# CORSO DI PETROFISICA INTEGRATA
# MODULO DI WELL-LOGGING

# *STRUTTURA DEL CORSO E MODALITA' DI ESAME*

- 2CFU PER 16 ORE DI LEZIONE FRONTALE
- ESAME ORALE

*TESTI CONSIGLIATI:*

- Asquith G., Gibson C., Basic Well Log Analysis for Geologists, Ed. The American Association of Petroleum Geologists
- Serra O. & L., Well Logging: data acquisition and applications, Ed. Serralog
- Serra O. & L., Well Logging and Geology, Ed. Serralog
- Serra O., Well Logging and Reservoir Evaluation, Ed. Technip

# Basics of
# Geophysical Well Logs:
# Introduction

**www.spwla.org**

**www.glossary.oilfield.slb.com**

# Obiettivi del modulo:

- Misure in pozzo: fondamenti e utilizzo per la determinazione dei parametri della formazione
- Metodi:

✳ Resistivita' e potenziali spontanei

✳ Log di porosita' (sonic, density,neutron, combinazione neutron-density)

✳ Log di litologia e resistivita'

✳ Electrical resistivity imaging (RAB-FMS)

✳ VSP

- Principi ed esempi di interpretazione

# 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

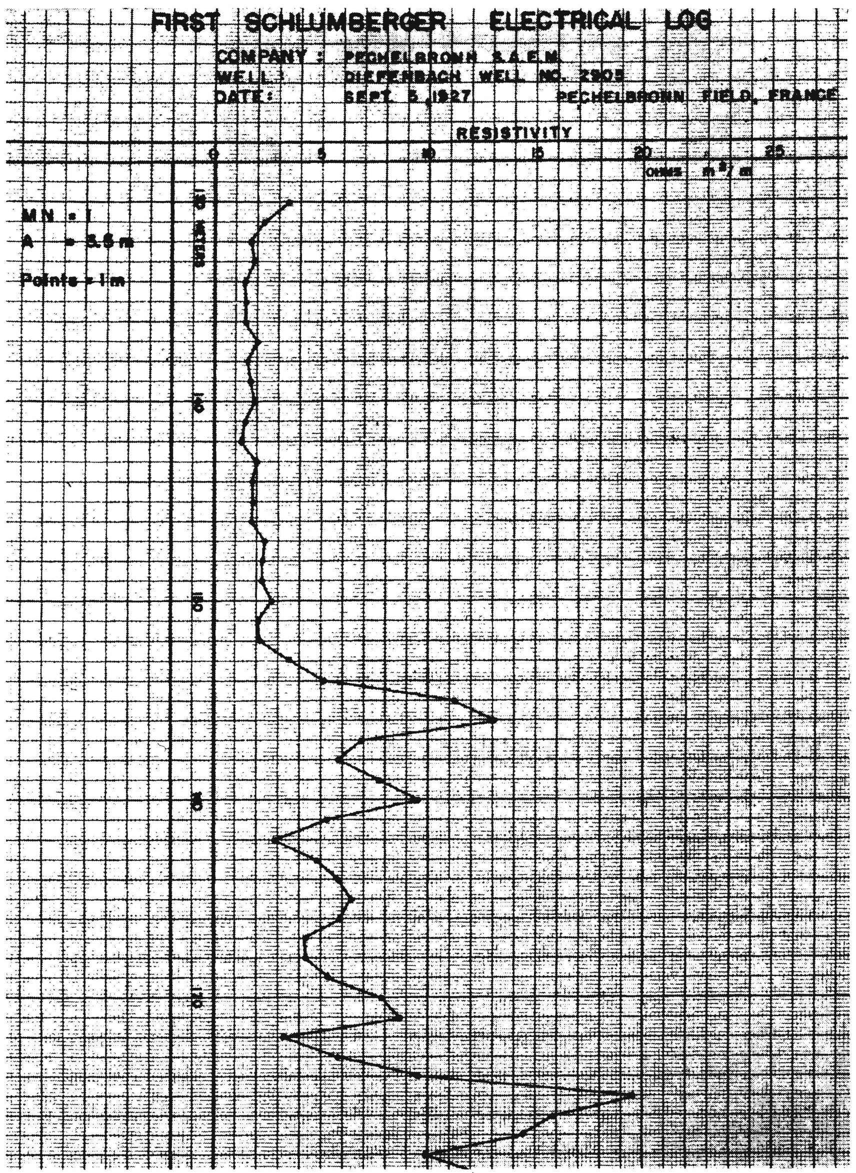



FIG. 1. The first electric log; Pechelbronn, France, September 5, 1927.

