Petrophysics

Geoff Page

Region Petrophysics Advisor

June 11, 2018

Disclaimer

Baker Hughes, a GE company, LLC and its affiliates (“BHGE”) provides this information on an “as is” basis for general information purposes and believes it to be accurate as of the date of publication. BHGE does not make any representation as to the accuracy or completeness of the information and makes no warranties of any kind, specific, implied or oral, to the fullest extent permissible by law, including those of merchantability and fitness for a particular purpose or use. BHGE hereby disclaims any and all liability for any direct, indirect, consequential or special damages, claims for lost profits, or third party claims arising from the use of the information, whether a claim is asserted in contract, tort, or otherwise. The BHGE logo is a trademark of Baker Hughes, a GE company, LLC. GE and the GE monogram are trademarks of General Electric Company used under trademark license.

Agenda

- What is Petrophysics
- History
- What do we want to know?
- Where do the answers come from?
- The Future

Definition

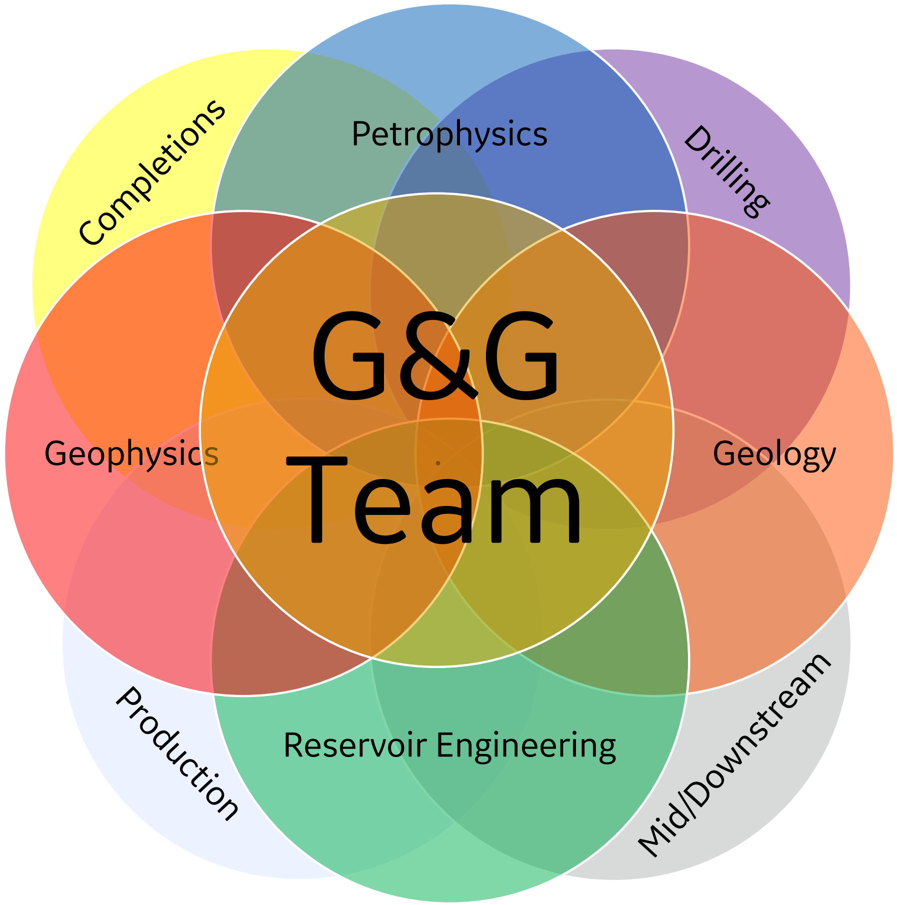
"Petrophysics"

From the Greek πέτρα, petra, "rock" and φύσις, physis, "nature", is the study of physical and chemical rock properties and their interactions with fluids."

"Petrophysicists" are employed to help reservoir engineers and geoscientists understand the rock properties of the reservoir, particularly how pores in the subsurface are interconnected, controlling the accumulation and migration of hydrocarbons"

(Tiabb, D. & Donaldson, E.C. (2004). Petrophysics.)

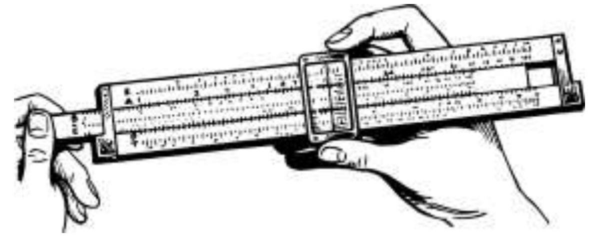
Todays Subsurface Evaluation Team



History

Timeline

- 1927 First Electric wireline log (Electrolog)
- 1940 Gamma Ray (for perforating!)
- 1941 Neutron log
- 1942 Archie Equation
- 1944 Reverse concentric logging cable
- 1947 Induction log
- 1949 Lateralog
- 1950 "Petrophysics" Defined*
- 1954 Acoustic log
- 1959 Density log
- 1963 Pulsed neutron
- 1978 Formation tester
- 1978 MWD
- 1990's NMR
- 2000 Tensor/Directional Resistivity
- 2018+ 3D?



1977

1988

Today

*The term "petrophysics" was coined by G.E. Archie and J.H.M.A. Thomeer in a quiet bistro in The Hague

DEVEX2018

What do we want to know?

Hydrocarbon Reserves

STOIIP – Stock Tank Oil Initially In Place

Alternative: STOOIP – Stock Tank Oil Originally In Place

$$STOIIP = \frac{AH\phi S_o}{B_o}$$

(A x H) Also expressed as "Gross rock volume"

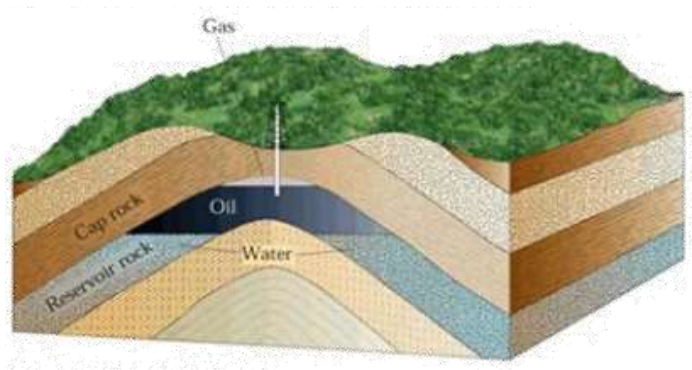
A – Reservoir area

H– Reservoir net thickness

Φ – Average porosity

S_o – Oil Saturation

B_o – Oil formation factor



Recovery factor?

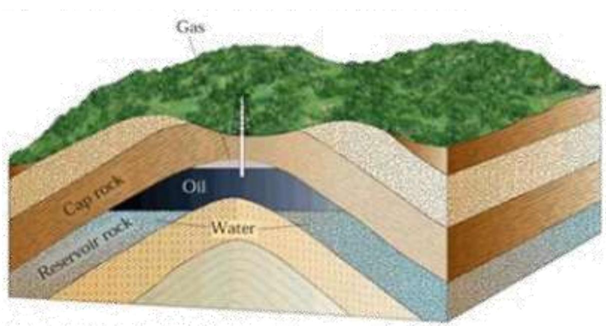
The Value of Data - Volumes

- A reservoir of 1 square mile (640 acres), that has an oil column 200ft thick, has a porosity of 20%, a Sw of 10% and a B_o of 1.2 contains?

  7758 x 640 x 200 x .2 x (1-0.1) / 1.2 = 150 million Stock tank bbls

  = $11.25 billion (@$75/bbl)

  - An error of 1ft in depth/thickness is worth +/- $56 million
  - An error of 1pu porosity is worth +/- $563 million
    - 1 Chart division on standard density scales is 0.05g/cc = 3% porosity = $1.5B+
  - An error of 1% Sw is worth +/- $125 million

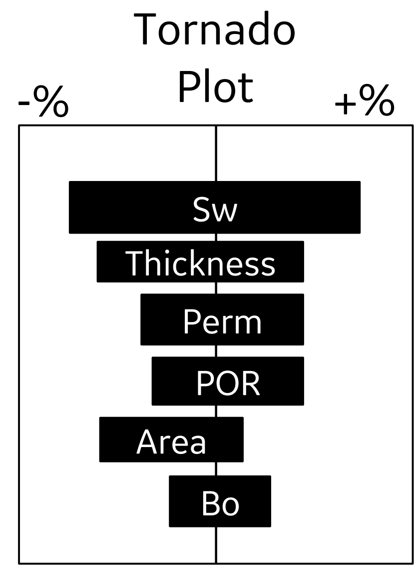


Uncertainties

- The uncertainties on all the reservoir properties are combined to determine the most likely value of the reservoir.
  - The data is also used to determine the probable minimum and maximum values e.g. P10/50/90 probabilities

- This allows a judgement on:
  - Will the reservoir be developed now, later, or at all?
  - Size/cost of production facilities
  - Number and type of wells

- Any budget for more data?
  - What is needed to reduce uncertainty?



Instrument Responses

No logging device measures porosity, saturation, permeability, or fluid type directly. Logs do not identify color of rock or define the texture of rock.

Log Response

Nevertheless,

Logging devices respond to properties that are related to lithology, porosity, saturation, permeability, fluid type e.t.c.

Combinations of different log measurements can be used to define the above.

