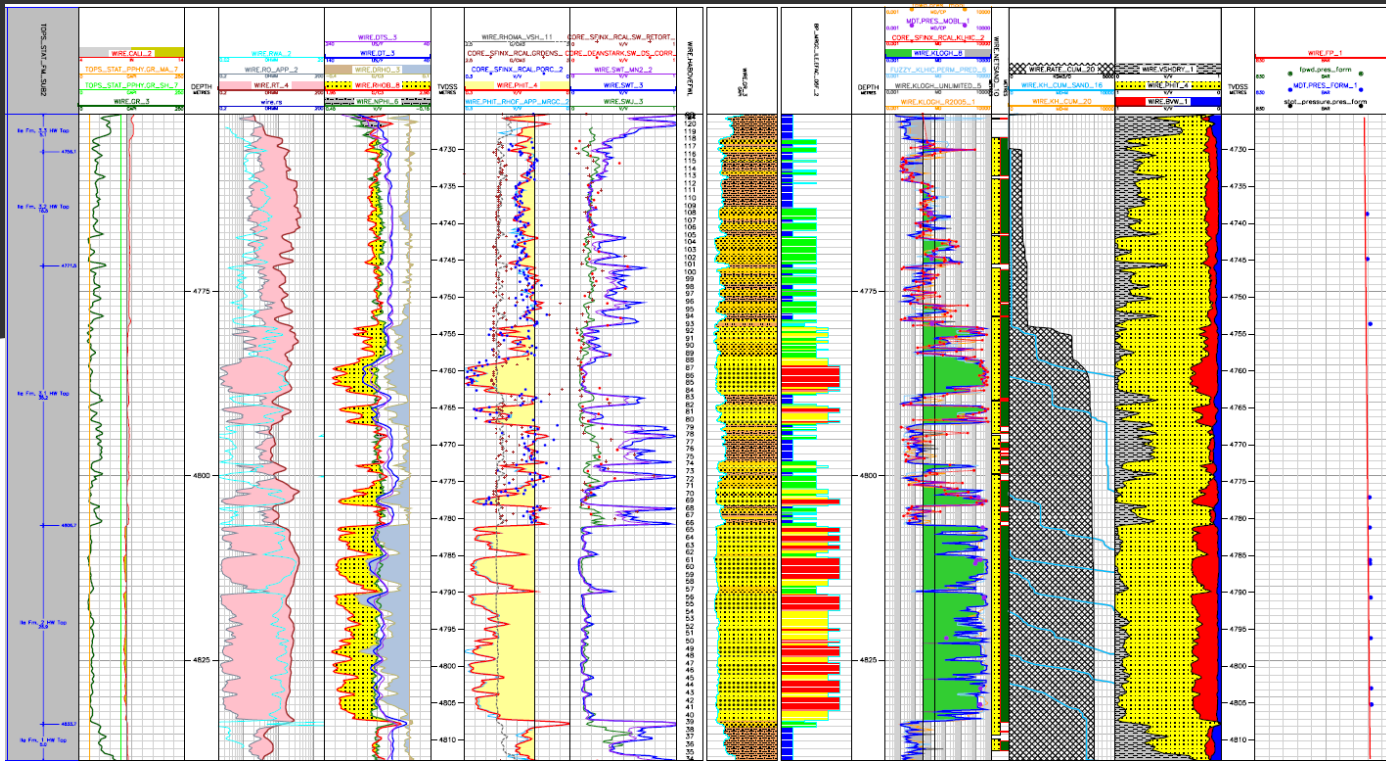




Formation Evaluation

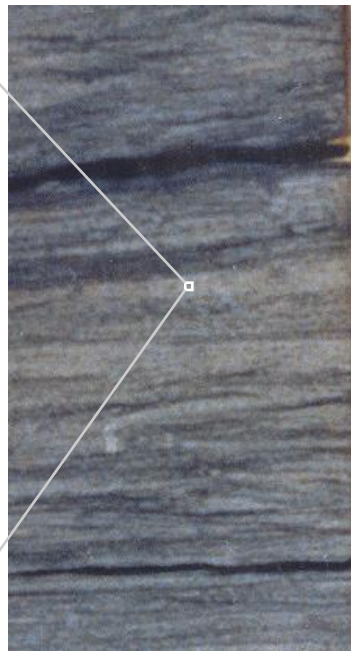
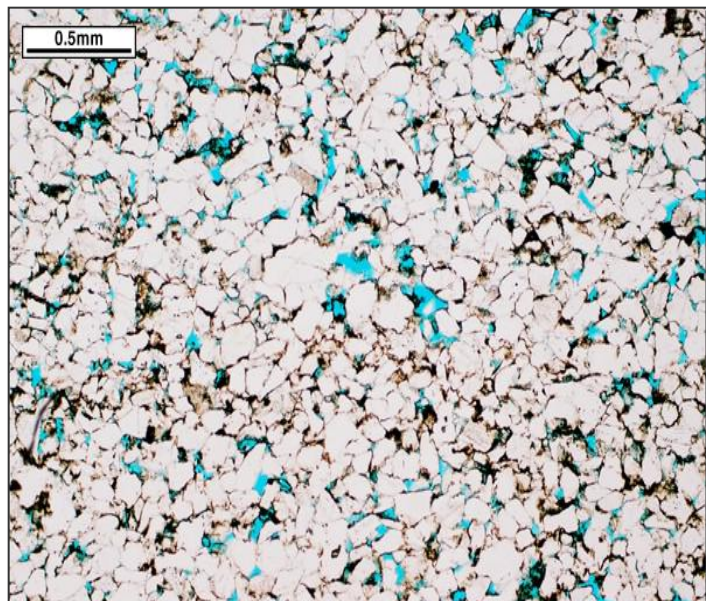
Outline

- Objectives of Petrophysics
- Data Acquisition
- Quicklook Evaluation
- Formation Pressure
- Permeability

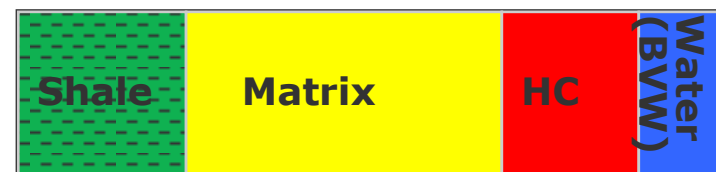
Objectives of Petrophysics

- **Identify and quantify hydrocarbon resources in the subsurface and evaluate rock properties**
- Objectives for this course:
 - What data we acquire
 - Describe basic principles of common open hole logging tools
 - Quick look evaluation on a standard set of open hole logs:
 - Lithology
 - Volume of Shale
 - Porosity
 - Saturation
 - Net / Gross

What it is all about



- Schematically



- Porosity (Φ): Fraction (or %) of rock not occupied by solids
- Porosity contains fluids: Water/oil/gas
- Water saturation (S_w): Fraction (or %) of porosity filled with water



Petrophysics - Basic deliverables for a well

Petrophysical variables at each relevant depth:

- Porosity
- Water saturation
- Shale volume
- Net Reservoir (Net Sand)
- Permeability

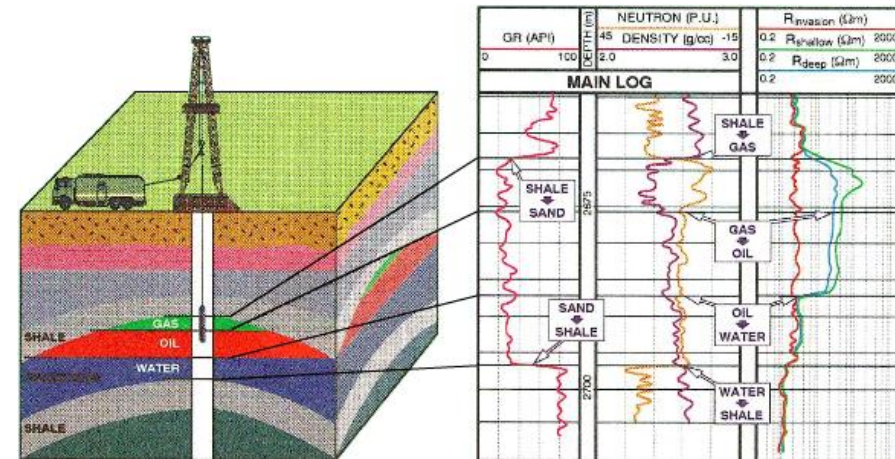
NONE OF these are measured by **LOGS** in the well **!!!!**

The petrophysical variables are estimated based on **mathematical relations** including log measurements and parameter values

Data Acquisition Methods

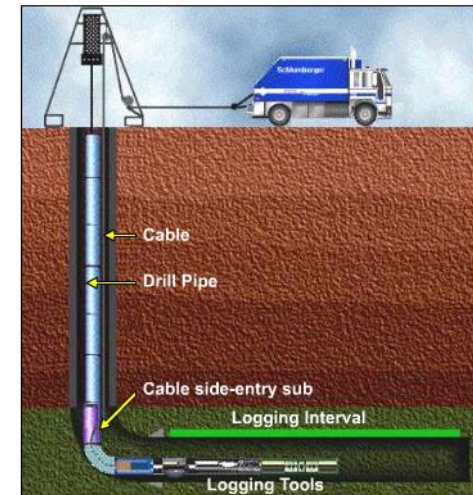
- **Wireline (EWL)**

- Vertical or low angle wells
- Logging tools conveyed by electrical wireline
- Generally most advanced and highest quality logs



