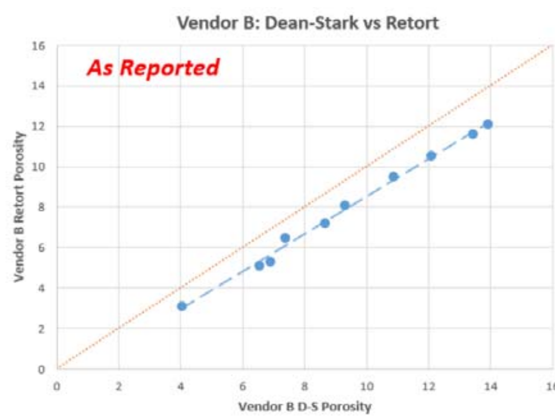
The typical process

- The weight of the recovered water is subtracted from the weight delta of the sample. This difference is assumed to be the weight of oil.



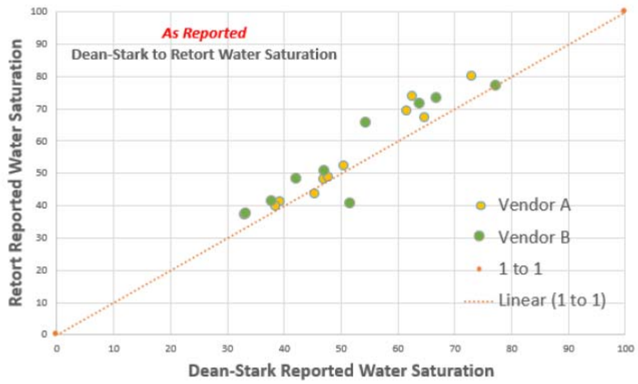
## Example: Retort vs. Dean-Stark




Source: Blount, A., et al., 2017, SPWLA.

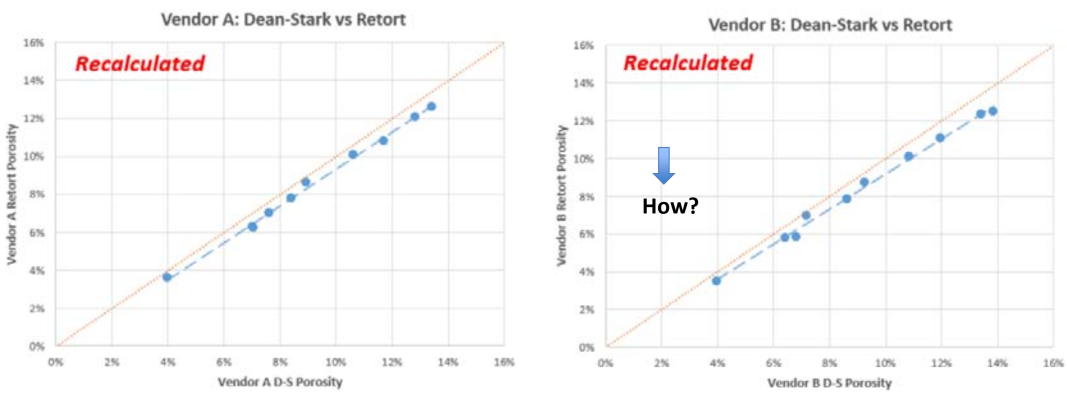
# Example: Retort vs. Dean Stark




Source: Blount, A., et al., 2017, SPWLA.



# Example: Retort vs. Dean Stark




Source: Blount, A., et al., 2017, SPWLA.

Please read the paper by Blount, A., et al., 2017, SPWLA.

## What is the reason behind this difference?

- The bucketing of the "missing weight"
  - ➔ Lower the Dean-Stark porosities
- Not recovering all oil during the retort process
  - ➔ Increase the retort porosities





# Advanced Petrophysics: Fluid Saturation in Porous Media, Part 2 of 3

Instructor: Zoya Heidari, Ph.D.

Associate Professor
The University of Texas at Austin

## What Do We Learn in This Lecture?

- What is fluid saturation?
- How to estimate fluid saturation in the laboratory?
- **How to estimate fluid saturation in-situ condition?**
- **How does presence of clay minerals affect water/hydrocarbon saturation estimates?**
- **How to quantitatively take into account the effect of clay minerals in fluid saturation assessment**
- **Laboratory vs. in-situ estimates of fluid saturations**
- How to calculate total hydrocarbon reserves?

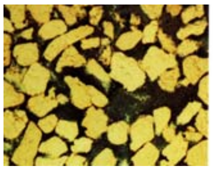
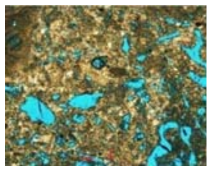
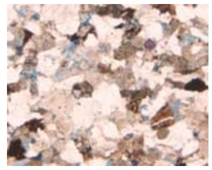
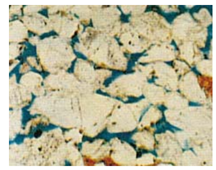
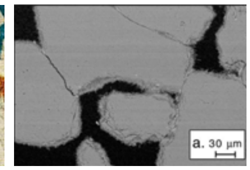


## In-situ Assessment of Water/Hydrocarbon Saturation using Well Logs

- **What well logs can be used for fluid saturation assessment?**
  - **Electrical conductivity/resistivity measurements**
  - **2D NMR measurements**
  - **Dielectric dispersion measurements**
  - **Sigma (neutron capture cross section) measurements**

## Resistivity Measurements

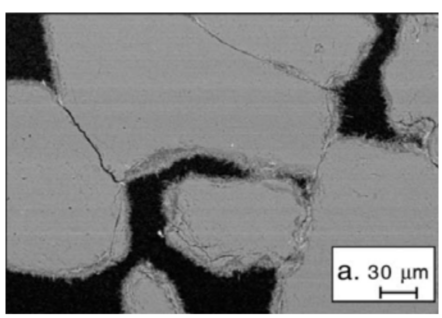
- **What parameters affect electrical resistivity of rocks?**

- **What information about reservoir petrophysics do we get from resistivity measurements?**



## What about this one?

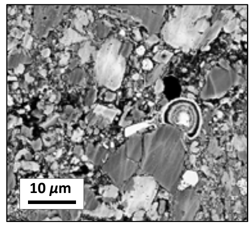


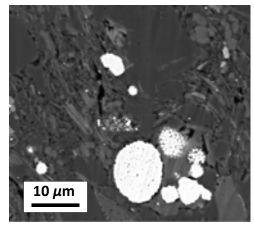

Source: Rabaute, A., A. Revil, and E. Brosse, 2003.

# Distribution of Conductive Components

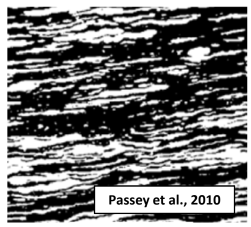
**Does the distribution of conductive components matter?**

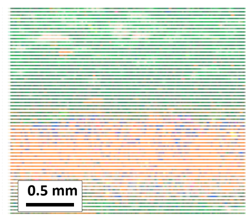
Dispersed distribution




Layered distribution

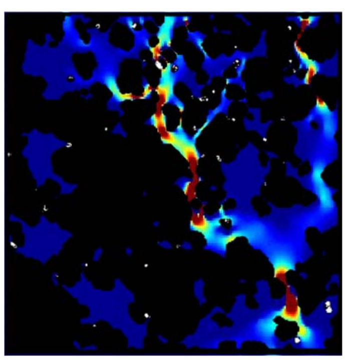


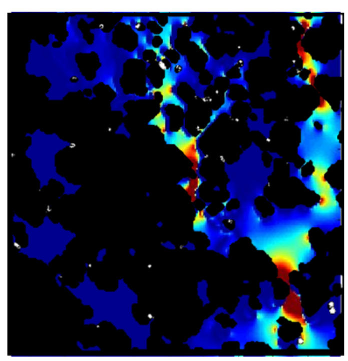


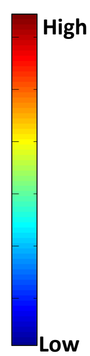

# Electric Current and Fluid Flow

**Fluid Flow**



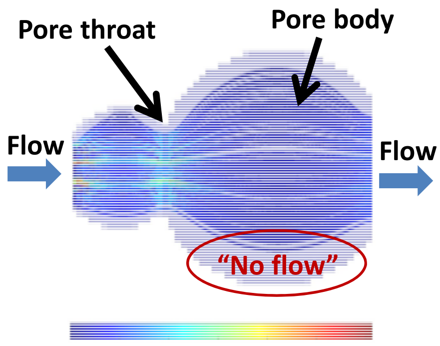
**Electrical Current**





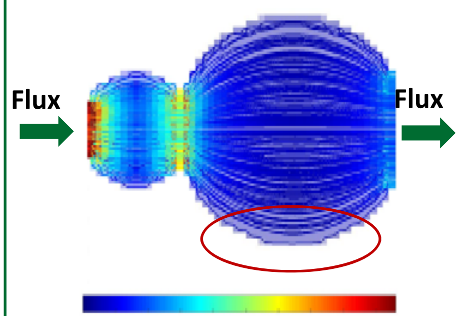
# Fluid Flow versus Electric Current Flux

