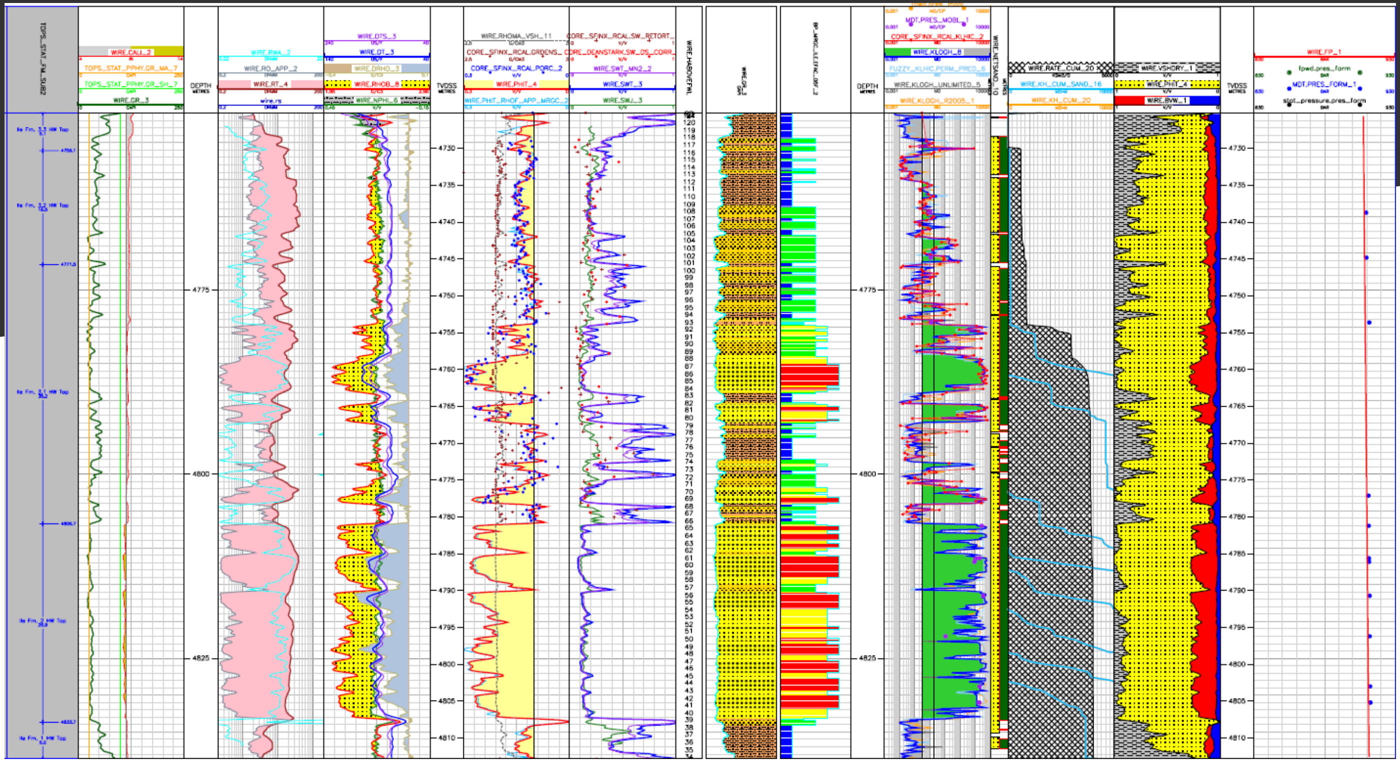
2.12
Exploration and Petroleum Technical & IOR Networks: Introduction course to new employees

Statoil



Introduction to Petrophysics

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Classification: Internal 2012-02-01

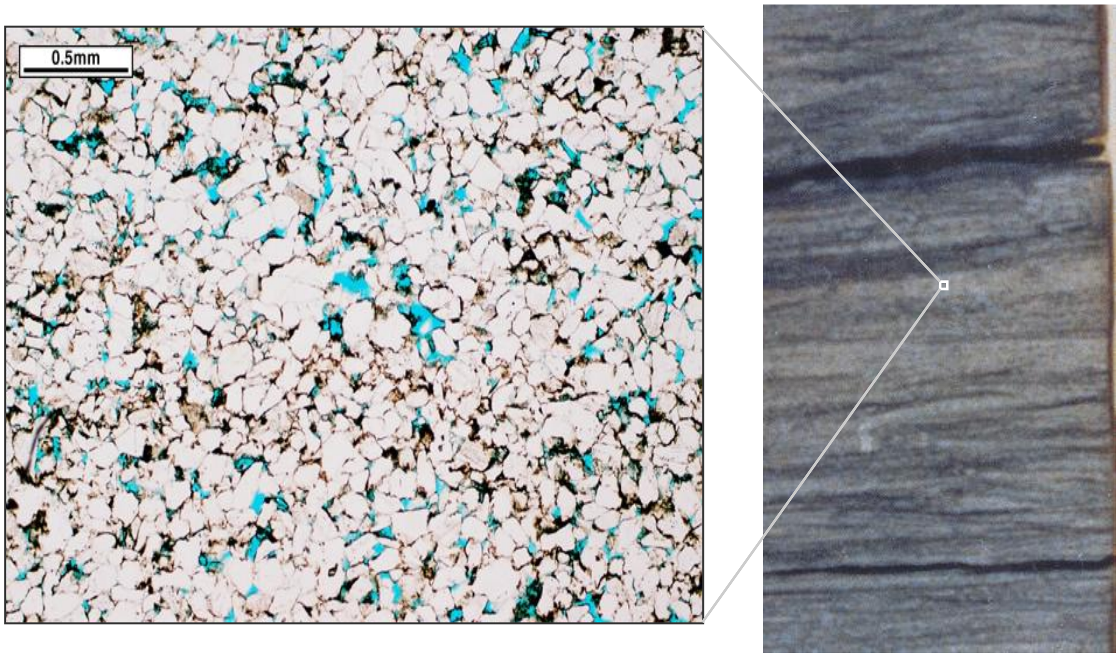
Outline

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

Petrophysics - Basic deliverables for a well

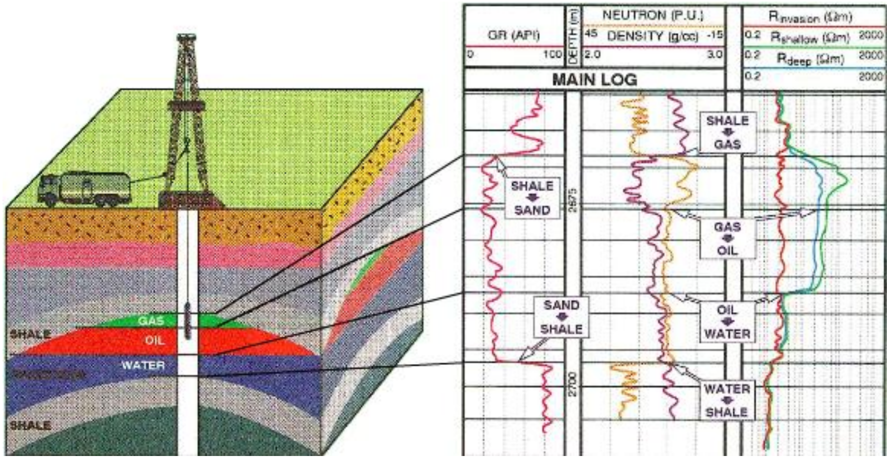
Petrophysical variables at each relevant depth:

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

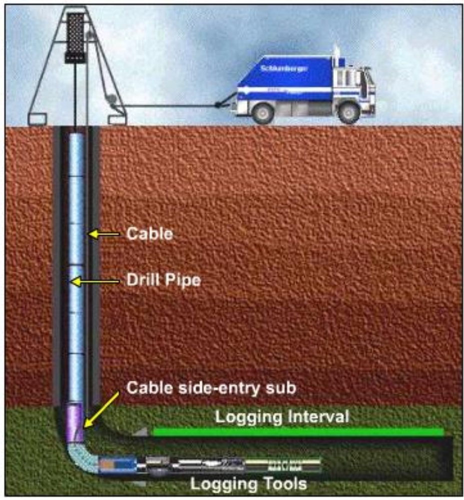
NONE OF these are measured by **LOGS** in the well **!!!!**