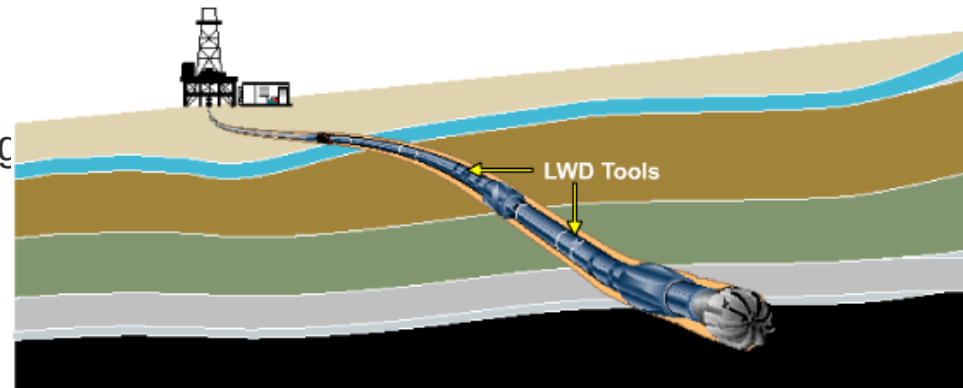
- **Pipe Conveyed Logging (PCL)**

- Highly deviated wells
- Logging tools are lowered down the well by drill pipe, with the tool connected at the end



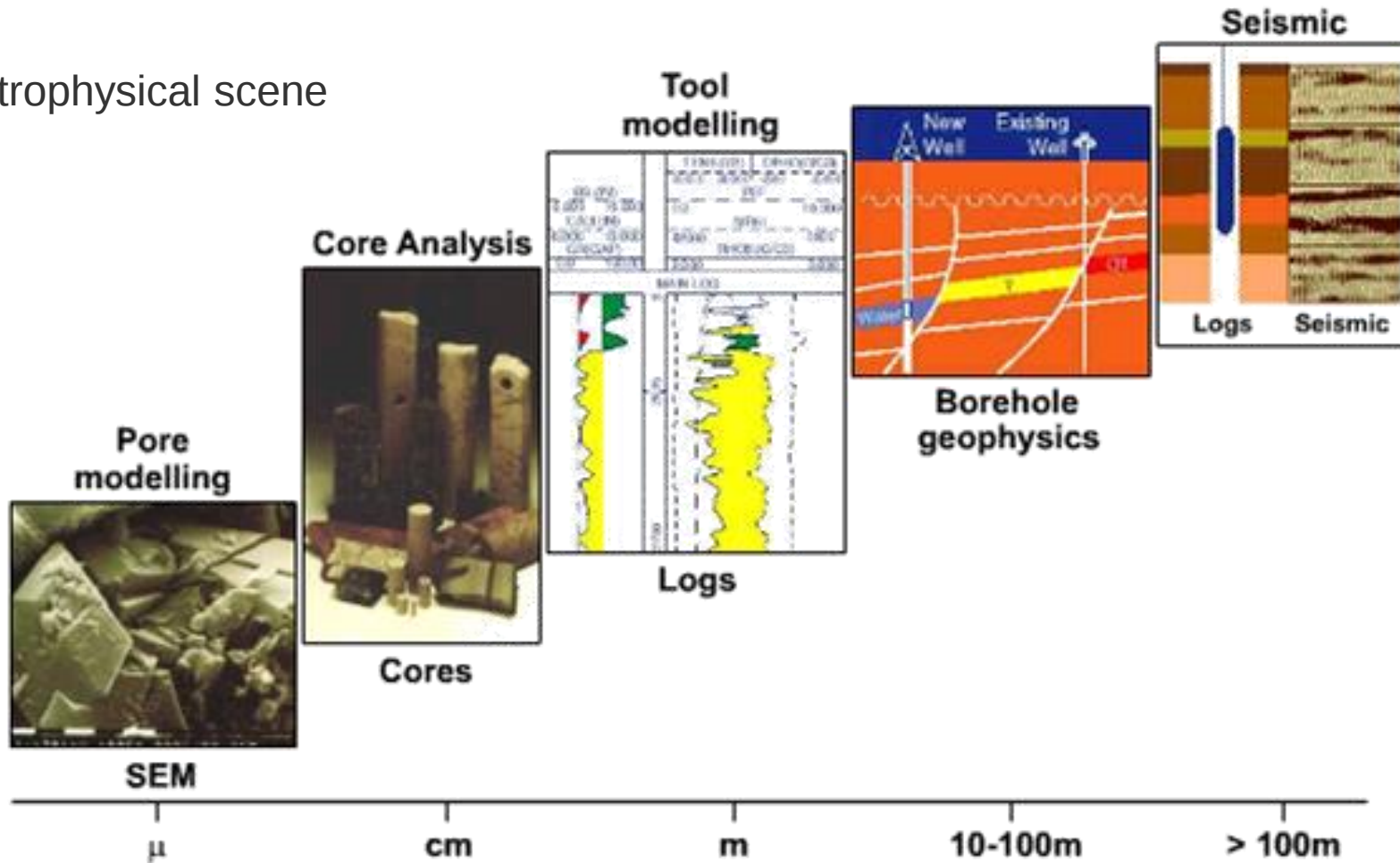
- **Logging while drilling (LWD)**

- Sensors as a part of the drilling assembly
- Sending real time signals through the drilling mud



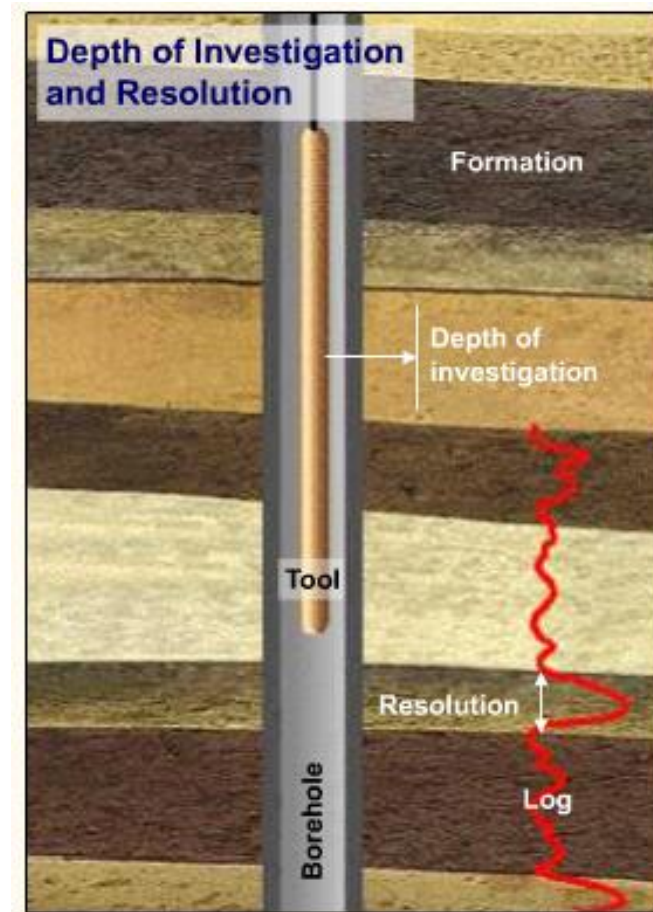
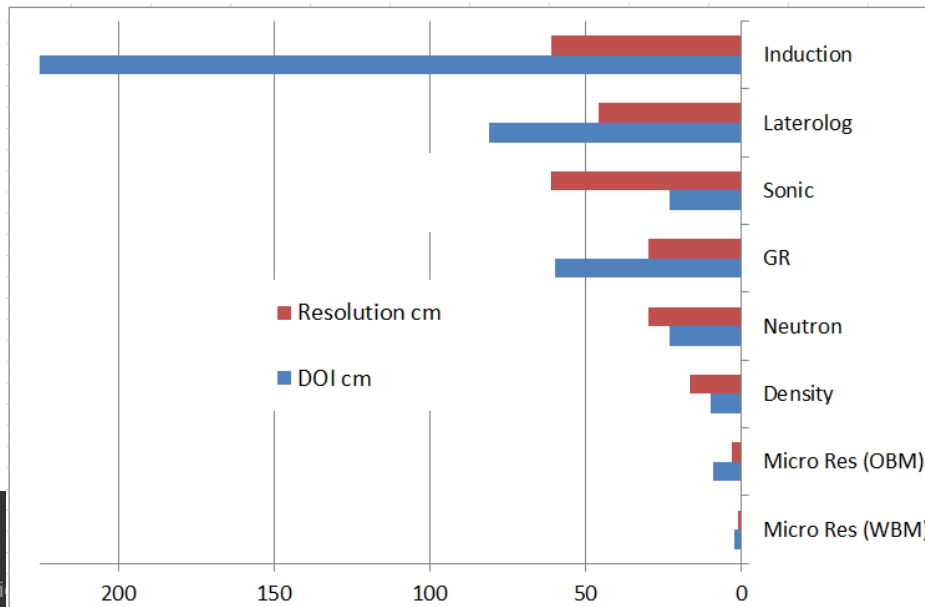
Scale