# 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.

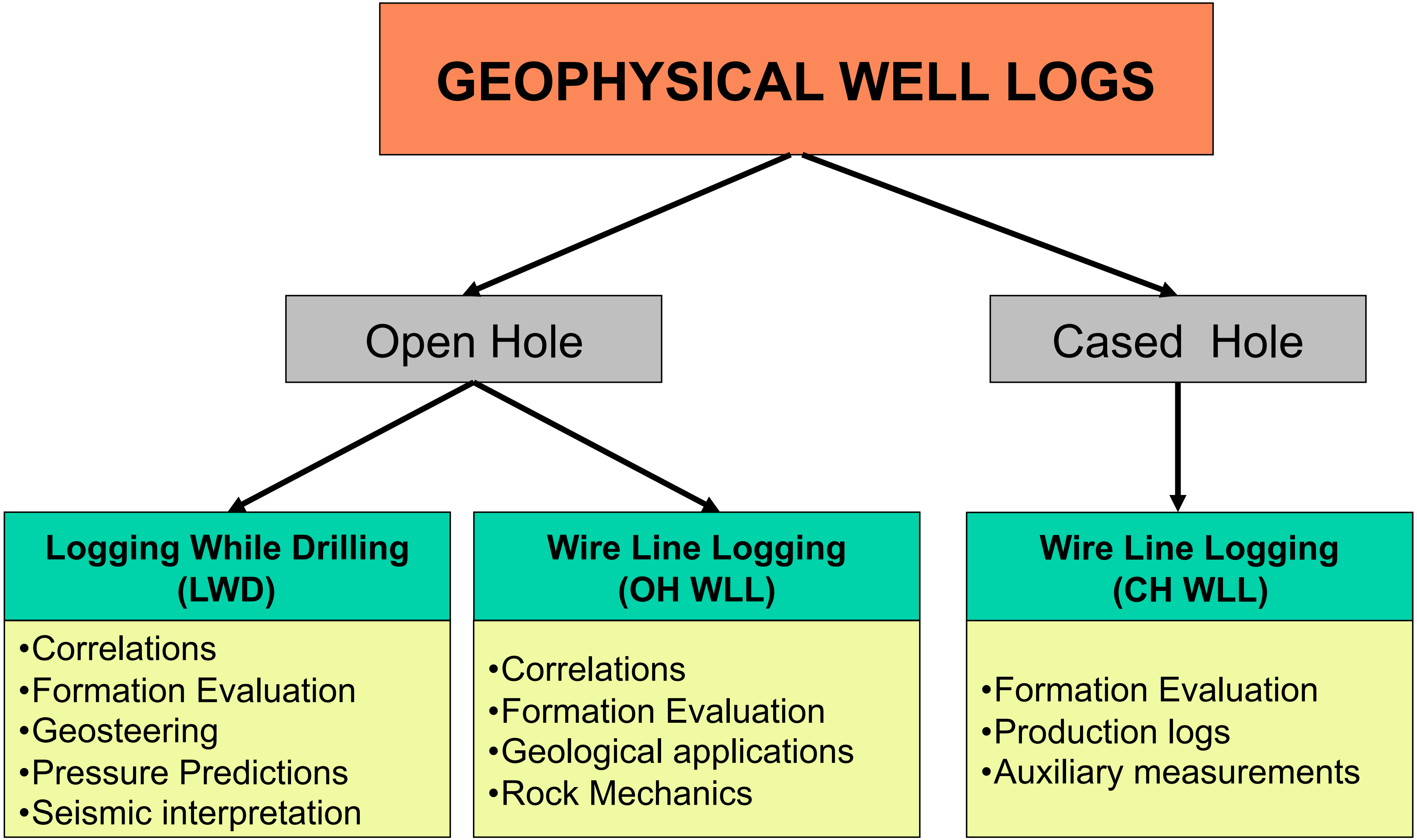
Well logging technology is now used in all the phases of the E&P process from the drilling of the first wildcat well in a field up to the abandonment of the last productive level in the same field.

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?