## Fluid Flow




No slip boundary condition

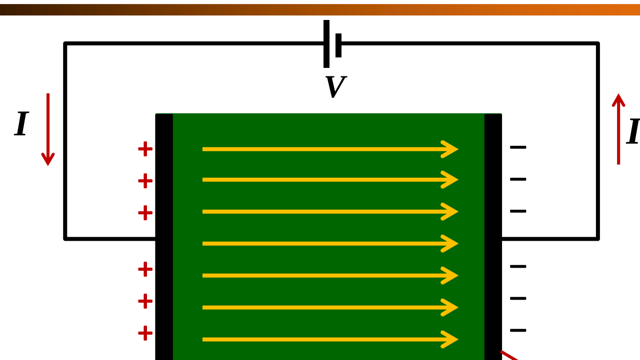
## Electric Current Flux




No flux perpendicular to the grain



# Ohm's Law




$A$ Cross-sectional area

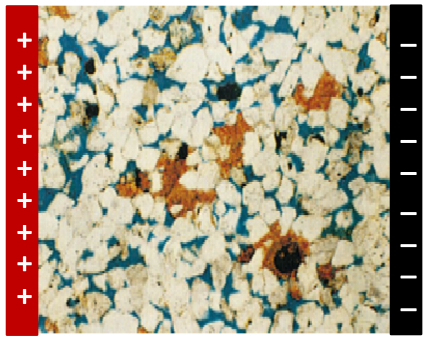
Homogeneous Medium

$$R = \frac{V}{I} = \rho \frac{L}{A}$$

Electrical Resistance (ohm)

Electrical Resistivity (ohm-m) → We call it R in well logging applications

# What are the Conductive Pathways?




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

Electrical Conductivity
(mho/m or S/m)

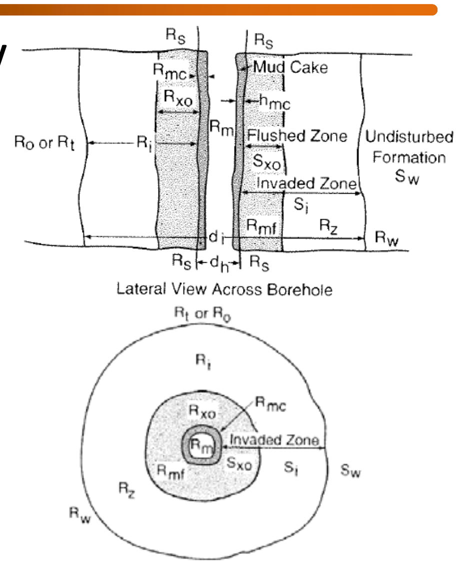
**Assumption:**

**Electrical currents pass through the conductive pore space.**



# Definitions

- **Formation water resistivity**
  - $R_w$
- **Mud-filtrate resistivity**
  - $R_{mf}$
- **Salt concentration**
  - $C_w$, $C_{mf}$
  - NaCl, KCl, ……




Source: Baker Atlas, 2002, Introduction to Wireline Log Analysis.

# Electrical Conduction in Solutions

Static electric field

Viscosity of water

effective radius of the ion

Charge of each charge carrier

$$\underbrace{q\vec{E}}_{\text{The applied force}} = \underbrace{6\pi\eta r\vec{v}}_{\text{The viscous force, exerted by the fluid on the hydrated ion}}$$

Ion velocity

Ion mobility

$$\vec{v} = \mu\vec{E} \quad \Rightarrow \quad \mu = \frac{q}{6\pi\eta r}$$

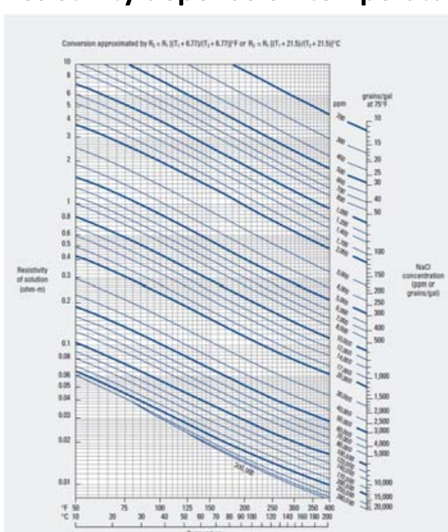
Ionic concentration

Ionic conductivity $\sigma_w = qn\mu = \dfrac{nq^2}{6\pi\eta r}$



# Resistivity of Solution, Salt Concentration, and Temperature

- **Resistivity depends on temperature and salt concentration**



$$R_2 = R_1 \frac{T_1 + 6.77}{T_2 + 6.77}, \qquad T \text{ in } ^\circ F$$

$$R_2 = R_1 \frac{T_1 + 21.5}{T_2 + 21.5}, \qquad T \text{ in } ^\circ C$$

Courtesy of Schlumberger

# Resistivity of Solution, salt Concentration, and Temperature

**Resistivity varies with variation of temperature and salt concentration**

$$R_2 = R_1 \frac{T_1 + 6.77}{T_2 + 6.77}, \qquad T \text{ in } ^\circ F$$

$$R_2 = R_1 \frac{T_1 + 21.5}{T_2 + 21.5}, \qquad T \text{ in } ^\circ C$$

$$R_w = \left(0.0123 + \frac{3647.5}{\left[NaCl_{ppm}\right]^{0.955}}\right) \cdot \left(\frac{81.77}{T + 6.77}\right), \qquad T \text{ in } ^\circ F$$

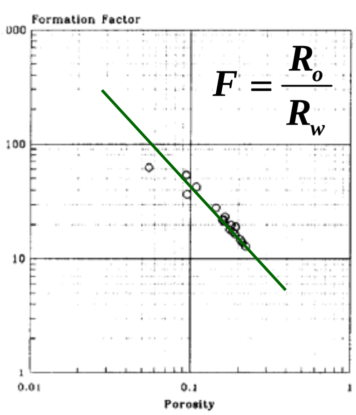


# An Empirical Correlation

**Archie's first law (1942)**

**(Clay-free sandstones saturated with saline brine)**

**Sandstone**




Source: Mao et al., 1995.

$$\log(F) = \log(a) - m \log(\phi)$$

$$\longrightarrow \log(F) = \log\left(\frac{a}{\phi^m}\right)$$

$$\longrightarrow F = \frac{1}{\phi^m} = \frac{R_o}{R_w}$$

Porosity exponent
(Lithology exponent, Cementation exponent)

## Archie's First Law

- **Clay-free water-saturated sandstones**

$$R_o = R_w \frac{1}{\phi^m}$$

**Resistivity of the fully water-saturated rock**

**Porosity exponent (Lithology exponent, Cementation exponent)**

**F**

**Formation factor**

**Resistivity of formation water**



## Formation Factor

- **Parameters affecting formation factor:**
  - **Porosity**
  - **Pore geometry**
  - **Cementation**
  - **Type and volumetric concentration of clay**

**Winsauer factor, 1952**

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

**Sandstones:**

$a = 0.8\ ,\quad m = 2$ — **Typical consolidated sandstone**

or

$a = 0.62\ ,\quad m = 2.15\quad (Humble)$ — **Typical unconsolidated sandstone**

**Carbonates:** $a = 1\ ,\quad m > 2$

**Archie's equation is not always valid in carbonates!**

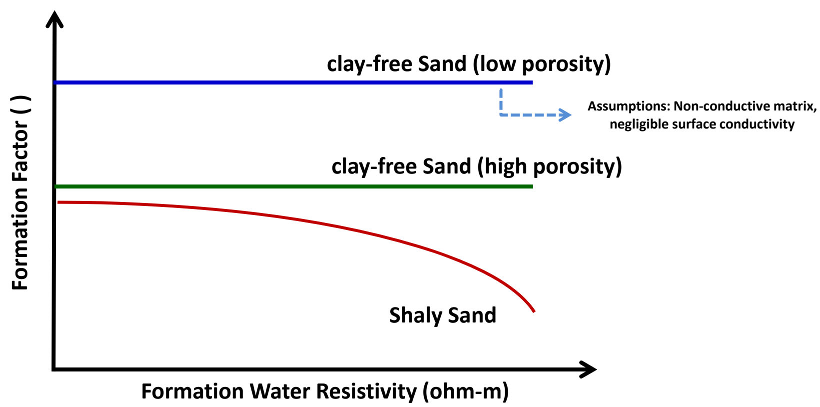
# Formation Factor

$$\underset{\text{Formation Factor}}{F} = \frac{R_o}{R_w}$$

Formation Factor ← $F$: Intrinsic property of the porous medium

$R_o$ → Resistivity of the fully water-saturated rock

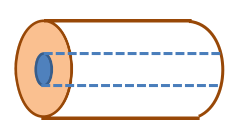
$R_w$ → Resistivity of formation water






# How does Porosity affect Formation Factor?

- **If the pore volume is modeled by straight capillary tubes:**



- **If the pore volume is modeled by spheres:**

**Maxwell's equation** $F = \dfrac{3-\phi}{2\phi}$

**Fricke's equation** $F = \dfrac{(c+1)-\phi}{c\phi}$ $\quad c < 2 \quad$ for spheroids

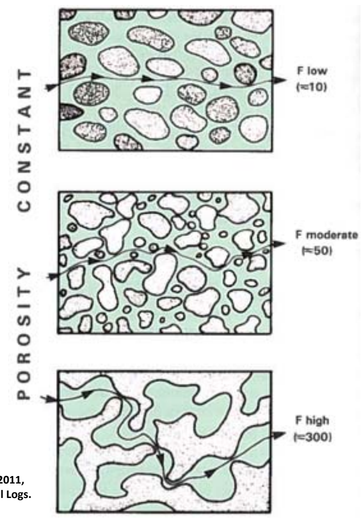
**Starwinsky's equation** $F = \dfrac{(1.3219-0.3219\phi)^2}{\phi}$ $\quad$ spheres in contact

# Formation Factor

**Role of matrix on formation factor:**

$$\tau_e \approx \phi F$$

**(Wylie, 1957)**

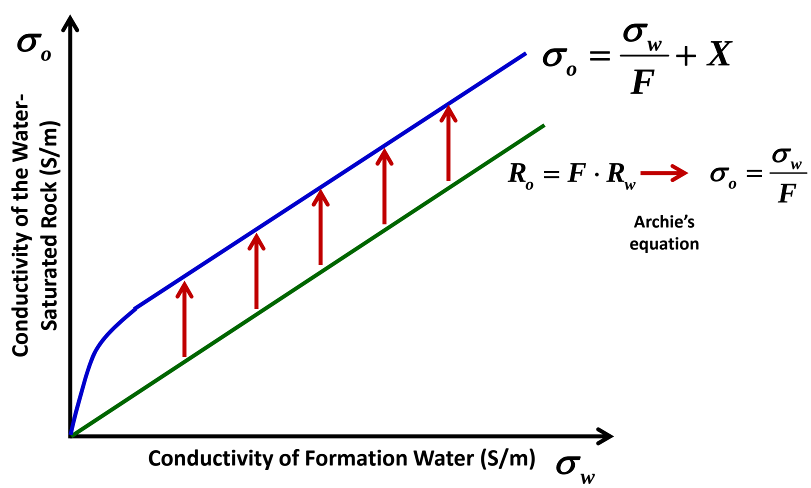



Source: Rider, M. and Kennedy, M., 2011, The Geological Interpretation of Well Logs.