Petrophysical scene



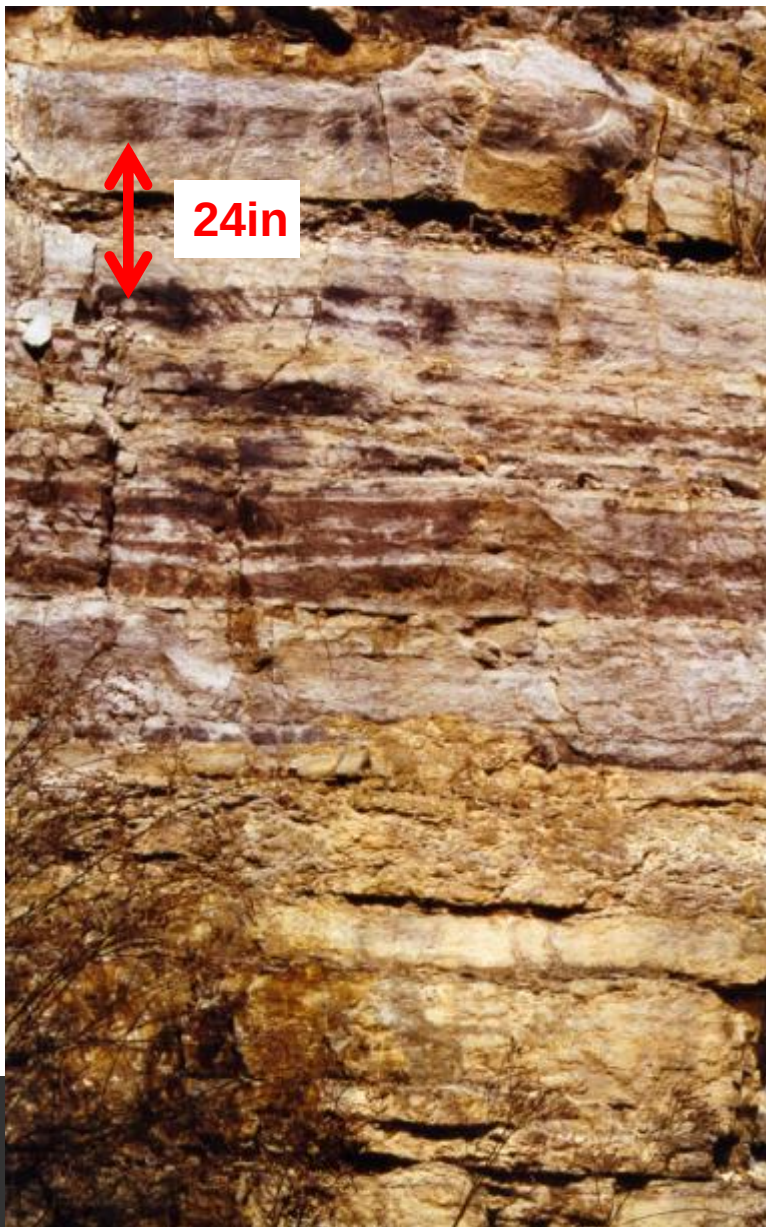
Data Acquisition

- **Depth of investigation**
 - The distance away from the borehole that a logging tool can measure
- **Resolution**
 - Capability to distinguish and properly measure thin beds



VERTICAL RESOLUTION OF WELL LOGS

Outcrop or Core



Sonic
24in



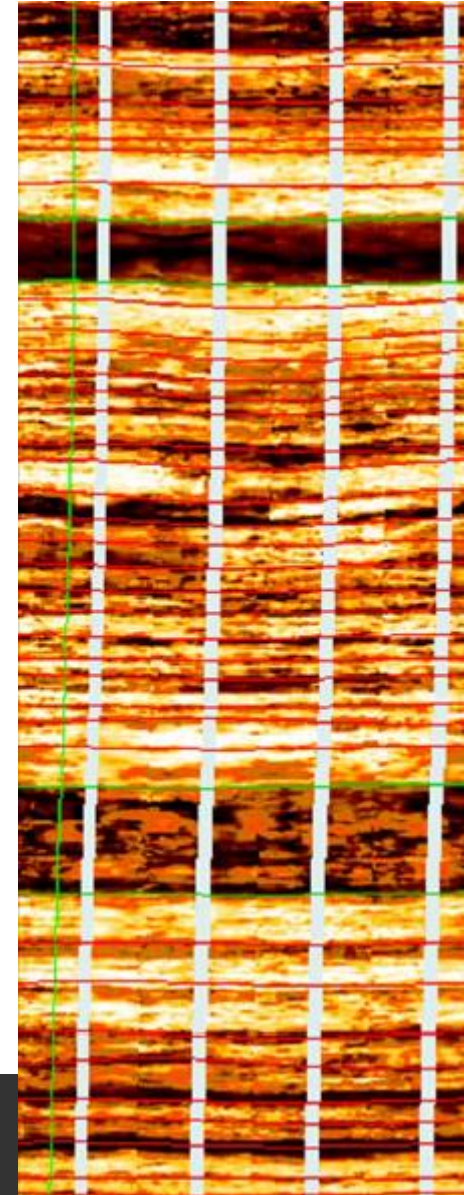
GR
12in



Density
6in



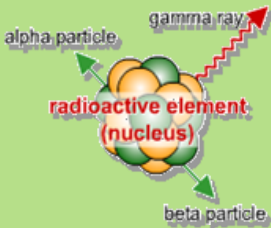
Resistivity Image
<1in



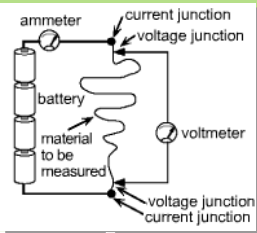
Petrophysical Measurements

Covered in this course

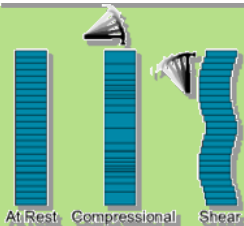
Radioactivity



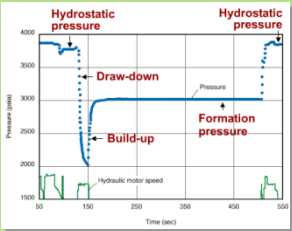
Resistivity



Sonic

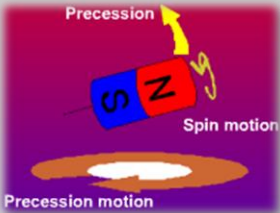


Pressure

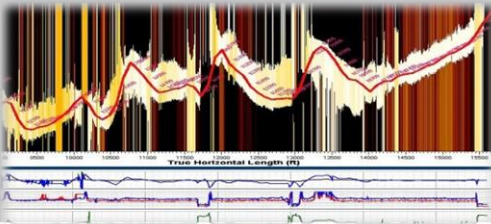


Not covered in this course

Nuclear Magnetic Resonance

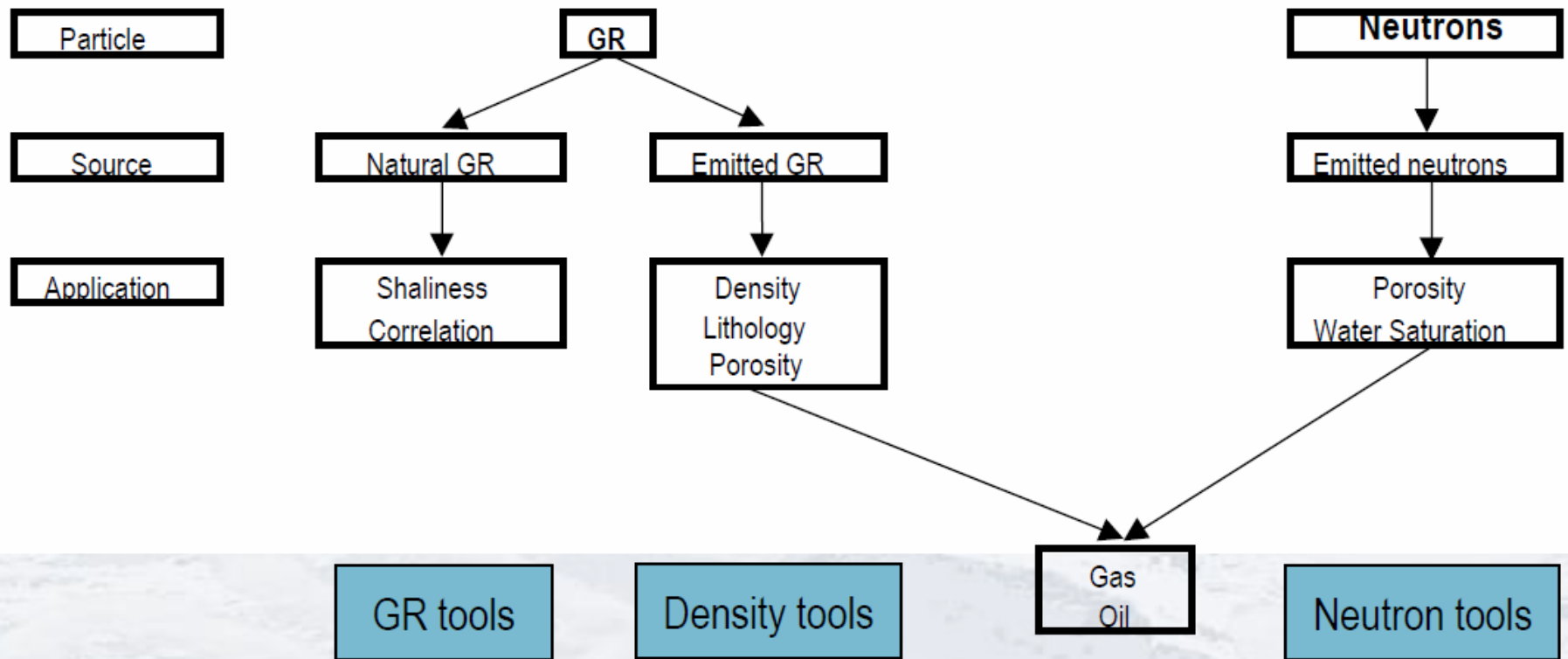


Geosteering



Family of Nuclear Tools

Radioactivity is a result of decay of an unstable nucleus through emission of particles or energy



Quick Look Evaluation

- **Lithology**
 - GR, DEN/NEU, Resistivity, Sonic
- **Volume of Shale**
 - GR
- **Porosity**
 - DEN
- **Saturation**
 - Resistivity, Porosity, etc
- **Net / Gross**
 - Cutoffs porosity and VSH

