Basics of Geophysical Well Logs: Introduction

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Well logs: what?

Well logs were developed with the objective of the indirect evaluation of the geological and petrophysical characterization of the subsurface formations.

This is achieved by the acquisition, along with the well bore of a drilled well, of a large number of physical measurements (resistivity, density, Hydrogen Index, acoustic waves velocity, etc.) which, by means of a complex interpretation process, are translated into petrophysical properties (Water Saturation, Porosity, Permeability, Volume of shale, etc.), geological characters of the formation (lithology, layer's dip, depositional environments, sedimentary facies, etc.) and thermodynamic data (temperature, fluid composition and viscosity, etc.).

Well logging history

The first electrical log was recorded in 1927 in the well Pechelbronn 7 in the form of a single graph of the electrical resistivity of the formations cut by the well recorded with a stationary method.

The resistivity profile was mainly used, at the beginning of the well logging technology, for correlation purposes and for location of potential hydrocarbon bearing levels

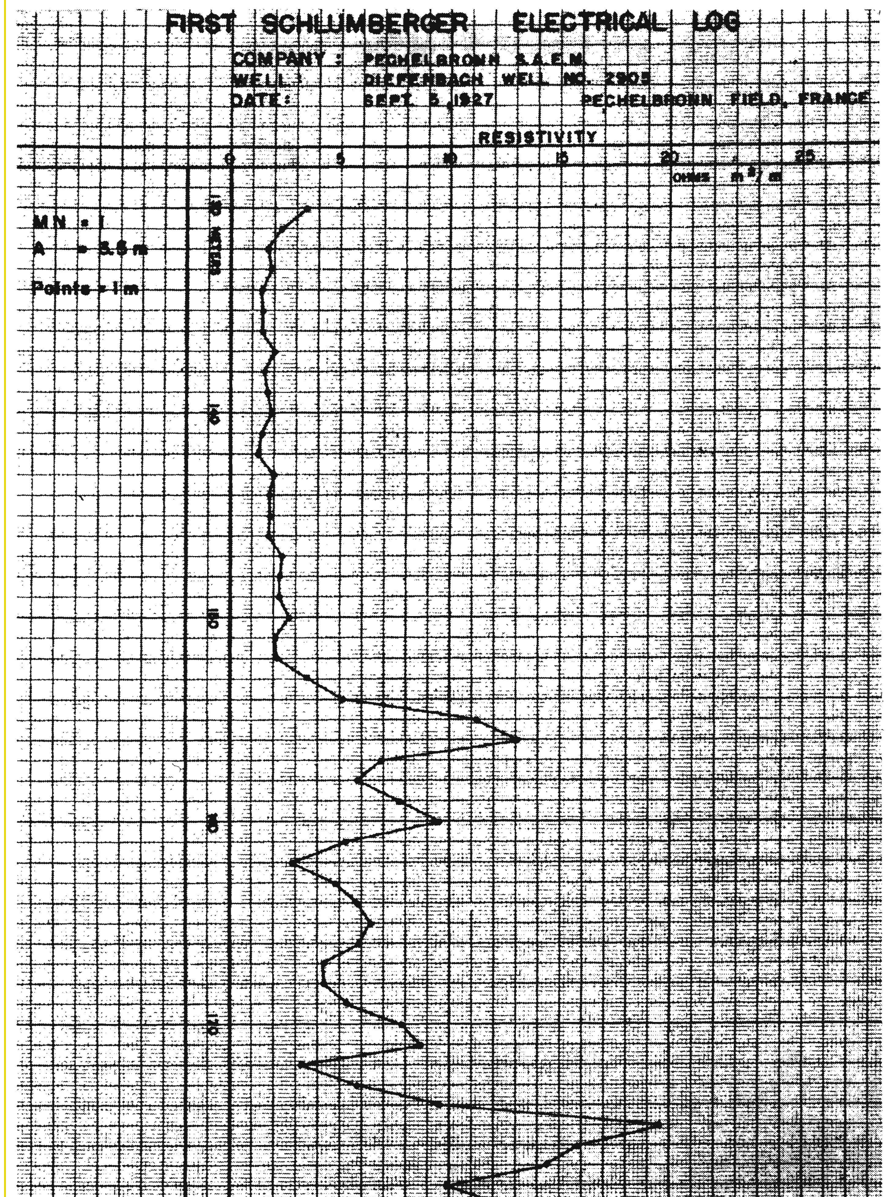


Fig. 1. The first electric log; Pechelbronn, France, September 5, 1927.

Evolution of well logging technology

Since this first log, the technology evolved very rapidly and, thanks to sophisticated developments, revolutionized the oil and gas Exploration and Production industry.

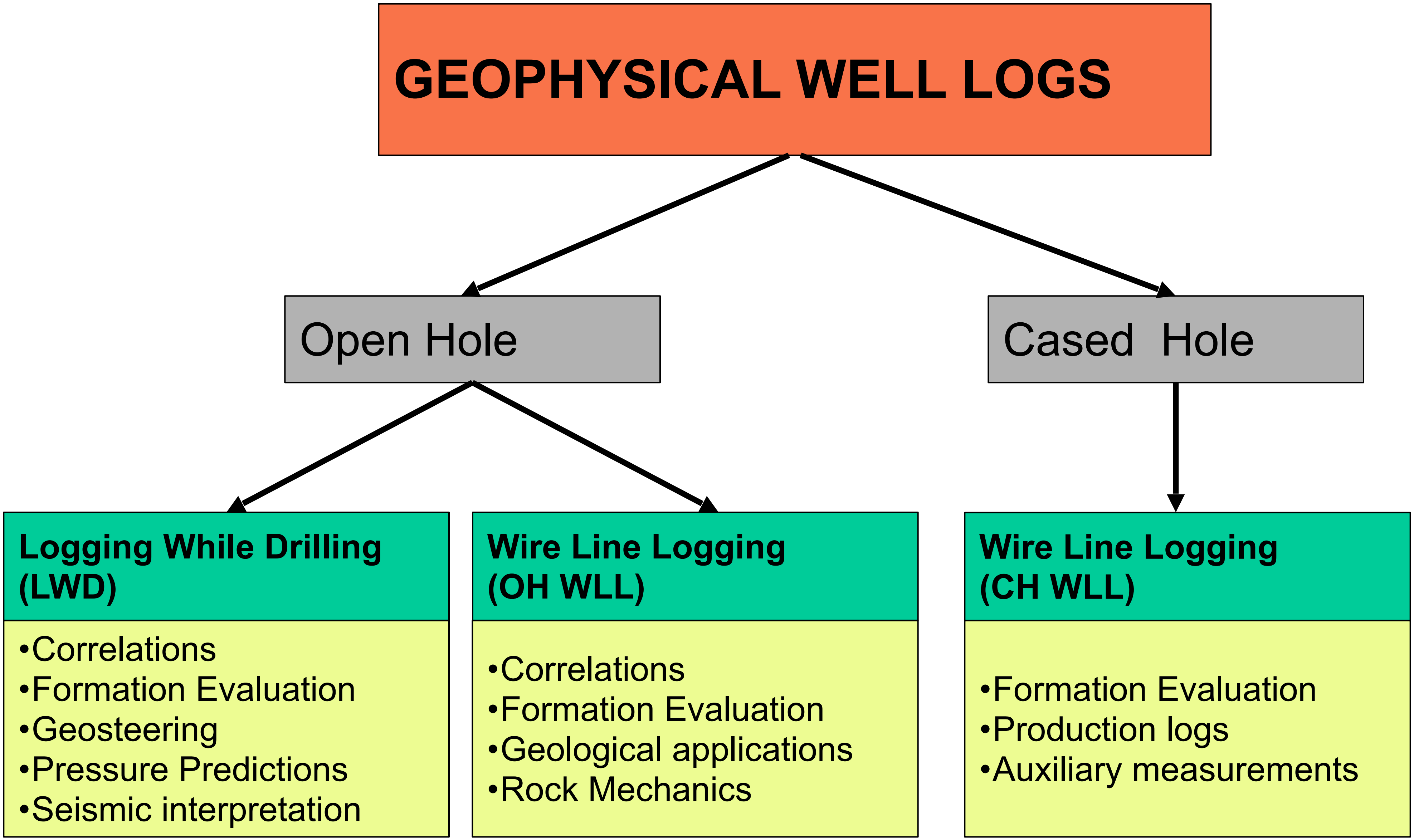
Well logging technology is now used in all the phases of the E&P process from the drilling of the first wildcat well in a field up to the abandonment of the last productive level in the same field.

Due to the exploitation of a large number of physical principles, well logs can now measure a large number of physical properties of the geological formation intersected by a well and both in open and cased hole conditions.

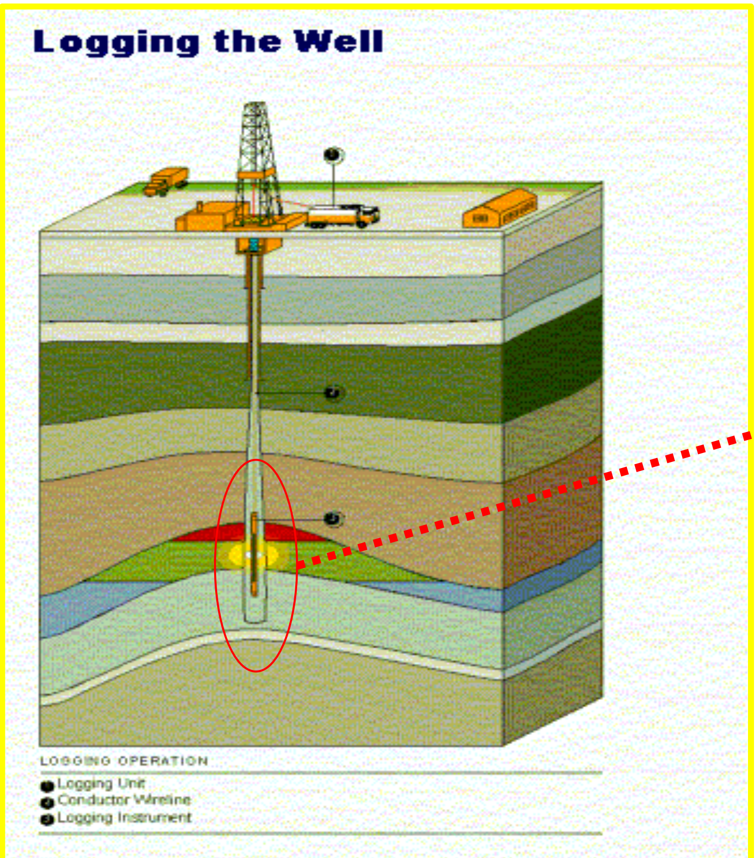
Well logs: what?