# Reliability of Archie's Equation in Shaly Sands

- **Archie's equation fails in shaly sands**



# An Empirical Correlation

Humble Formula:

$$F = \frac{a}{\phi^{m_1}}$$

a and $m_1$ are not independent

Typical values for a and $m_1$:

$$a = 0.62$$
$$m_1 = 2.15$$

$$m_1 = m + \frac{1}{\log \phi} \log a$$

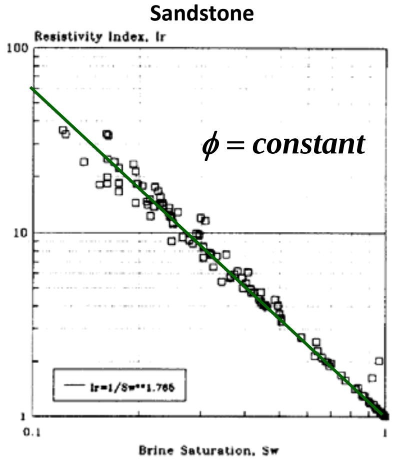


# Partially-Saturated Rocks

Resistivity index $I_R = \frac{R_t}{R_o}$

**Archie's second law**

Sandstone




Source: Mao et al., 1995.

$$\log(I_R) = -n\left[\log(S_w)\right]$$

$$\rightarrow \log(I_R) = \log\left(\frac{1}{S_w{}^n}\right)$$

$$\rightarrow I_R = \frac{R_t}{R_o} = \frac{1}{S_w{}^n}$$

Saturation exponent

## Assessment of Fluid Saturation

**Archie's equation:**

$$S_w^n = F\frac{R_w}{R_t}$$

*F*: Formation resistivity factor
$R_w$: Formation water resistivity
$R_t$: True formation resistivity

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

Proposed by Archie in 1941 and modified by Winsauer in 1952.

$$\boxed{R_t = R_w \frac{a}{\phi^m S_w^n}}$$

*a*: Tortuosity factor
(Winsauer factor in Archie's equation)
*m*: Porosity exponent
*n*: Saturation exponent

Empirical constants

Typical values:
a = 1
m = 2
n = 2



## Can We Derive Archie's Equation Analytically?

- **Please read the following papers:**
  - Berg, C. F. 2012. Re-examining Archie's law: Conductance description by tortuosity and constriction. *Physical Reviews* 86(4)
  - Kennedy, D. and Herrick, D. C. 2012. Conductivity models for Archie rocks. *Geophysics* 77(3): WA109–WA128.

# Reliability of Archie's Equation


Source: Kennedy and Herrick, 2012; Courtesy of Steve Bryant

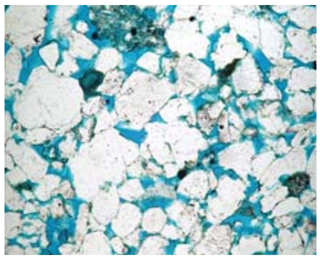


# Reliability of Archie's Equation

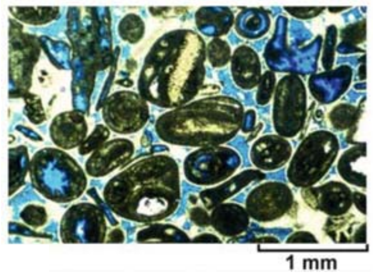
- **Reliability of Archie's equation:**
  - **Clay-free clastics (negligible clay)**
  - **Archie's equations work in the presence of clay if formation water resistivity is low ($C_w$>30,000 ppm) and water saturation is high**
  - **Porosity is assumed to be interconnected**
  - **Electrical conduction is assumed only within water, not grains or other fluids**
  - **Tortuosity is inversely proportional to porosity**
  - **Not reliable in non-clastic carbonate formations**
    - **Archie's equation works in Grainstones similar to silciclastic formations**

# Reliability of Archie's Equation

Sandstone



Grainstone

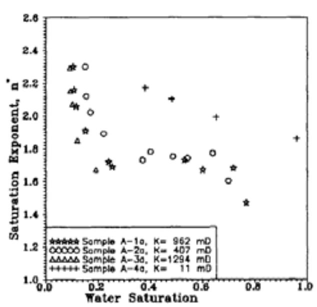



Source: Lucia, J., 2007, Carbonate Reservoir Characterization

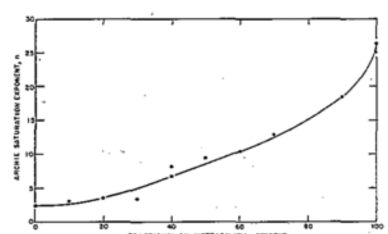


# Reliability of Archie's Equation

- **Reliability of Archie's second equation:**
  - **Breaks down in oil-wet rocks, when water saturation is low**
  - **n might vary with variation of water saturation**

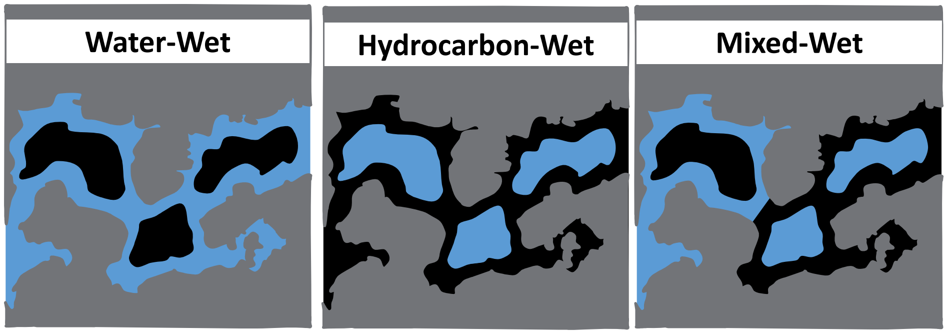



Source: Sondenaa et al., 1991.



Source:Anderson, 1986.

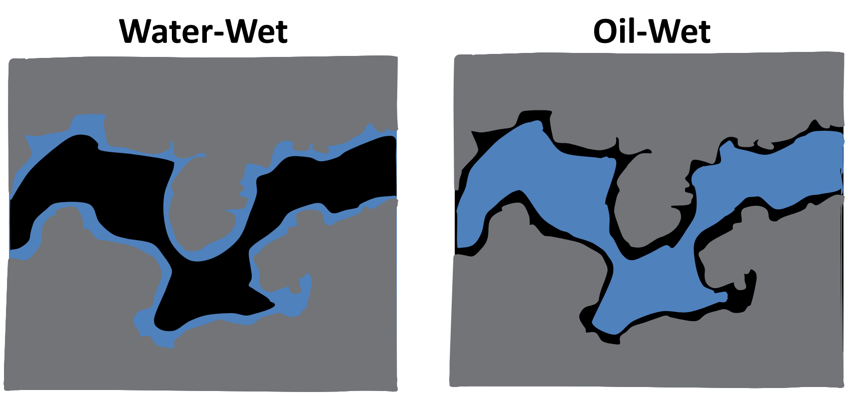
## Mixed-Wet and Hydrocarbon-Wet Rocks




| Water-Wet | Hydrocarbon-Wet | Mixed-Wet |
|---|---|---|
| Water makes a conducting film for any oil saturation. | Water is isolated and does not conduct at low water saturations. | Water may or may not make a conducting network. |

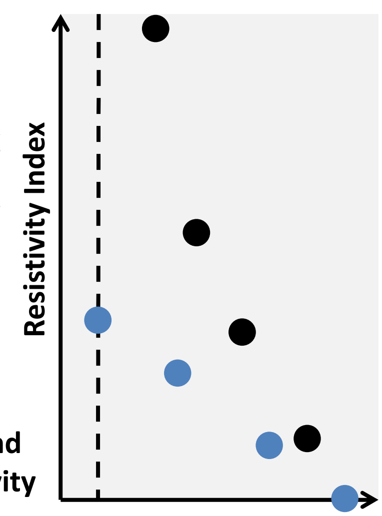


## Impact of Wettability on Resistivity Measurements

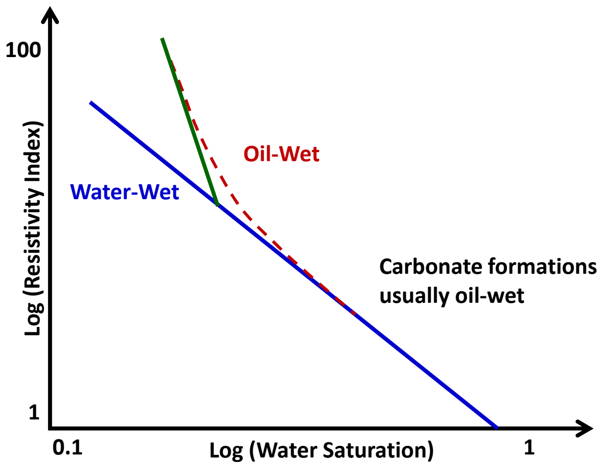



Grain (Resistive)
Oil (Resistive) Water (Conductive)