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

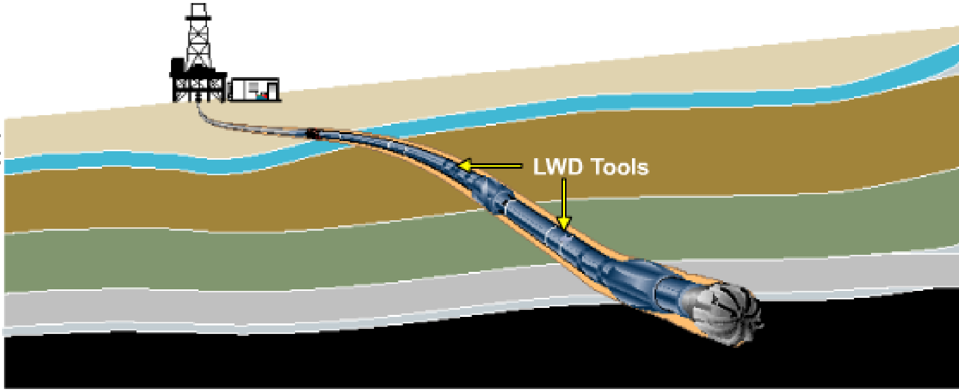
Data Acquisition Methods



- **Wireline (EWL)**
  - Vertical or low angle wells
  - Logging tools conveyed by electrical wireline
  - Generally most advanced and highest quality logs



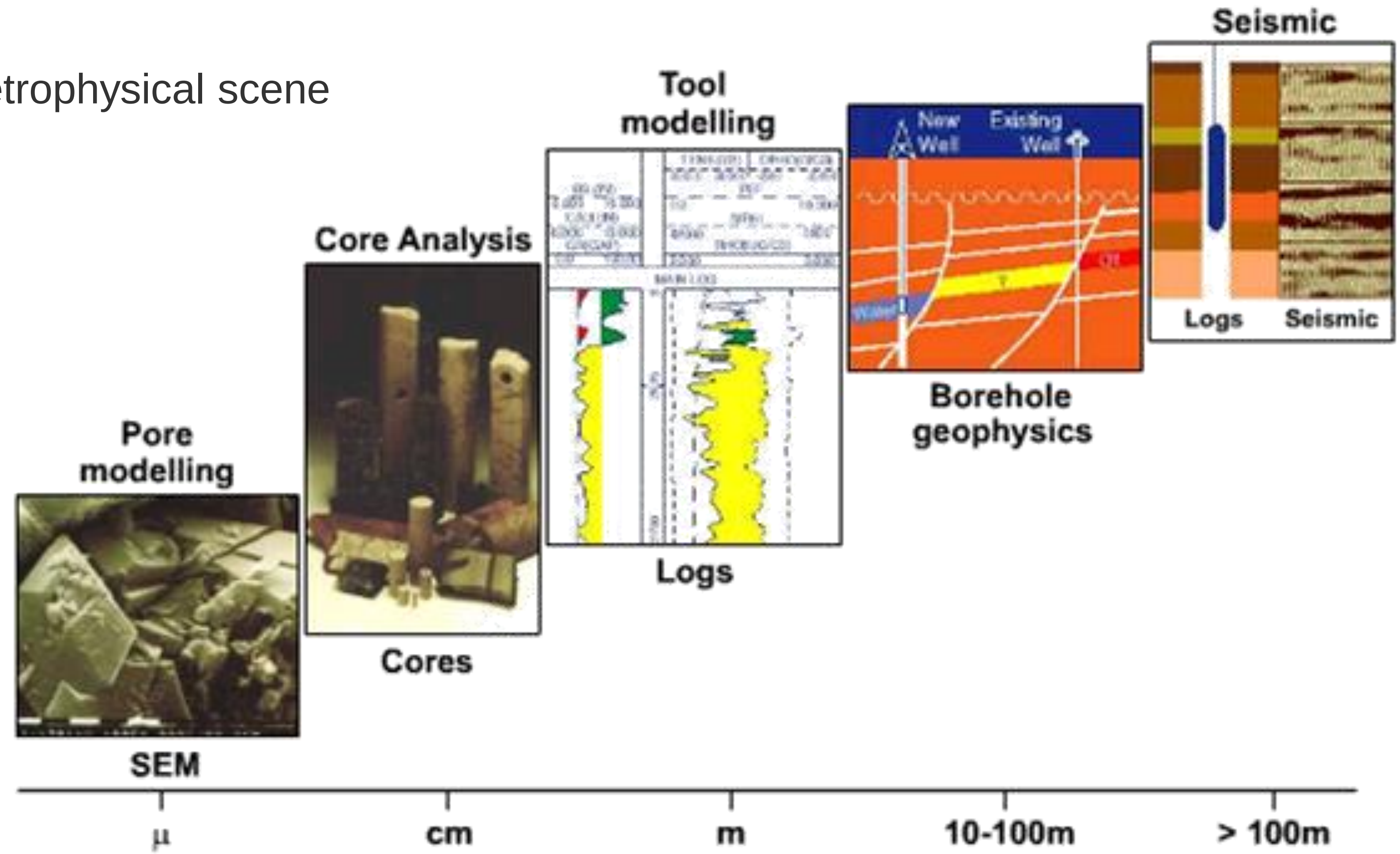
- **Pipe Conveyed Logging (PCL)**
  - Highly deviated wells
  - Logging tools are lowered down the well by drill pipe, with the tool connected at the end



- **Logging while drilling (LWD)**
  - Sensors as a part of the drilling assembly
  - Sending real time signals through the drilling mud