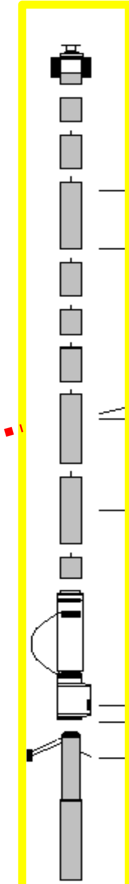
Well logs are acquired and used in all phases of the E&P process:

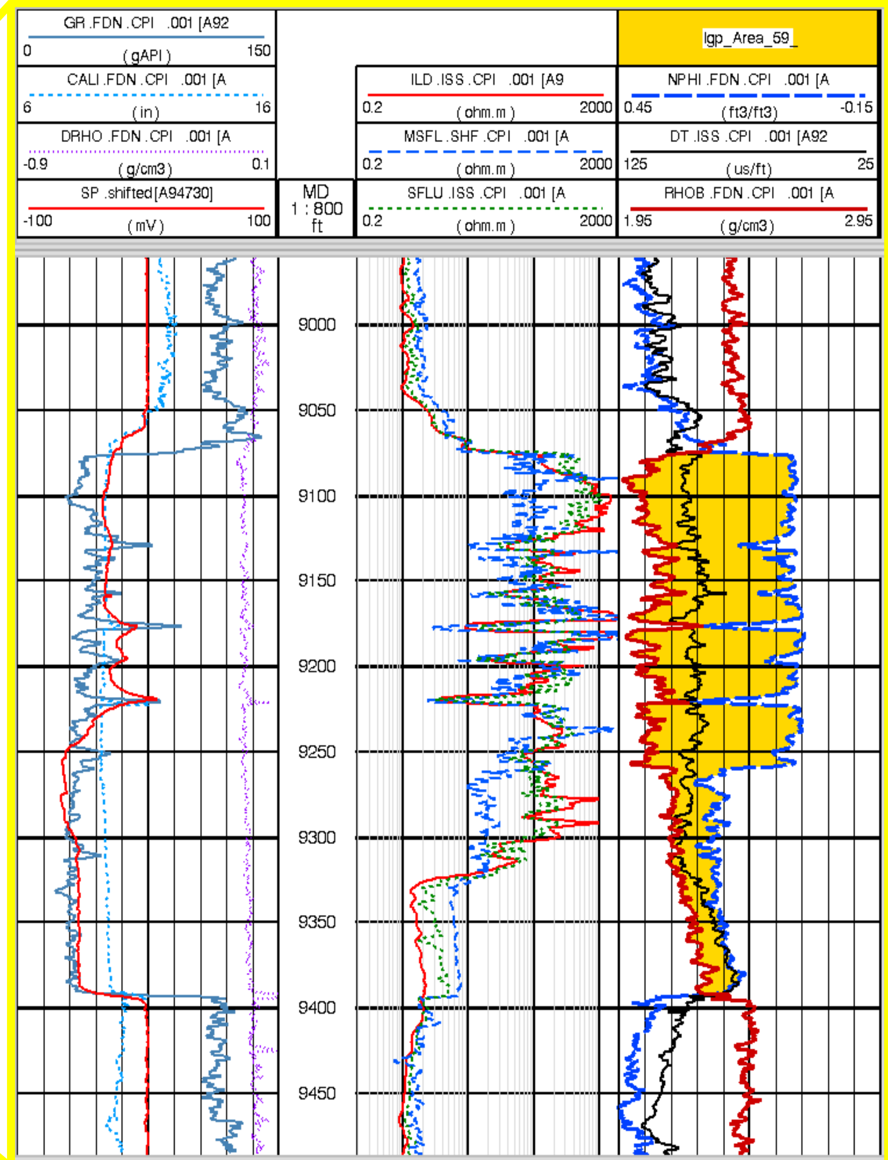
- during the drilling phase (Logging While Drilling);
- soon after the drilling phase (Open Hole Wire Line Logging);
- after the completion of the well and during the exploitation phase up to the end of the reservoir life (Cased Hole Wire Line Logging and Production Logging).


GEOPHYSICAL WELL LOGS
Open Hole
Cased Hole
Logging While Drilling (LWD)
•Correlations
•Formation Evaluation
•Geosteering
•Pressure Predictions
•Seismic interpretation
Wire Line Logging (OH WLL)
•Correlations
•Formation Evaluation
•Geological applications
•Rock Mechanics
Wire Line Logging (CH WLL)
•Formation Evaluation
•Production logs
•Auxiliary measurements

Modern well logging
(Open Hole Wire Line)

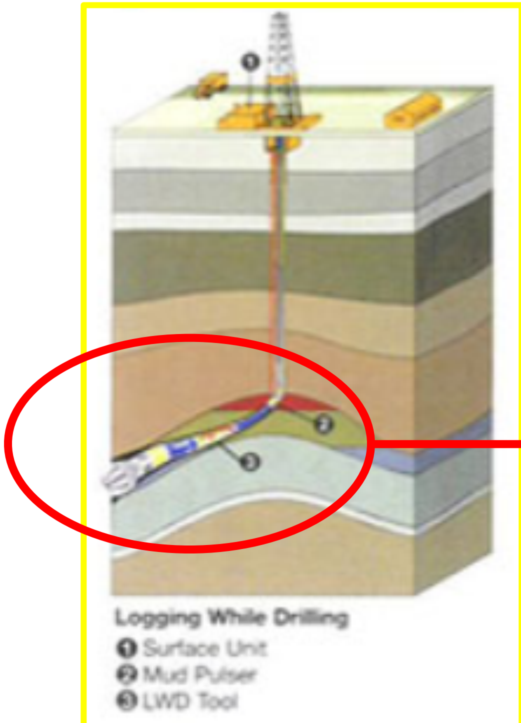


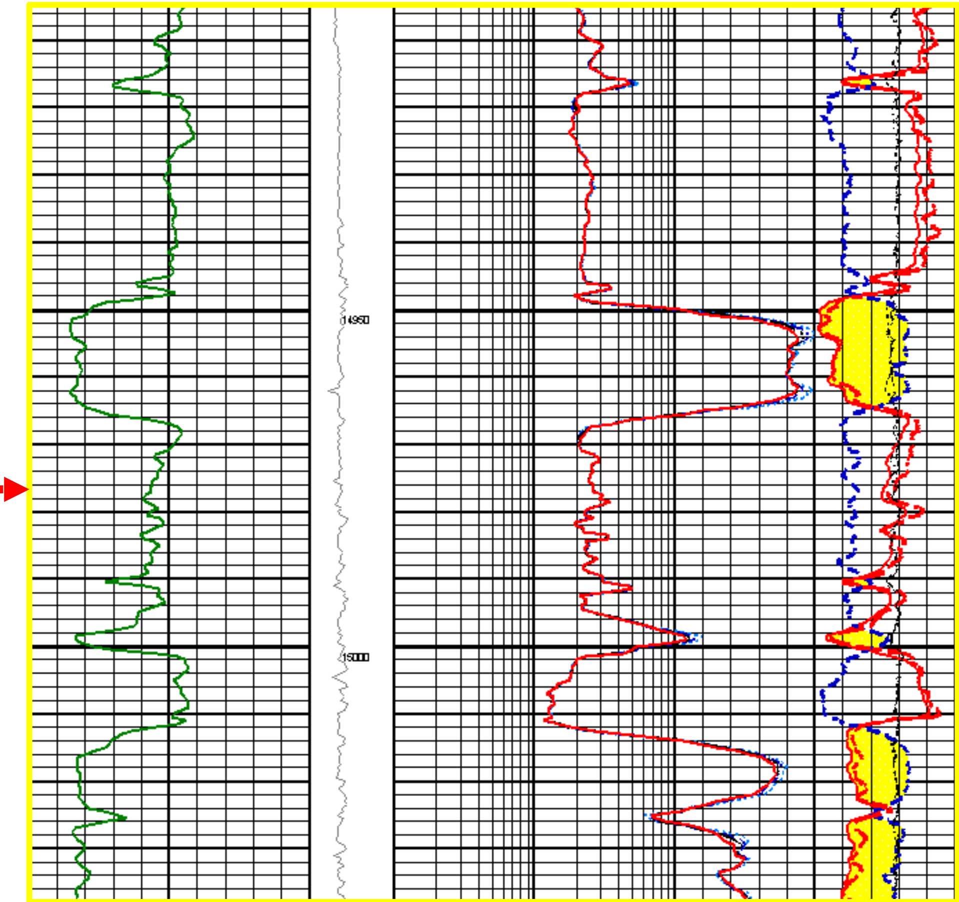




A well log is the product of a survey operation consisting of one or more curves, providing a permanent record of one or more physical measurements as a function of depth in a well bore

Modern well logging
(Open Hole Logging While Drilling)