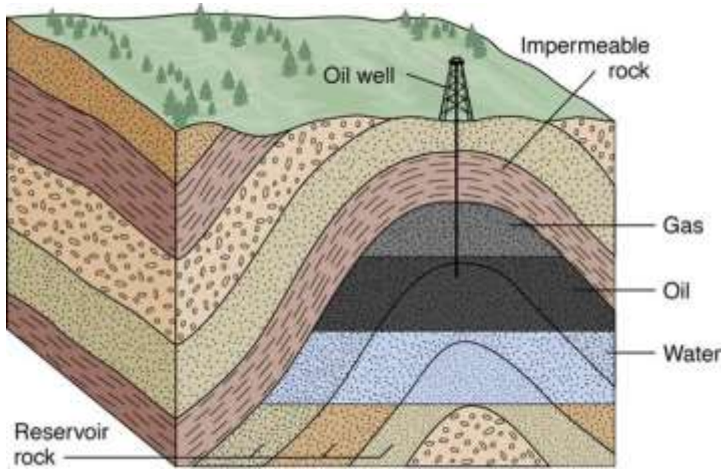
→***Need a Petrophysicist!***

Where do the answers come from?

What do We Need to Determine?

Formation properties

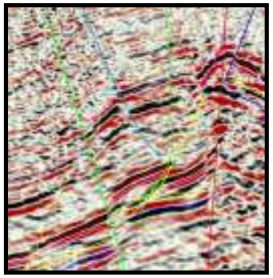
- Reservoir Structure/Volume/Thickness
- Rock type - Net/Non-Net, Mineralogy
- Fluid volumes
- Fluid saturations
- Fluid properties
- Permeability (Ease of flow)
- Geomechanics

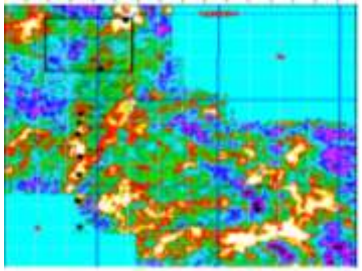


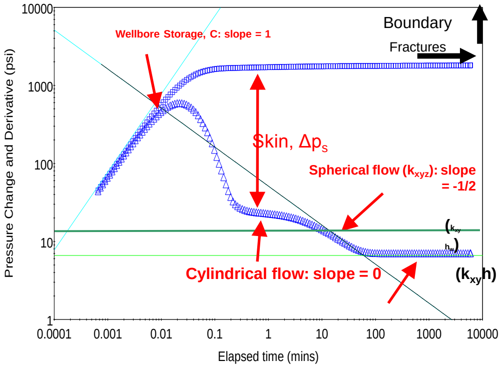
Where do we get the information?

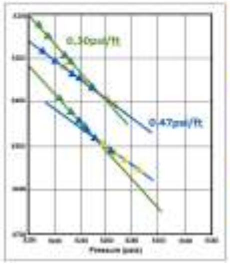
Reservoir Structure/Volume/Thickness

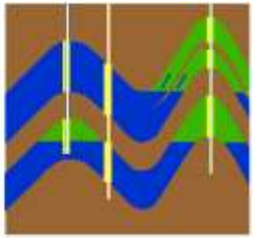
- Surface seismic, CSEM, Magnetotellurics, Gravity
  - The big picture, resolution 10m – 1Km
- Downhole seismic
  - Partial reservoir coverage around wellbore, larger 3D VSP.
  - Improved resolution than surface (higher frequency)
- Well test
  - Reservoir (connected) volume, barriers, permeability
  - Longer test = further away from wellbore, whole field.
  - Formation tester mini welltest 40-150ft (Straddle Packer)
- Formation Tester Pressures
  - Connectivity, Fluid contacts
- Logs
  - The fine detail
    - Depth = Layer thickness, Net/Gross
    - High Resolution (Image = structure, sedimentology), close to wellbore.
    - Acoustic Imaging up to 100ft (X-DSWI)
    - Tensor Resistivity Anisotropy dips (3DEX), 1-2m depth "layers"
- Core
  - Whole core needed for thickness – but how continuous? Rubble?



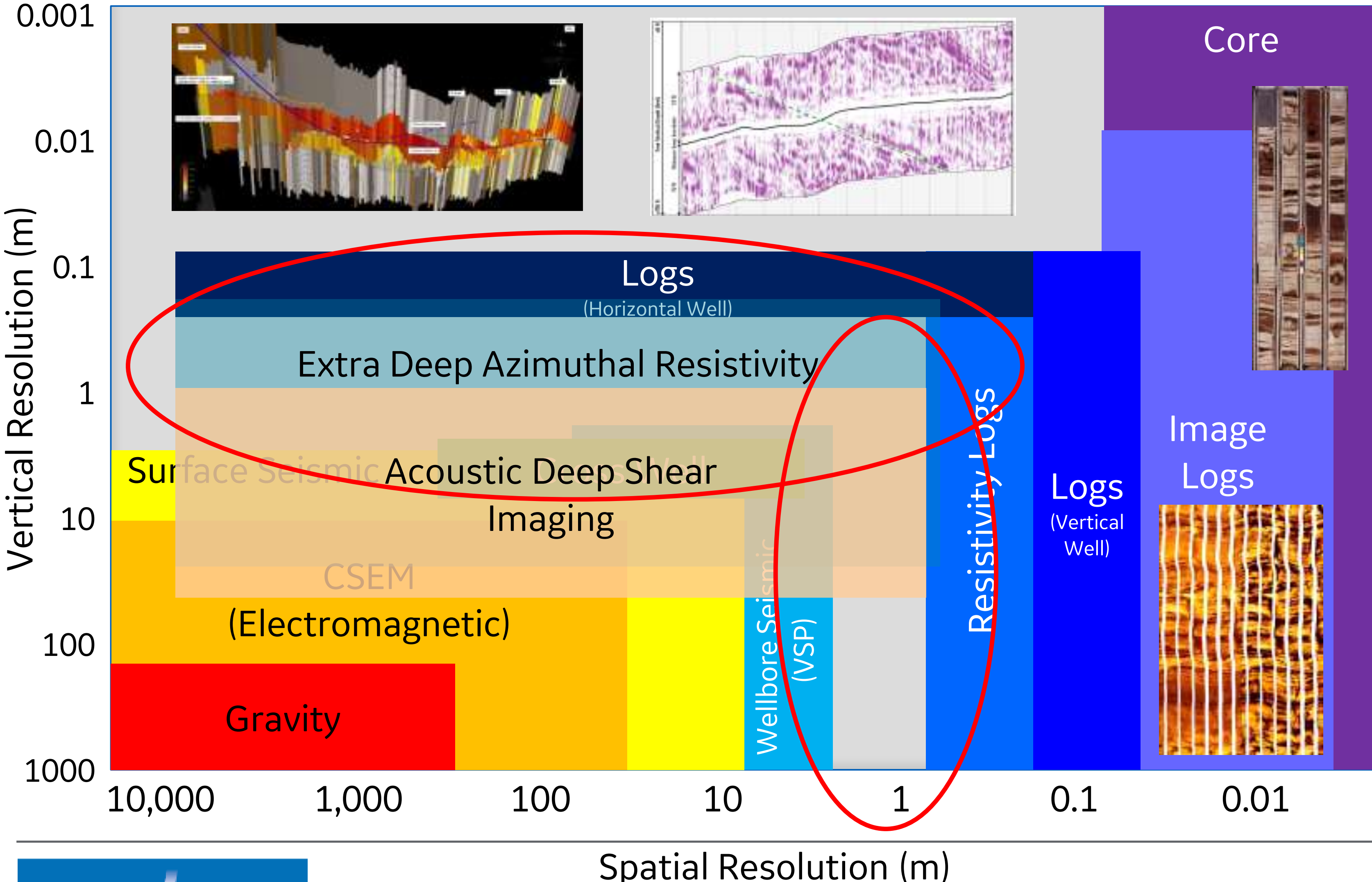








Imaging Scales



DEVEX2018

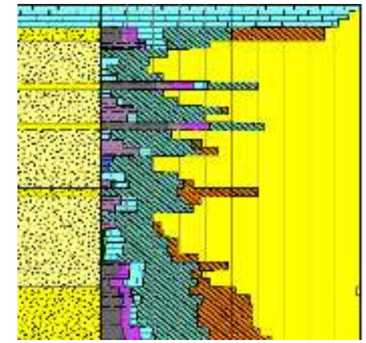
Rock Type - Net/Non-Net, Mineralogy

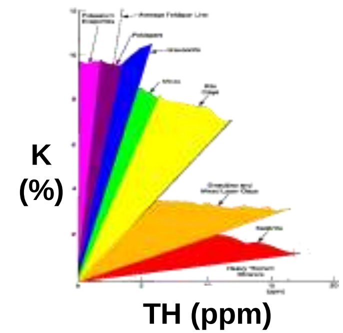
- SLS, "Mud log", cuttings, Gas
  - Microscope, Acid, XRD, XRF
- Core
  - Whole core
  - Wireline SWC, Rotary cores
- Field trip – Analogues
- Simple logs = GR, SP
  - Spectral GR for clays, Minerals
- Standard logs
  - Deterministic Crossplots: D/N/AC
  - Volumetric analysis (Stochastic "best fit")
- Pulsed neutron mineralogy
  - Detailed Mineralogy

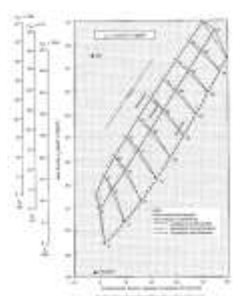
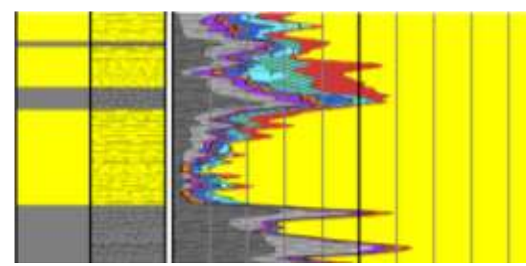
- **But calibrate logs to core!**