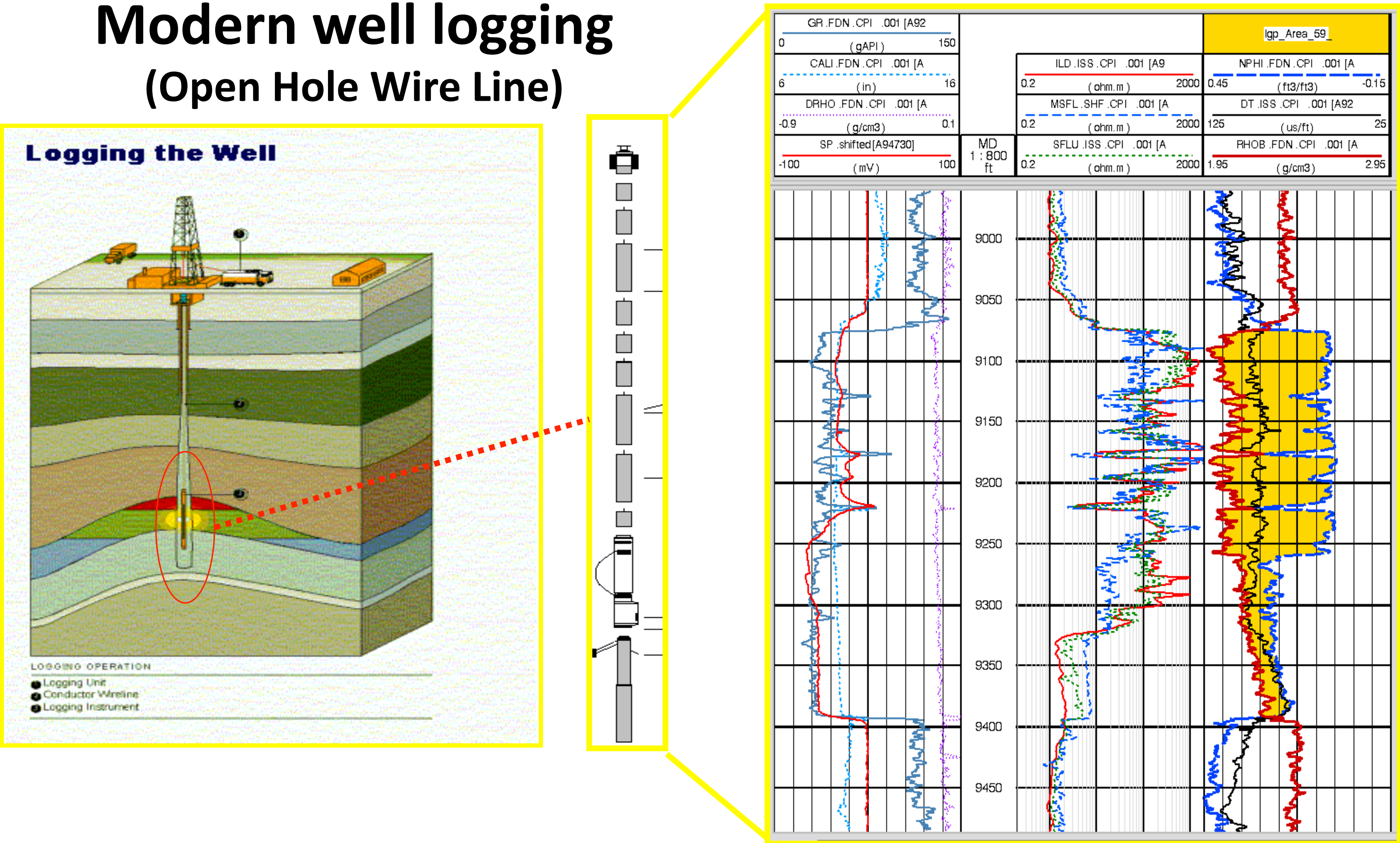
**Well logs are acquired and used in all phases of the E&P process:**