Quick Look Evaluation - Lithology

- Quicklook Evaluation

 - Lithology
 - Volume of Shale
 - Porosity
 - Saturation
 - Net / Gross

Density / Neutron Combinations (Limestone compatible scale)

Water-filled sands

- Density left of neutron porosity

Oil-filled sands

- Density slightly lower than in water
- Neutron slightly lower than in water

Gas-filled sands

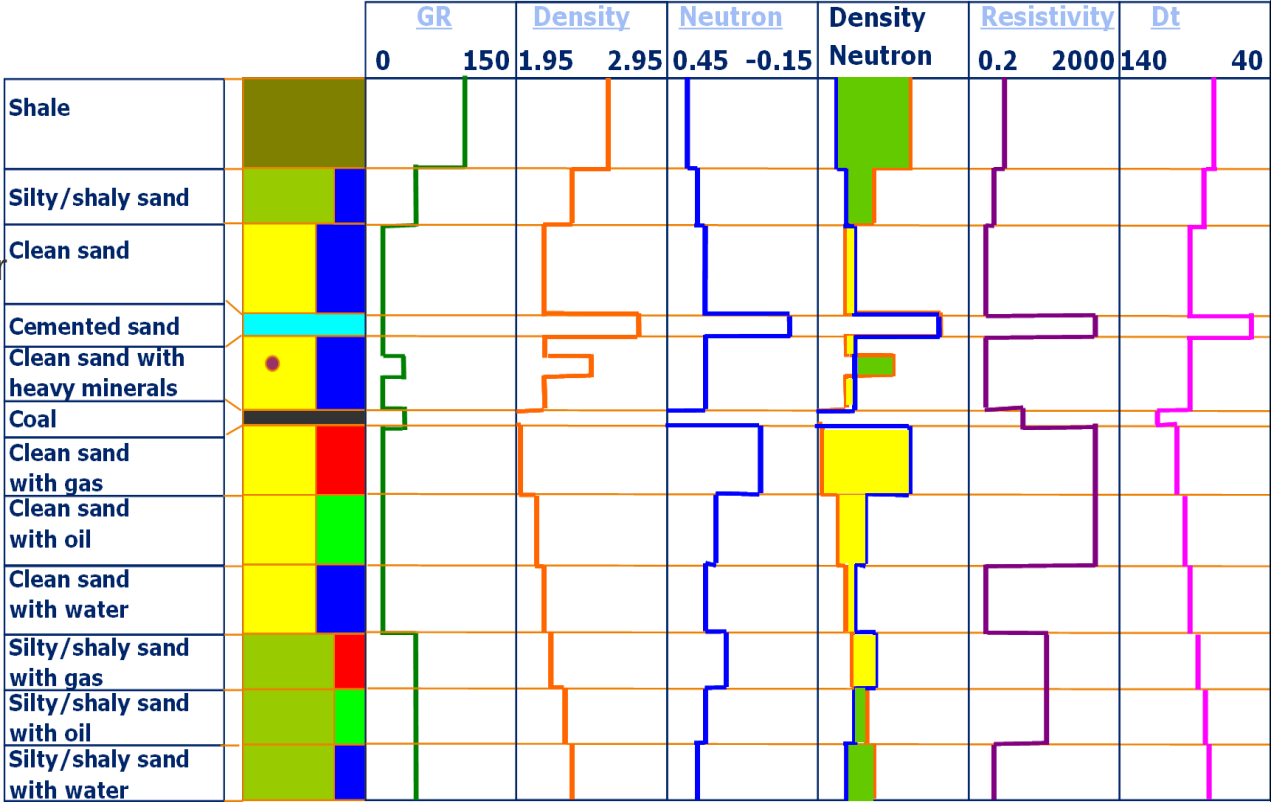
- Density read lower than oil/water
- Neutron porosity low (low HI)

Shale

- High neutron porosity (bound water)
- Slightly higher density than sands
- neutron plots left of density

Calcites:

- high density, low neutron



- Lithology
- **Volume of Shale**
- Porosity
- Saturation
- Net / Gross

Shale Fraction

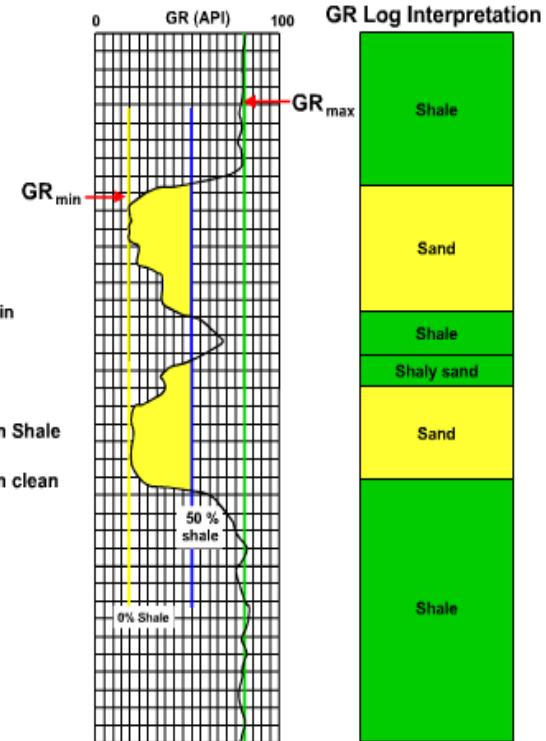
- Shale fraction: The fraction of the rock containing fine grained material and consisting of clay- and silt-sized particles. Shale contains clay minerals as well as particles of quartz, feldspar, mica, iron oxide and organics and other minerals
- VSH: The shale fraction including the water bound to the shale constituents
- VSHDRY: The shale fraction without the water bound to the shale constituents;
$$VSHDRY = VSH * (1 - PHISH)$$
- VCL: The volume of the clay mineral including the clay bound water

GR - VSH Quick Look Evaluation

- Gamma Ray (GR) Evaluation Technique
 - Natural occurring radioactive elements in nature:
 - K^{40} , Potassium
 - Th^{232} , Thorium
 - U^{238} , Uranium
- Spectral GR tool can discriminate between these elements, standard GR tool only provides the total GR counts
 - Reservoir rocks (Sandstone/Limestone/Dolomite)
 - low GR
 - Shale has large amount of Th and K atoms
 - high GR

$$V_{sh} = \frac{GR - GR_{min}}{GR_{max} - GR_{min}}$$

V_{sh} : Shale volume
GR : GR Log reading
 GR_{max} : GR Log reading in Shale zone
 GR_{min} : GR Log reading in clean Sand zone

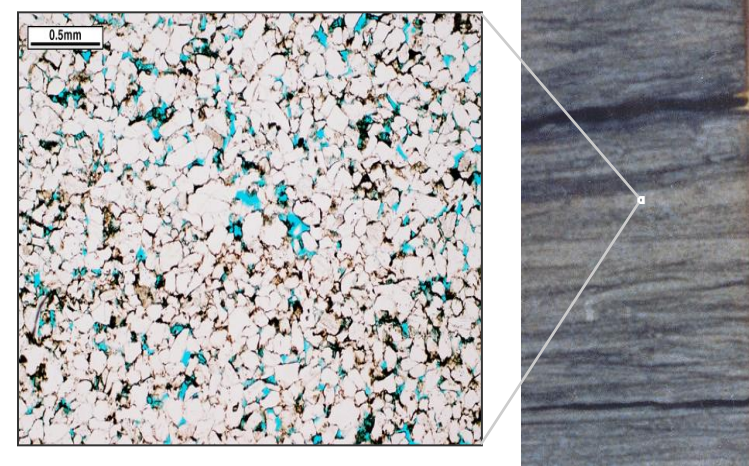


Porosity

Quicklook Evaluation

- Lithology
- Volume of Shale
- **Porosity**
- Saturation
- Net / Gross

Porosity (Φ): Fraction of rock not occupied by solids



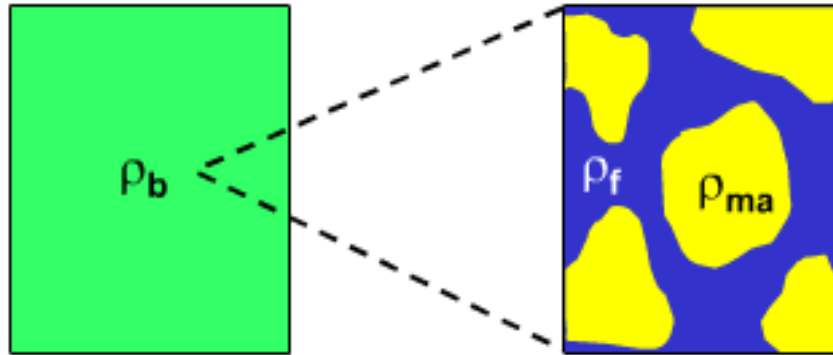
1. Core porosity evaluated at reservoir conditions shall normally be the reference Φ
2. Our default assumption is that standard core porosity is equivalent to a total porosity (PHIT)
3. In massive intervals with beds resolved by logs, log-estimated Φ shall be consistent with core measurements =>
 - **PHIT estimated from a density log shall generally be consistent with core porosity.**
4. Effective porosity: $PHIE = PHIT - VSH * PHISH$

Interpretation/Uses

- The density tool is extremely useful as it has high accuracy and exhibits small borehole effects.
- Major uses include:
 - Porosity
 - Lithology (in combination with the neutron tool)
 - Gas identification (in combination with neutron tool)
 - Mechanical properties (in combination with the sonic tool)
 - Acoustic properties (in combination with the sonic tool)