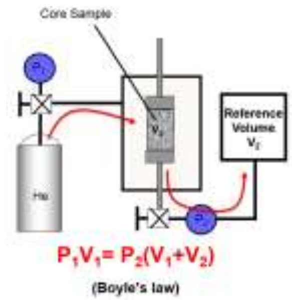



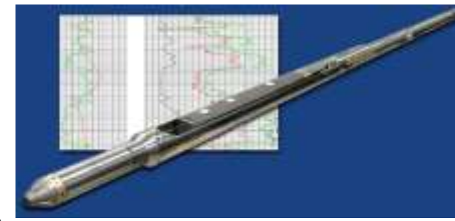



Fluid Volumes

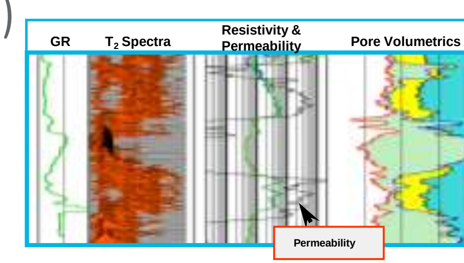
Porosity

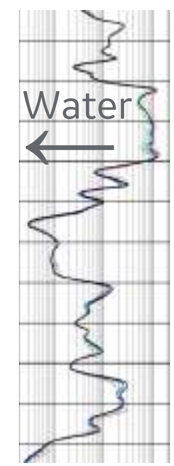
$$\Phi = \frac{\text{Pore Volume}}{\text{Total Volume}}$$





- Core
- Logs
  - Density is primary measurement (Calibrated to core)
  - Crossplot porosity (D/N/A, Volumetric analysis)
  - NMR: Lithology independent, texture
  - Acoustic – secondary indicator
  - Resistivity/Dielectric
    - NOTE: sees the water, NOT Hydrocarbons.
- Welltest
  - Total (connected) reservoir pore volume
- Seismic
  - Inversion for porosity





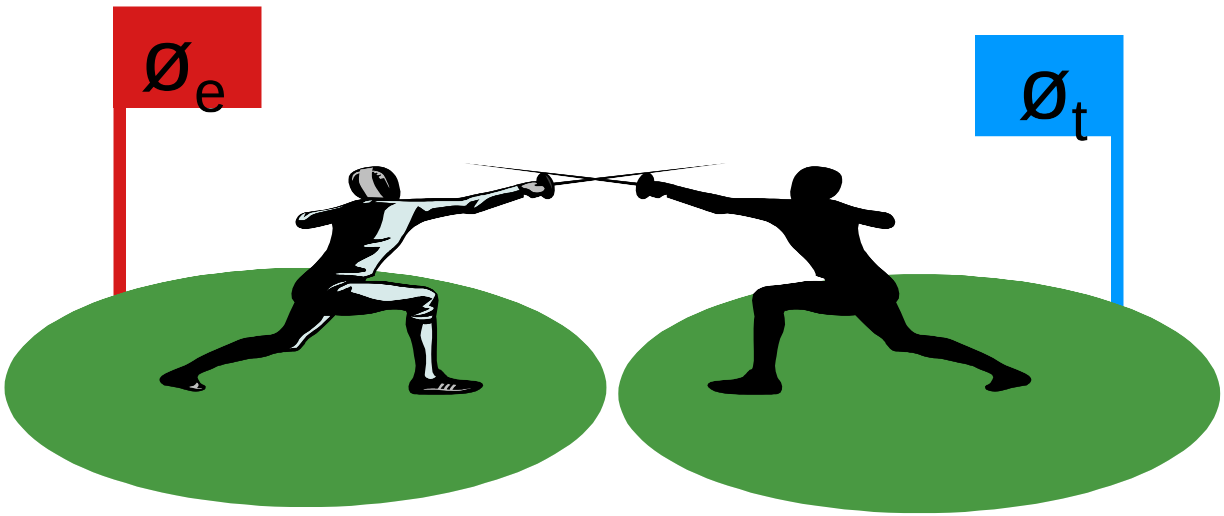
DEVEX2018

Porosity Definitions

(i)	Total porosity	Everything, all fluids, ratio of “void” space to gross rock volume
(ii)	Effective porosity	The total porosity minus the volume of clay bound water.
(iii)	Connected porosity	The ratio of the connected pore volume to the total volume.
(iv)	Primary porosity	The porosity of the rock resulting from its original deposition.
(v)	Secondary porosity	The porosity resulting from diagenesis.
(vi)	Microporosity	The porosity resident in small pores (< 2 μm) commonly associated with detrital and authigenic clays
(vii)	Intergranular porosity	The porosity due to pore volume between the rock grains.
(viii)	Intragranular porosity	The porosity due to voids within the rock grains
(ix)	Dissolution porosity	The porosity resulting from dissolution of rock grains
(x)	Fracture porosity	The porosity resulting from fractures in the rock at all scales.
(xi)	Intercrystal porosity	Microporosity existing along intercrystalline boundaries usually in carbonate rocks.
(xii)	Moldic porosity	A type of dissolution porosity in carbonate rocks resulting in molds of original grains or fossil remains.
(xiii)	Fenestral porosity	A holey (‘bird’s-eye’) porosity in carbonate rocks usually associated with algal mats.
(xiv)	Vug porosity	Porosity associated with vugs, commonly in carbonate rocks.

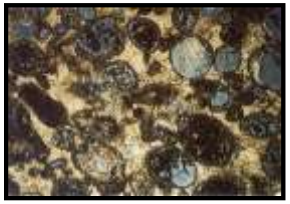
Total or Effective?

- There is an ongoing discussion within the log analysis/petrophysical community as to the measurement and proper use of porosity in petrophysics.
  - One group believes in working in an effective porosity system
  - Others believe in working in a total porosity system



Porosity in Carbonates

- Carbonates have complex pore structures, micro to macro pores



Oomoldic Porosity

Intrafossil Pore Space

Fossil Molds in a Wackestone

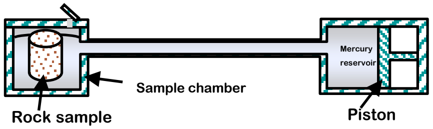
Anhydrite Molds

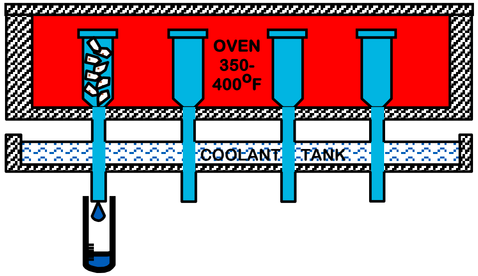
- Are these pores all connected??

"I am on record saying that all pore space in carbonate rocks is interconnected, and that the question is how and how well is it interconnected."

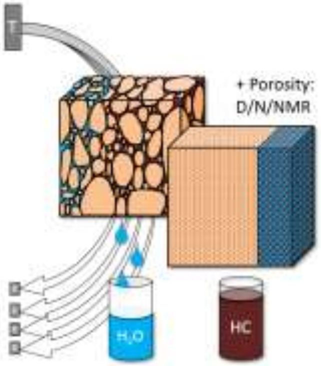
Jerry Lucia, Bureau of Economic Geology, The University of Texas at Austin, December 21, 2002

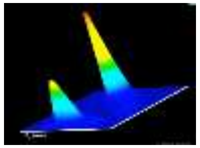
Fluid Saturations

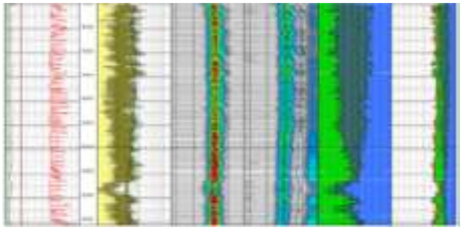


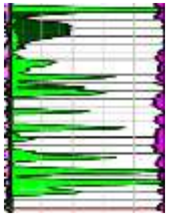


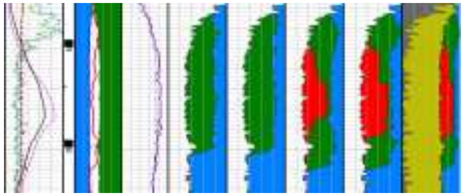
- Seismic
  - AVO for fluids (Amplitude Vs Offset) – Indication only
- Welltest
  - What fluids flow – mobile phase
- Core
  - Saturations, Capillary pressure curves
- Resistivity – Commonest Method!
  - Water only, Combined with porosity → Hydrocarbons.
- Dielectric
  - Water filled, Combined with porosity → Hydrocarbons.
- NMR
  - Porosity split CBW/BVI/BVM
  - 2/3D plots
- Pulsed neutron Mineralogy
  - Excess carbon curve
- Pulsed Neutron Saturations
  - Sigma, C/O
  - Long term reservoir monitoring in cased wellbores









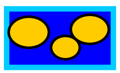


Archie 'Clean Sand' Equation

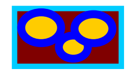
$$Ro = \frac{a \times Rw}{\Phi^{m}} \rightarrow Sw^{n} = \frac{a \times Rw}{\Phi^{m} Rt} \leftarrow Sw^{n} = \frac{Ro}{Rt}$$

$Ro/Rw = a/\Phi^m$ = Formation (Resistivity) Factor = "F"

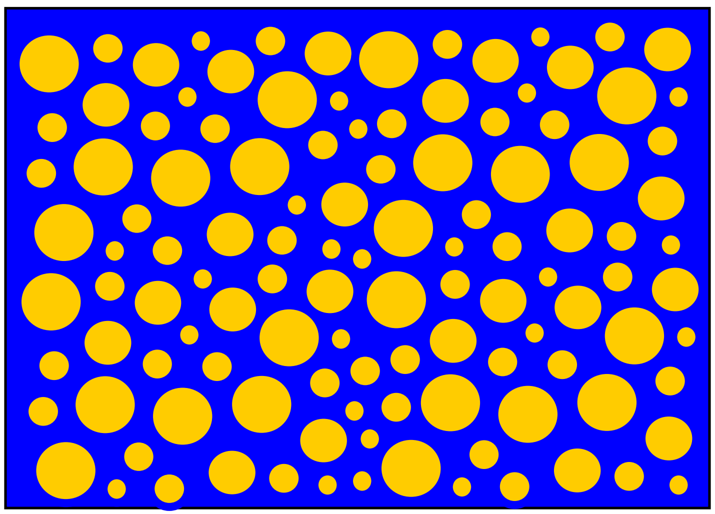
$Rt/Ro = 1/Sw^n$ = Resistivity Index = "I"