- 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

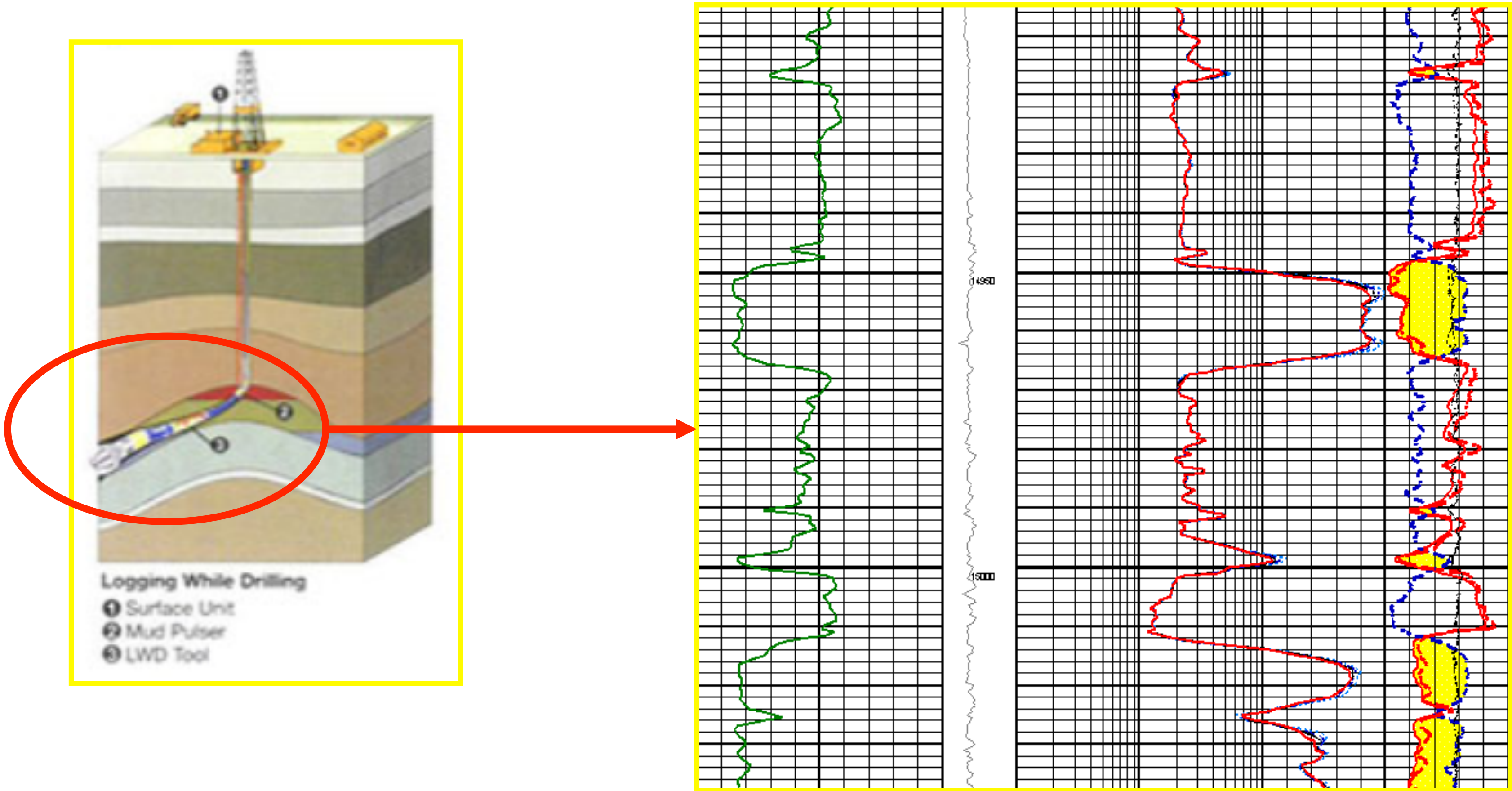
# Modern well logging

## (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

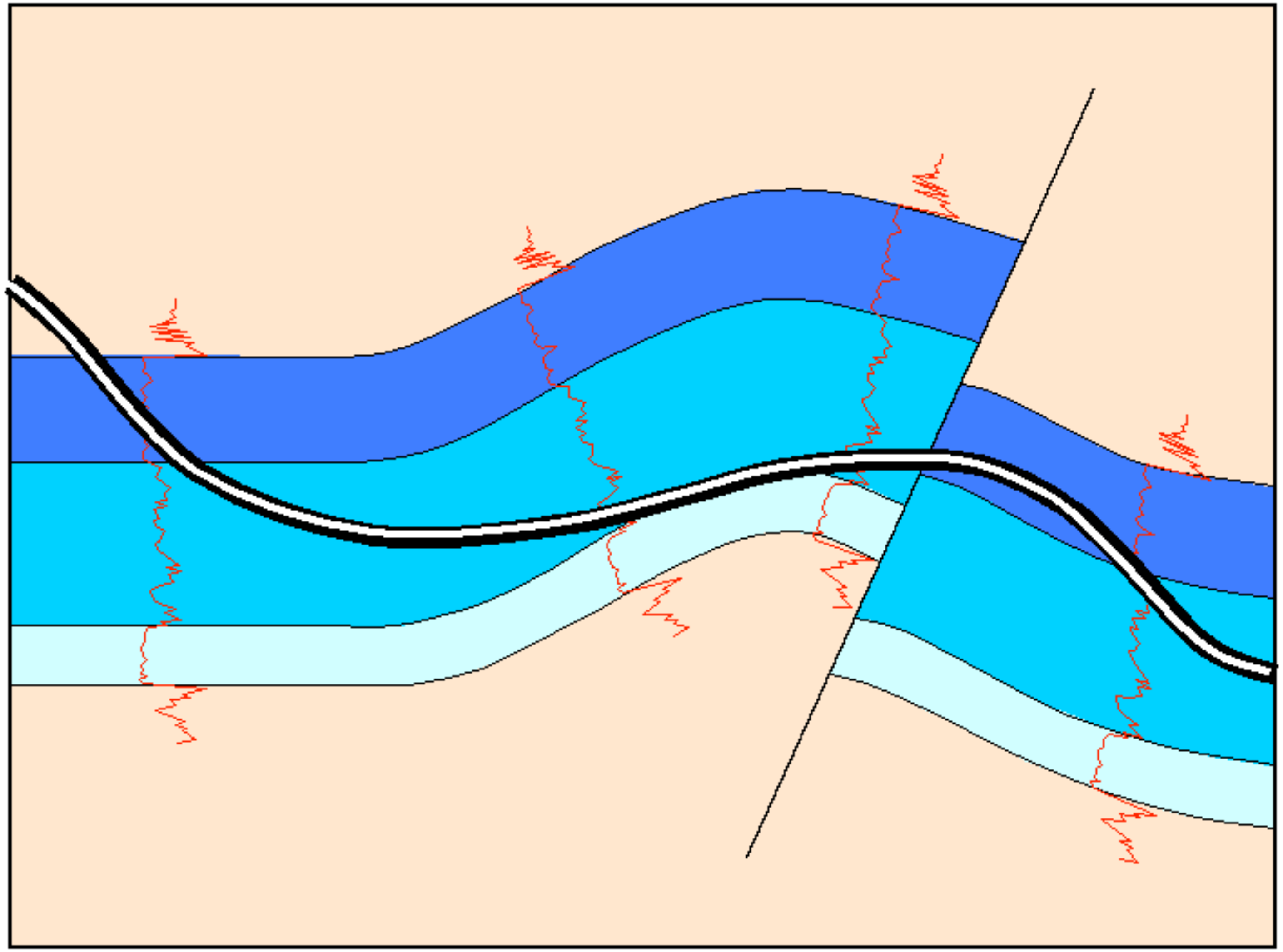
# Modern well logging
## (Open Hole Logging While Drilling)