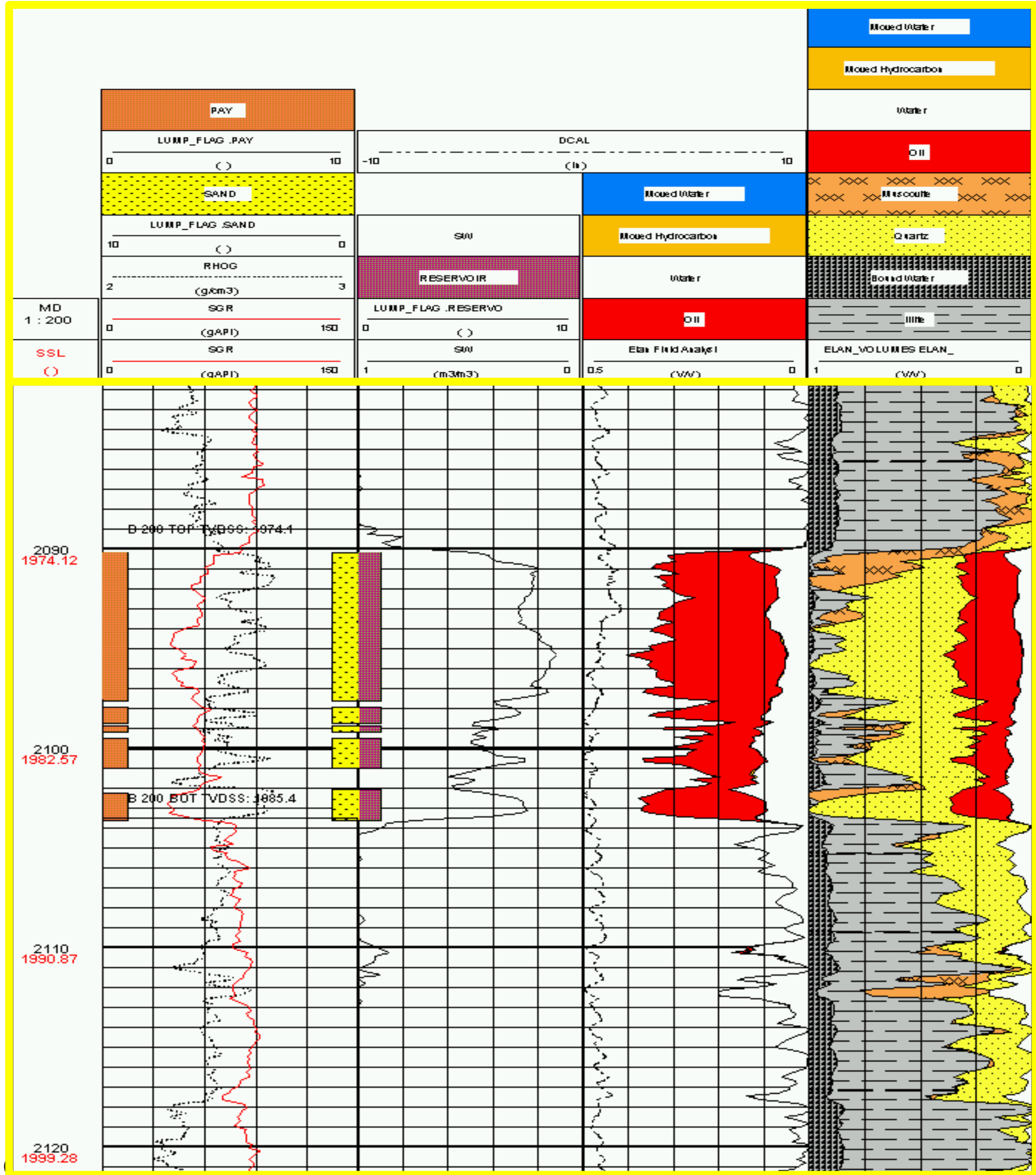




Modern Logging While Drilling technologies allow the acquisition of high quality logging curves (both in Real Time and Memory modes) for Real Time &/or Near Real Time Formation Evaluation and Geosteering.

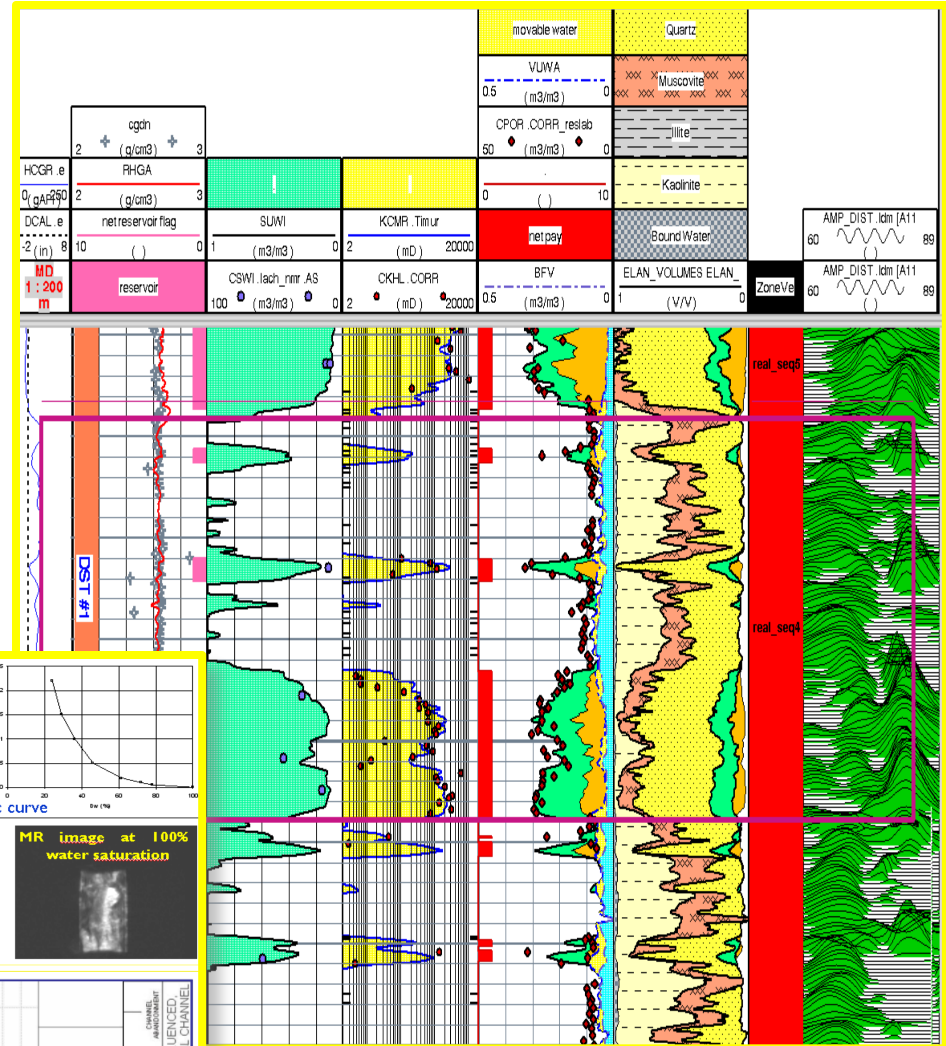
Scope of log interpretation

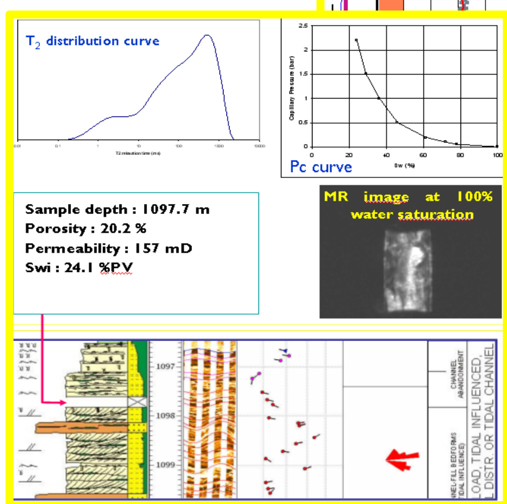
Log interpretation is the process by which the large number of formation properties measured in a well bore are translated into a desired formation characteristics and petrophysical parameters such as porosity, hydrocarbon saturation, permeability, lithology, reservoir geometry and structure.



Well logging applications

Petrophysics is the study of the physical properties of (sedimentary) rocks and their interstitial fluids for purposes of interpreting down hole measurements in terms of reservoir rock characteristics.