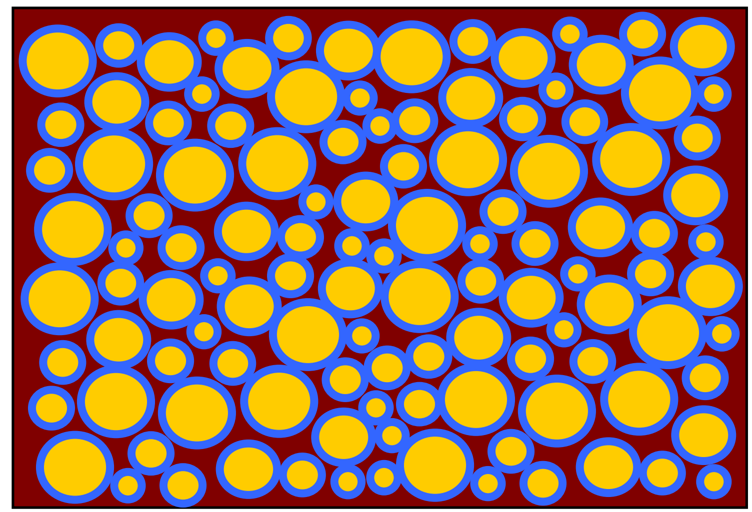


Water Sand, Ro



Hydrocarbon Sand, Rt





Φ = Porosity

m = Cementation Exponent

n = Saturation Exponent

Rw = Fm Water Resistivity

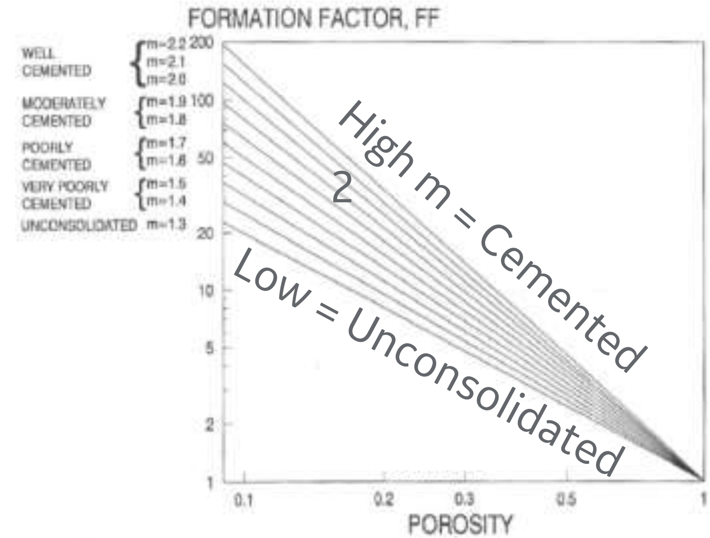
Sw = Water Saturation

Archie G. E.(1942) The electrical resistivity log as an aid in determining some reservoir characteristics. Transactions of the **American Institute of Mechanical Engineers** 146:54–67.

Archie Parameters

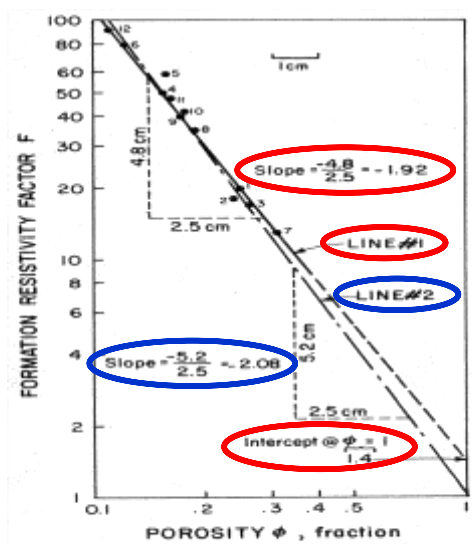
- m is related to cementation and Tortuosity

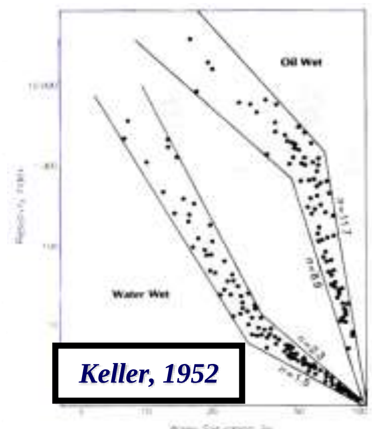
$$\tau = \left(\frac{\Phi}{\Phi^m} \right)^{0.5}$$



- n is related to pore size, pore connectivity, and wettability

- a is NOT an "Archie" parameter! It was introduced by Winsaur et al in 1952, 10 years later.
  - It is the Intercept at 100% porosity
  - Still debated today is needed!!

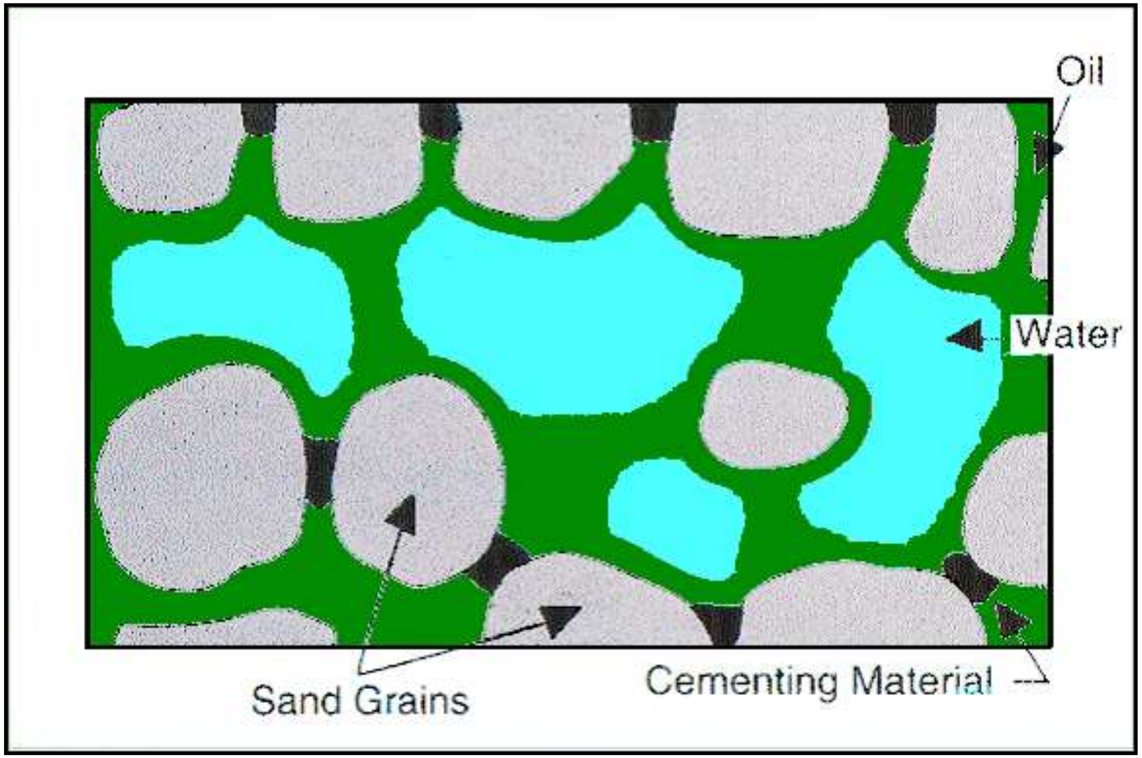




Oil or Water Wet?

- Generally assumed most reservoirs are water wet
  - Water coats the sand grains in water-wet rocks providing a continuous path for ion conduction at any saturation

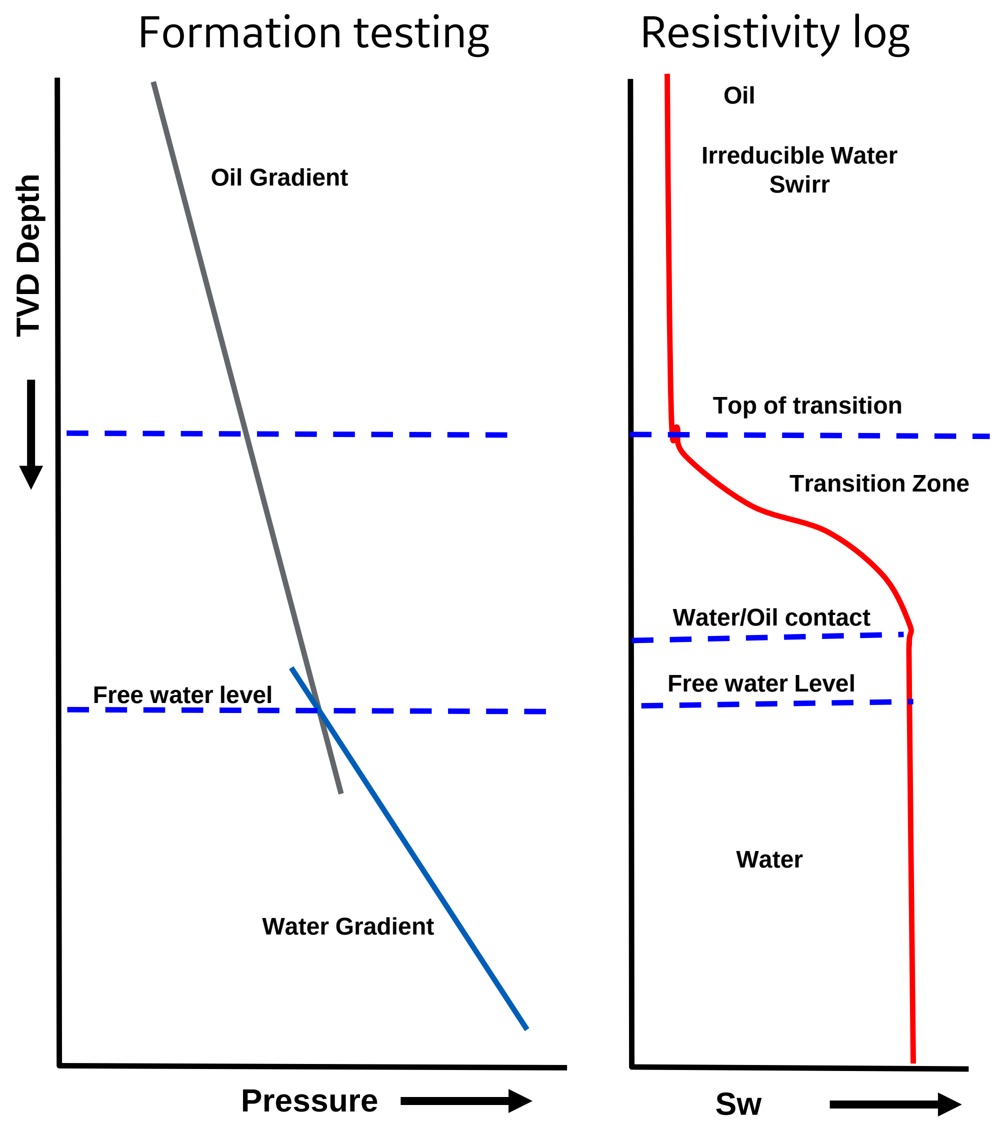
- Oil-coated grains trap water in the middle of the pore
- At low Sw's the water is separated from water in adjacent pores
  - The result is a higher resistivity and high "n" values