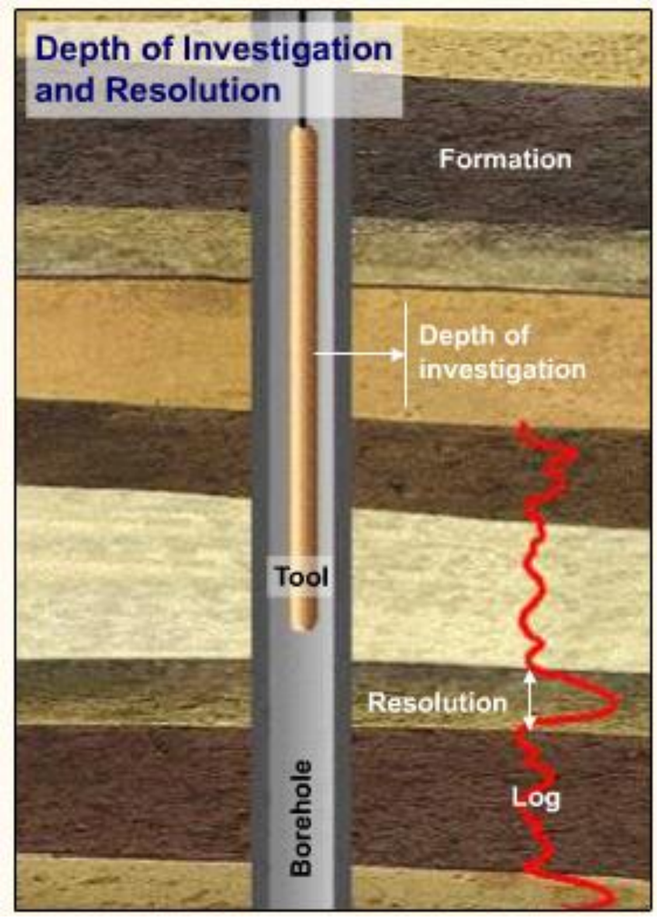
Scale

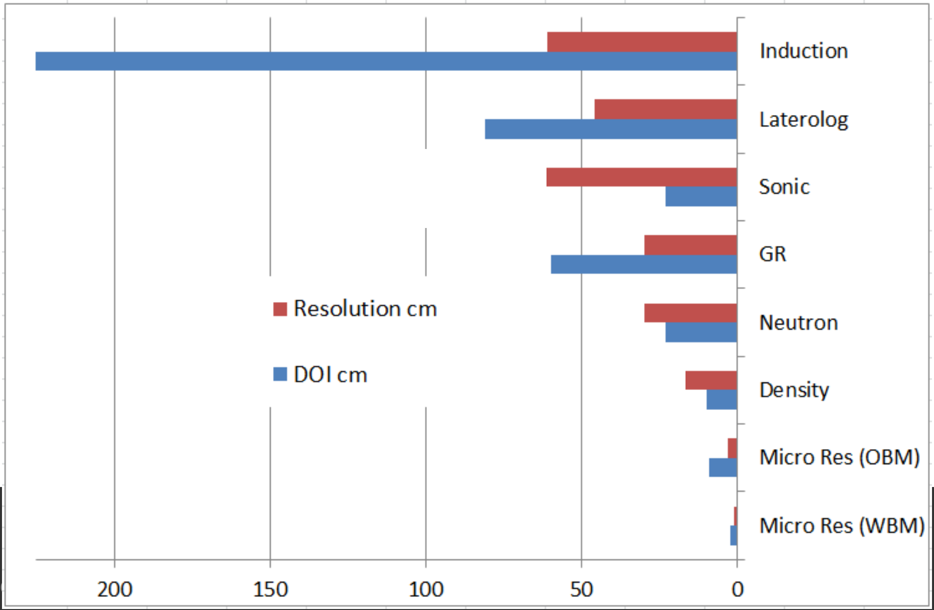
Petrophysical scene



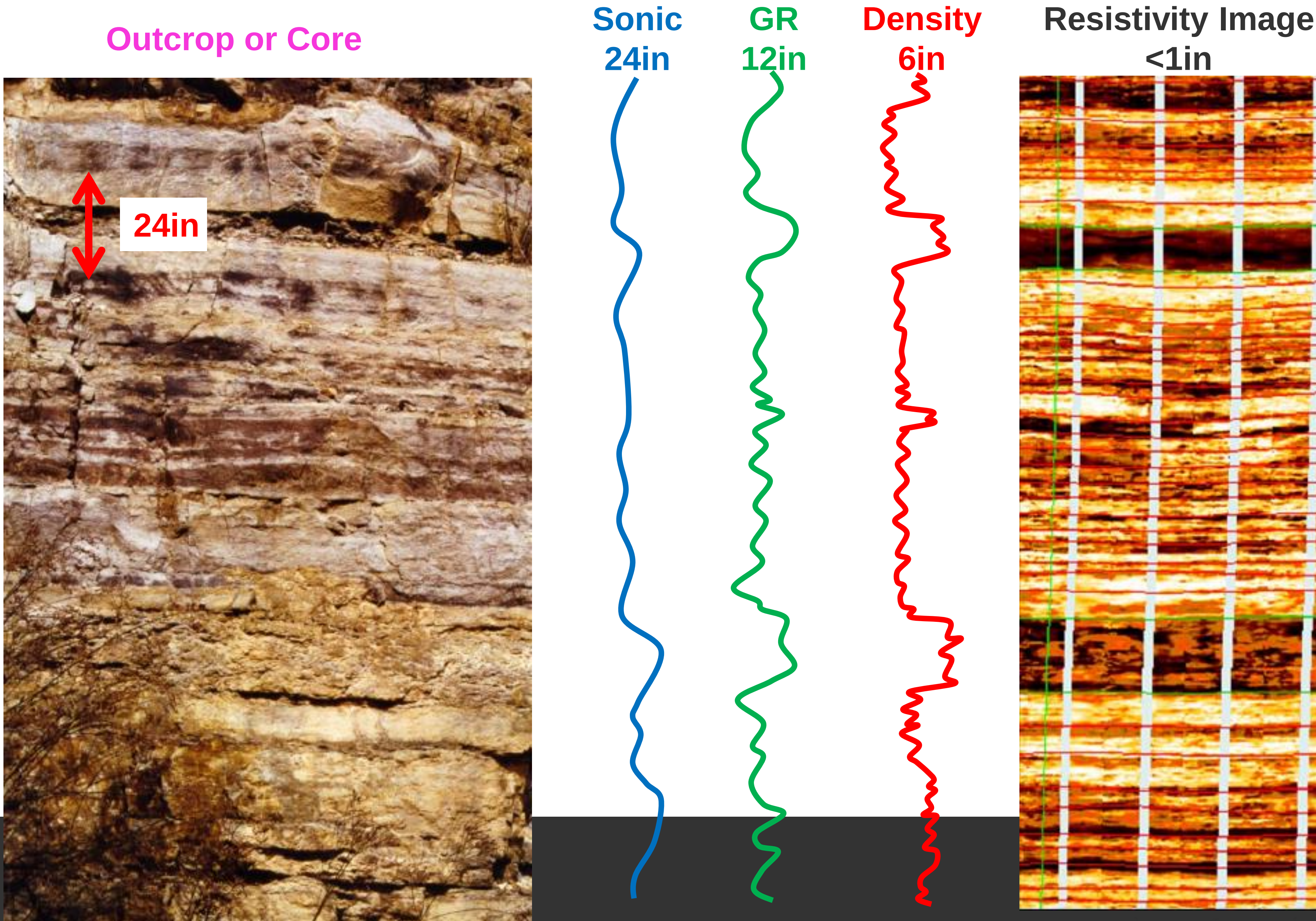
Data Acquisition

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





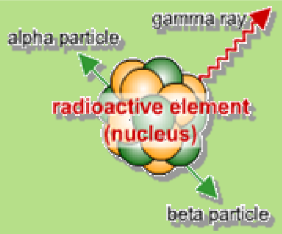
VERTICAL RESOLUTION OF WELL LOGS



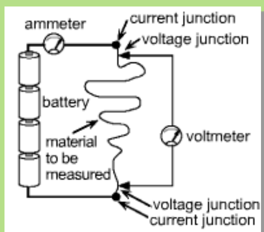
Petrophysical Measurements

Covered in this course

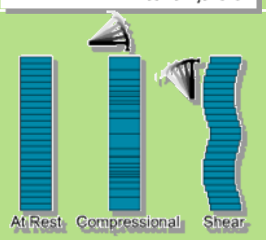
Radioactivity



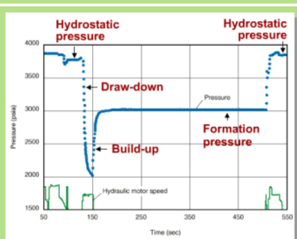
Resistivity



Sonic

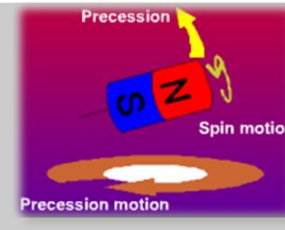


Pressure

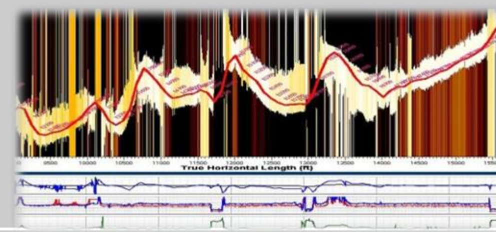


Not covered in this course

Nuclear Magnetic Resonance



Geosteering



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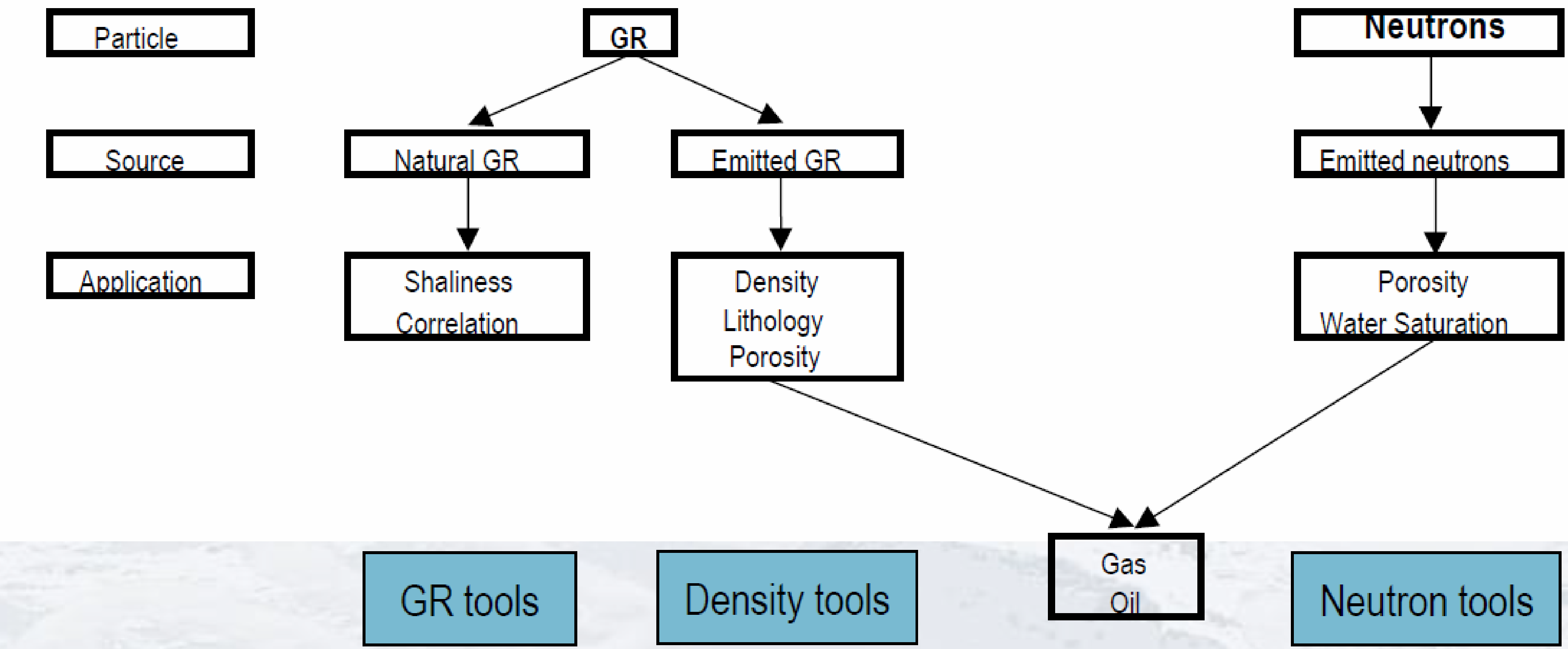
Family of Nuclear Tools