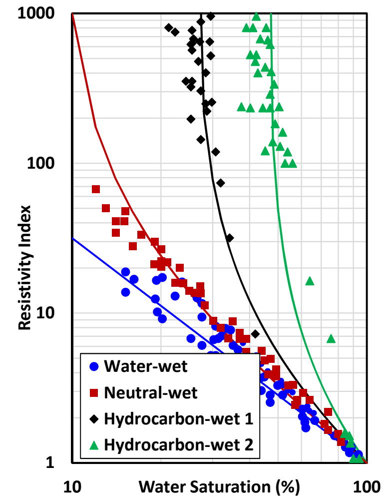
Both water saturation and wettability affect resistivity measurements.



# Mixed-Wet and Hydrocarbon-Wet Rocks



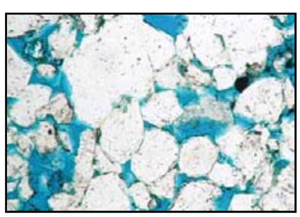

Carbonate formations are usually oil-wet






# Reliability of Archie's Equation

- Reliability of Archie's second equation:
  - m might also vary with variation of porosity in carbonate formations



**Be aware of limitations and assumptions behind the analytical/experimental correlations that you use!**

## Archie's Equation

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

Identify the known and the unknown parameters!

How do we estimate the unknown parameters?

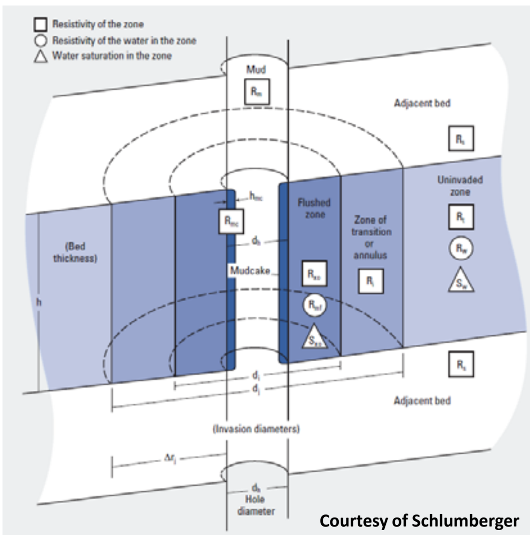
How would you estimate Rw?



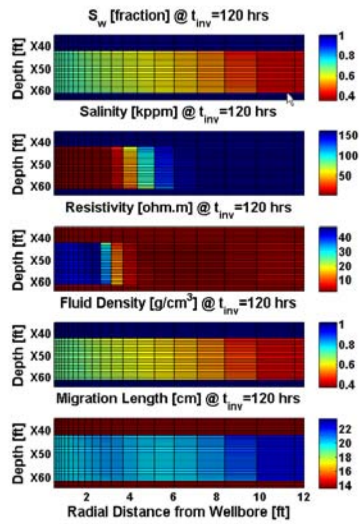
## Let's Practice!

- Examples:
  - Where can you find hydrocarbon?
  - Detect fully water-saturated zones
  - Estimate formation water resistivity
  - Estimate water saturation at different depths
  - What is the type of hydrocarbon in this formation? How can you identify the type of hydrocarbon?
  - What information do you need to estimate water saturation?

# How Does Mud-filtrate Invasion Affect Resistivity Measurements?




Courtesy of Schlumberger



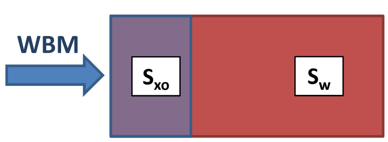

Source: Z. Heidari et al., 2011, Assessment of residual hydrocarbon saturation with the combined quantitative interpretation of resistivity and nuclear logs: *Petrophysics*, vol. 52, no. 3, pp. 1-35.



# Can We Estimate Movable Hydrocarbon Saturation?

**WBM**

**In ideal cases**




$S_h = 1 - S_w$

How much of this hydrocarbon is movable?

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

Deep resistivity measurement → Initial water saturation, $S_w$

Shallow resistivity measurement → Water saturation in the invaded zone, $S_{xo}$

$$R_{xo} = R_{mf} \frac{a}{\phi^m S_{xo}^n}$$

$$S_{h,movable} = S_h - (1 - S_{xo})$$

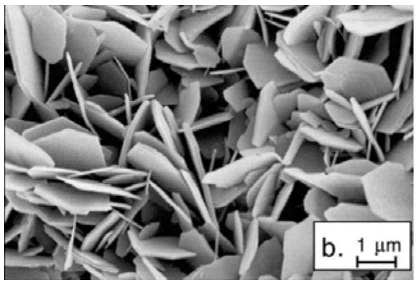
$$\rightarrow S_{h,movable} = S_{xo} - S_w$$

What if drilling mud is OBM?

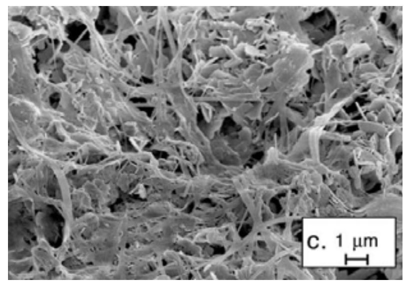
## What about Shaly-Sand Formations?

- What are the main differences between these two clay types?
- How can these differences impact electrical conductivity of the rocks?

Chlorite



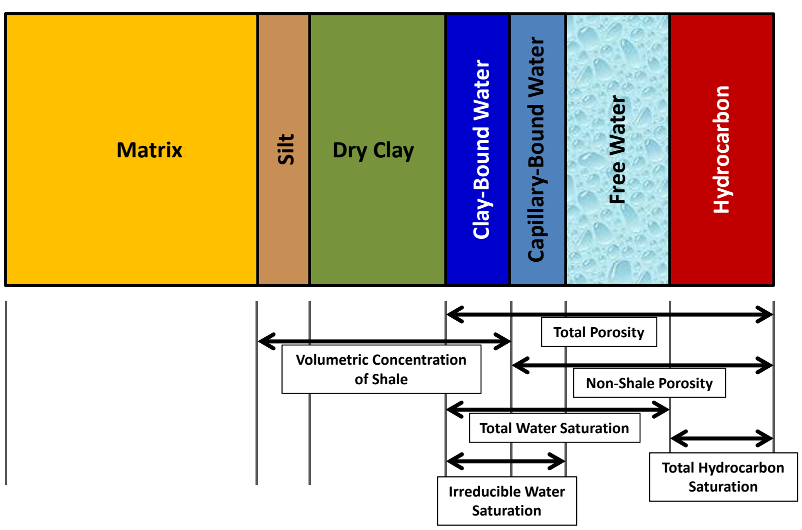

Illite




Source: Rabaute, A., A. Revil, and E. Brosse, 2003, In situ mineralogy and permeability logs from downhole measurements: Application to a case study in clay-coated sandstone formations: Journal of Geophysical Research, 108, no. B9, 2414, 1–16.

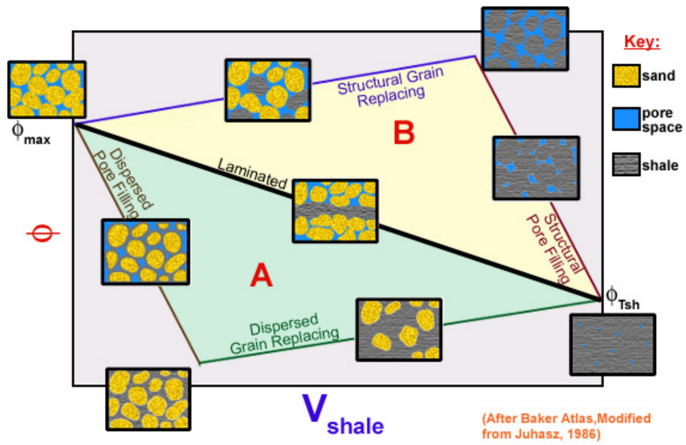


## Shaly-Sand Petrophysical Model



# Impact of Shale/Clay Distribution on Electrical Conductivity

## Thomas-Stieber Diagram





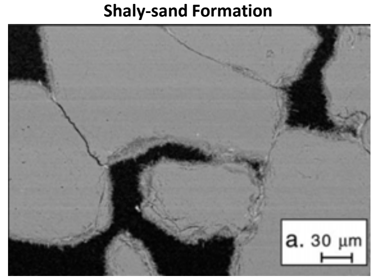

# Impact of Clay Minerals on Electrical Properties

Clay-free Sandstone Formation


Source: Passey, Q., et al., 2010.

Electrolyte conductivity is uniform
Mobile ions are uniformly distributed

Shaly-sand Formation




Source: Rabaute, A., A. Revil, and E. Brosse, 2003.