More Likely in Carbonates

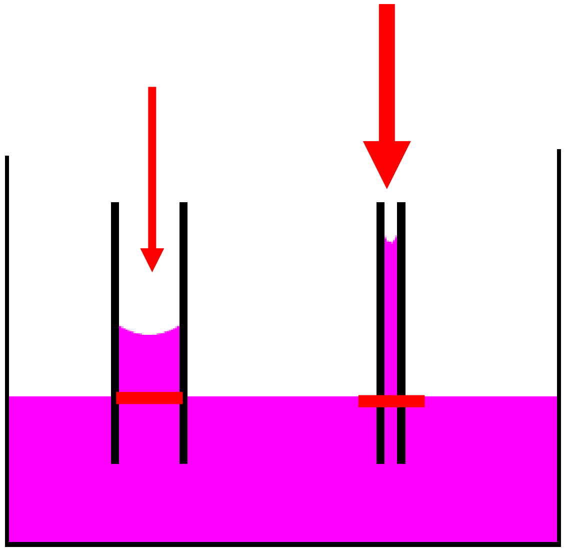
Fluid Contacts

Logs and Pressure often see different contacts WHY??



Capillary Pressure

- Surface tension forces pull wetting fluid into fine tubes until balanced by gravitational force
- **Capillary Pressure** is the force required to displace the wetting phase back to original position
- Measure on Core samples
  - MICP (Mercury Intrusion Capillary Pressure)
- Estimate from NMR
  - Calibrated to core
- Useful for:
  - Fluid saturations
  - Permeability
  - Rock quality



CP ∝ 1 / radius

Pc Height Function

Red

- Thick sand

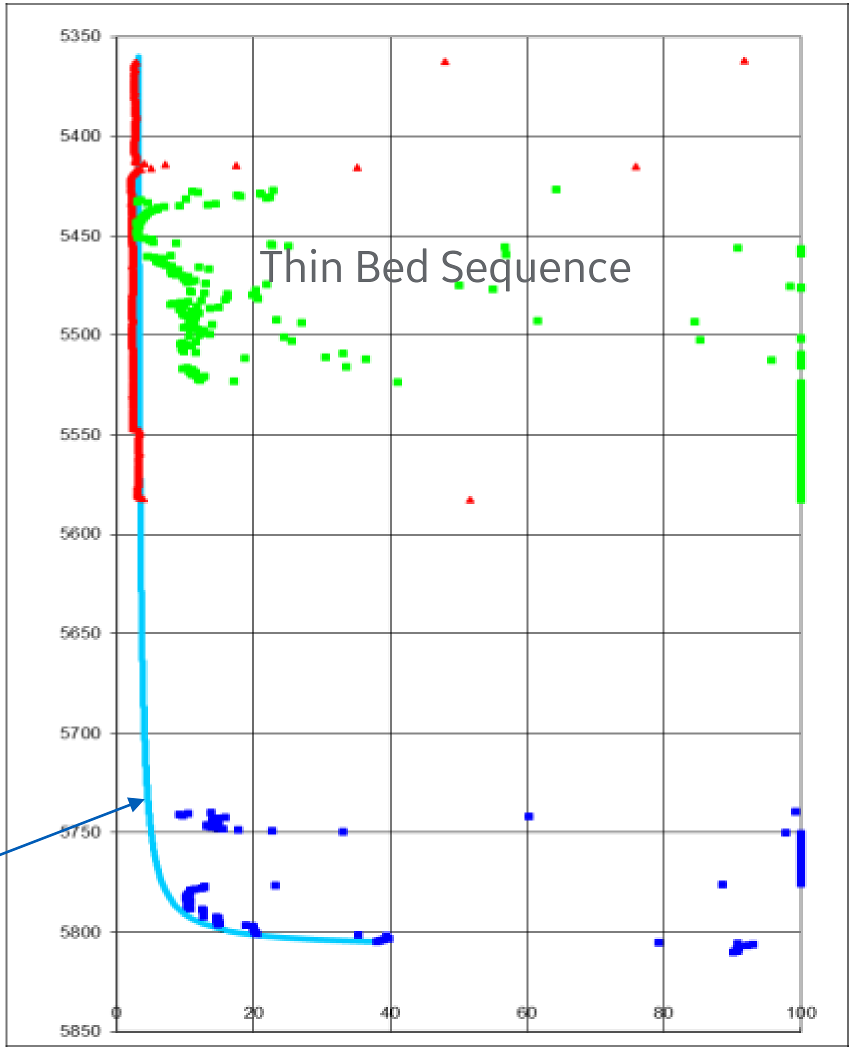
Blue

- Thick sand penetrated water

Green

- encountered thin bedded sequence

Capillary height Function



Other Sw Equations

Archie

$$C_t = \frac{C_w}{F} \cdot S_w^2$$

Modified Simandoux

$$C_t = \frac{C_w}{F} \cdot S_{we}^2 + V_{sh} \cdot \frac{0.4}{C_{sh}}$$

Simplified Indonesian

$$C_t = \frac{C_w}{F} \cdot S_{we}^2 + 2 \cdot \sqrt{\frac{C_w \cdot V_{sh} \cdot C_{sh}}{F}} \cdot S_{we}^2 + V_{sh}^2 \cdot C_{sh} \cdot S_{we}^2$$

Total Shale (Modified Bardon-Pied)

$$C_t = \frac{C_w}{F \cdot (1 - V_{sh})} \cdot S_{we}^2 + V_{sh} \cdot C_{sh} \cdot S_{we}$$

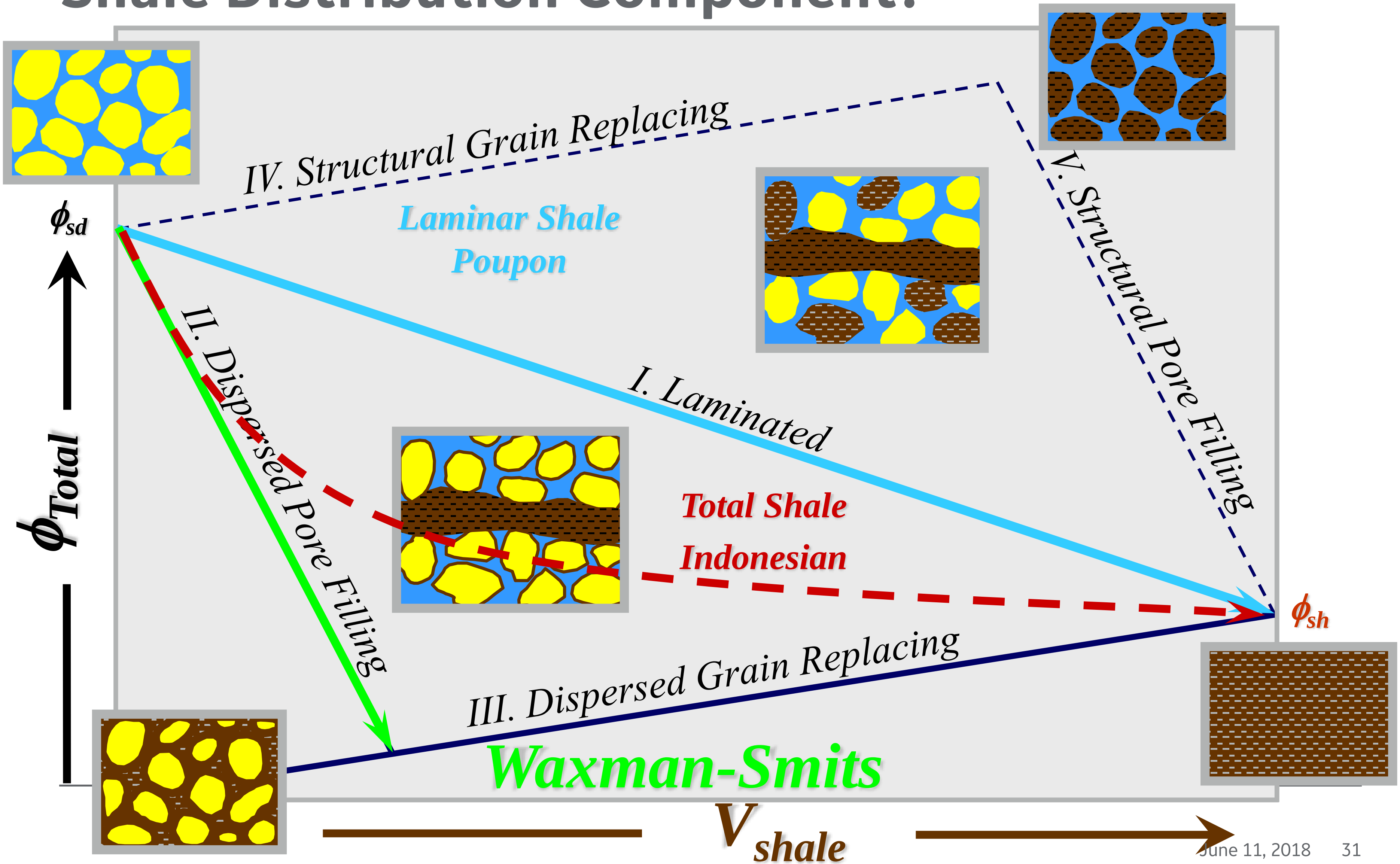
Poupon Laminar Shale

$$C_t = \frac{a \cdot Cw}{F} \cdot S_w^n \cdot (1 - V_{sh_{lamr}}) + C_{sh} \cdot V_{sh_{lamr}} \quad \text{where} \quad F = \frac{a}{\phi_e^2}$$