Quick look Evaluation - Porosity

Density Evaluation technique



$$\rho_b = \rho_f \phi + \rho_{ma} (1 - \phi) \Rightarrow \phi = \frac{\rho_{ma} - \rho_b}{\rho_{ma} - \rho_f}$$

where

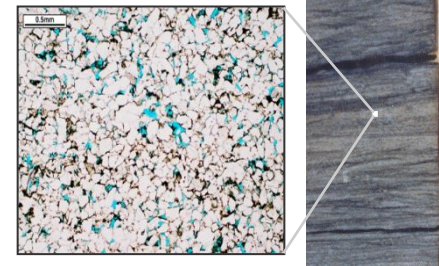
ρ_b = Density log reading

ρ_f = Density of the saturating fluid

Φ = Porosity

ρ_{ma} = Density of the matrix material

Porosity (Φ): Fraction of rock not occupied by solids



Typical density of common minerals/fluids

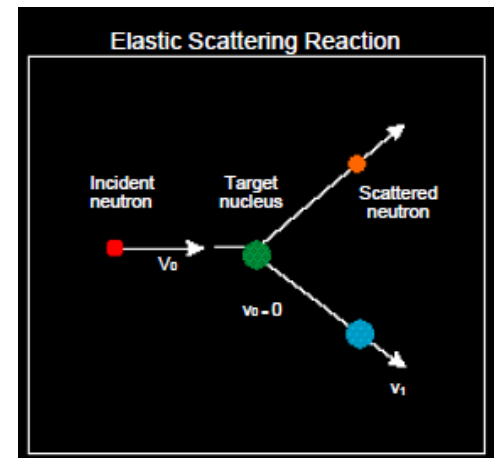
Quartz sand	2.65 g/cc
Calcite	2.71 g/cc
Shale	2.6-2.7 g/cc
Gas	0.3 g/cc
Oil	0.8 g/cc
Water	1.0 g/cc

Neutron Logging

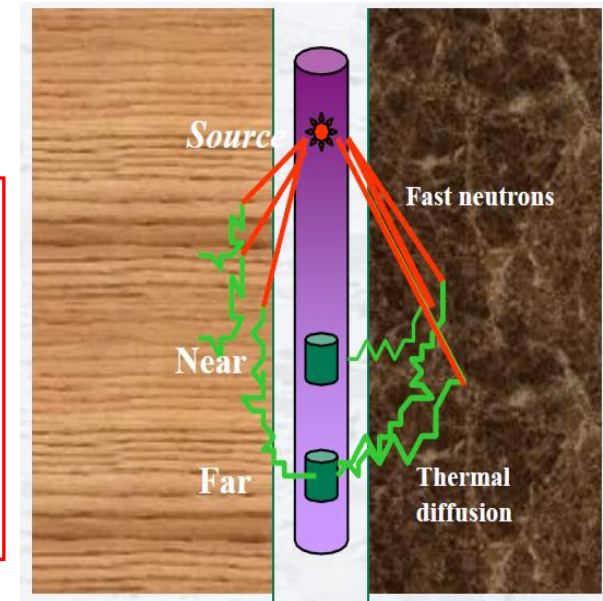
- Source: Neutron source (chemical or electronic),
- Detectors: Neutron (thermal or epithermal)
- Measures neutron porosity (counts) which is a measure of the hydrogen index of the formation (H in the rock)
- HI in shales high
- HI of Gas $\ll$ HI of water and oil

Applications:

- **Lithology (w/ DEN or Sonic)**
- **Gas identification (w/ DEN or Sonic)**
- Correcting porosity for lith. and HC effects (w/ DEN or Sonic)
- Quantification of Gas fraction (w/ DEN or Sonic)
- Porosity (w/ DEN or Sonic)
- VSH

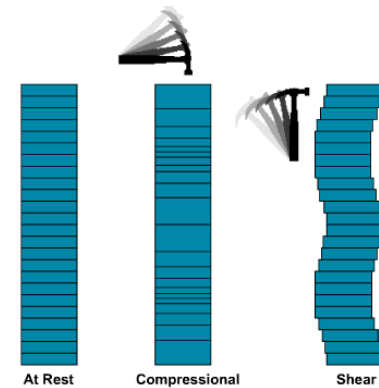


Large HI	Low HI
High NEU Porosity	Low NEU Porosity
Low Count Rate	High Count Rate

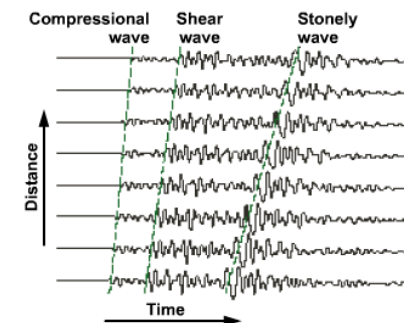


Sonic Logging

- The *sonic* or *acoustic* log measures the travel time (slowness) of an elastic wave through the formation
 - Increasing with decreasing porosity
 - Can also derive the velocity of elastic waves through the formation
- Compressional waves (P-waves):
 - parallel to the direction of propagation
- Shear waves (S-wave):
 - perpendicular to the direction of propagation
- Stoneley wave:
 - propagate along the walls of a fluid-filled borehole



Array Sonic



Typical values for transit times (matrix value without porosity)

Sandstone – 51 - 58 $\mu\text{s}/\text{ft}$

Limestone – 47.5 $\mu\text{s}/\text{ft}$

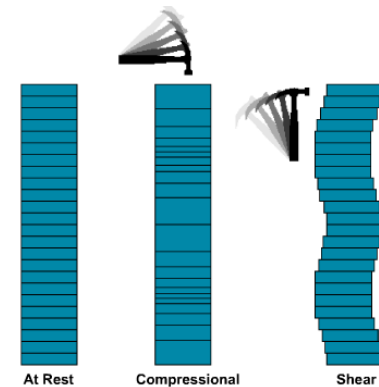
Shale – 62 to 167 $\mu\text{s}/\text{ft}$

Filtrate – 189 - 200 $\mu\text{s}/\text{ft}$

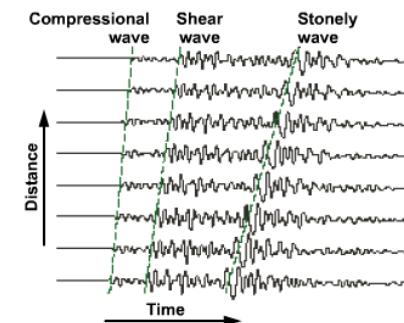
Casing – 57 $\mu\text{s}/\text{ft}$

Sonic Logging

- The *sonic* or *acoustic* log measures the travel time (slowness) of an elastic wave through the formation
- Applications:
 - Geophysical interpretation:
 - Synthetic seismograms (calibration of seismic surveys)
 - Acoustic Impedance ($V_p(\text{m/sec}) \cdot \rho(\text{g/cc})$)
 - Porosity estimation (Wyllie or Raymer-Hunt Gardner)
 - Rock mechanical properties (elastic properties, rock strength)
 - Identification of gas (DT slower in gas)
 - Fracture indicator and Qualitative permeability from Stoneley
 - Cement Bond Logging



Array Sonic



Typical values for transit times (matrix value without porosity)

Sandstone – 51 - 58 $\mu\text{s/ft}$

Limestone – 47.5 $\mu\text{s/ft}$

Shale – 62 to 167 $\mu\text{s/ft}$

Filtrate – 189 - 200 $\mu\text{s/ft}$

Casing – 57 $\mu\text{s/ft}$

Saturation

- Saturation

- the fraction of the formation pore volume occupied by a specified fluid

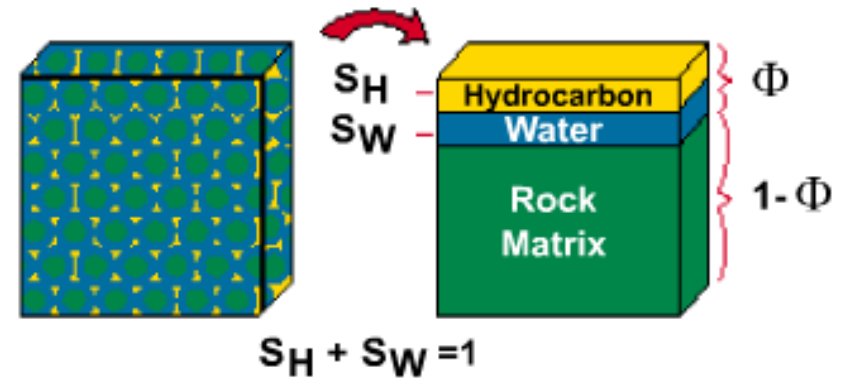
Fraction of gas+oil+water=1=100%

- Water Saturation (S_w)

- the fraction of the pore volume that contains formation water

Quicklook Evaluation

- Lithology
- Volume of Shale
- Porosity
- **Saturation**
- Net / Gross



S_H = Hydrocarbon saturation (oil and gas)

S_W = Water saturation

Φ = Porosity

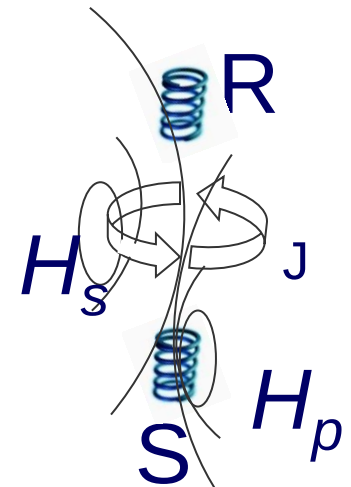
Resistivity – Induction & Laterolog

Electrical resistivity - resistance to current, inverse of conductivity

Induction principle (Faradays Law):

- Current in a source coil (S) induces a magnetic field in the formation (H_p)
- The magnetic field sets up a geo-electric current in the formation (J), which generate a secondary magnetic field (H_s)
- A current is induced in the receiver coil (R) with change in amplitude and phase
- Works best in resistive mud (OBM)