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



Statoil

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)

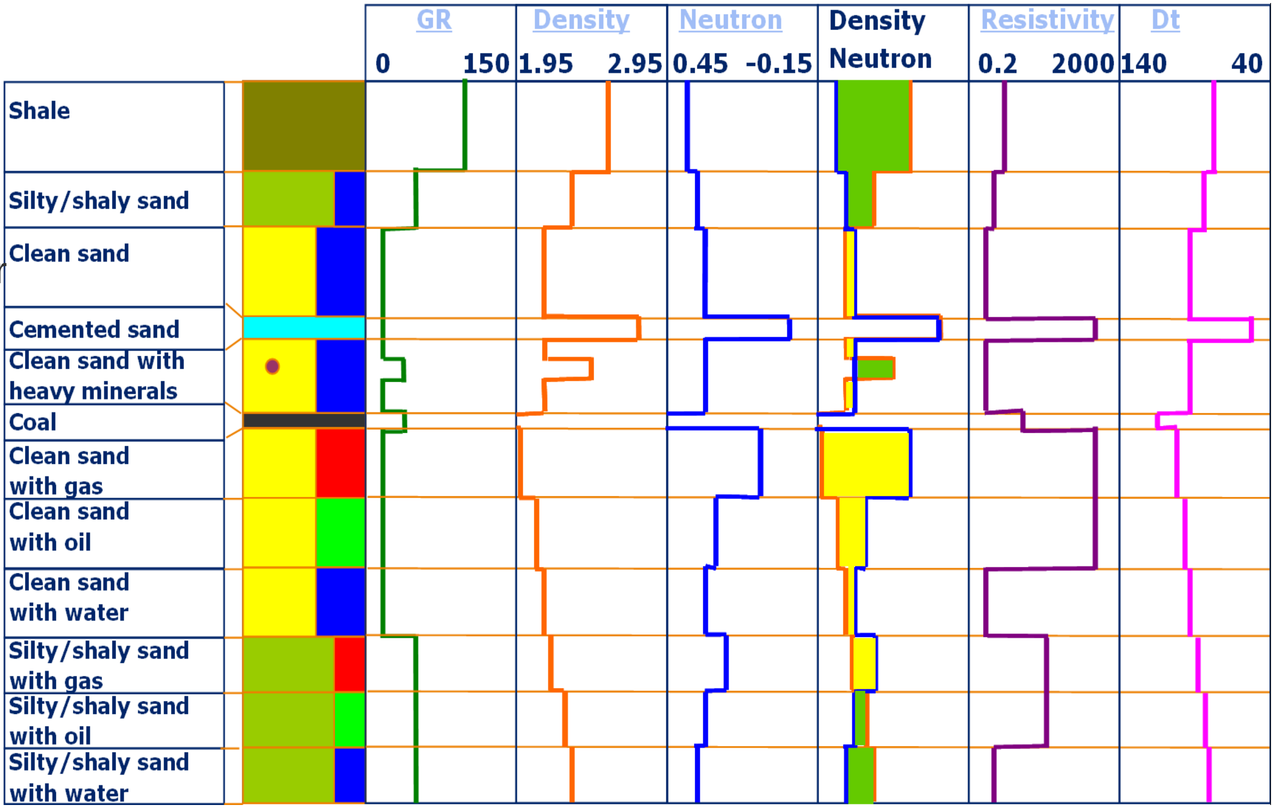
Water-filled sands
- Density left of neutron porosity

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



Quicklook Evaluation

- 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)

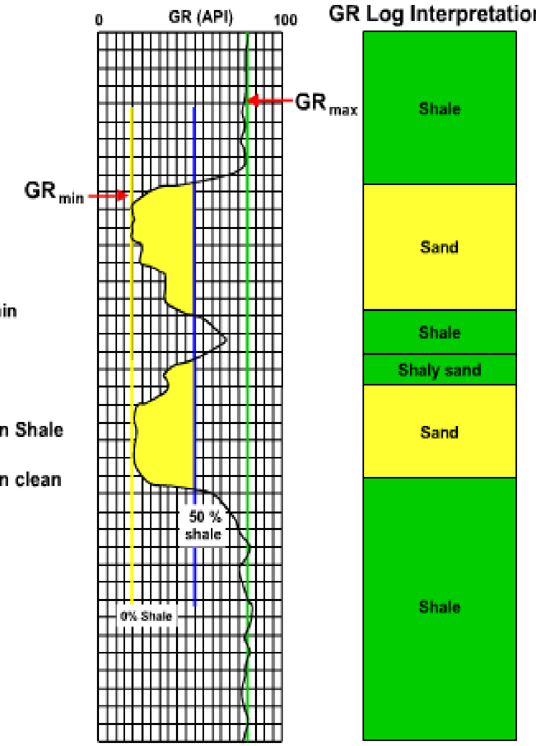
- VCL: The volume of the clay mineral including the clay bound water

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

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

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



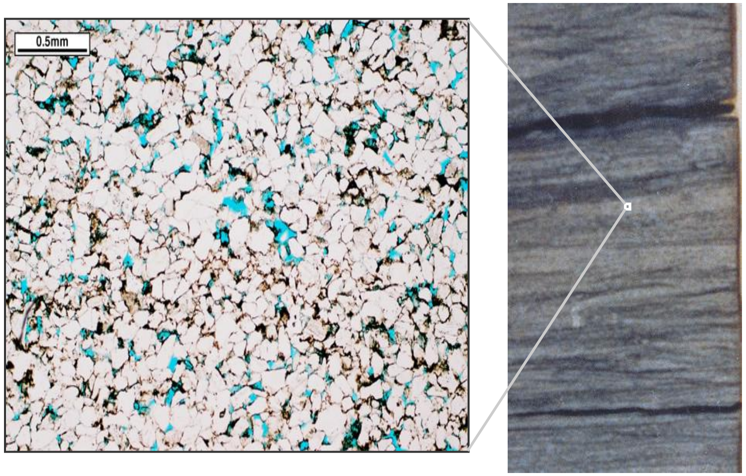
- Spectral GR tool can discriminate between these elements, standard GR tool only provides the total GR counts
  - Reservoir rocks (Sandstone/Limestone/Dolomite) → low GR
  - Shale has large amount of Th and K atoms → high GR

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

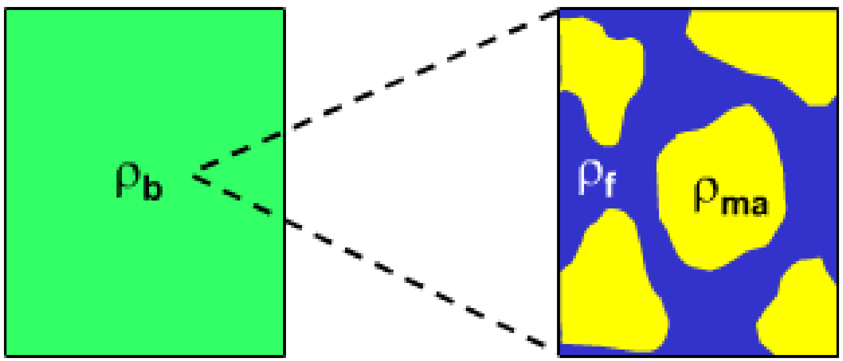
Interpretation/Uses

- 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

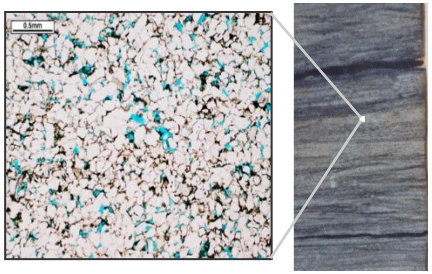
ρ_b = Density log reading

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

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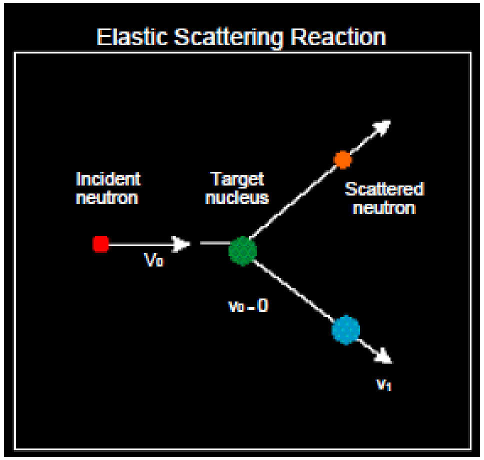
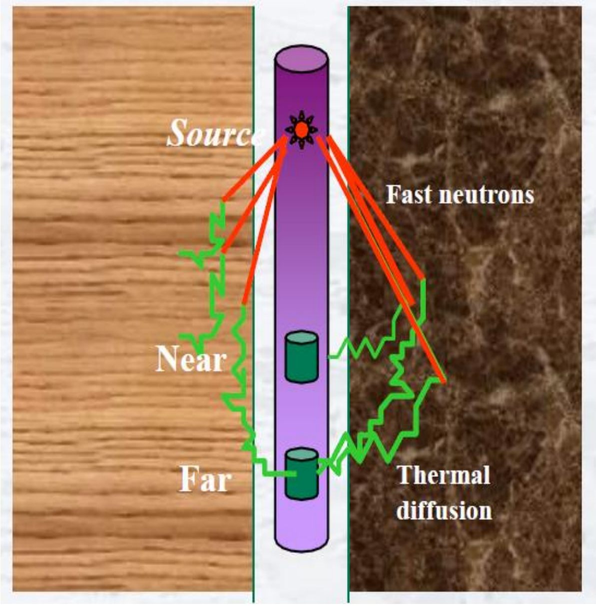
Neutron Logging