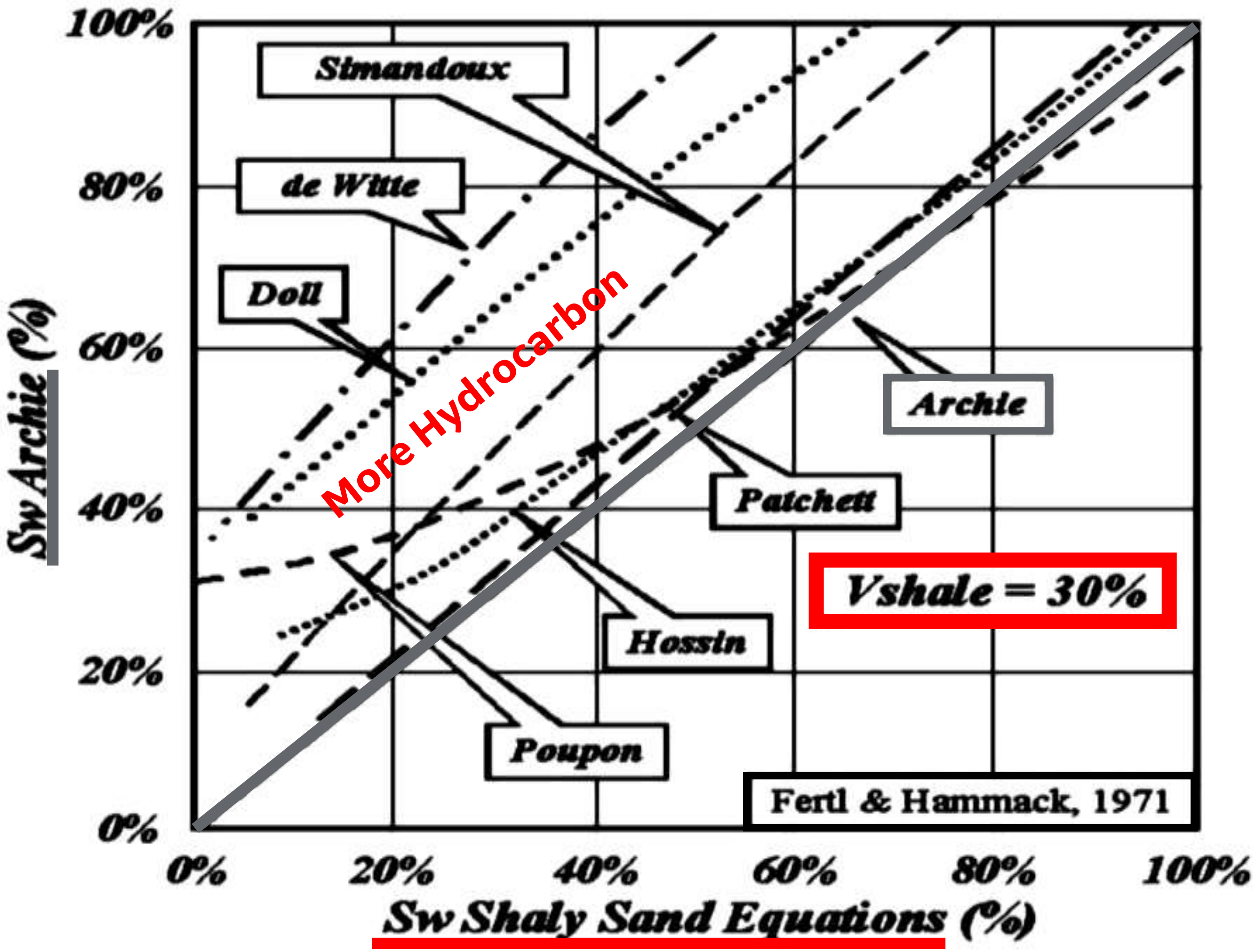
- Archie is only designed for "clean" clay free formations.
- Other Equations were progressively designed/modified to take account of conductivity due to clay or shale content

DEVEX2018

<u>All</u> Shaly Sand Sw Equations have an Inherent Shale Distribution Component!



Sw Equations: Difference to Archie



Worthington 1985

DEVEX2018

Which Saturation Equation do I use???

Worthington, 1985:

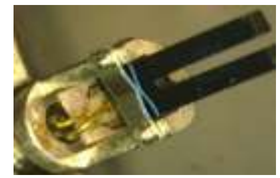
- Started out with 30 models / equations
- Reduced the form into 4 type-equations
- Concluded all models were derived to provide either
  - a localized predictive result
  - to satisfy a scientific conceptual model

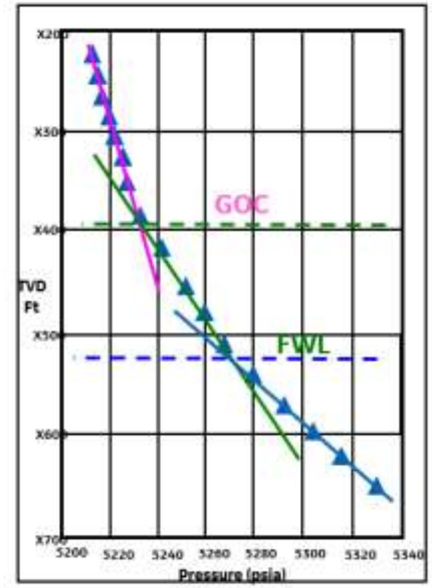
What do the experts say:

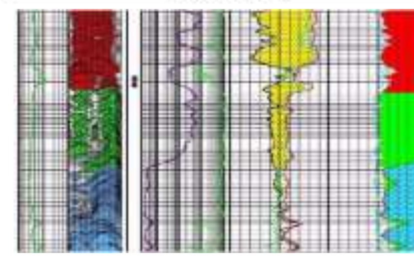
- Doll (1953) - “no satisfactory solutions”
- Dewan (1983) - “as much of an art as a science”
- Worthington (1985) - “some progress is being made”
- Zemanek (1989) - “the task is indeed formidable”
- Murphy (1992) - **“use the model that works”**

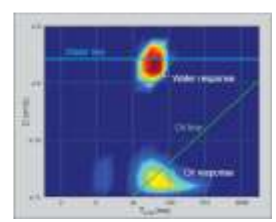
Fluid Properties

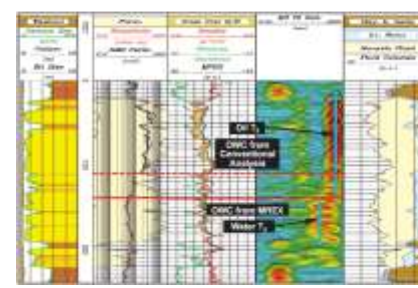
- Welltest
  - Large fluid sample for refining tests
  - However at surface conditions, may not be representative
- Formation Testing
  - Fluid gradients = density/API
  - Downhole fluid measurements
  - Single phase samples, preserved conditions → Bo, Bg
- Crossplots, Volumetric analysis
  - Oil/Water/Gas, estimate apparent fluid density.
- NMR
  - 2/3D fluid properties, compositional gradients
- N.B. Native formation fluid? or Invaded fluid?
  - Check mud type, properties
  - Time since drilling
  - Overbalance pressure
  - Permeability
  - Invasion vs Depth of Investigation











Permeability

- Permeability is a measure of a rock's ability to allow fluids or gases to move through its pore avenues.
  - Major impact on the value of a reservoir
  - One of the most important petrophysical parameters required by reservoir engineers.