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.

# Modern well logging

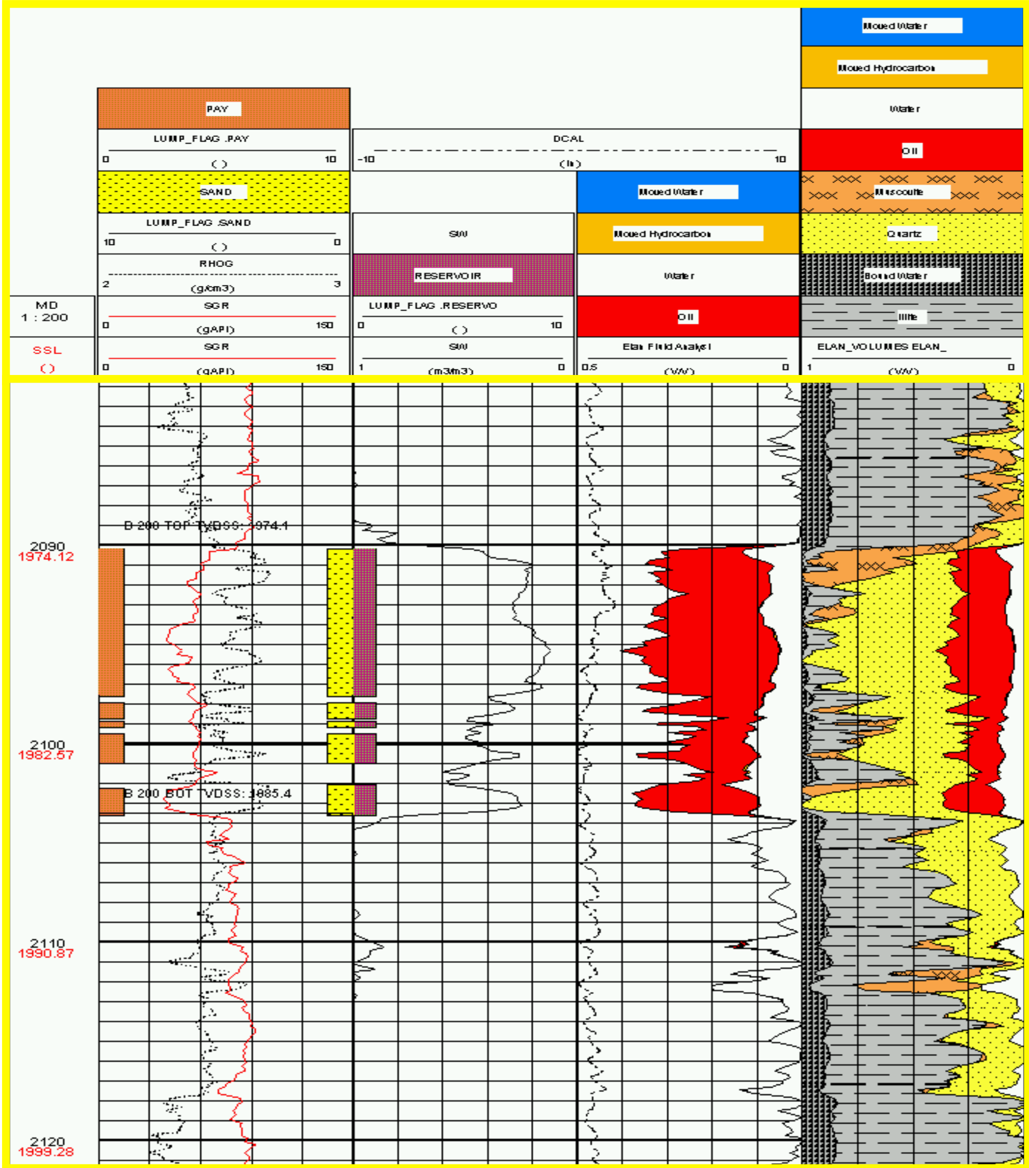
## (Open Hole Logging While Drilling)



Geosteering.