- 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 << HI of water and oil



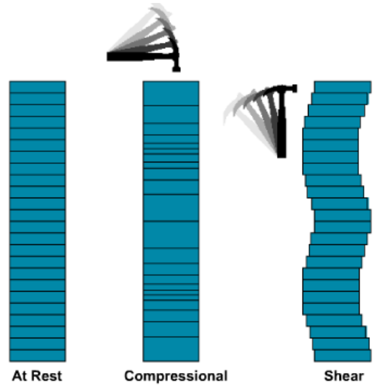
Large HI High NEU Porosity Low Count Rate	Low HI Low NEU Porosity High Count Rate



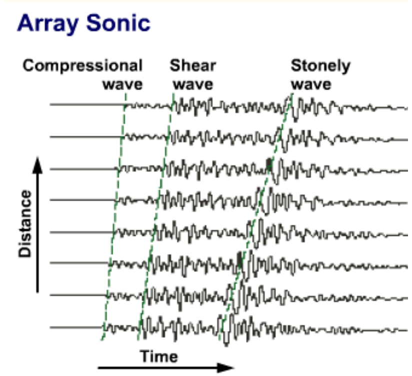
Applications:
- **Lithology (w/ DEN or Sonic)**
- **Gas identification (w/ DEN or Sonic)**
- Correcting porosity for lith. and HC effects (w/ DEN or Sonic)
- Quantification of Gas fraction (w/ DEN or Sonic)
- Porosity (w/ DEN or Sonic)
- VSH

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



Typical values for transit times (matrix value without porosity)

Sandstone – 51 - 58 µs/ft

Limestone – 47.5 µs/ft

Shale – 62 to 167 µs/ft

Filtrate – 189 - 200 µs/ft

Casing – 57 µs/ft

Sonic Logging

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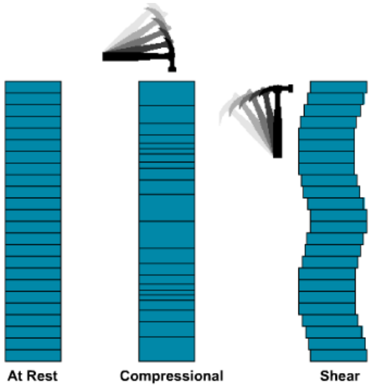
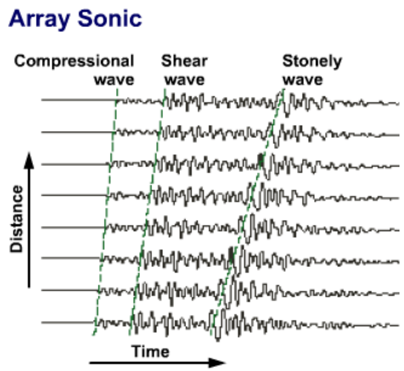


- Applications:
  - Geophysical interpretation:
    - Synthetic seismograms (calibration of seismic surveys)
    - Acoustic Impedance (Vp**(m/sec)***ρ**b (g/cc)**)
  - Porosity estimation (Wyllie or Raymer-Hunt Gardner)
  - Rock mechanical properties (elastic properties, rock strength)
  - Identification of gas (DT slower in gas)
  - Fracture indicator and Qualitative permeability from Stoneley
  - Cement Bond Logging



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Saturation

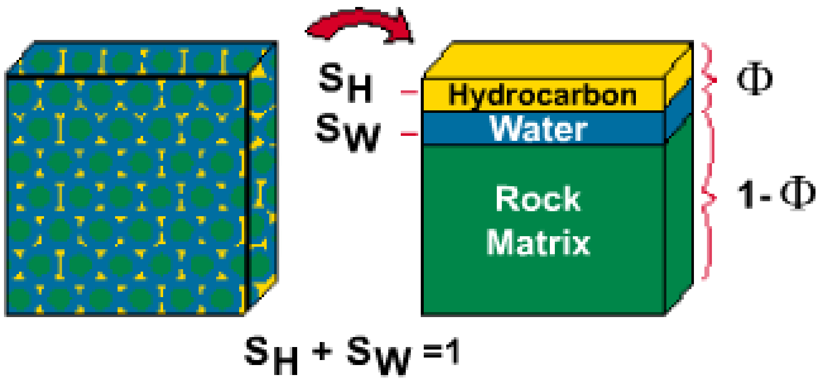
Quicklook Evaluation

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

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

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

- Water Saturation **(Sw)**
  - the fraction of the pore volume that contains formation water



S_H = Hydrocarbon saturation (oil and gas)
S_W = Water saturation
Φ = Porosity

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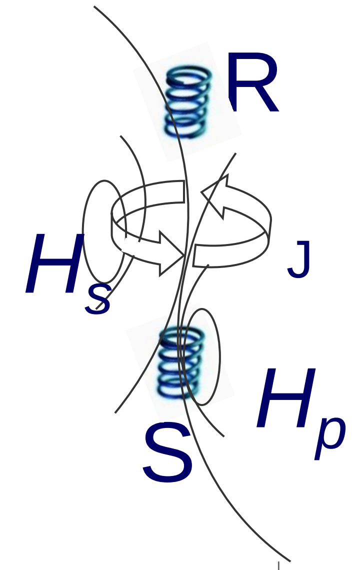
Resistivity – Induction & Laterolog

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)

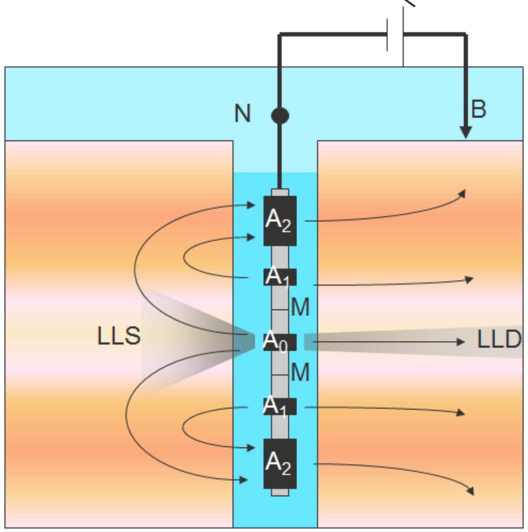
Induction



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



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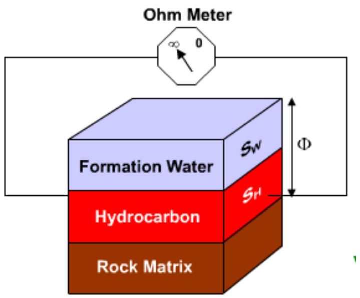
Quick look Evaluation - Saturation



- 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:

$$\boxed{Sw = \left(\frac{aRw}{\Phi^m Rt}\right)^{1/n}}$$

a = tortuosity factor

m = cementation exponent

n = saturation exponent

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

Archie with standard values:

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

If Sw = 1 (in water zone):