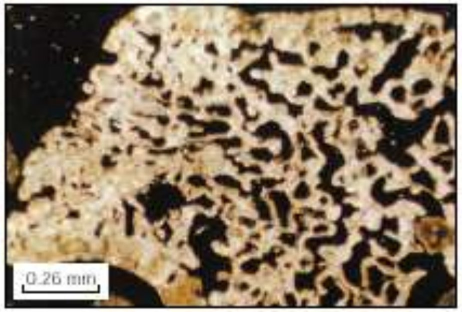
Depends on:

- Size of the pore openings
- Degree and size of pore connectivity
- Degree and type of cementing material
- Between the rock grains

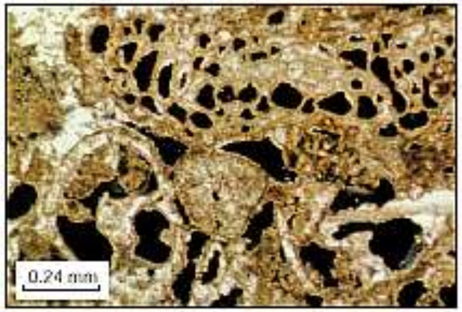
Difficult to measure in-situ. Most logs are a volumetric average and do not show texture

DEVEX2018

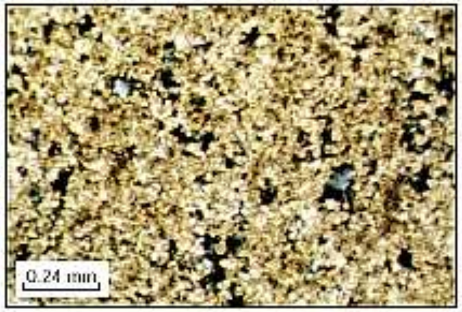
Carbonates – Difficult to Analyse (Texture)



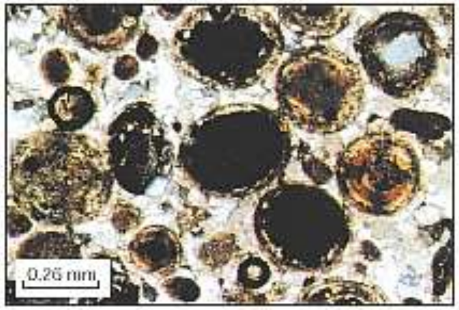
Unfilled Intraparticle Porosity (Black), Holocene Olithe



Interparticle and Intraparticle Porosity (Black) In Foraminifera and Mollusks



Intercrystal Porosity (Black) In A Fine To Medium-crystalline Replacement Dolomite.

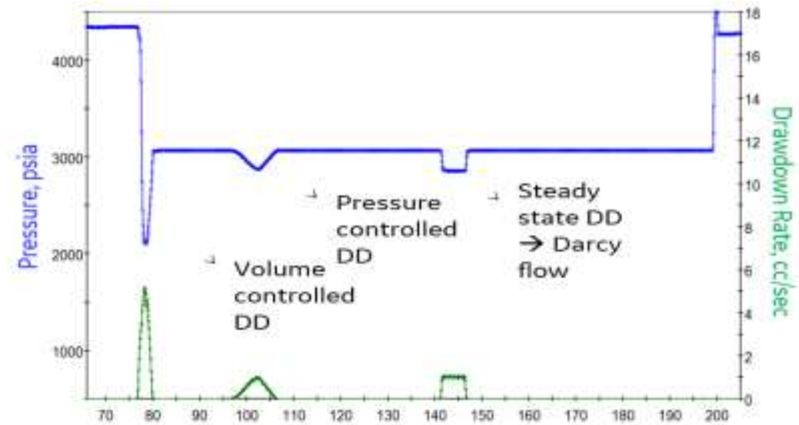


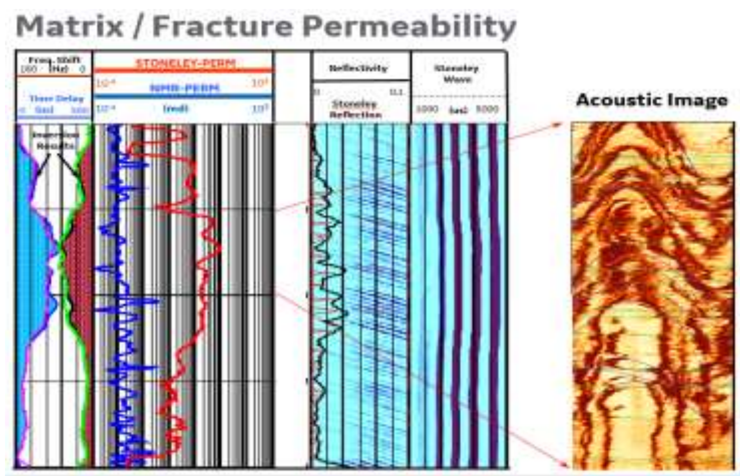
Moldic Porosity (Black), Oolite

[1]picures from: Akbar, M., Petricola, M. Watfa, W. et al., 1995, Classic Interpretation Problems: Evaluating Carbonates, Oilfield Review, Jan 1995, 38-56

Permeability

- Measure core
  - Small volume, needs upscale
- Drillstem test
  - Large volume
- Formation tester drawdown
  - Small volume “Mobility” (Add viscosity of fluid for Permeability)
  - Straddle packer – Kv/Kh
- Estimate from porosity
  - Core porosity/permeability correlation → Apply to log porosity
  - "Timur" type equation based on porosity and Sw
- Magnetic resonance
  - NMR provides textural information
- Acoustic stoneley waves
  - Connectivity to the wellbore

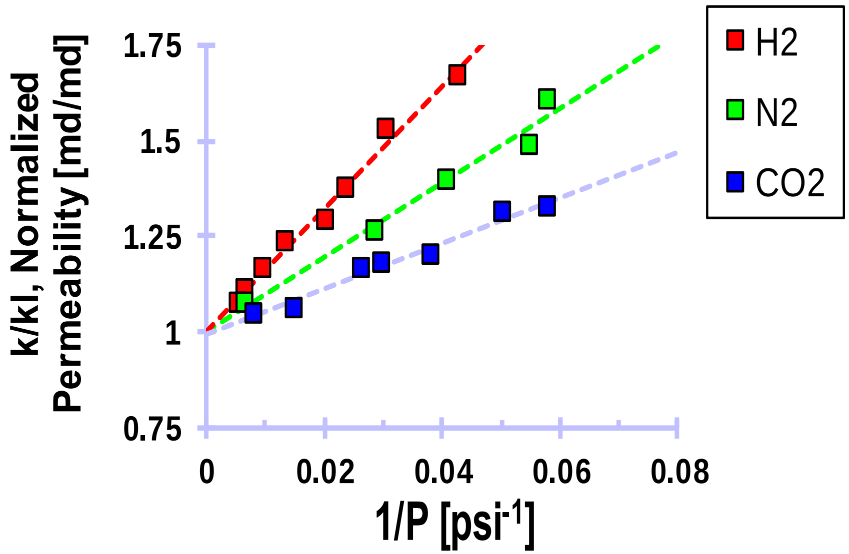


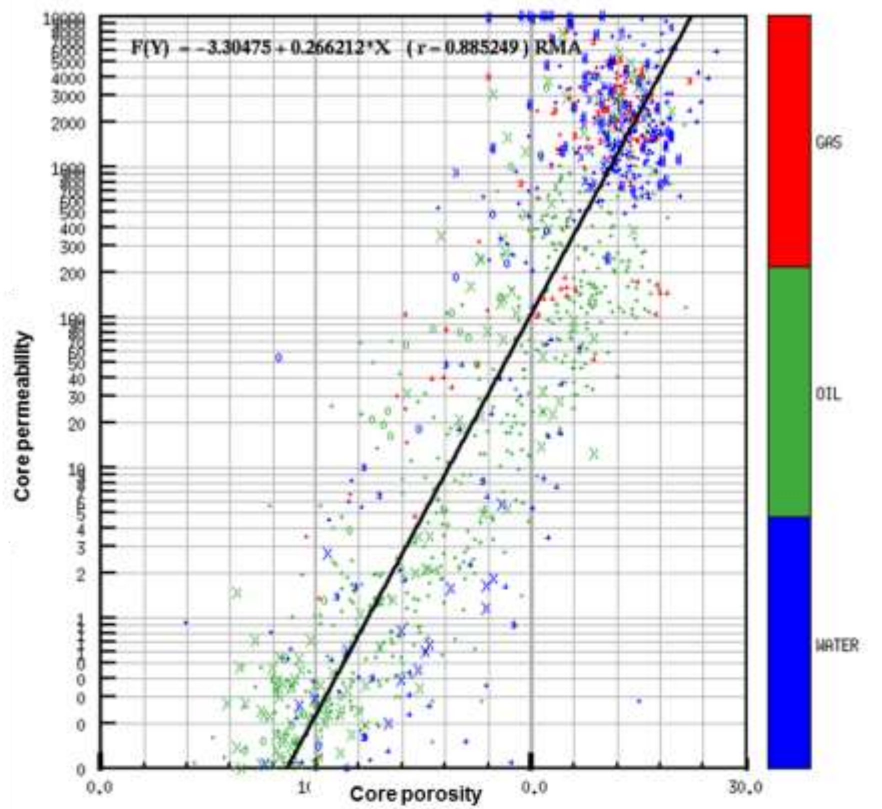


DEVEX2018

Core Permeability

Klinkenberg Corrected for gas density and slippage





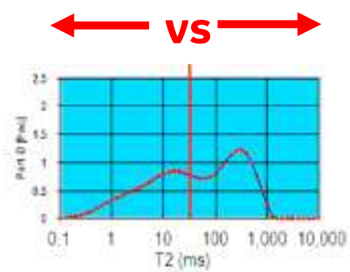
As the gas density increases "slippage" decreases and $k_{gas} \rightarrow k_{liquid}$

NMR Permeability - k_{nmr}

Two **models** in use (Permeability is estimated not measured)

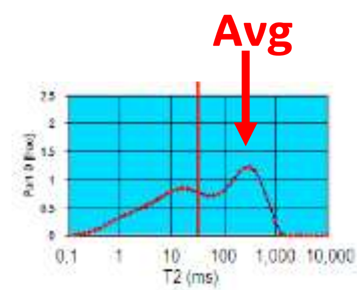
Coates-Timur Model :

$$k_{nmr} = \left(\frac{\phi_{NMR}}{C}\right)^m \bullet \left(\frac{BVM}{BVI}\right)^n$$



SDR/Kenyon Model:

$$k_{nmr} = C \bullet \left(\phi_{NMR}\right)^m \bullet \left(T_{2\ \text{Geo. Mean}}\right)^n$$