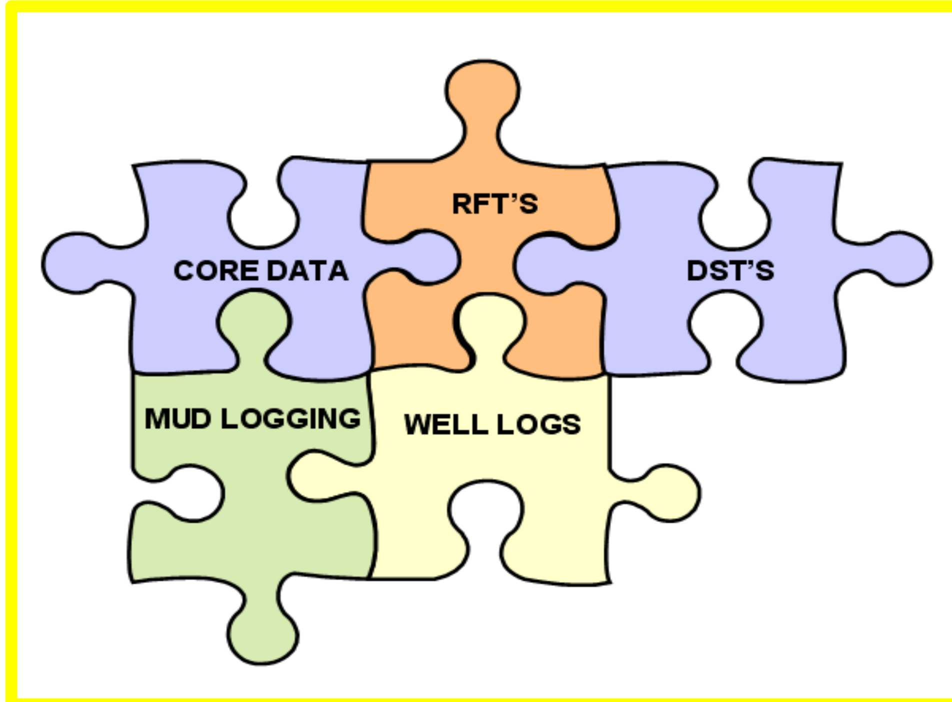




Well logging applications

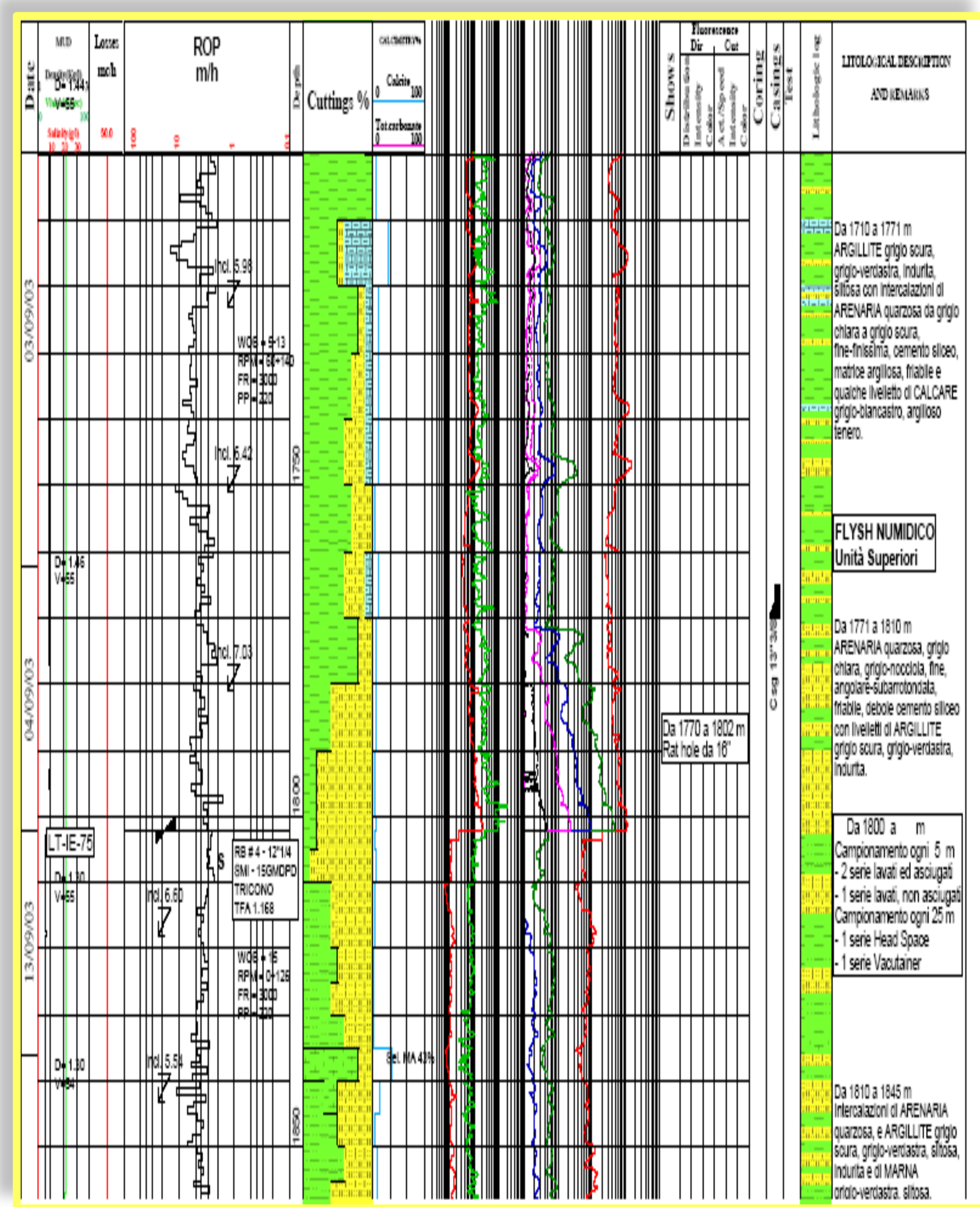
Formation Evaluation is the analysis and interpretation of well log data, drill stem tests, etc. in terms of the nature of the formations and their fluid content. The objectives of formation evaluation are:

- to determine the best means for their recovery, and
- to ascertain if commercially producible hydrocarbons are present,
- to derive lithology and other information on formation characteristics for use in further exploration and development.



Source: SPWLA Glossary

Master log

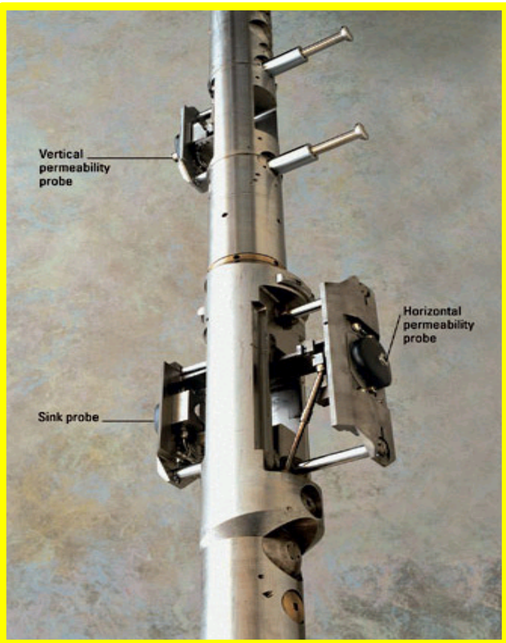


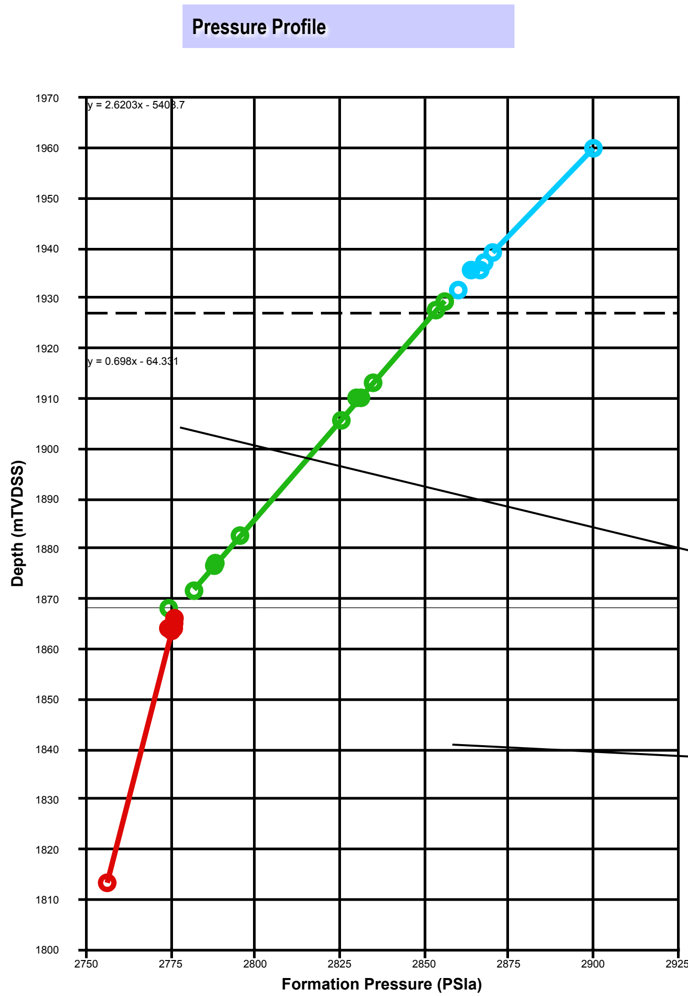
The Master Log (or Mud Log) is a document showing (in the form of a log) the variation of drilling parameters and while drilling information which are essential to the geological and petrophysical interpretation of well data (well logs included):

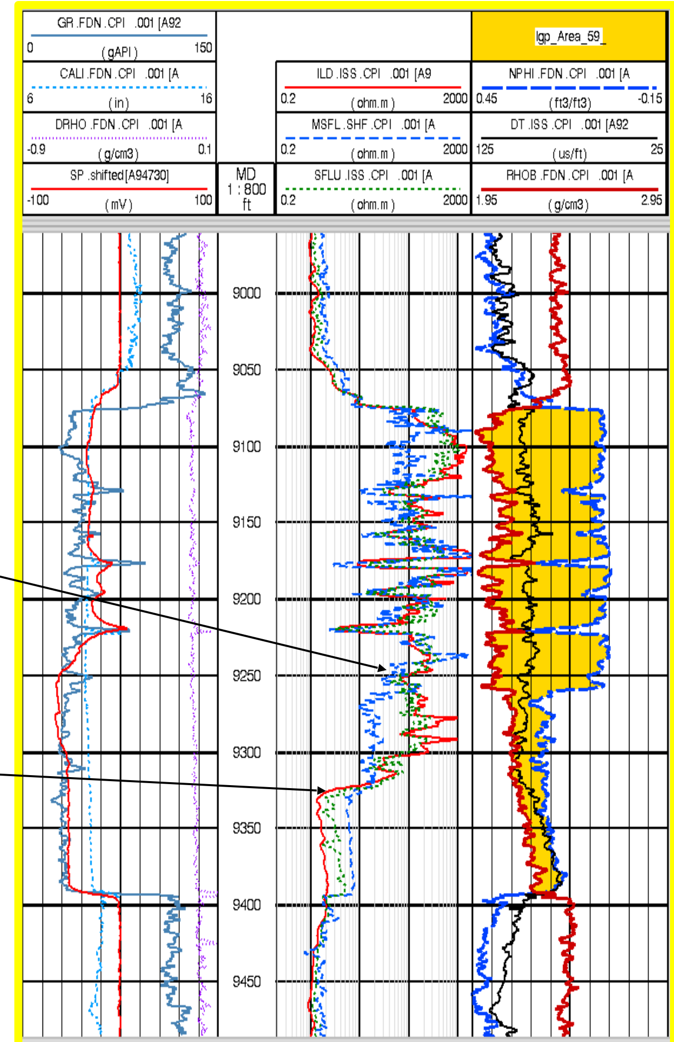
- rate of Penetration (ROP),
- drilling parameters,
- lithological description of cuttings,
- chemical composition and calcimetry,
- gas curves,
- mud data,
- drilling operation (i.e. coring, etc.)
- others.

Pressure Measurements

Localization of fluid contacts within the reservoir



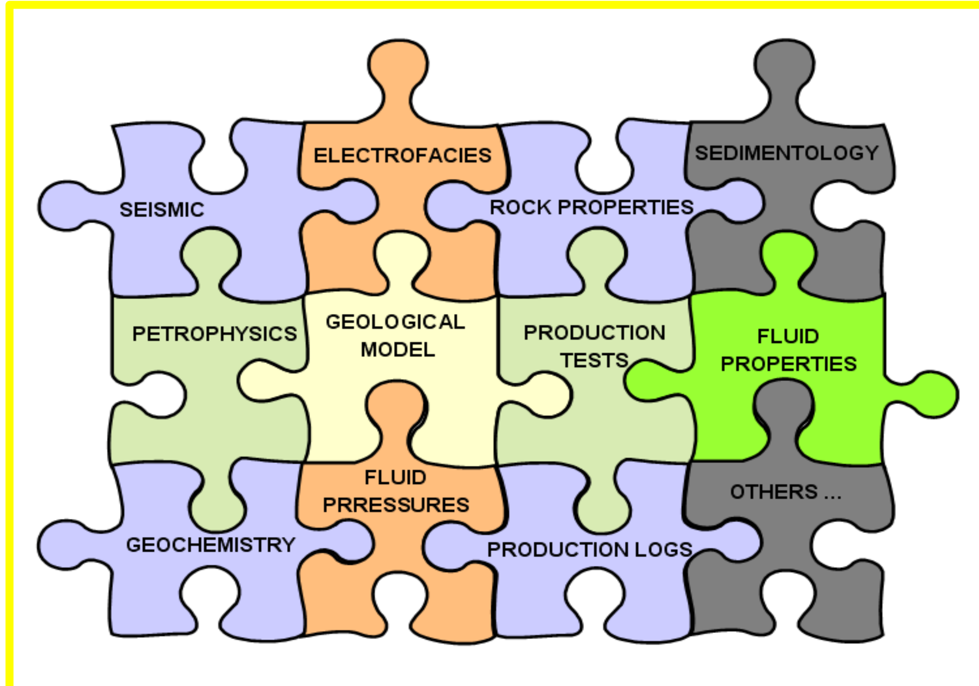




Well logging applications

Reservoir Characterization corresponds to the identification of a model for the reservoir, **the dynamic behaviour** of which **must be as similar as possible to that of the reservoir**.