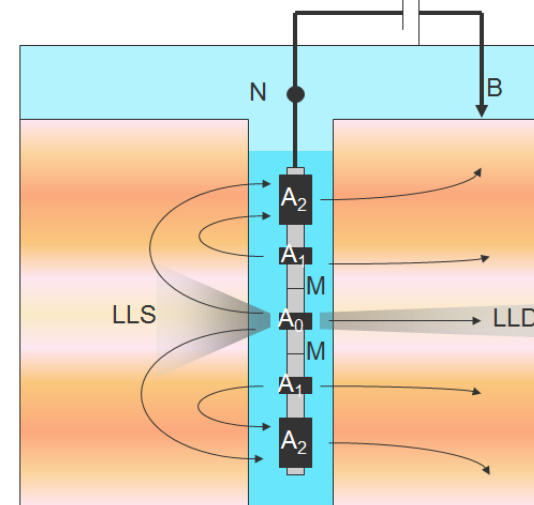
Induction



Laterolog:

- Focusing of current from the tool into the rock by focusing electrodes making the current flow only in the lateral direction
- Need electrical contact with the formations, i.e. conductive drilling mud (WBM)

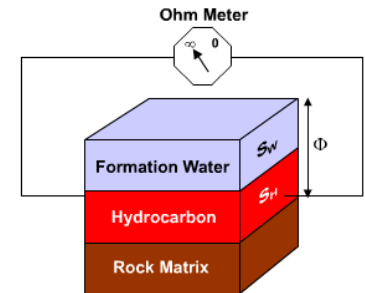
Laterolog



Quick look Evaluation - Saturation

- Water saturation (S_w) from **resistivity logs**

- Matrix (dry rock) is a good insulator → **high** resistivity
- Oil and gas is a good insulator → **high** resistivity
- Water is a good conductor → **low** resistivity
- Shales contain bound water and is therefore a conductor → **low** resistivity



Archie Equation:

$$S_w = \left(\frac{a R_w}{\Phi^m R_t} \right)^{1/n}$$

a = tortuosity factor

m = cementation exponent

n = saturation exponent

Standard values: $a=1, m=2, n=2$

Archie with standard values:

$$S_w = \frac{1}{\Phi} \sqrt{\frac{R_w}{R_t}} \Rightarrow \text{If } S_w = 1 \text{ (in water zone): } R_w = \Phi^2 R_t$$

R_w = Formation water resistivity

R_t = True formation resistivity

Φ = Total porosity

Net / Gross

- **Gross Rock:** Comprises all the rock within the thickness under consideration
- **Net Reservoir:** Net sand intervals which have useful reservoir properties
 - From cutoffs on Porosity and VSH
- (**Net Pay:** Net reservoir intervals which contain significant hydrocarbons)

For reservoir modelling purposes we present the distribution of Net Reservoir (and Net/Gross), while the presence of hydrocarbons (pay) is modelled based on estimated Saturation-Height functions and fluid levels

Quicklook Evaluation - Summary

$$V_{sh} = \frac{GR - GR_{min}}{GR_{max} - GR_{min}}$$

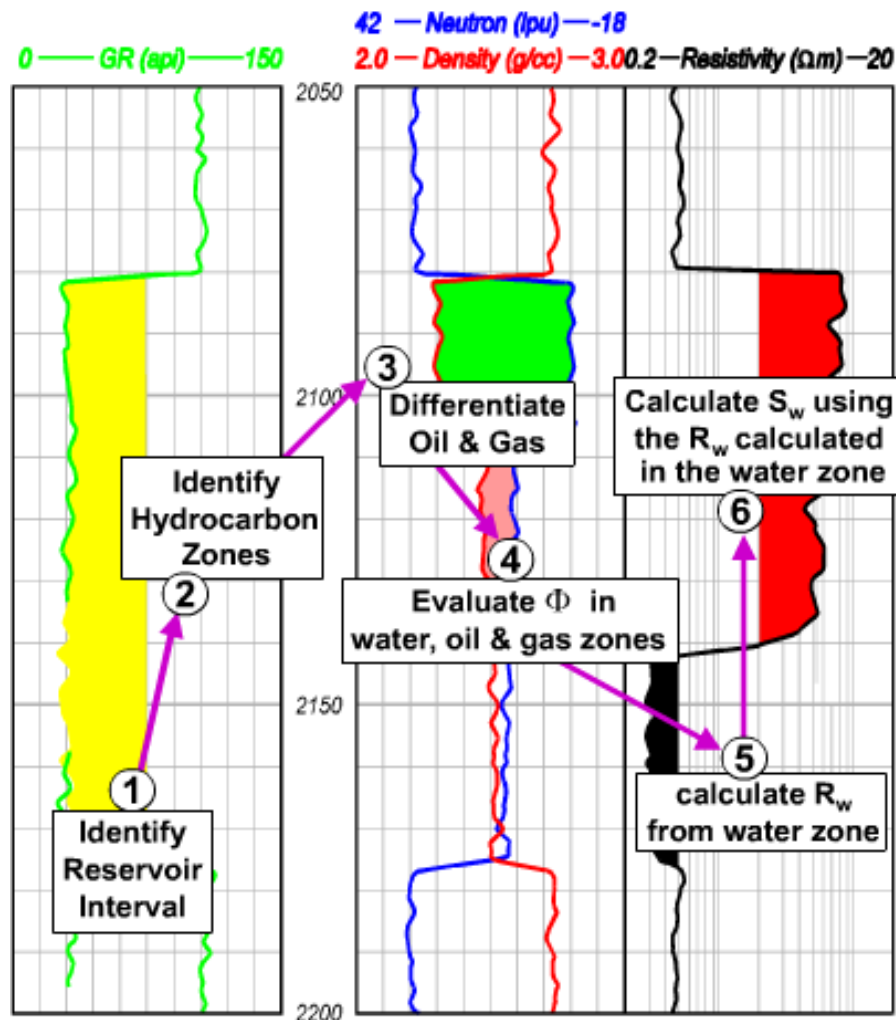
$$\Phi = \frac{\rho_{ma} - \rho_b}{\rho_{ma} - \rho_{fl}}$$

$$S_w = \frac{1}{\Phi} \sqrt{\frac{R_w}{R_t}}$$

In clean water bearing formations ($S_w = 1$):

$$R_w = \phi^2 R_t$$

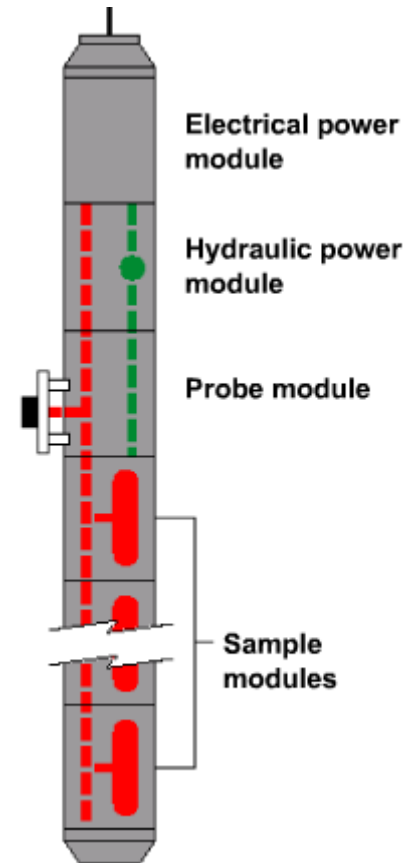
assuming $a = 1$, $m = n = 2$



Formation Pressure

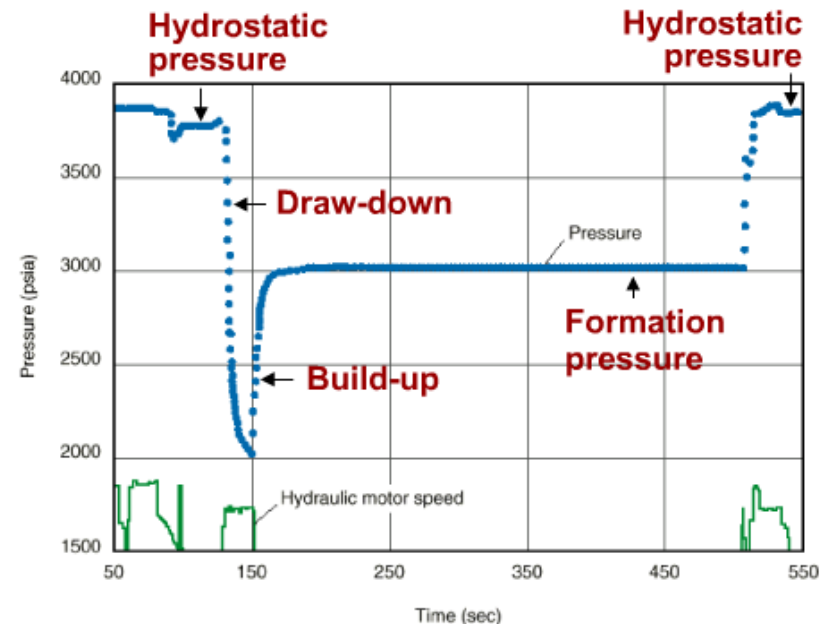
- Formation Pressures (EWL and LWD)
 - Fluid densities (fluid type)
 - Fluid contact levels (free fluid levels)
- Formation fluid samples (EWL)

MDT (SLB), RDT (HAL), RCI (Baker)