$$Rw = \phi^2 Rt$$

Rw = Formation water resistivity

Rt = 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

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

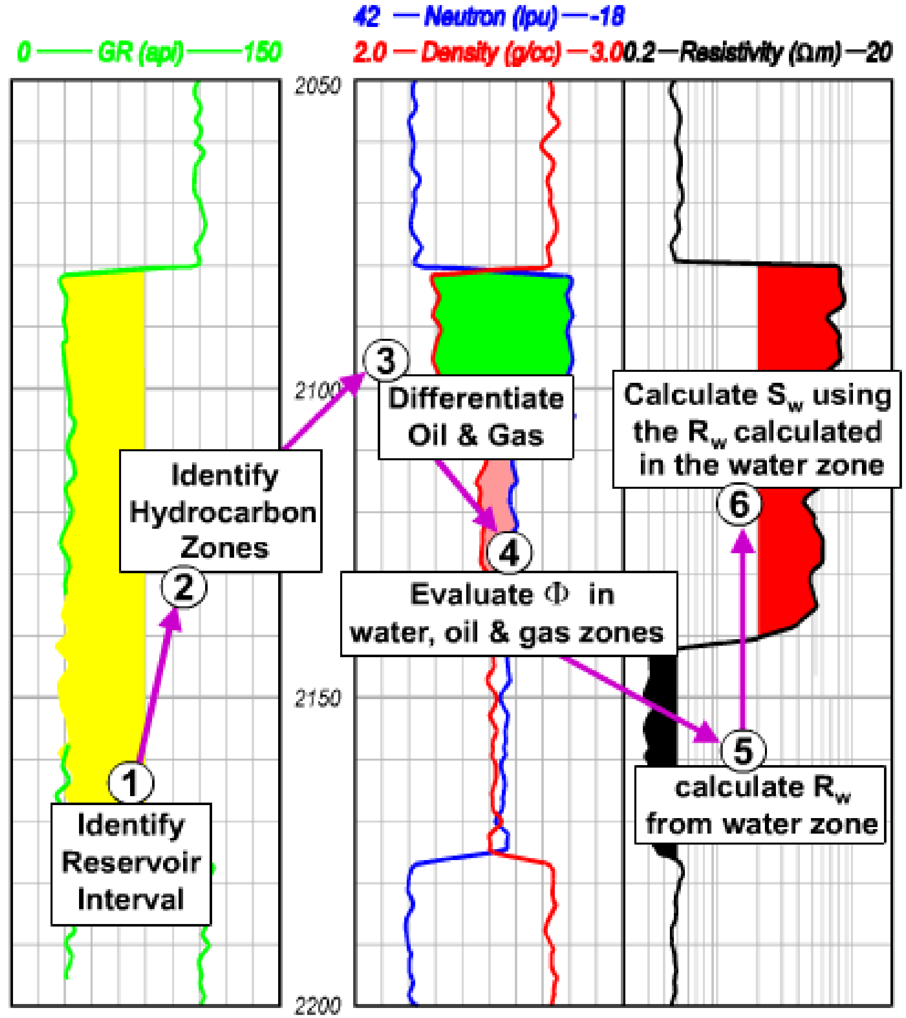
$$\Phi = \frac{\rho_{ma} - \rho_b}{\rho_{ma} - \rho_{fl}}$$

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

In clean water bearing formations (Sw = 1):

$Rw = \phi^2 Rt$

assuming a = 1, m = n = 2



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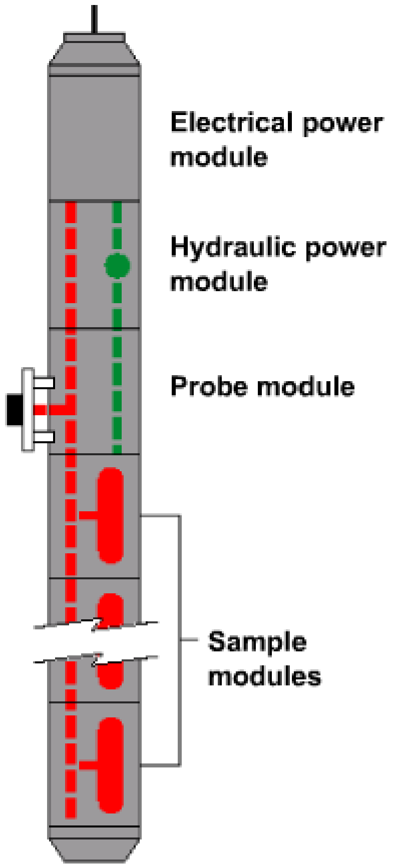
Formation Pressure

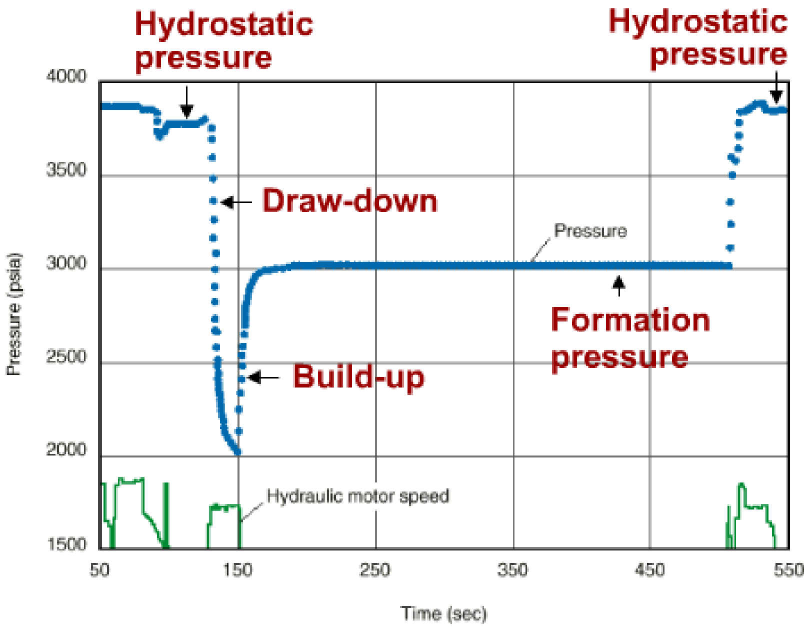
- Formation Pressures (EWL and LWD)
  - Fluid densities (fluid type)
  - Fluid contact levels (free fluid levels)
- Formation fluid samples (EWL)