Charge carriers close to solid surface

Surface conductivity

Additional conductance along the surface

# Electrical Double Layer

- **Clay Minerals**
  - Plate-like form
  - Large surface area
  - Negative surface charge
    - Clays are aluminosilicates (contain $Al^{+3}$ and $Si^{+4}$) in which some of the aluminium and silicon ions have been replaced by elements with different valence or charge (e.g., Substitution by $Mg^{+2}$)
  - Polar water molecules are attracted to clay surface

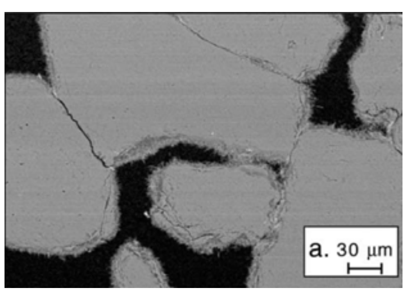
→ Clay-Bound Water

  - Then we have the sodium chlorite as the second layer

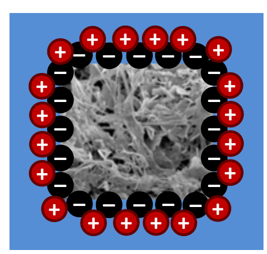


# Electrical Properties of Clays

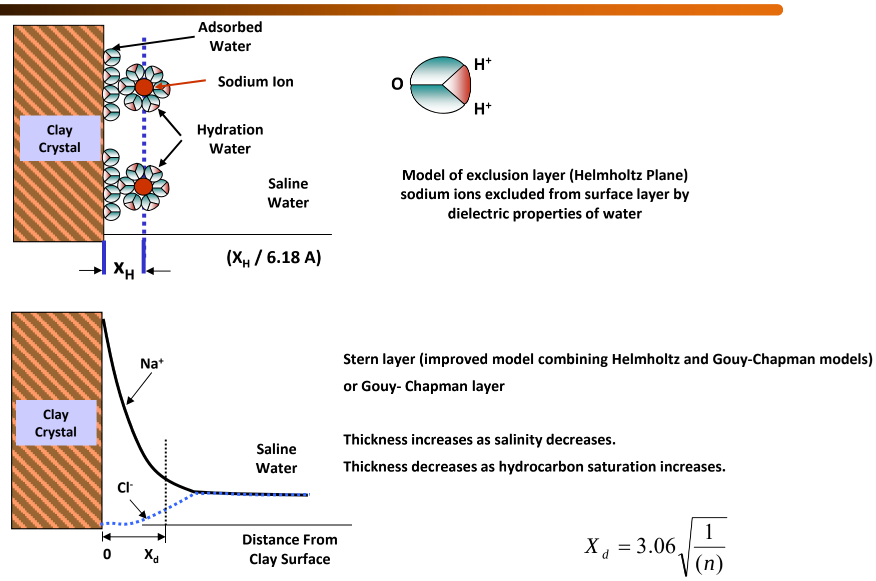
## Electrical Double Layer




Source: Rabaute, A., A. Revil, and E. Brosse, 2003.



## Electrical Double Layer






## Parameters Affecting Electrical Double Layer

- **Double-layer thickness is controlled by:**
  - **Salt concentration of formation water**
  - **Surface to volume ratio of clay**
  - **Hydrocarbon saturation**
  - **Temperature**

## Cation Exchange Capacity

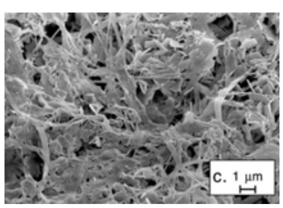
- The quantity of positively charged ions (cations) that a clay mineral or similar material can accommodate on its negatively charged surface is expressed as milli-ion equivalent per 100 g, or more commonly as milliequivalent (meq) per 100 g or cmol/kg.

- The cation-exchange capacity is often expressed in terms of its contribution per unit pore volume, *Qv*.

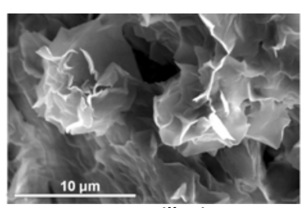


## Surface to Volume Ratio in Clays

| Mineral | S/V Ratio (ft2/ft3) |
|---|---|
| Sand | 4.3-4.7 thousand |
| Kaolinite | 15.2 million |
| Illite | 85.4 million |
| Montmorillonite | 274 million |

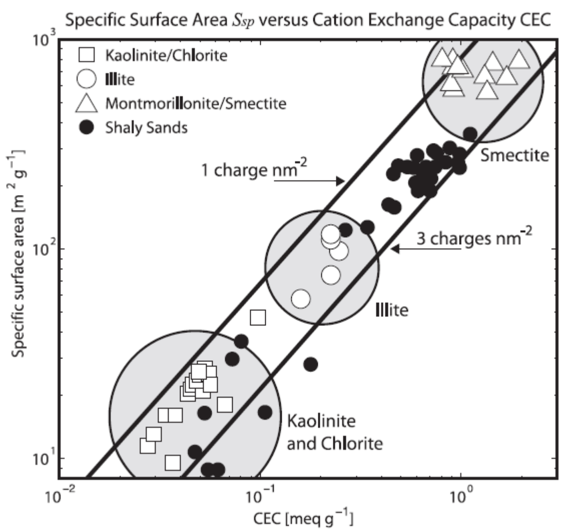


Illite



Montmorillonite

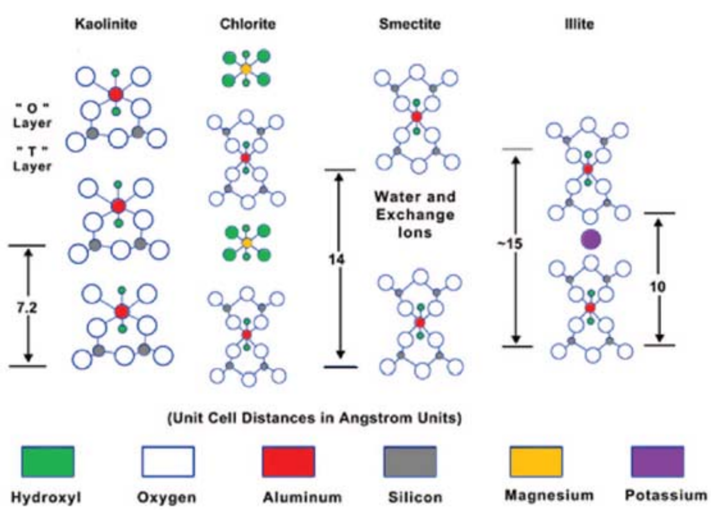
# Surface to Volume Ratio in Clays




Source: Woodruff and Revil, 2011



# CEC of Pure Clay Minerals




| Clay Type | Range of CEC (meq/100 g rock) |
|---|---|
| Smectite | 80 to 100 |
| Illite | 20 to 30 |
| Kaolinite | 2 to 3 |
| Chlorite | 0 to 1 |

**Reading Assignment:**
**Thomas, E. C., 2018, Shaly sands tutorial.**

Source: Thomas, E. C., 2018, Shaly sands tutorial.

# CEC of Pure Clay Minerals

**CEC of Smectite in different formations**

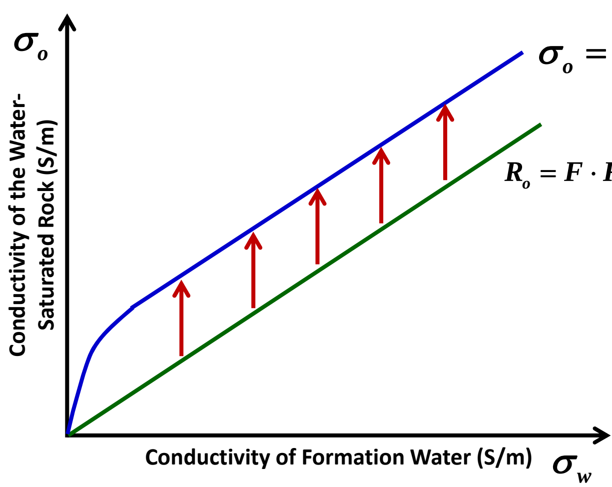
| Clay Formation | Exchange Capacity (meq/100 g clay) |
|---|---|
| Belle Fourche, South Dakota | 85 |
| Upton, Wyoming | 100 |
| Otay, California | 52 |
| Bayard, New Mexico | 127 |
| Polkville, Mississippi | 63 |
| Cheto, Arizona | 96 |

Source: Thomas, E. C., 2018, Shaly sands tutorial.