Well logs contribute mostly to the static part of the model by gathering information about geological, geochemical, petrophysical and geomechanical characters of the reservoir.



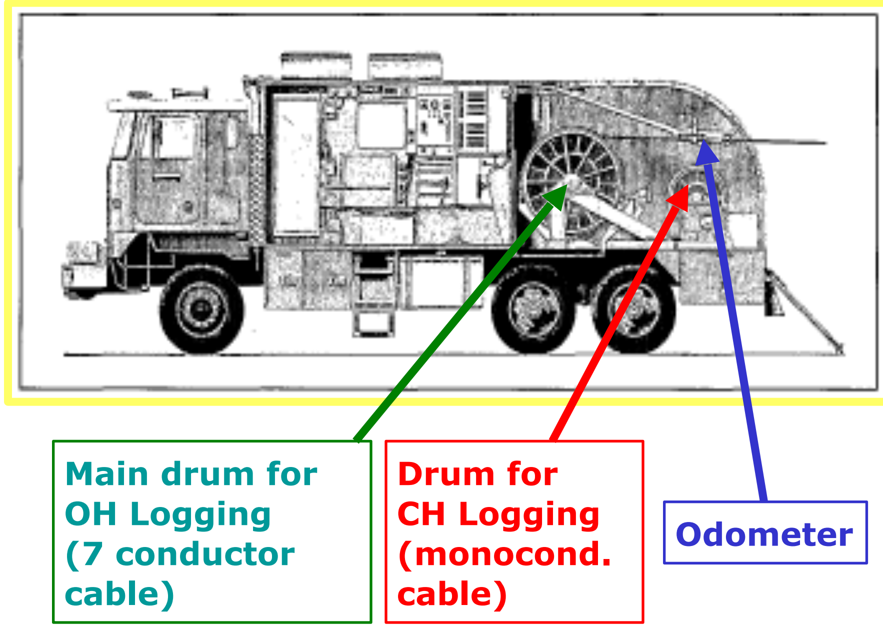
The most important log measurement: depth!

The fundamental measurement provided by the Service Company is depth.

An accurate description of the reservoir may not have a high value without an accurate depth location of the events.

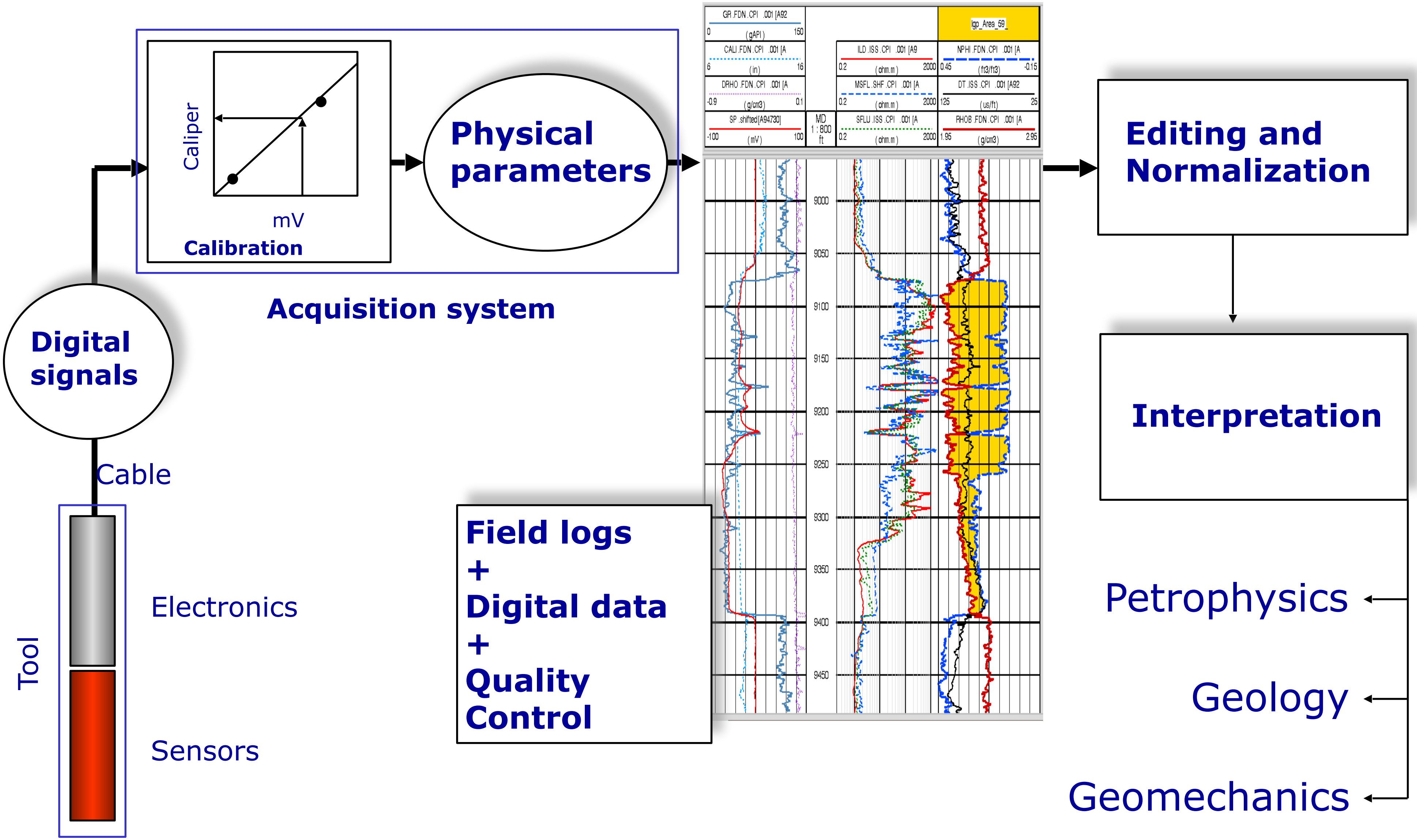
Depth control is of very high importance for the success of any log operation aimed exploration, completion and production of hydrocarbons.

In case of wireline operations the accuracy of depth measurement is of +/- 1 foot (0,3 m), thanks to the techniques in use based on odometers (calibrated wheels), accurate checks (magnetic markers) and while drilling corrections as function of depth, tool weight type of cable, type of mud, etc..



In case of While Drilling (LWD) operations, depth uncertainty is much higher since absolute depth is based on drill pipe length measurements (Drillers depth).

Well logs: what?



The Formation Evaluation Process

Main steps of the process are:

- planning of the well data acquisition,
- acquisition phase with Quality Control,
- pre and/or post processing,
- interpretation,
- delivery of the results and integration.

Petrophysical parameters

Main petrophysical parameters evaluated by means of well log interpretation are:

- porosity (Φ),
- water saturation (Sw),
- permeability (K)

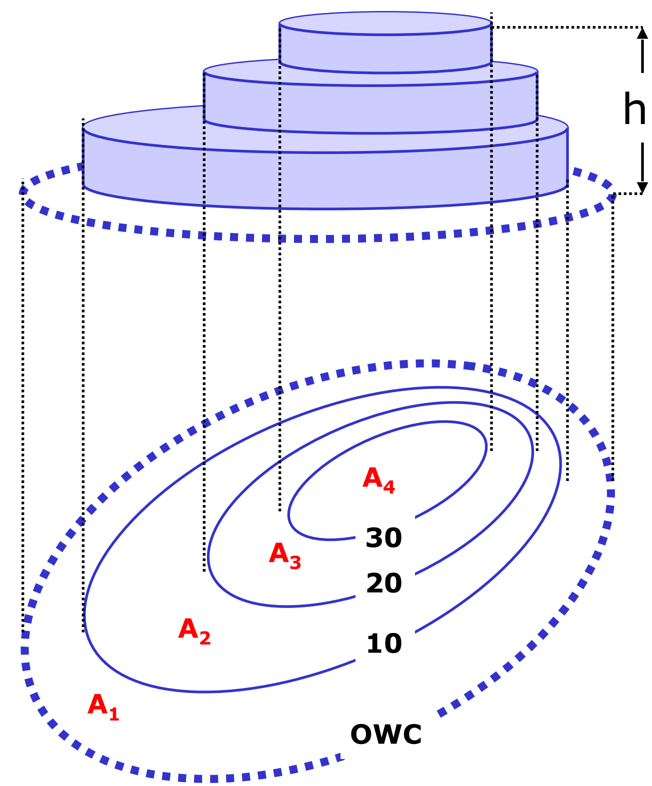
By means of well log interpretation, the thickness of productive levels, can be easily evaluated:

- gross pay,
- net sand,
- net reservoir,
- net pay and net to gross.

Well logs: what?

The petrophysical parameters derived from well log interpretation can, therefore, be used to compute the volume of hydrocarbon (oil and/or gas) originally in place.

$$STOOIP = \frac{7758 \bullet A \bullet h \bullet \Phi \bullet (1-Sw)}{Boi} \text{ (stb)}$$

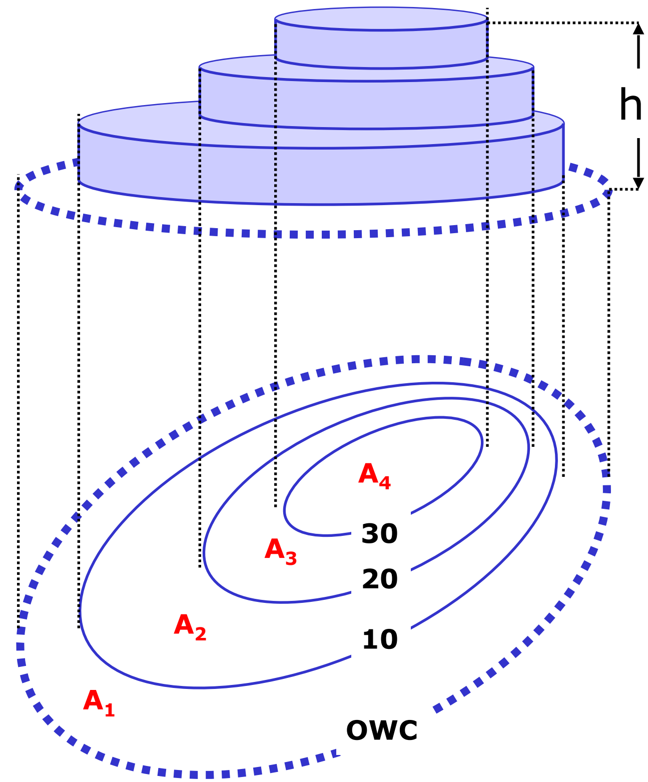


A • h = Bulk reservoir volume
Φ = average effective porosity (%)
1- Sw = initial oil saturation
Sw = average Water Saturation
Boi = oil volume factor

Well logs: what?