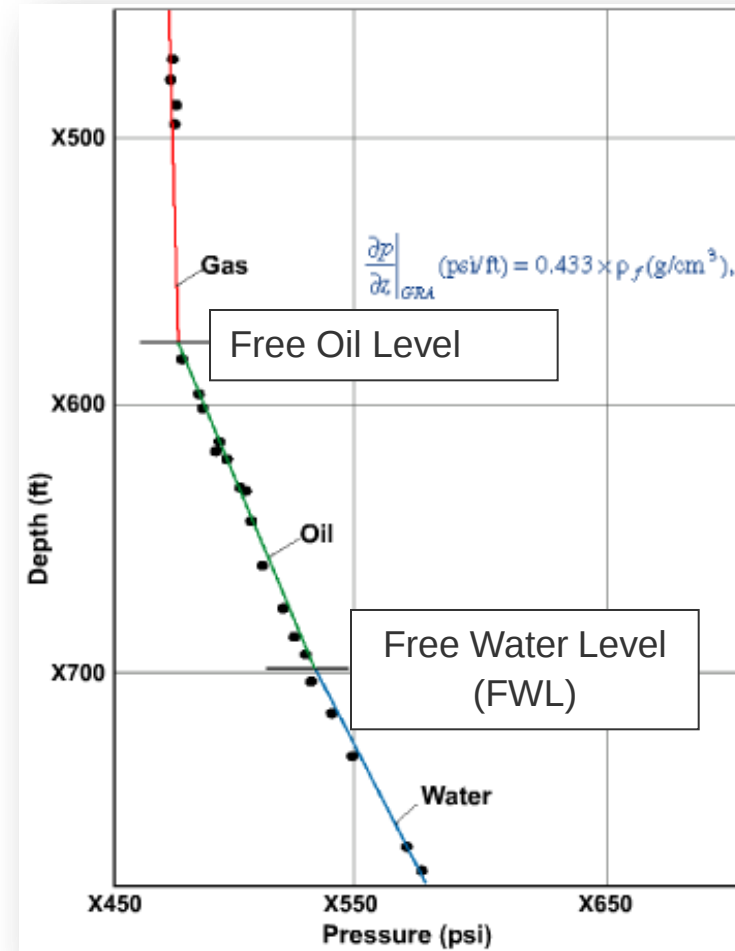
Formation Pressure

1. The probe is pushed against the formation
2. Formation pressure obtained by withdrawing a small amount of fluid from the formation to generate a short transient test.
3. Formation pressure is the stable pressure reached after shut-in
4. How fast the formation equalize the pressure indicates its permeability (mobility)

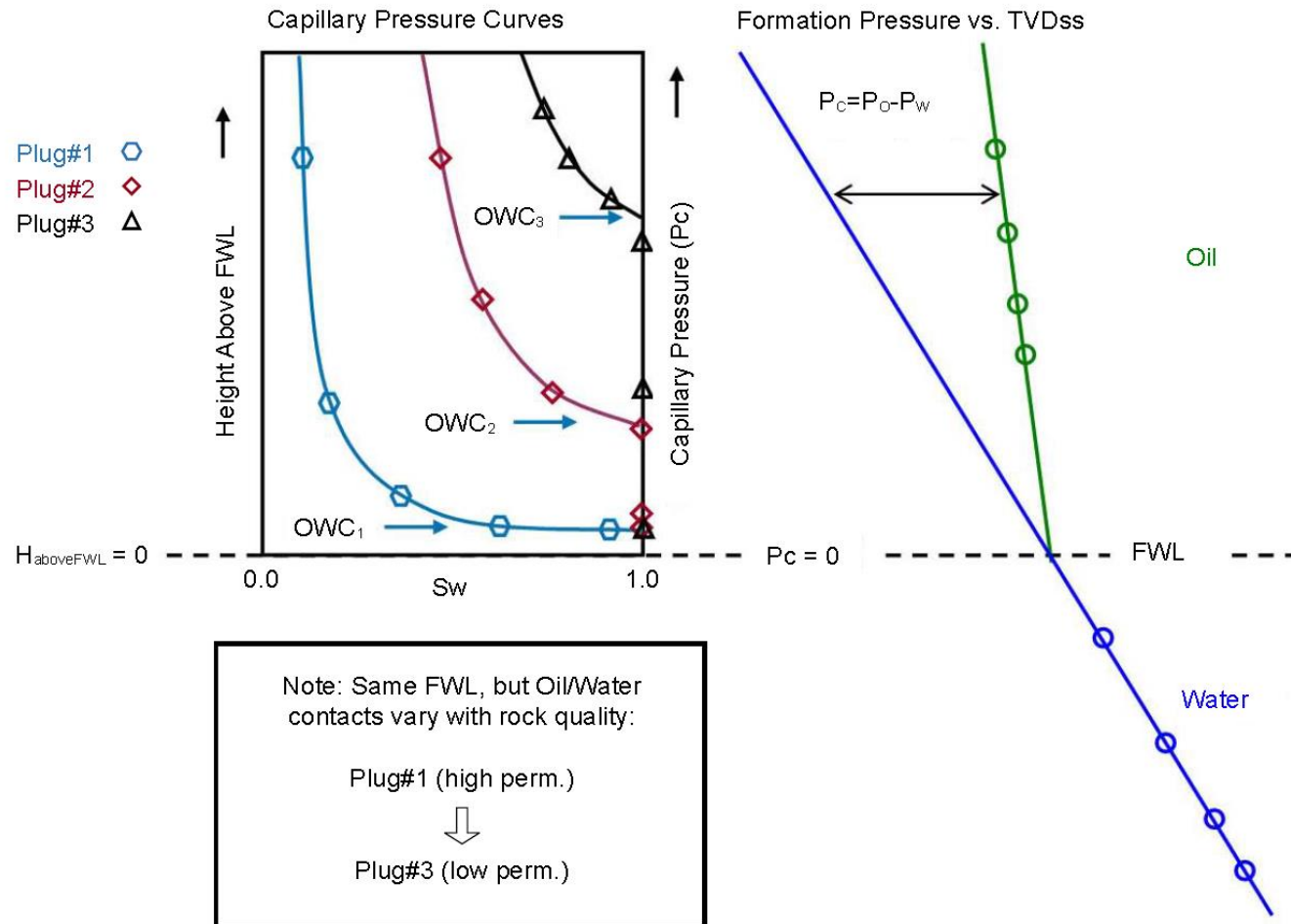


Formation Pressure

- Evaluation Technique
 - An unlimited number of pressure tests (minimum 3 good) can be performed at different depths to produce a pressure profile
 - The slope of the line defines fluid density
 - The intersection defines free fluid levels