- **What would be the influence of this uncertainty on formation evaluation outcomes?**
- **How can we quantify CEC?**



# Reliability of Archie's Equation in Shaly Sands




$$\sigma_o = \frac{\sigma_w}{F} + X$$

$$R_o = F \cdot R_w \rightarrow \sigma_o = \frac{\sigma_w}{F}$$

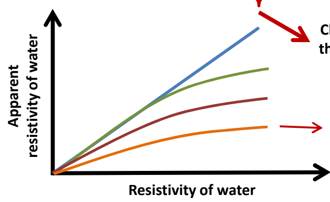
## How to Quantify the Effect of Clay Minerals on Electrical Properties

Surface conductivity

$$\sigma_{eff} = \frac{1}{F}\left(\sigma_w + \frac{\sigma_{surf}}{\underbrace{(\Lambda/2)}}\right)$$

Characteristic length of the rock microstructure

$$(\Lambda/2) \simeq \frac{pore\ volume}{pore\ surface}$$




Number of ions per unit surface area

$$\sigma_{surf} = n'qB$$

Mobility of ions

charge

$$\sigma_{eff} = \frac{1}{F}\left(\sigma_w + B\frac{n'qS_p}{V_p}\right) = \frac{1}{F}\left(\sigma_w + BQ_v\right)$$

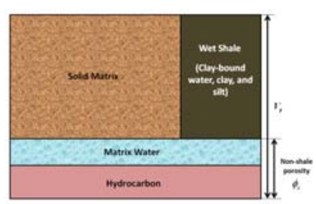
Total charge in the double layer per unit pore volume



## Dispersed Shaly-Sand Formations

$$\rho_b = \phi_s\rho_f + \left(1 - \phi_s - C_{sh}\right)\rho_m + C_{sh}\rho_{sh}$$

Dispersed shale




**Derivation:**

## Dispersed Shaly-Sand Formations

Density porosity and neutron porosity correction for the effect of shale:

$$\phi_{D,m}^{sh} = \phi_{D,m} - C_{sh}\left(\phi_{D,m}\right)_{sh}$$

$$\phi_{N,m}^{sh} = \phi_{N,m} - C_{sh}\left(\phi_{N,m}\right)_{sh}$$

<u>Derivation:</u>



## Non-Shale Porosity and Total Porosity

**What is next?**

Oil
$$\phi_s = \frac{\phi_D^{sh} + \phi_N^{sh}}{2}$$

Gas
$$\phi_s = \sqrt{\frac{\left(\phi_D^{sh}\right)^2 + \left(\phi_N^{sh}\right)^2}{2}}$$

$$\phi_t = \phi_s + C_{sh}\phi_{sh}$$

What about assessment of $S_w$?

## Assessment of Water Saturation

- **Resistivity models for shaly-sand analysis:**
  - Waxman-Smits
  - Dual water
  - Poupon's Method
  - Indonesian (Poupon-Leveaux)
  - Simandoux
  - Modified Simandoux



## Shaly-Sand Resistivity Models

**Waxman-Smits**

$$\boxed{\frac{1}{R_t} = \frac{\phi_t^{m*} S_{wt}^{n*}}{a \cdot R_w} \cdot \left(1 + B \cdot Q_v \frac{R_w}{S_{wt}}\right)}$$

**How to estimate B and $Q_v$?**

**Thomas-Haley solution for BQv in water-bearing shaly sands (Thomas and Haley, 1977)**

## Other Form of Waxman-Smits Equation

$$\frac{R_t}{R_o} = S_{wt}^{-n^*} \cdot \left( \frac{1 + R_w B Q_v}{1 + R_w B Q_v / S_{wt}} \right)$$

How can we solve this equation to estimate $S_w$?

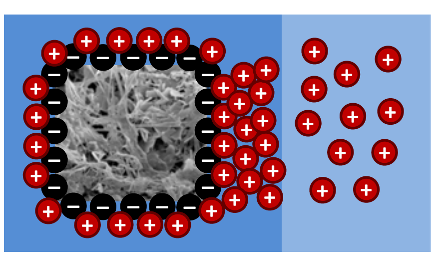
$$R_o = \left( \frac{F^* R_w}{1 + R_w B Q_v} \right) \qquad F^* = \phi^{-m^*}$$



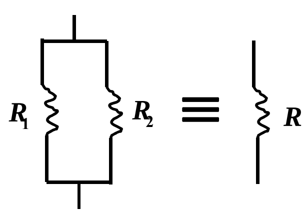
## Shaly-Sand Resistivity Models

### Dual Water

$$\boxed{\frac{1}{R_t} = \frac{\phi_t^m S_{wt}^n}{a} \cdot \left( \frac{1}{R_w} + \frac{S_{wb}}{S_{wt}} \left( \frac{1}{R_{wb}} - \frac{1}{R_w} \right) \right)} \qquad S_{wb} = C_{sh} \frac{\phi_{sh}}{\phi_t}$$



$R_1$ $R_2$




$$\frac{1}{R} = \frac{1}{R_1} + \frac{1}{R_2}$$

## Shaly-Sand Resistivity Models

### Indonesian (Poupon-Leveaux)

$$\frac{1}{\sqrt{R_t}}=\left(\sqrt{\frac{\phi_s^m}{a\cdot R_w}}+\frac{C_{sh}^{\left(1-\frac{C_{sh}}{2}\right)}}{\sqrt{R_{sh}}}\right)\cdot S_{ws}^{n/2}$$



## Shaly-Sand Resistivity Models

### Simandoux

$$\frac{1}{R_t}=\frac{\phi_s^m S_{ws}^n}{a\cdot R_w}+\frac{C_{sh}S_{ws}}{R_{sh}}$$

### Modified Simandoux

$$\frac{1}{R_t}=\frac{\phi_s^m S_{ws}^n}{a\cdot R_w\left(1-C_{sh}\right)}+\frac{C_{sh}S_{ws}}{R_{sh}}$$

## $S_{wb}$, $S_{ws}$, and $S_{wt}$

$$S_{wb} = C_{sh}\frac{\phi_{sh}}{\phi_t}$$

$$S_{wt} = \frac{\phi_s \cdot S_{ws}}{\phi_t} + S_{wb}$$

$$S_{ws} = \frac{S_{wt} - S_{wb}}{1 - S_{wb}}$$



## Laminated Shaly-Sand Formations

**Laminated shale** $$\rho_b = \left(1 - C_{sh}\right)\rho_s + C_{sh}\rho_{sh}$$

$$\phi_s = \frac{\rho_s - \rho_m}{\rho_f - \rho_m}$$

**Derivation:**

## Laminated Shaly-Sand Formations

**Density porosity and neutron porosity correction for the effect of shale:**

$$\phi_{D,m}^{sh} = \frac{\phi_{D,m} - C_{sh}\left(\phi_{D,m}\right)_{sh}}{1 - C_{sh}}$$

$$\phi_{N,m}^{sh} = \frac{\phi_{N,m} - C_{sh}\left(\phi_{N,m}\right)_{sh}}{1 - C_{sh}}$$

**Derivation:**



## Non-Shale Porosity and Total Porosity

**What is next?**

**Oil** $$\phi_s = \frac{\phi_D^{sh} + \phi_N^{sh}}{2}$$

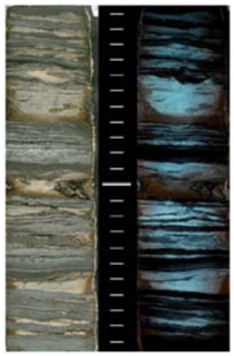
**Gas** $$\phi_s = \sqrt{\frac{\left(\phi_D^{sh}\right)^2 + \left(\phi_N^{sh}\right)^2}{2}}$$

$$\phi_t = \left(1 - C_{sh}\right)\phi_s + C_{sh}\phi_{sh}$$

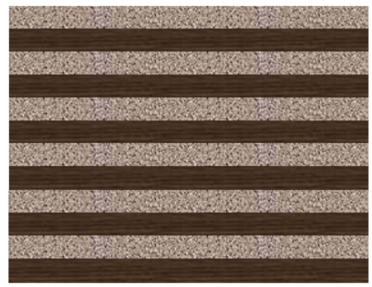
**What about assessment of $S_w$?**

## Thinly-bedded Shaly Formations

$$\frac{1}{R_t} = \frac{C_{sh}}{R_{sh}} + \frac{1 - C_{sh}}{R_s} \Rightarrow R_s$$



Source: Passey et al., 2006



**Please take notes**

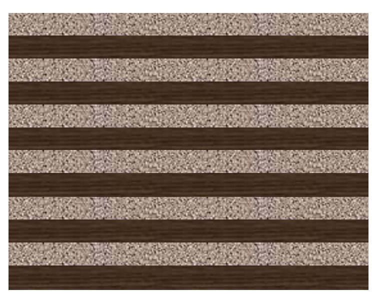


## Thinly-bedded Shaly Formations

**In the presence of horizontal and vertical resistivity:**

$$R_V = (1 - C_{sh}) R_s + C_{sh} R_{sh,V}$$

$$\frac{1}{R_H} = \frac{(1 - C_{sh})}{R_s} + \frac{C_{sh}}{R_{sh,H}}$$

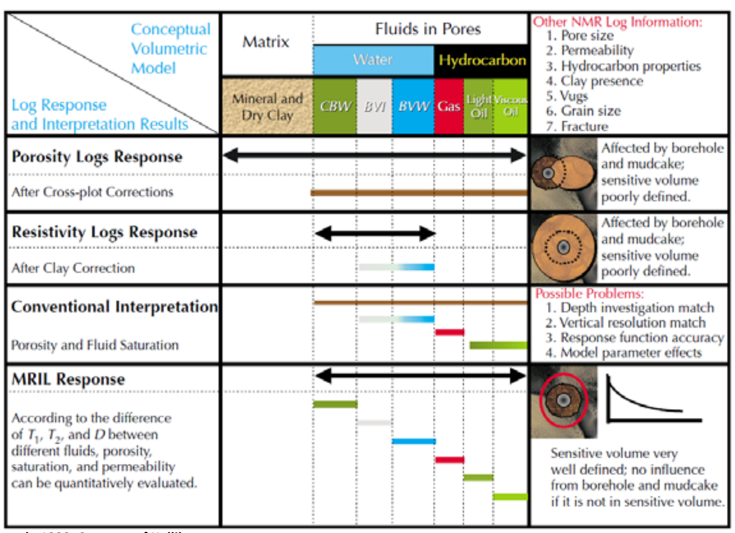


**Please take notes!**

# Let's Practice!



# $T_2$, $T_1$-$T_2$, and D-$T_2$ NMR Measurements



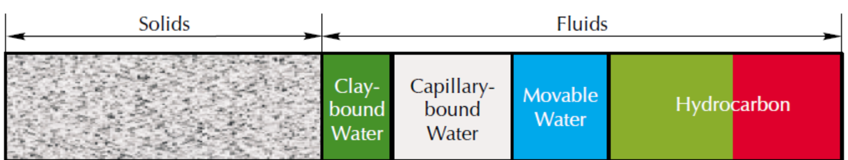

Source: Coates et al., 1999. Courtesy of Halliburton.