Oil volume factor

Oil and dissolved gas volume
at reservoir conditions divided by oil volume at standard conditions. Since most measurements of oil and gas production are made at the surface, and since the fluid flow takes place in the formation, volume factors are needed to convert measured surface volumes to reservoir conditions. Oil formation volume factors are almost always greater than 1.0 because the oil in the formation usually contains dissolved gas that comes out of solution in the wellbore with dropping pressure.



Petrophysical parameters: porosity

Porosity is the pore volume per unit volume of formation (ratio between pore volume and rock volume).

$$\Phi_t (\%) = Vp/Vt * 100$$

Porosity is expressed in percentage.

Porosity is evaluated by means of the, so called, porosity logs: density, neutron, acoustic, dielectric and Magnetic Resonance.

Porosity logs are sensitive to total porosity (Φ_t) while the effective porosity (Φ_e) is evaluated, in clastic sequences, by means of empirical relationships between Φ_t, Φ_e and Volume of shale (Vsh), according to the distribution of the shales.

In case of laminated shale: $\Phi e = \Phi t (1-Vsh)$

Total porosity vs effective porosity

Effective porosity

- Core analysis context: pore space that is accessible to helium (or water)
- Log analysis context: pore space that is occupied by free water and hydrocarbons (excludes clay bound water)

Total porosity:

- Core analysis context: coincides with effective porosity (totally inaccessible pores are rare)
- Log analysis context: porosity normally measured by logs (with reference to the pore space occupied by free and bound water)

Porosity	The ratio of the pore volume to the bulk volume. The pore volume is available for the accumulation and storage of oil, gas and water. Porosity is either expressed as a fraction or percentage of bulk volume.
Total porosity	The ratio of the volume of all the pores to the bulk volume, regardless of whether or not the pores are interconnected.
Effective porosity	The ratio of the interconnected pore volume to the bulk volume.

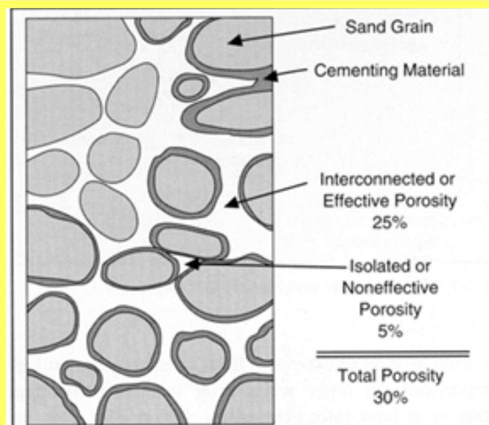


Fig 1-2
Graphic depiction of effective, noneffective, and total porosity

Porosity: primary vs secondary

Formation Porosity can be classified as:

primary and **secondary**:

- **Primary porosity** is the porosity of rock formed at the moment of the deposition and modified only for the compaction (therefore not considering the changes due to chemical effects (i.e. fluid migration through the sediments).
- **Secondary porosity** is the additional porosity generated by post depositional events and generated (or canceled) by chemical dissolution, diagenesis, dolomitization or tectonic events such as the generation of fractures and joints.

Petrophysical parameters: porosity

With respect the origin of the pores, porosity can be classified as:

Primary porosity

pores formed at the moment of the deposition of the sediment:

- intergranular (spaces between grains, typical of clastic formations such sandstones)
- intercrystalline (spaces between crystals typical of the carbonates)

Secondary porosity

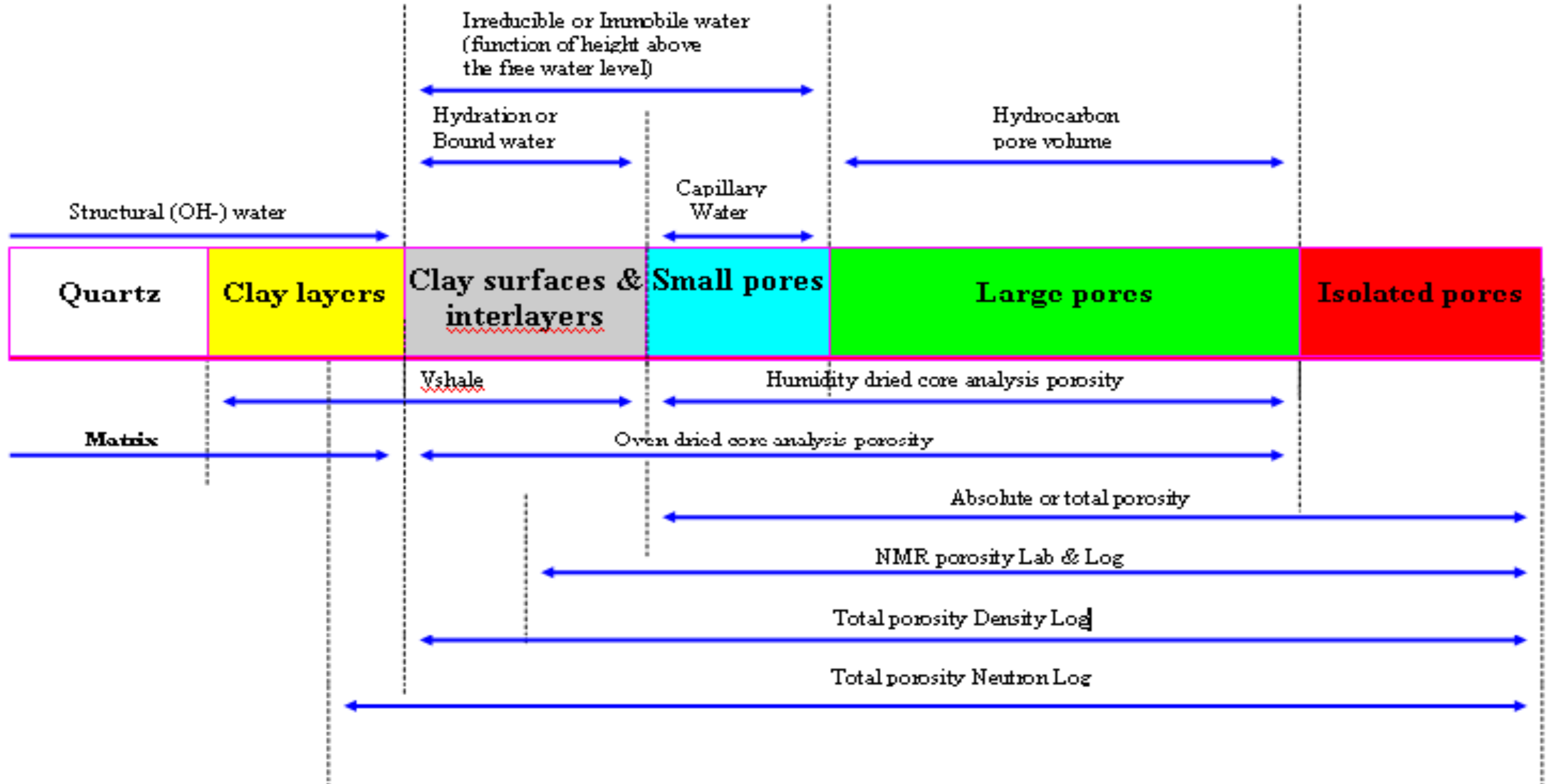
pores formed after the deposition of the sediment:

- due to fracturing (especially in competent rocks),
- due to dissolution (i.e. vuggy porosity),
- due to diagenetic effects (dolomitization, recrystallization, silicification, etc.)

Laboratory petrophysical measurements

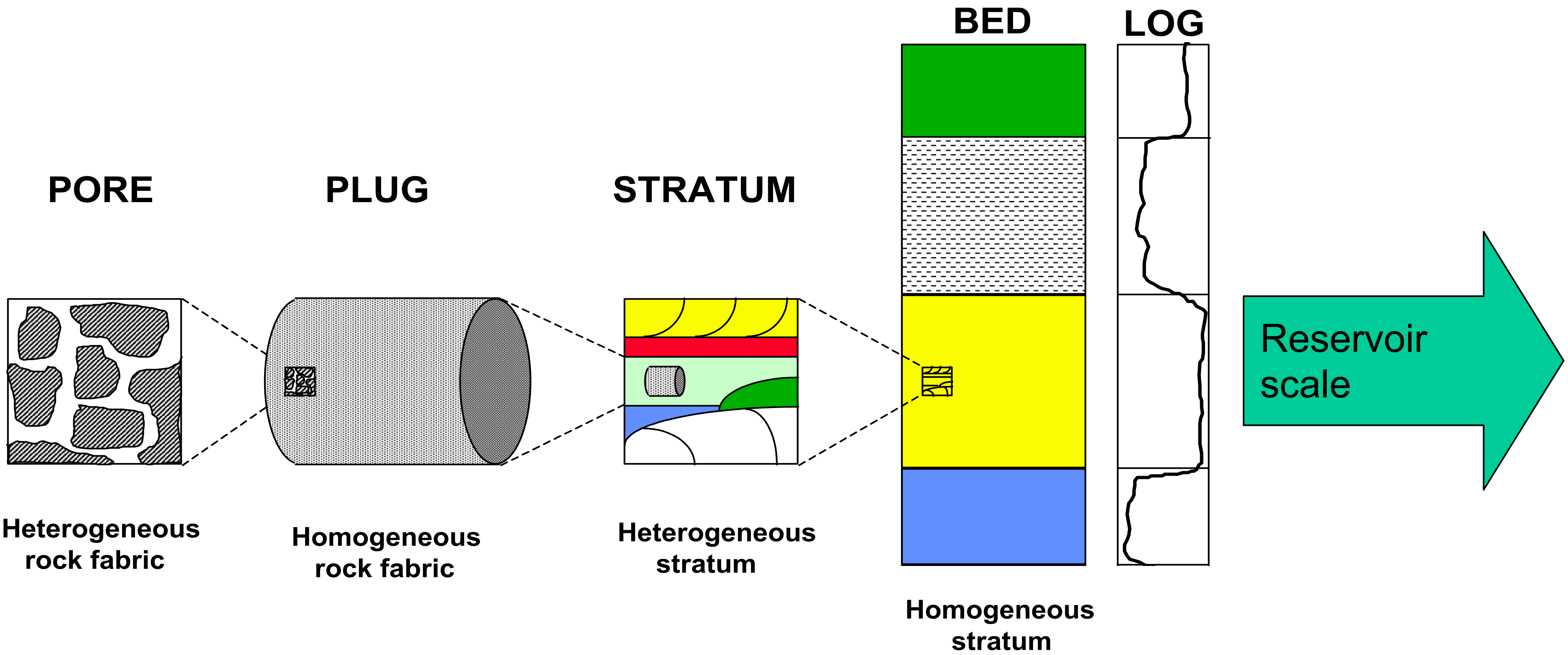
Analysis	**Derived Reservoir Description Parameters**
Lithology description	Texture, sedimentary structures, rock types, facies
X-ray Diffraction, X-ray Fluorescence	Mineral identification/quantification
Thin section petrography	Mineral identification /rock-pore relationships / petrophysical micro-characterization
Scanning electron microscopy (SEM)	Determination of pore-associated mineralogy
Petrographic image analysis	Description/quantification of visible pore geometry
Porosity	Storage capacity – stress sensitivity
Residual fluid analysis (So, Sg, Sw)	- Fluid identification - Fluid distribution with depth - Amount of filtrate invasion
Grain density	Grain densities for calibration of density logs
Permeability	- Flow capacity, distribution and profile - Transmissivity – stress sensitivity - Zonation of reservoir units
Electrical properties - Formation factor / m - Resistivity index / n	Log-calibration parameters with respect salinity, confining stress and lithology
Cation exchange capacity	Petrophysical correction for clay conductance in shaley sands
Pore volume compressibility	Storage reduction with pore pressure depletion
Capillary pressure - Centrifuge / Porous plate - High pressure Hg intrusion	- Pore throat geometry and size distribution - Rock typing, texture, lithology - Residual wetting/non wetting phase saturation - Fluid distribution with height - Differentiation of pay from non-pay zones
NMR properties - T2 distribution curve	- T2 cut-off for NMR log calibration - Permeability estimator - Initial saturation - Porosity
Acoustic properties	- Lithology and porosity log-calibration - In-situ stress computation for sand control, fracture mechanics, selection of appropriate confining stresses - Seismic amplitude calibration and interpretation
Relative permeability	- Rock-fluid interactions - Reservoir performance prediction, recovery factors