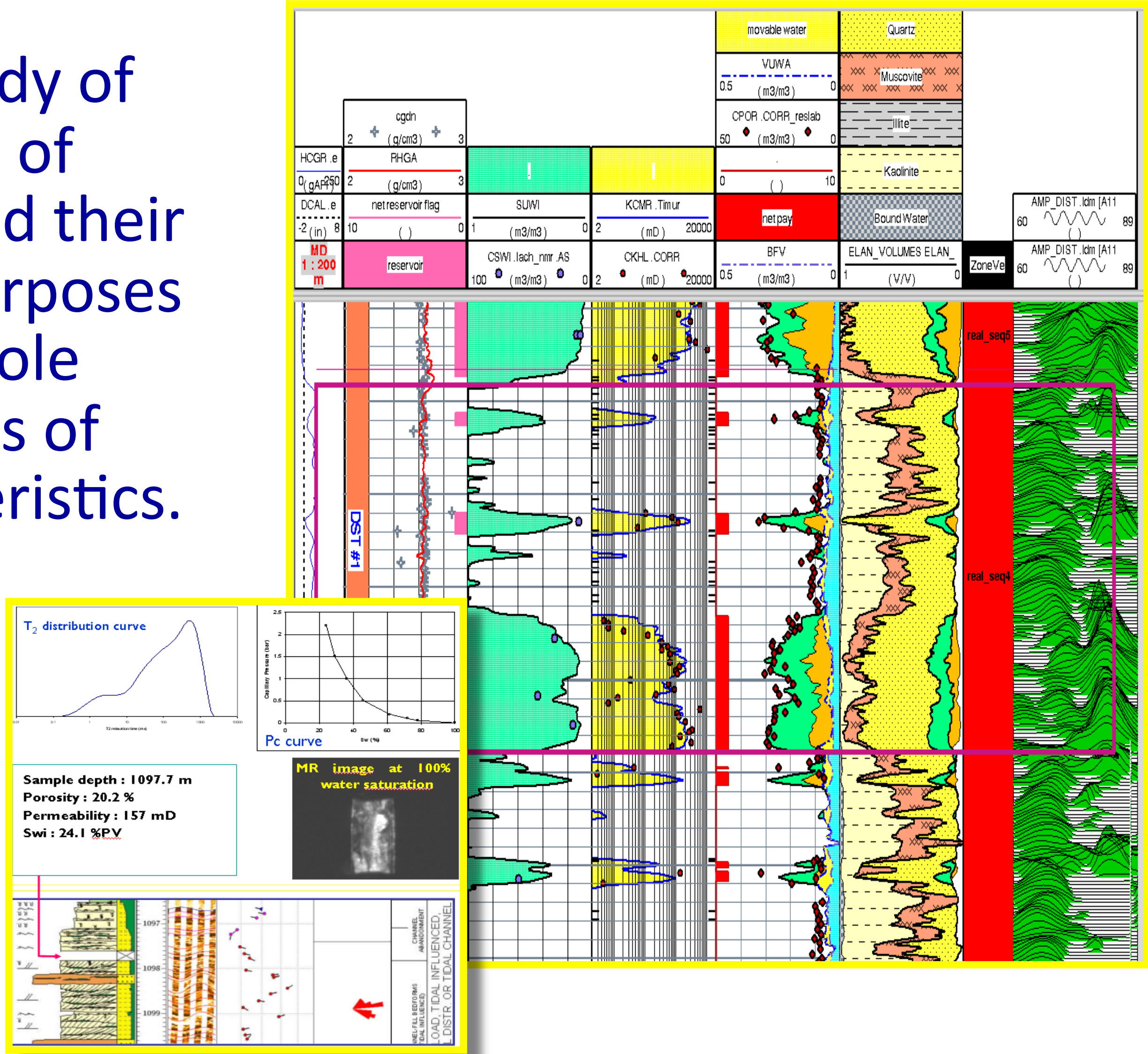
# Scope of log interpretation

**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

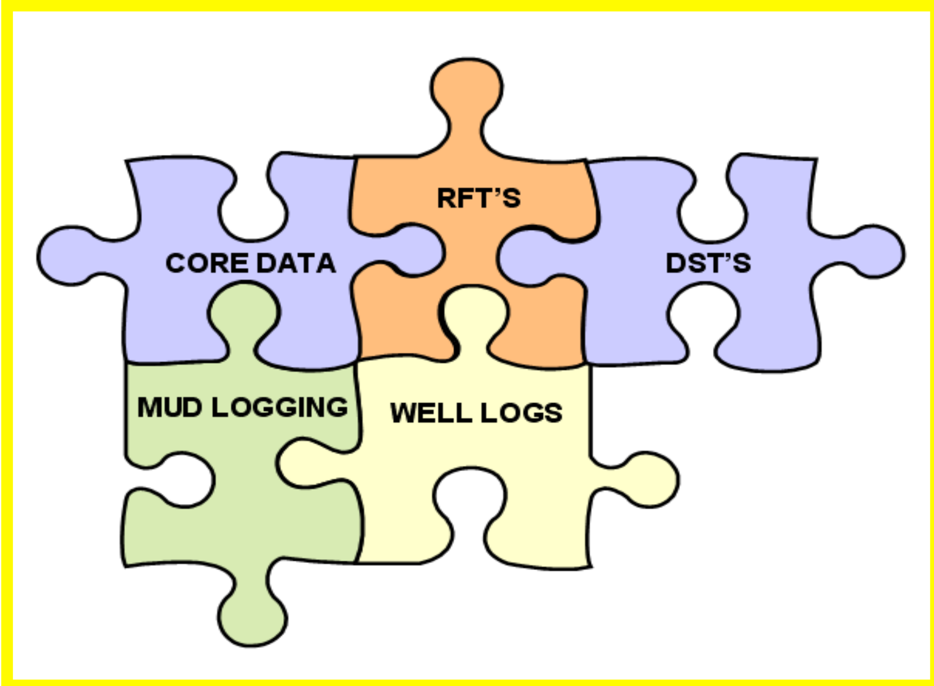
**Petrophysics** is the study of the physical properties of (sedimentary) rocks and their interstitial fluids for purposes of interpreting down hole measurements in terms of reservoir rock characteristics.