# Reminder: The Decay of Spin-Echo Train

- **What parameters affect spin-echo trains?**
  - **HI (Hydrogen Index)**
    - **Measure of the density of hydrogen atoms in the fluid**
  - **$T_1$ (Longitudinal relaxation time)**
    - **How fast the tipped protons in the fluid relax longitudinally (relative to the axis of the static magnetic field)**
  - **$T_2$ (Transverse relaxation time)**
    - **How fast the tipped protons in the fluid relax transversely (relative to the axis of the static magnetic field)**
  - **D (Diffusivity)**
    - **Measure of the extent to which molecules move at random in the fluid**



# Fluid Characterization




| | Bound Water | Movable Water | Heavy Oil | Light Oil | Gas |
|---|---|---|---|---|---|
| $T_1$ | Very Short | Medium Long | Short | Long | Long |
| | | | (Viscosity-Dependent) | | |
| $T_2$ | Very Short | Medium Long | Short | Long | Short |
| | (Inter-Echo Spacing TE, Diffusion Coefficient D, and Field Gradient G-Dependent) | | | | |
| $D$ | Slow | Medium | Slow | Medium | Very Fast |

Source: Coates et al., 1999. Courtesy of Halliburton.

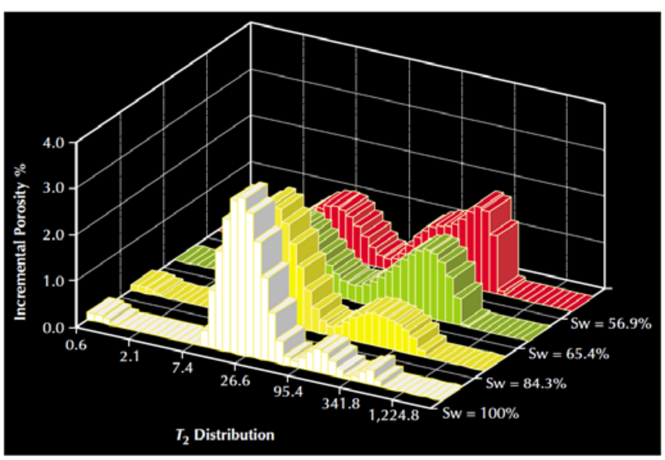
# NMR Properties of Reservoir Fluids

| Fluid | $T_1$ (ms) | $T_2$ (ms) | Typical $T_1/T_2$ | *HI* | $\eta$ (cp) | $D_0 \times 10^{-5}$ ($cm^2/s$) |
|---|---|---|---|---|---|---|
| Brine | 1 - 500 | 1 - 500 | 2 | 1 | 0.2 - 0.8 | 1.8 - 7 |
| Oil | 3,000 - 4,000 | 300 - 1,000 | 4 | 1 | 0.2 - 1,000 | 0.0015 - 7.6 |
| Gas | 4,000 - 5,000 | 30 - 60 | 80 | 0.2 - 0.4 | 0.011 - 0.014 methane | 80 - 100 |

Source: Coates et al., 1999. Courtesy of Halliburton.

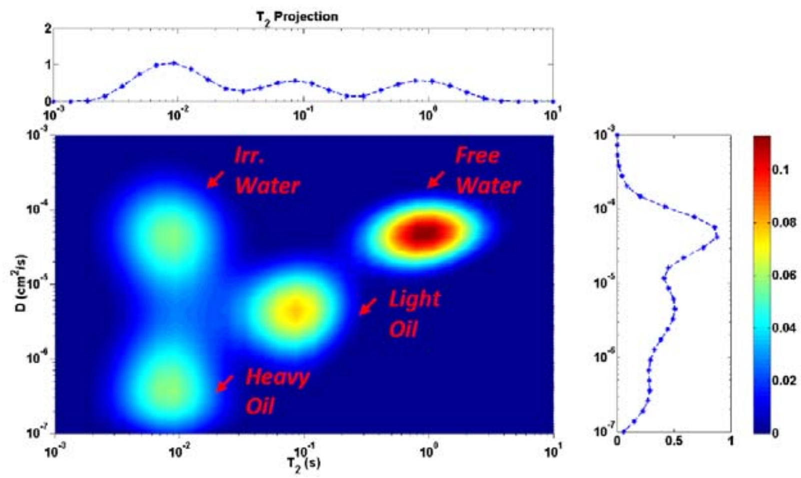


# Fluid Characterization




Source: Coates et al., 1999. Courtesy of Halliburton.

# Fluid Characterization




Source: Jerath, K., 2012



# Water Saturation Assessment using Dielectric Measurements

$$\varepsilon^*(\omega)=\varepsilon'(\omega)+i\varepsilon''(\omega)=\varepsilon'(\omega)+i\frac{\sigma(\omega)}{\omega\varepsilon_0}=\varepsilon'(\omega)+i\frac{\sigma(\omega)}{2\pi\varepsilon_0 f}$$

**Dielectric permittivity**

**Dielectric constant**

**Dielectric loss**

**Angular frequency of the electric field**

**Vacuum permittivity**

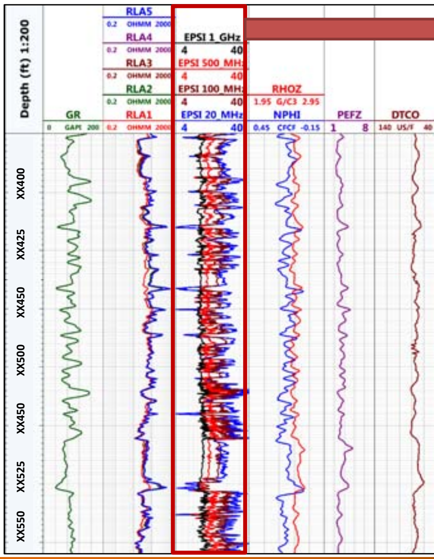
$$\varepsilon_r=\frac{\varepsilon}{\varepsilon_0}$$

**Relative permittivity**

| Substance | $\varepsilon_r$ | Substance | $\varepsilon_r$ |
|---|---|---|---|
| Quartz | 4.5–4.7 | Gas | 1 |
| Calcite | 6.4–8.5 | Oil | 2.2 |
| Dolomite | 6.1–7.3 | Water | 80 |
| Anhydrite | 5.7–6.5 | | |
| Halite | 5.7–6.2 | Shale (dry) | 13–16 |

$$\varepsilon_0=8.854\left[pF/m\right]$$

# Water Saturation Assessment using Dielectric Measurements




**Conventional Dielectric Permittivity Models**

**Water-Filled Porosity/Hydrocarbon Saturation**

**Complex Refractive Index Method (CRIM)**

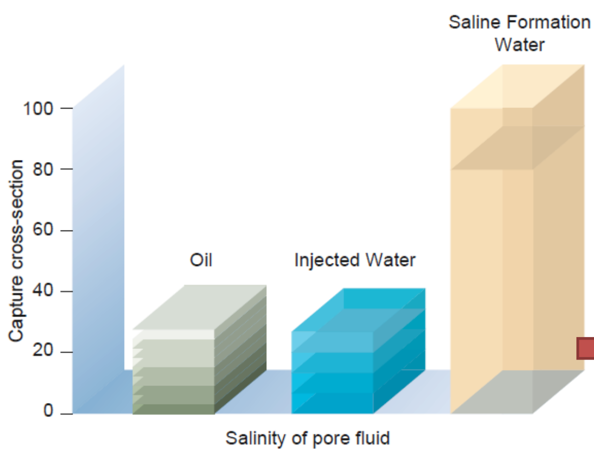
**CRIM**

$$\sqrt{\varepsilon} = \sum_{j=1}^{n_c} C_j \sqrt{\varepsilon_j}$$

$$S_w = \frac{\sqrt{\varepsilon_{mix}} - (1-\phi)\sqrt{\varepsilon_m} - \phi\sqrt{\varepsilon_{hc}}}{\phi\sqrt{\varepsilon_w} - \phi\sqrt{\varepsilon_{hc}}}$$



# Water Saturation Assessment using Sigma Measurements




$$S_w = \frac{\left(\Sigma_{\log} - \Sigma_{grain}\right) - \phi_s\left(\Sigma_{hc} - \Sigma_{grain}\right)}{\phi_s\left(\Sigma_w - \Sigma_{hc}\right)} - C_{sh}\frac{\left(\Sigma_{sh} - \Sigma_{grain}\right)}{\phi_s\left(\Sigma_w - \Sigma_{hc}\right)}$$

**How would you estimate $\Sigma_w$?**

**Sigma logs work well for water saturation assessment where formation water has high salt concentration**

Source: Middle East Well Evaluation Review, 1996

## Laboratory vs. In-situ Estimates of Fluid Saturations

- Why do we experience differences in fluid saturation estimates from the laboratory and in-situ measurements
  - Drilling mud can affect fluid saturations
    - What are the impacts of water-based and oil-based muds on water/oil saturation estimates?
  - Impacts of temperature and pressure on fluid saturations
    - What are the impacts of pressure and temperature on the fluid volume?
    - What are the impacts of pressure and temperature on the pore volume?