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



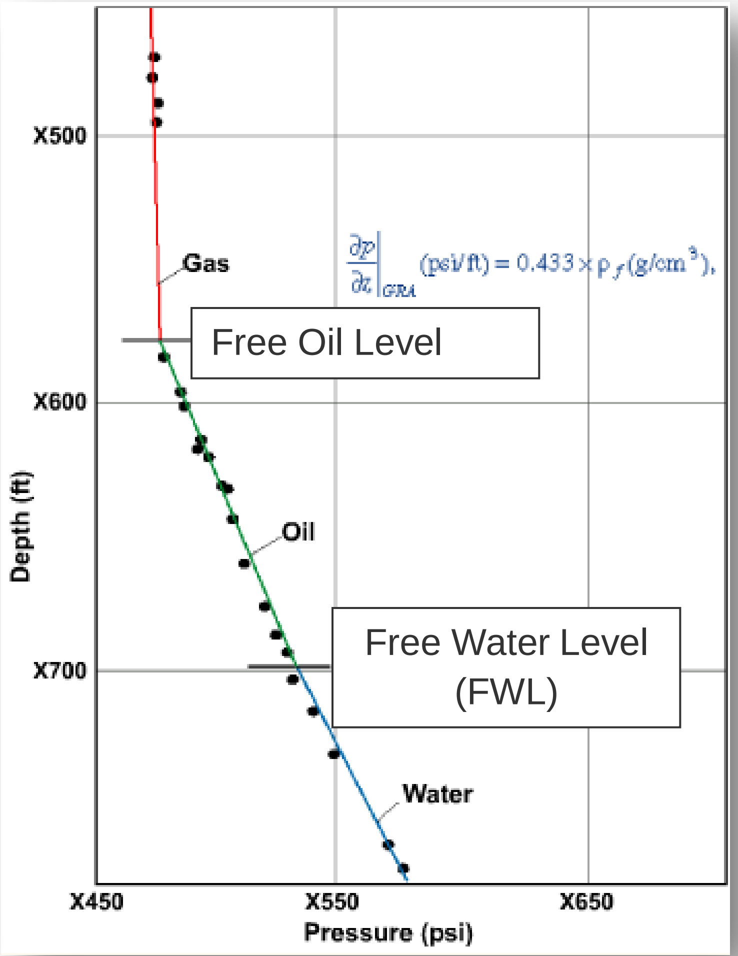
Formation Pressure

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



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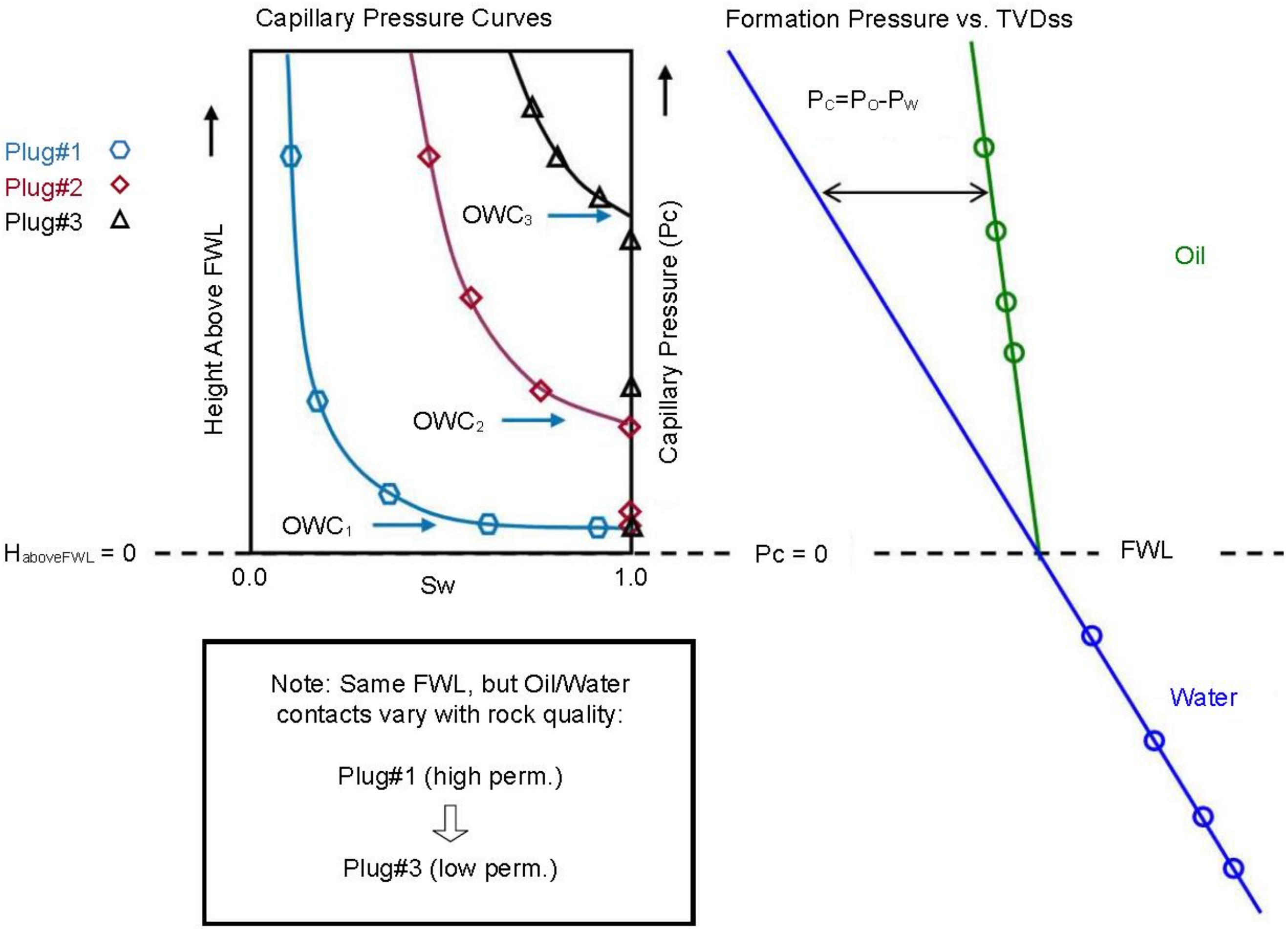
Free Water Level vs Oil Water Contact



Note: Same FWL, but Oil/Water contacts vary with rock quality:

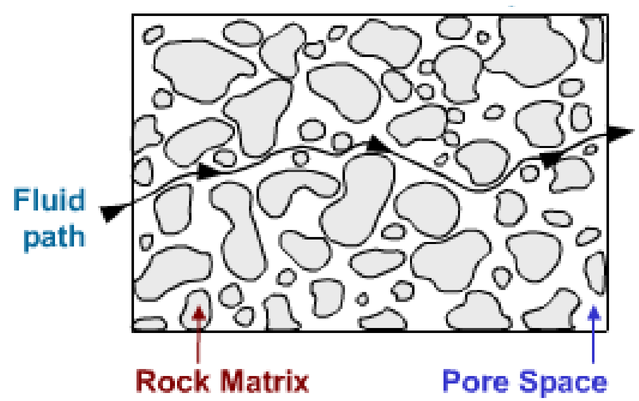
Plug#1 (high perm.)

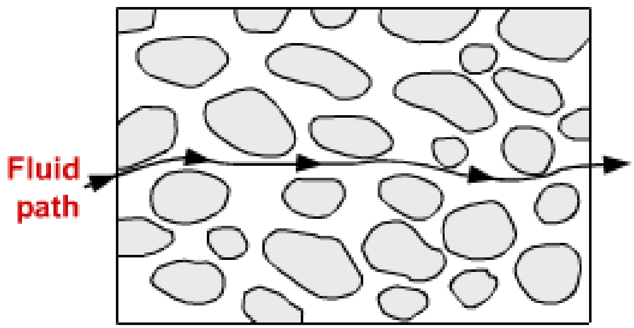
⇩

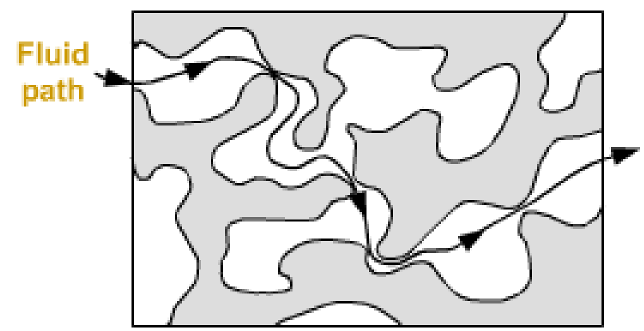
Plug#3 (low perm.)

Permeability - fundamentals

- Permeability quantifies the capability of rocks to transmit fluid







Permeability - fundamentals

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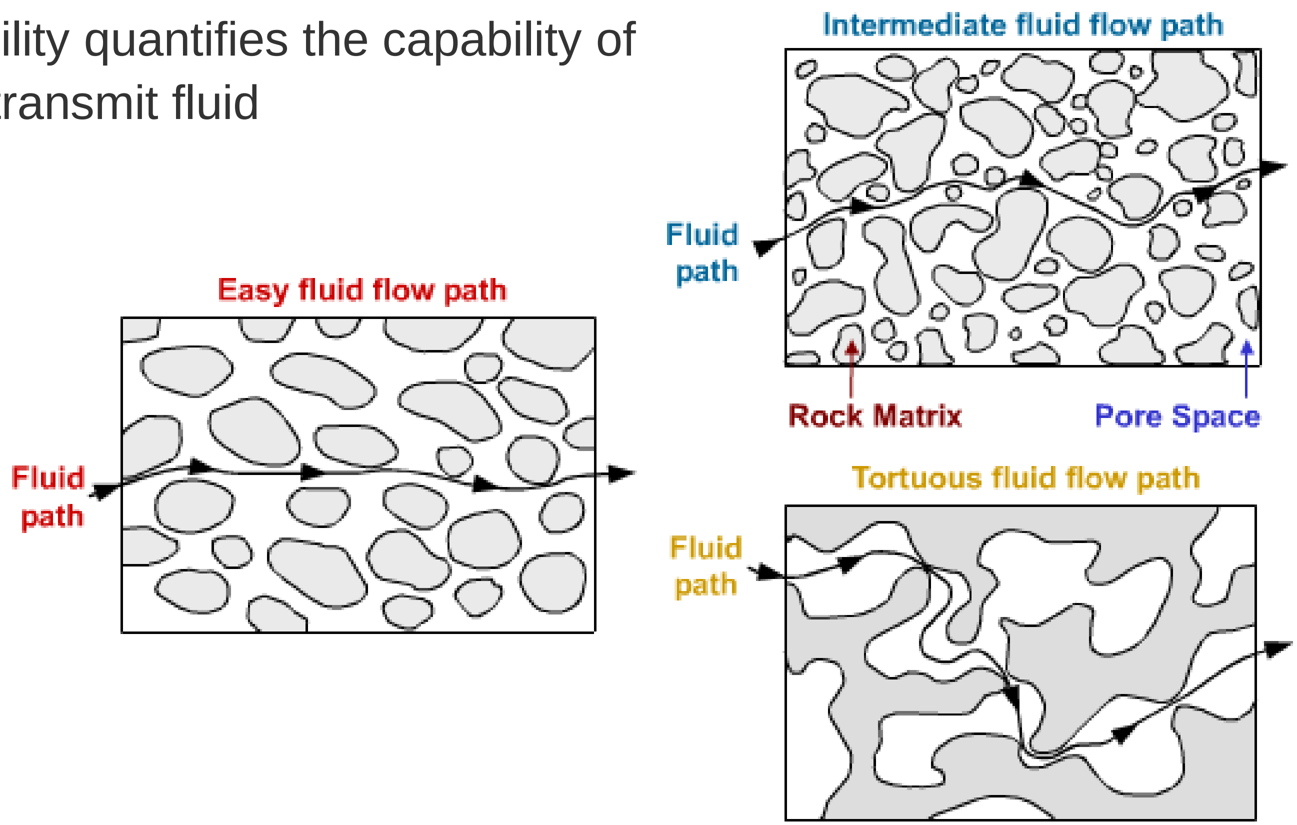
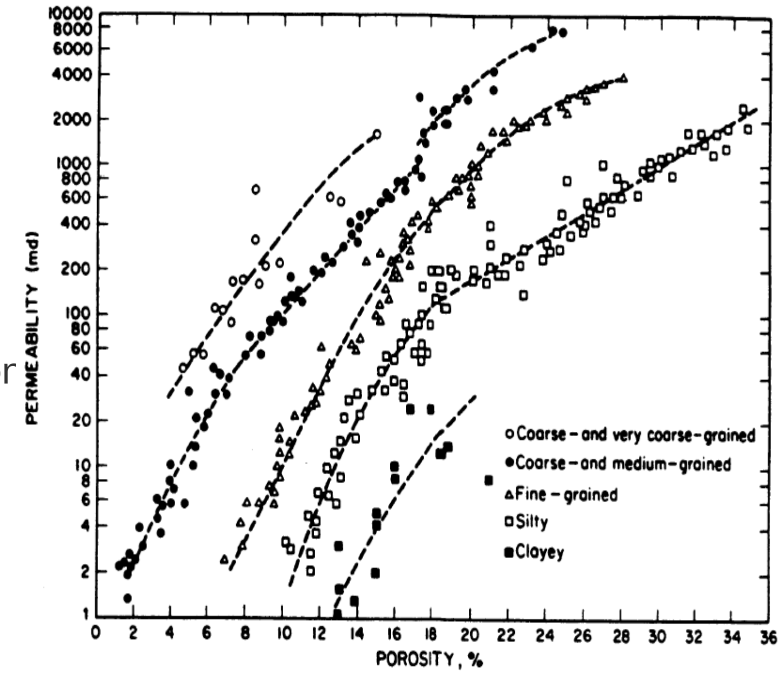