Porosity measurements



Porosity definitions for hydrocarbon reservoirs

The problem of different scales of the measurements



Porosity distribution in sedimentary rocks

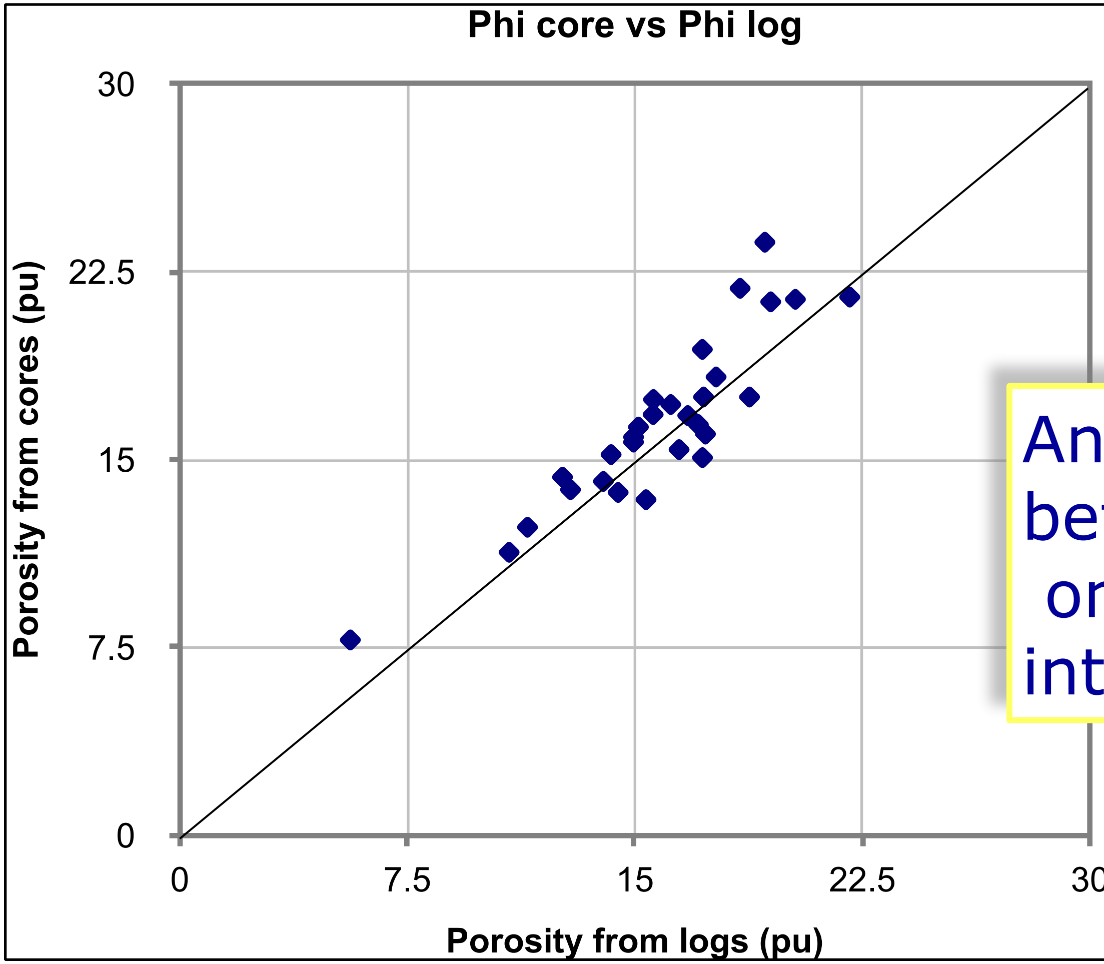
Porosities of subsurface formation can vary widely:

- carbonates (limestone/dolomites):
  - from 0 to 45 %
- evaporites (salt, anhydrite, gypsum, silvite, ecc.):
  - practically 0 porosity
- consolidated sandstones:
  - from 5 to 15 %
- unconsolidated sands:
  - 30% and more
- shales or clays:
  - often more than 40 %

Porosity distribution in typical sedimentary rocks

Field	Φ (%) min	Φ (%) max	Lithology
Nigeria	18	35	Clean Sands
Adriatic Sea	25	35	Clean Sands
Adriatic Sea (below 3500 m)	10	15	Clean Sands
Po Valley	20	30	Clean Sands
Persian Gulf (Nowrouz Fm.)	20	25	Clean Sands
Lybia (Bu Attifel)	12	15	Sandstones
Sicily (Gagliano Fm.)	2	6	Low porosity sandstones
Monte Alpi	0	4	Low porosity carbonates
Sicily (Gela Fm.)	0	5	Low porosity carbonates
Cavone	8	12	Oolitic limestones
Persian Gulf (Arab Fm.)	8	15	Limestones
Lybia (off shore)	10	15	Limestones
Lybia (off shore)	20	24	Dolostones
Persian Gulf	25	35	Chalky limestones
North Sea	30	45	Chalky limestones

Petrophysical parameters: porosity



An example of correlation between porosity measuremen on cores and from log interpretation in sandstones

Petrophysical parameters: Water Saturation

Water Saturation of a formation is the fraction of its pore volume occupied by formation water.

Sw (%)= **Vw/Vp *100** (Vp pore volume, Vw volume of water)

Saturations are expressed in percentage.

Therefore oil or gas saturation is the fraction of pore volume that contains oil or gas.

The symbols used are:

- Sw for water saturation;
- Sh for general hydrocarbon saturation;
- So and/or Sg for oil and/or gas saturation.

The summation of all saturations, in a given formation rock, must total to 100% and therefore:

- Sh = 1 - Sw

Petrophysical parameters: Water Saturation

- Water Saturation (Sw) is generally evaluated by the relationships among resistivity and porosity of the reservoir rock.
- This relationship, in clean formations, is expressed by the Archie equations.
- Sw of a formation can vary from 100% to quite small amount (4-5%) always present in the pores: this amount is the, so called, irreducible or connate water saturation Sw_{irr}.

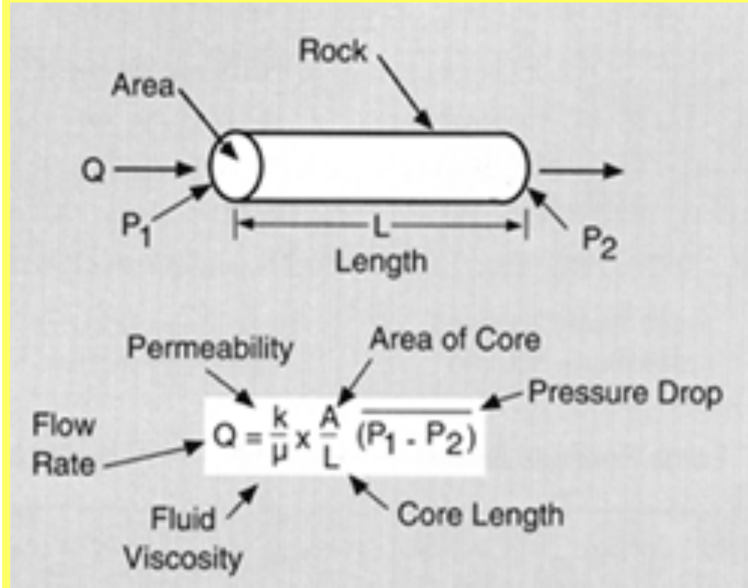
Petrophysical parameters: Water Saturation

Field	Swirr (%) min	Swirr (%) max	Lithology
Nigeria	5	7	Clean Sands
Po Valley	15	25	Clean Sands
Adriatic Sea	25	30	Clean Sands
Sicily (Gagliano Fm.)	10	20	Low porosity sandstones
North Sea	5	7	Chalky Limestones
Adriatic Sea	30	40	Fractured low porosity limestones
Persian Gulf (Arab Fm.)	50	60	Dolostones
Arabia (Mishrif Fm.)	60	70	Chalky Limestones

Irreducible water saturation (Sw_{irr}) in typical reservoir rocks

Petrophysical parameters: Permeability

- Permeability is a measure of the ease with which fluids can flow through the formation.
- The unit of permeability is the Darcy (D) and the symbol of permeability is K; the practical unit in use is the milliDarcy (1 mD = 1/1000 D).
- The permeability of 1D is defined as the permeability allowing to a fluid of 1cp of viscosity to flow in a section of rock of 1 cm^2 at a rate of 1 cm^3/sec with a pressure gradient of 1 atm/cm.
- 1D = 0,9869 10^{-12} m^2