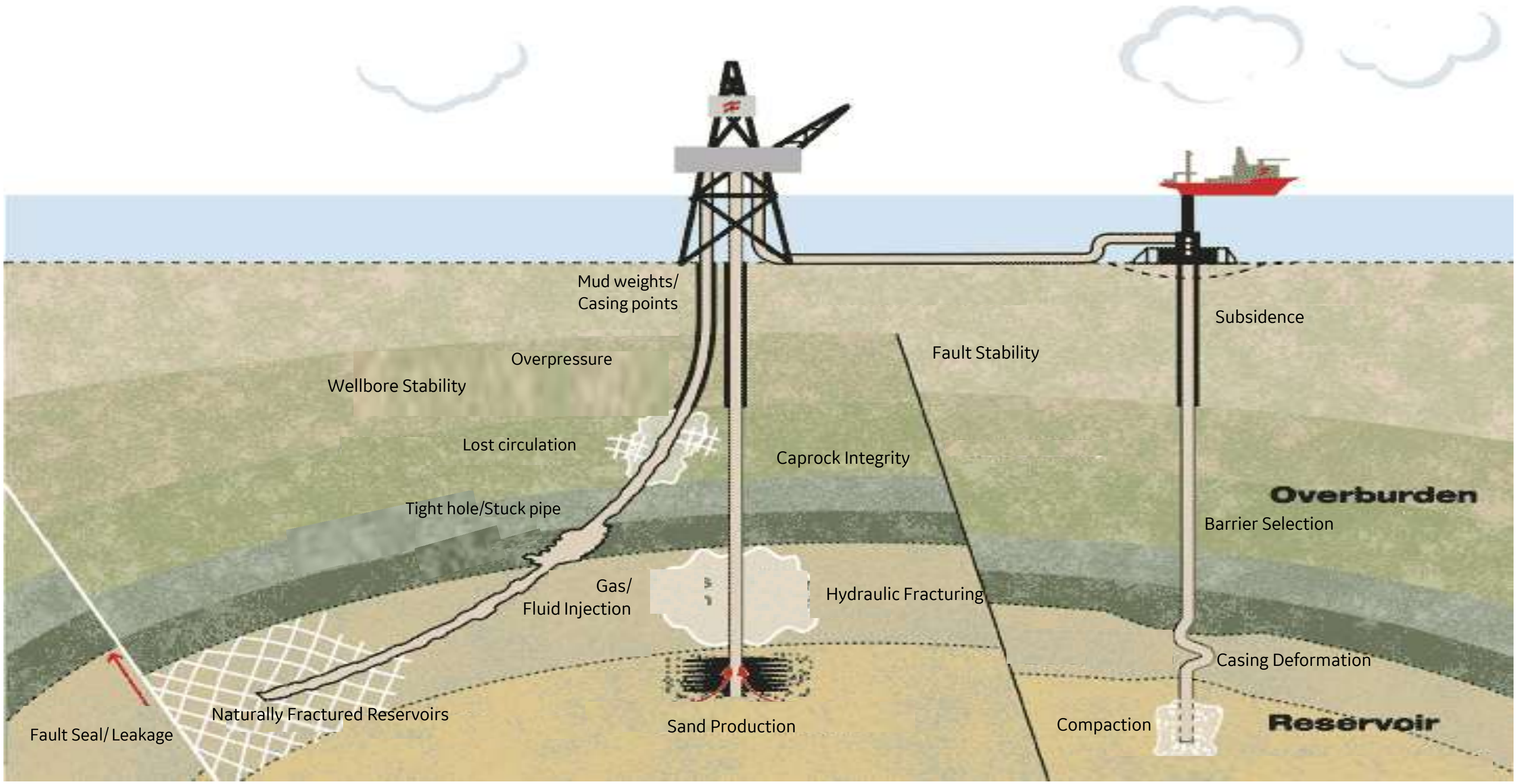
Where assumed default parameters are: C =10, m = 4 & n = 2

Note: k_{nmr} is an estimate of permeability based on a model.
For accuracy k_{nmr} should be calibrated to local reservoir data.

Applications of a Geomechanical Model

Reducing Cost, Improving Production & Optimizing Reservoir Life

Exploration → Appraisal → Development → Production → Rejuvenation → P&A

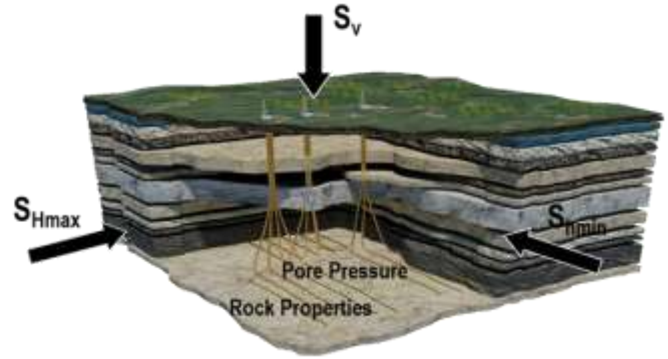


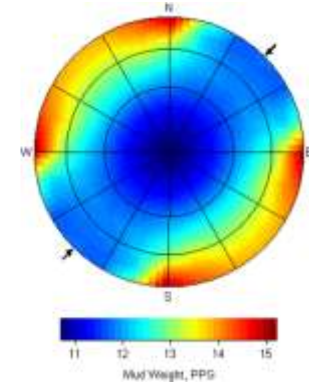
DEVEX2018

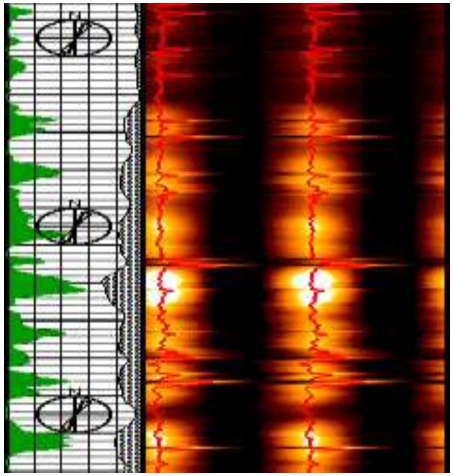
Geomechanical Information

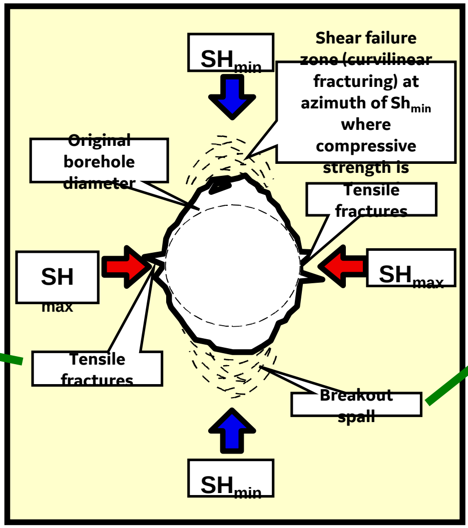
Magnitudes

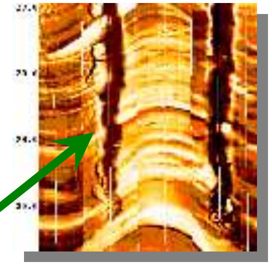
+ Azimuth











Drilling-induced tension fractures

Borehole breakout

In VERTICAL WELLS, the orientation of these features is a direct measure of the orientation of the stress field.

DEVEX2018

Summary

- Petrophysics integrates all available information
  - Rock samples - Cuttings, Core,
  - Logs – SLS, Wireline, LWD
- To determine Reservoir properties
  - Mineralogy
  - Porosity
  - Fluids
- To integrate in the subsurface model and determine the NPV of the prospect and define "Reserves"

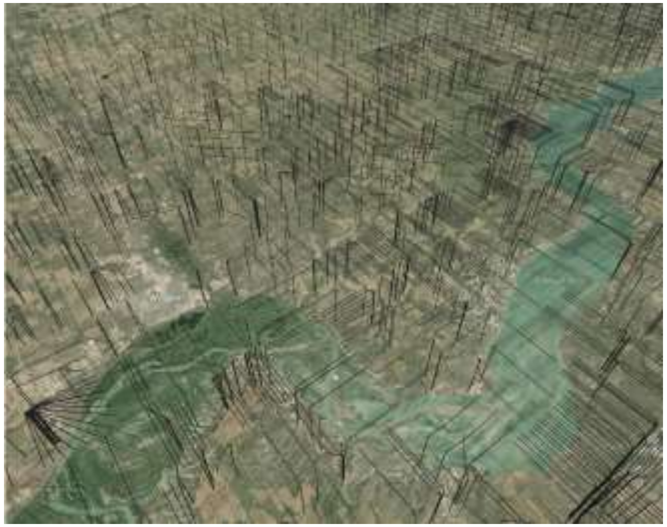
The Future..............

The Future of Petrophysics

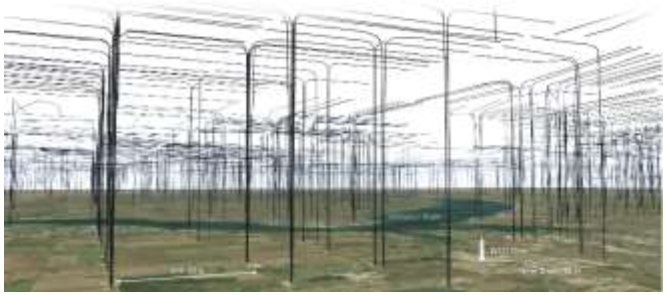
- Reservoirs are getting more complex
  - Most of the easy stuff has been found??
- Move into "Unconventionals"
  - "There is no reservoir in the shale"......
- N.Sea "Unconventionals":
  - Thin beds
  - Heavy Oil
  - Basement
  - Mature Reservoirs....

If you like a Challenge:
Become a Petrophysicist!

North Dakota



https://www.nytimes.com/interactive/2014/11/24/upshot/nd-oil-well-illustration.html



SPWLA 2018

Log time in London

ANNUAL SYMPOSIUM

LONDON, ENGLAND

June 2-6, 2018

spwla2018.com