Permeability – Sources of Information

- **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

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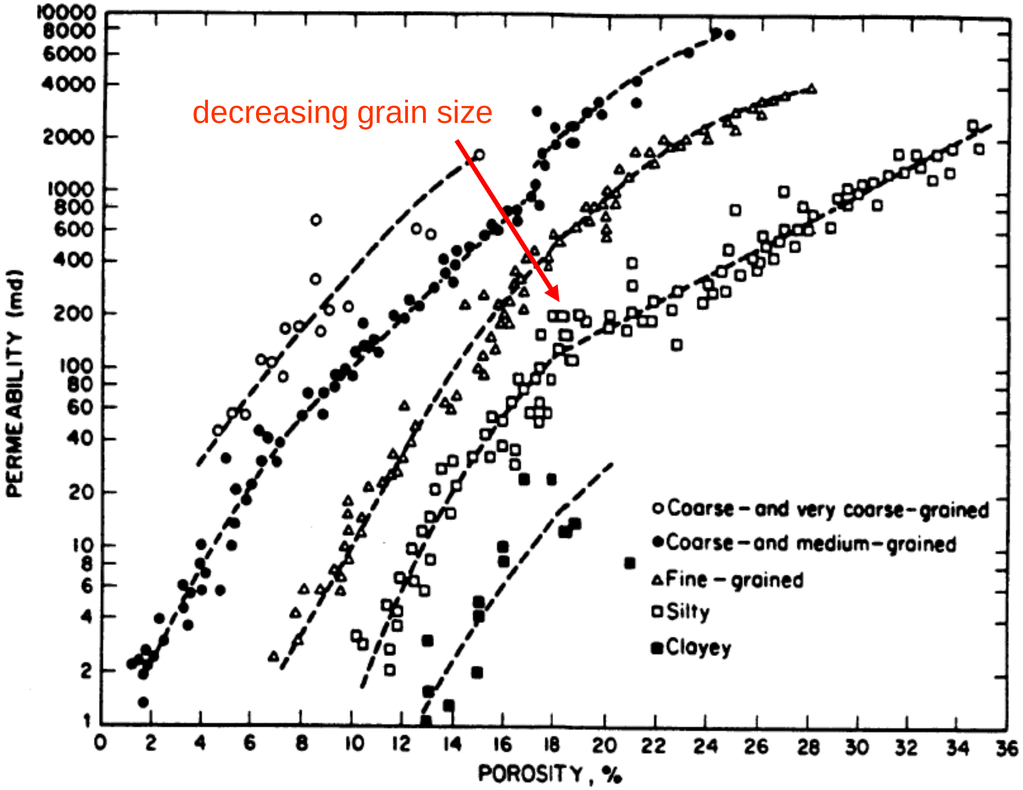
Permeability

Permeability vs Porosity trends

- Example where grain size affects the permeability – porosity relationship

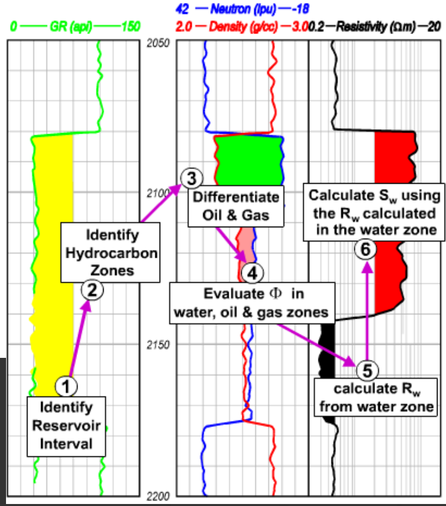


Statoil

Summary Petrophysics

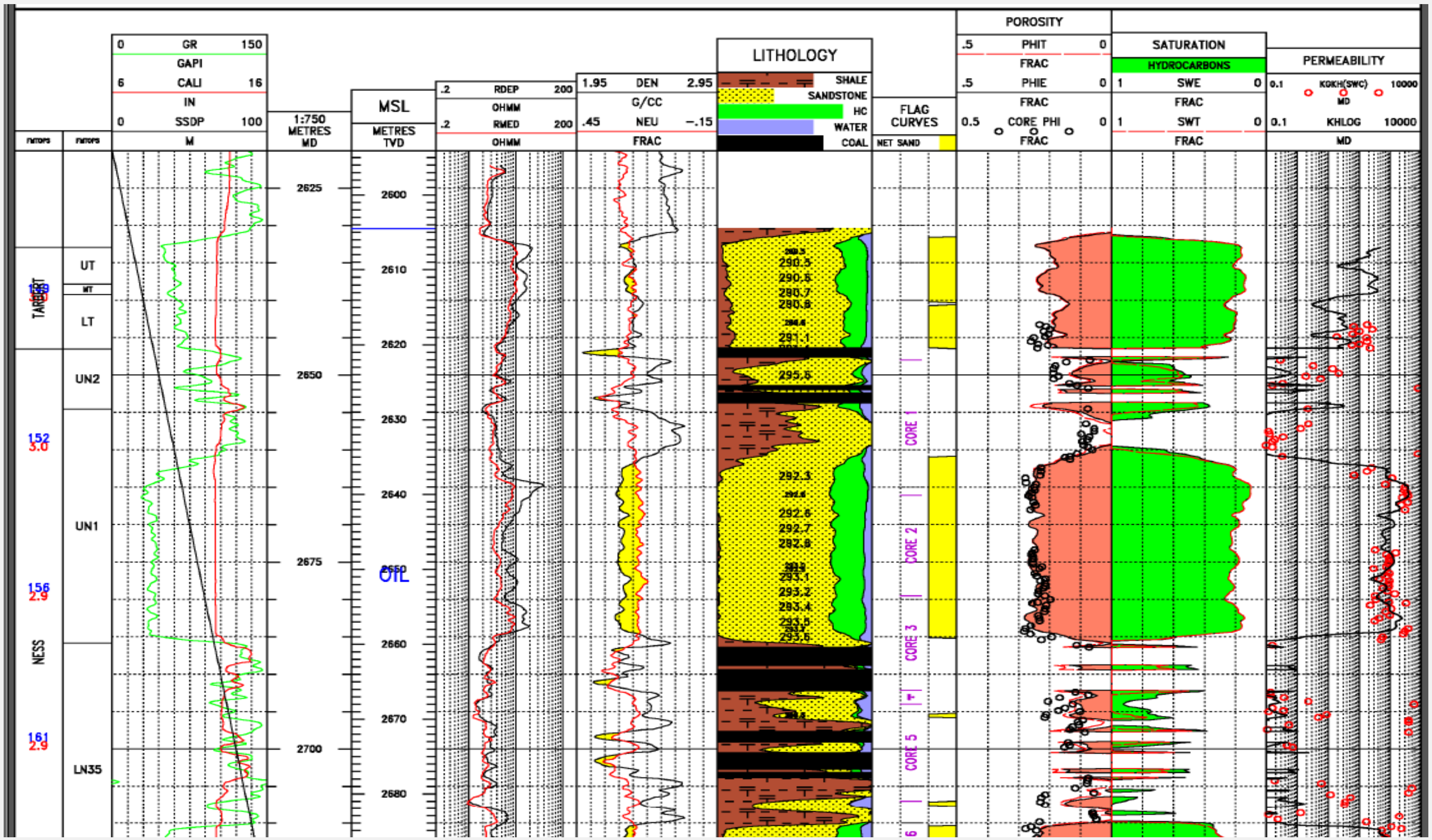
Objective: Identify and quantify hydrocarbon resources in the subsurface and evaluate rock properties

- 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
  - STOIIP
  - Recoverable reserves (producibility)



Summary Petrophysics - CPI Plot

Raw and Interpreted Curves



Statoil