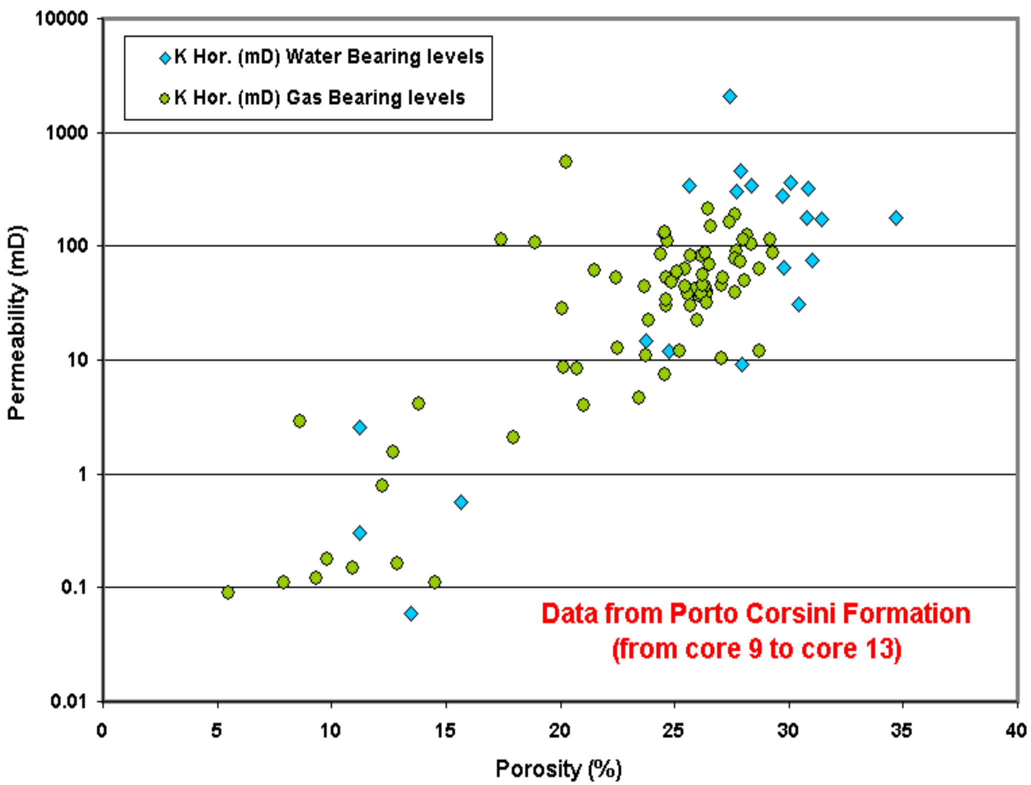
Permeability determination from core

Petrophysical parameters: Permeability

Geological control of permeability

- Shaly sands
  - layering,
  - grain size and sorting,
  - orientation and shape of the clasts,
  - packing,
  - cementation,
  - clay content.
- Carbonates
  - degree of diagenesis (i.e. dolomitization),
  - Porosity development,
  - Fracture presence and orientation.

Porosity/permeability relationships



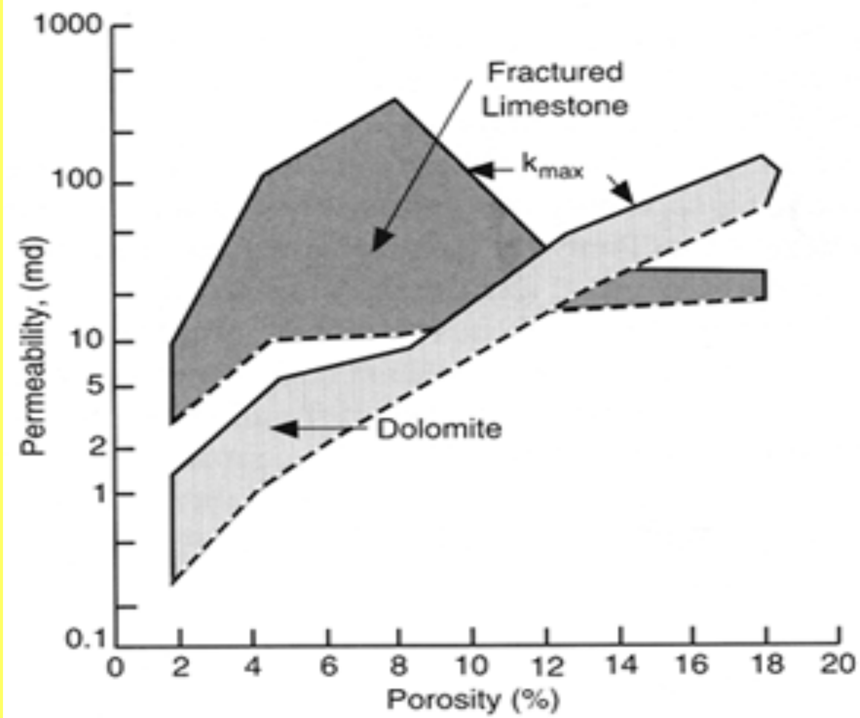


Fig 1-8
Reservoir rocks demonstrate a wide range of permeability that may not follow porosity trends.

Classification of permeability

Absolute Permeability

The permeability of the reservoir rock when the pores are filled by a single fluid

Relative permeability

The permeability of the reservoir rock when the pores are filled by more then one fluid; it is the ratio between the effective permeability to a fluid in presence of other fluids and absolute permeability.

Effective Permeability

Kw = effective permeability to water

Ko = effective permeability to oil

Kg = effective permeability to gas

Relative permeability

Krw	= Kw / K	K rel. to water
Kro	= Ko / K	K rel. to oil
Krg	= Kg / K	K rel. to gas

Horizontal Permeability (Kh) and vertical permeability (Kv)

Permeability is a tensorial property which depends on the direction of the measurements;

Kh e Kv in a sedimentary rock may vary as a function of the grain disposition and, in competent rocks, as a function of fracture distribution and orientation.

Classification of permeability

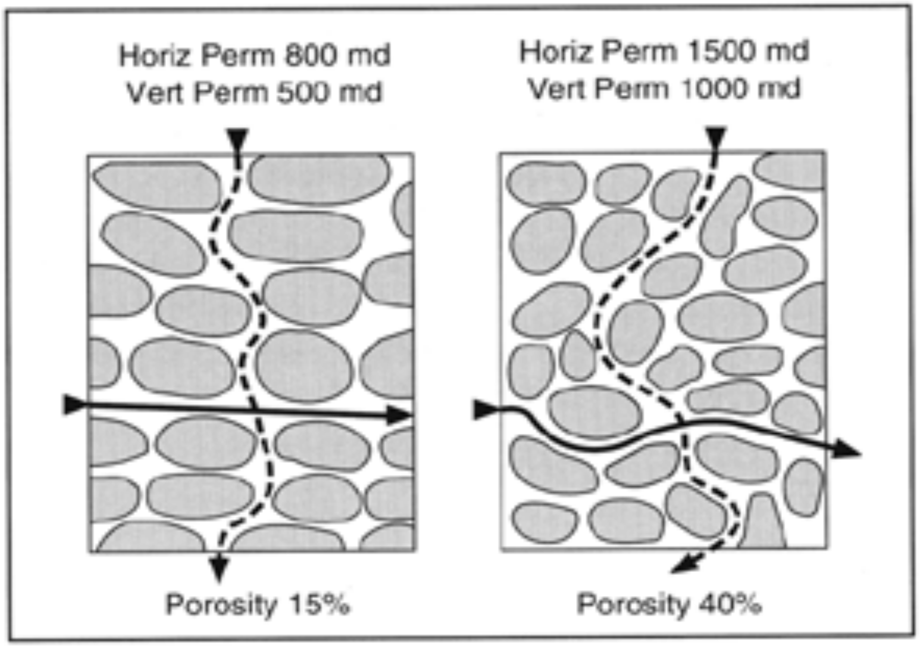
Effective permeability

The ability to preferentially flow or transmit a particular fluid when other immiscible fluids are present in the reservoir (e.g., effective permeability of gas in a gas-water reservoir). The relative saturations of the fluids as well as the nature of the reservoir affect the effective permeability. In contrast, absolute permeability is the measurement of the permeability conducted when a single fluid or phase is present in the rock.

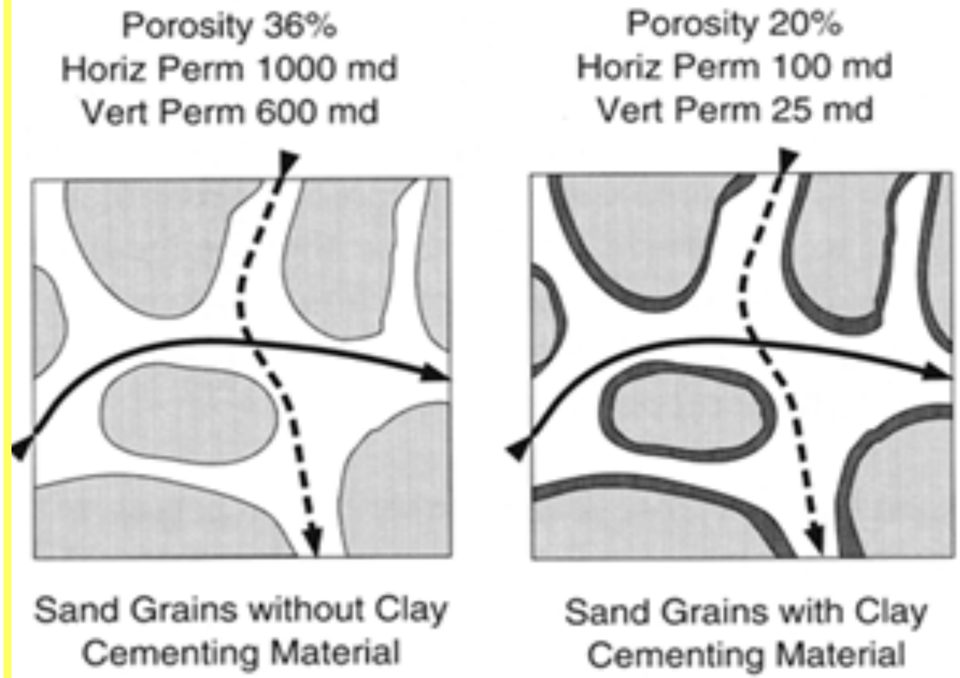
Relative permeability

A dimensionless term devised to adapt the Darcy equation to multiphase flow conditions. Relative permeability is the ratio of effective permeability of a particular fluid at a particular saturation to absolute permeability of that fluid at total saturation. If a single fluid is present in a rock, its relative permeability is 1.0. Calculation of relative permeability allows comparison of the different abilities of fluids to flow in the presence of each other, since the presence of more than one fluid generally inhibits flow

Horizontal vs vertical permeability



Arrangement of sand grains and pore structure affects permeability



Clay cement can affect porosity and permeability