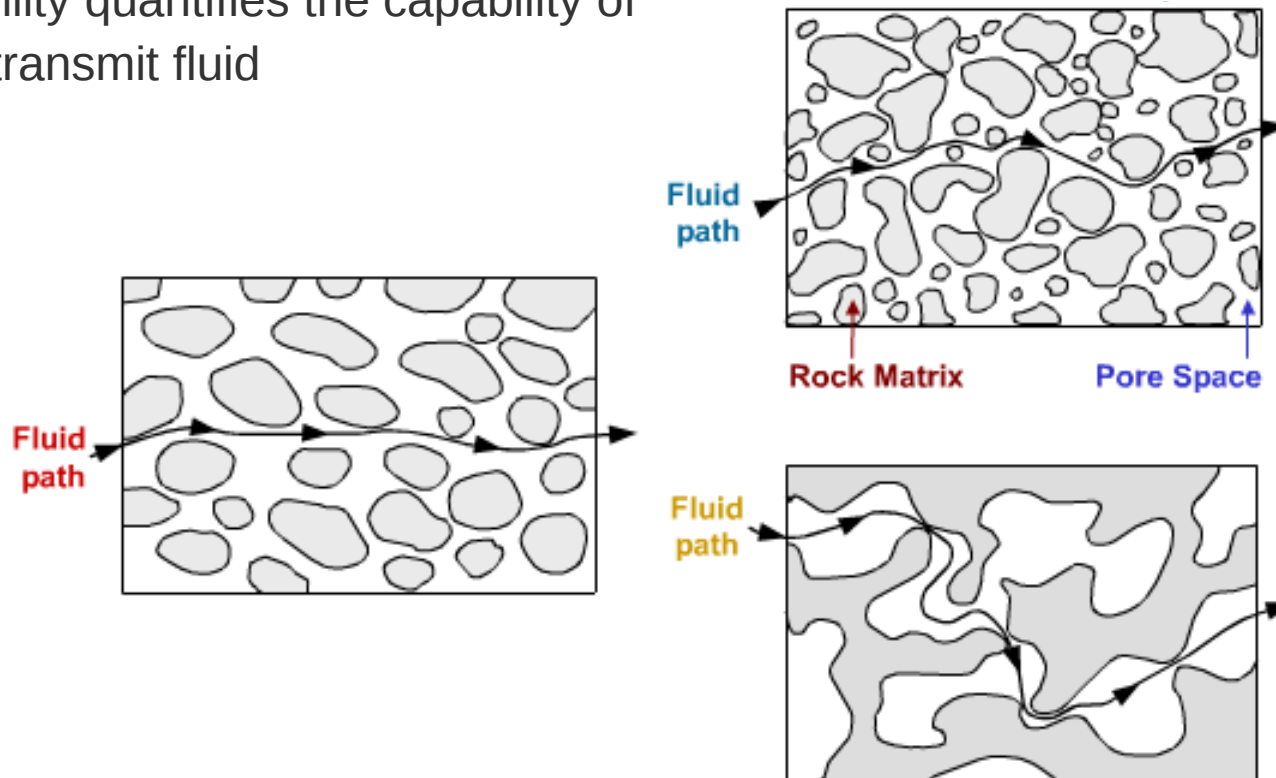


Free Water Level vs Oil Water Contact



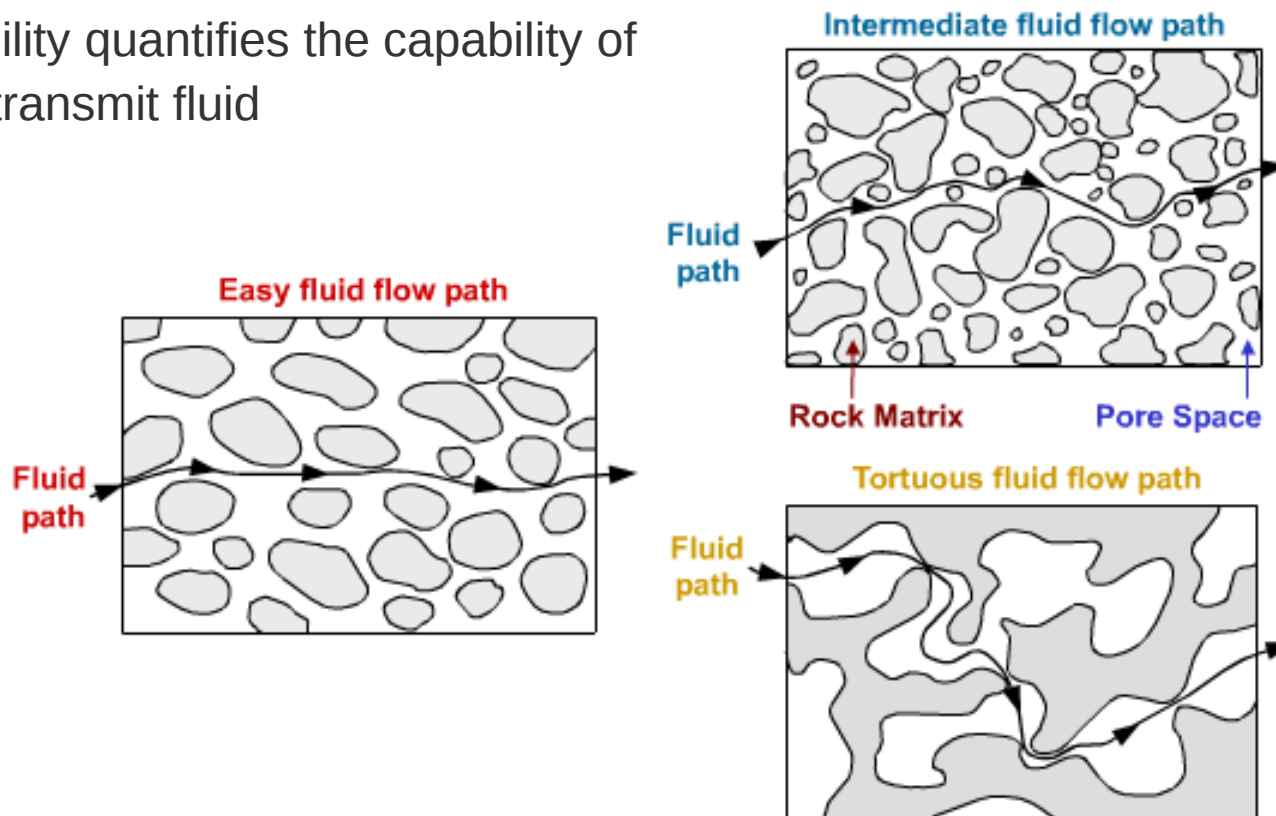
Permeability - fundamentals

- Permeability quantifies the capability of rocks to transmit fluid



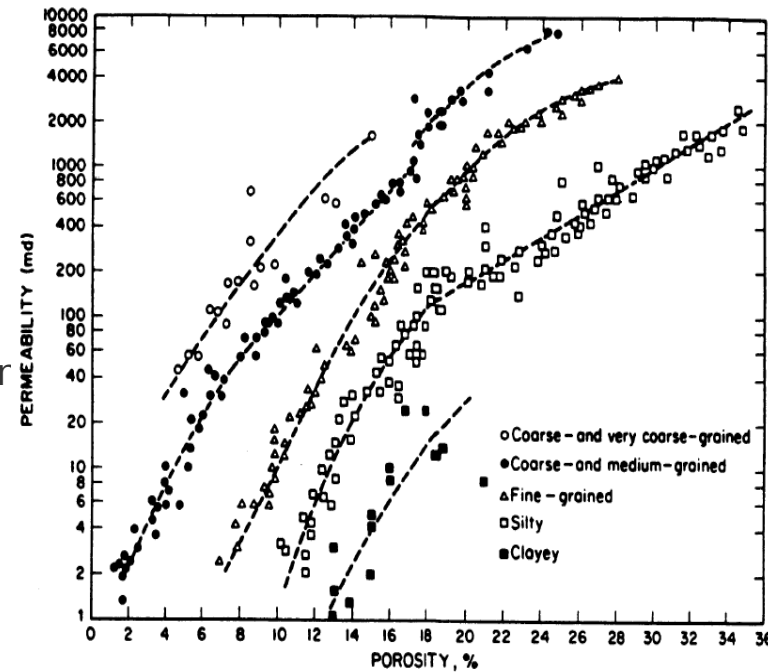
Permeability - fundamentals

- Permeability quantifies the capability of rocks to transmit fluid



Permeability – Sources of Information

- **Quantitative:**
 - Primary (Direct measurement):
 - Core measurement
 - Production test analysis
 - WFT analysis
 - Secondary (Indirect):
 - Core calibrated log correlation/regression
 - Multivariable linear regression/ neural network prediction
 - NMR, (Stoneley)
- **Qualitative** indication of permeable rock:
 - Invasion effects:
 - Presence of mud cake
 - Resistivity curve separation

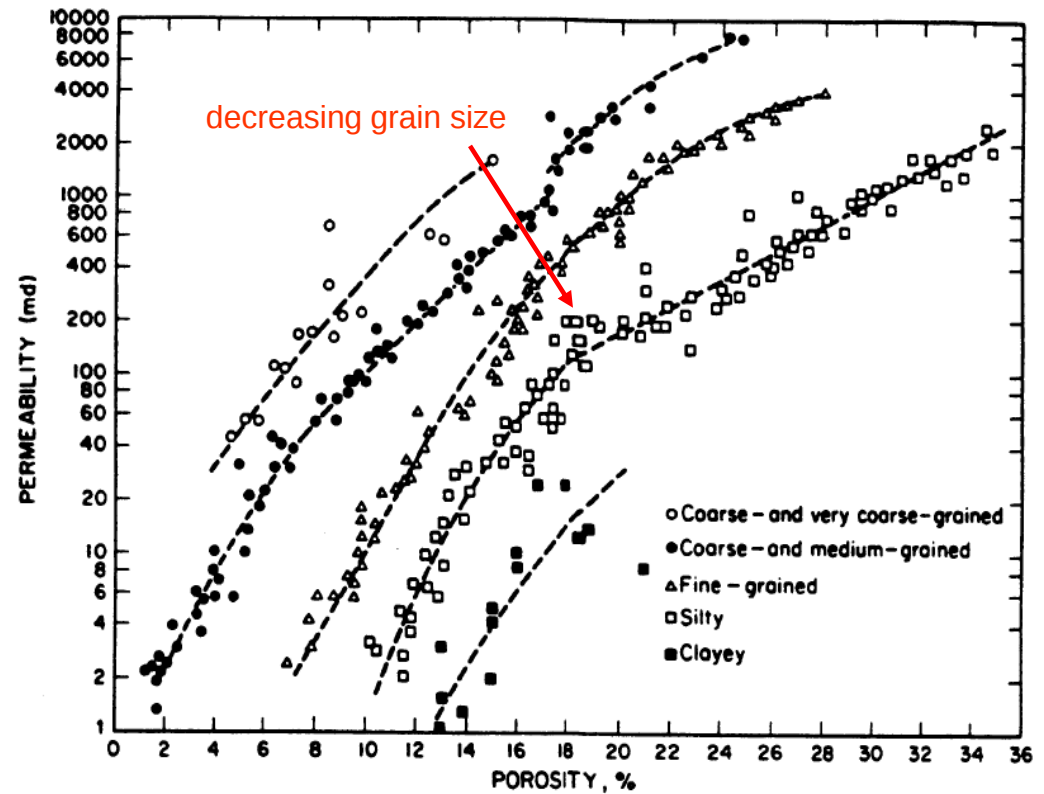


Permeability estimates are typically based on establishing empirical-/statistical relationships between permeability and porosity measured on core plugs and available logs

Permeability

Permeability vs Porosity trends

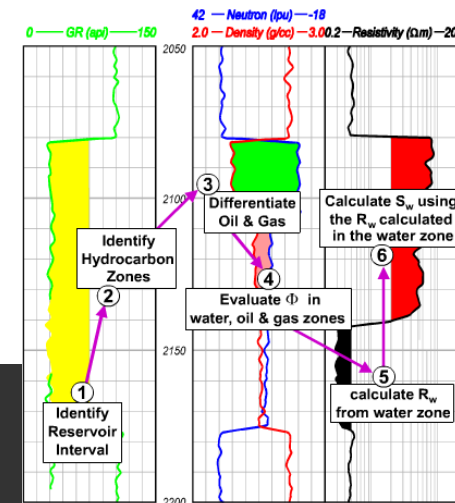
- Example where grain size affects the permeability – porosity relationship



Summary Petrophysics

Objective: Identify and quantify hydrocarbon resources in the subsurface and evaluate rock properties

- Logging techniques (EWL, PCL, LWD)
- Tools measuring physical properties of the rock and fluids present:
 - Gamma, Neutron porosity, Density, Sonic, Resistivity, Formation pressure
- Reservoir properties **interpreted** from tool measurements – a model!
 - Vshale, Porosity, Water saturation, Net reservoir, Permeability
- Average properties per zone calculated for input to geologist/reservoir engineer
- Results give
 - Reservoir quality and fluid type
- Results contribute to
 - STOIP
 - Recoverable reserves (producibility)



Summary Petrophysics - CPI Plot

Raw and Interpreted Curves