# Advanced Petrophysics: Fluid Saturation in Porous Media, Part 3 of 3

Instructor: Zoya Heidari, Ph.D.

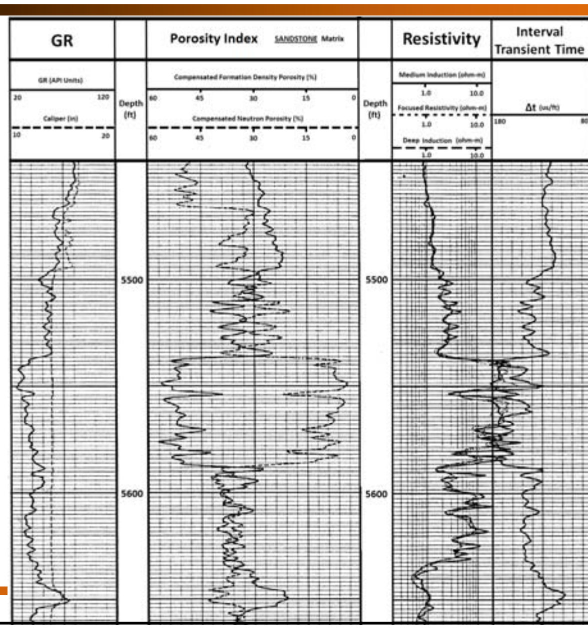
Associate Professor
The University of Texas at Austin

## What Do We Learn in This Lecture?

- What is fluid saturation?
- How to estimate fluid saturation in the laboratory?
- How to estimate fluid saturation in-situ condition?
- How does presence of clay minerals affect water/hydrocarbon saturation estimates?
- How to quantitatively take into account the effect of clay minerals in fluid saturation assessment
- Laboratory vs. in-situ estimates of fluid saturations
- **How to calculate total hydrocarbon reserves?**



## How to Calculate Total Hydrocarbon Reserves?



# Hydrocarbon Reserves

$$N = \frac{7758 \times \phi \times S_h \times A \times h}{B_o}$$

Oil Reserves (stock tank barrels, STB)

Conversion constant, (bbl/acre.ft)

Porosity, ( )

Oil Formation volume factor, (reservoir barrels/STB)

Hydrocarbon Saturation, ( )

Reservoir area, (acres)

Thickness of flow, Net pay thickness, (ft)



# Hydrocarbon Reserves

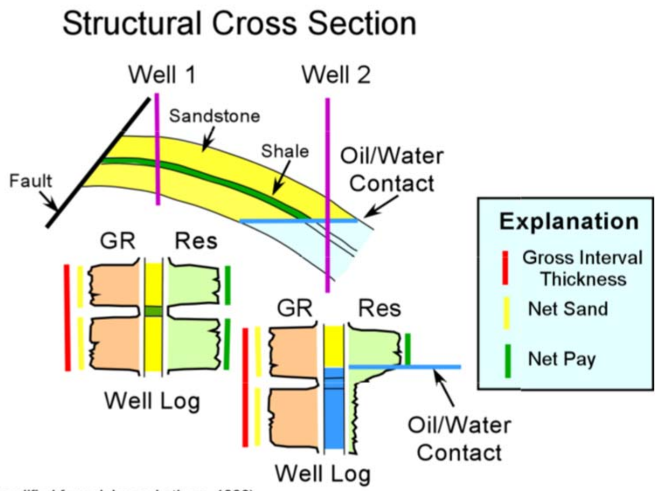
**How much of the total hydrocarbon reserves is recoverable?**

$$N_r = NR_f$$

Recoverable oil reserve, (stock tank barrels, STB)

Recovery Factor, ( )

## Gross Thickness, Net Sand, and Net Pay

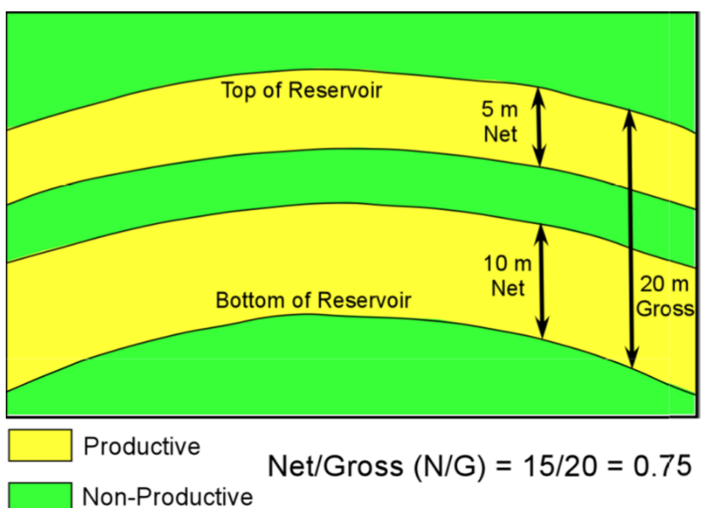


(modified from Jahn and others, 1998)

**Static vs. dynamic net pay?**



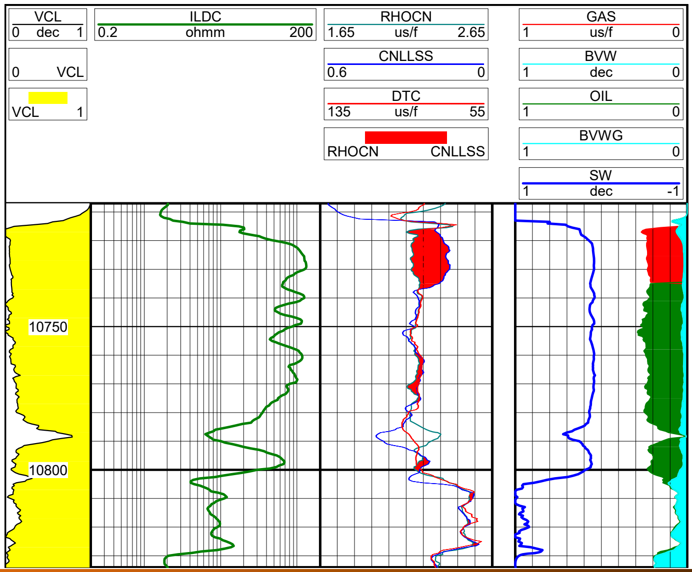
## Reservoir Column: Net-to-Gross Determination




Net/Gross (N/G) = 15/20 = 0.75

(modified from Jahn and others, 1998)

# Example



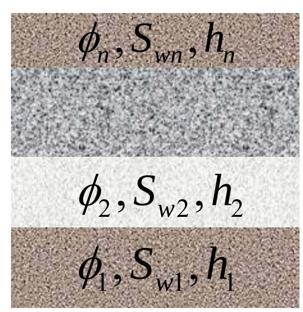



# How Do We Average Porosity and Water Saturation, if Needed?

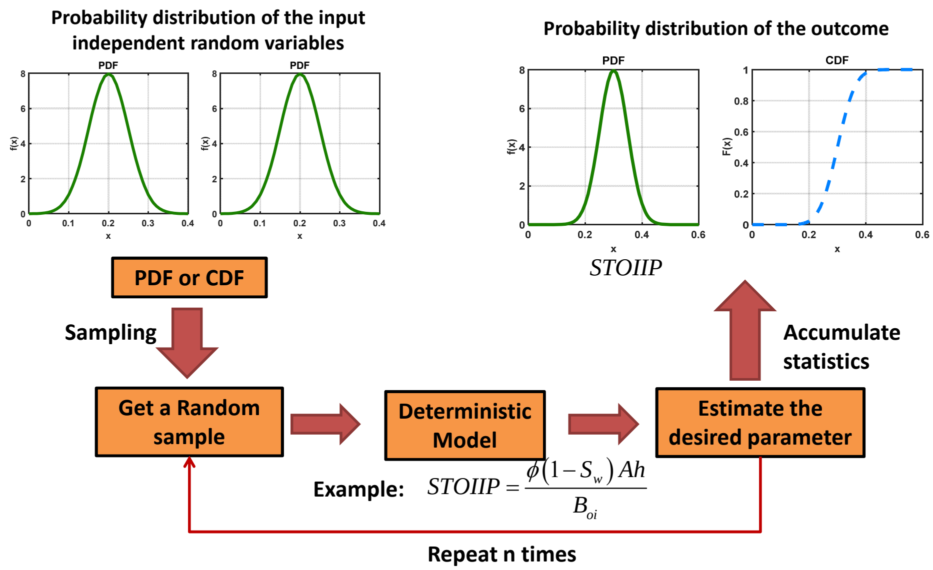
- **First ask the following questions:**
  - **Why is it needed?**
  - **Over what depth interval and geological environment are you averaging?**

$$\bar{\phi} = \frac{\int_0^h \phi dh}{\int_0^h dh} = \frac{\sum_{i=1}^{n} \phi_i h_i}{\sum_{i=1}^{n} h_i}$$

$$\bar{S}_w = \frac{\int_0^h \phi S_w dh}{\int_0^h \phi dh} = \frac{\sum_{i=1}^{n} \phi_i S_{wi} h_i}{\sum_{i=1}^{n} \phi_i h_i}$$



# Monte-Carlo-Based Assessment of Reserves






# Complementary References


- **Peters, E. J., 2012, Advanced Petrophysics. Live Oak Book Company. Chapter 2**
- **Zinszner, B. and Pellerin, F. M., 2007, A Geoscientist's Guide to Petrophysics. Editions Technip.**
- **Coates, G. R., Xiao, L., Prammer, M. G., NMR Logging: Principles and Applications. Halliburton Energy Services Publication.**