# Well logging applications

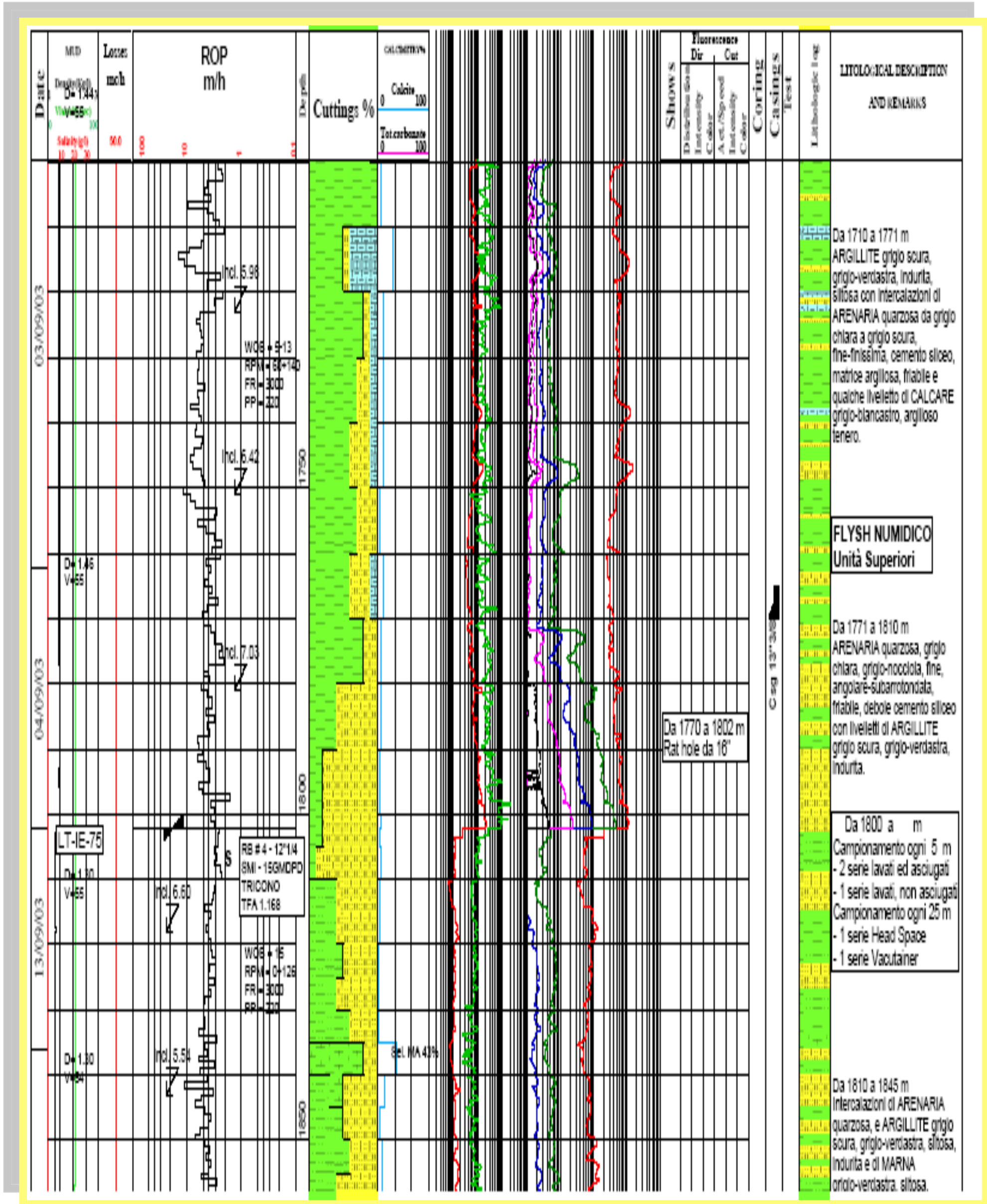
**Formation Evaluation** is the analysis and interpretation of well log data, drill stem tests, etc. in terms of the nature of the formations and their fluid content. The objectives of formation evaluation are:

- 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

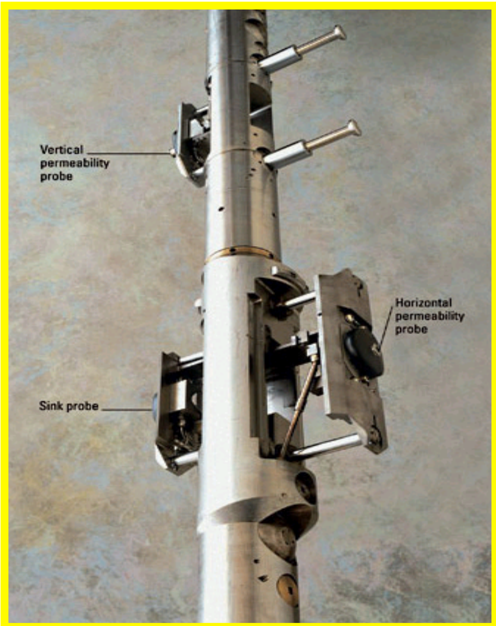


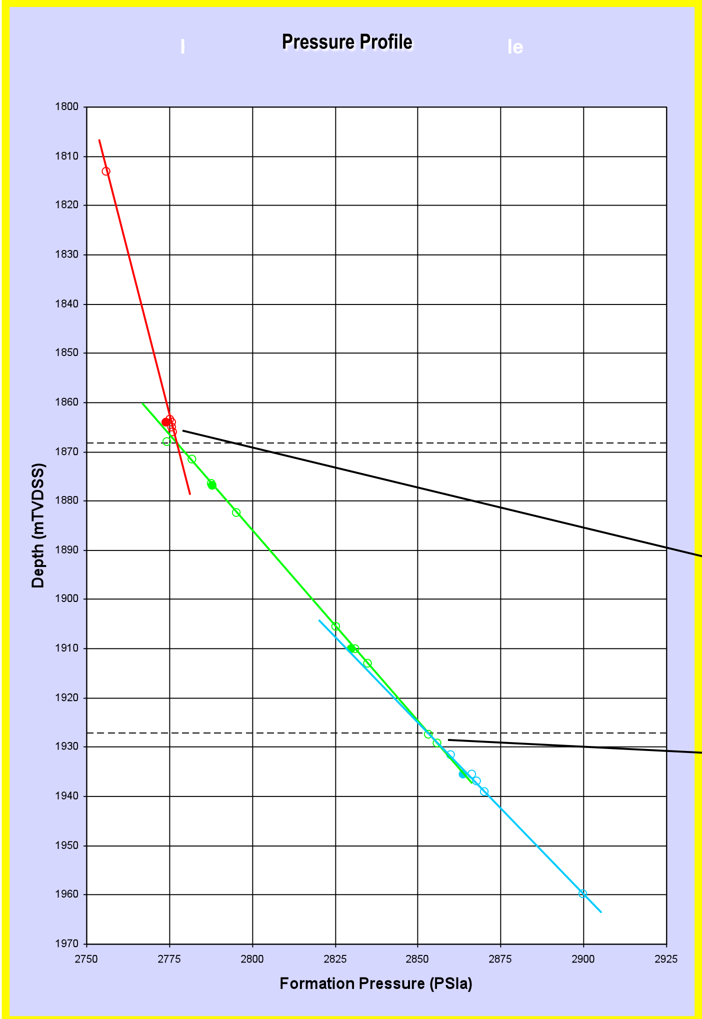

The Master Log (or Mud Log) is a document showing (in the form of a log) the variation of drilling parameters and while drilling information which are essential to the geological and petrophysical interpretation of well data (well logs included):

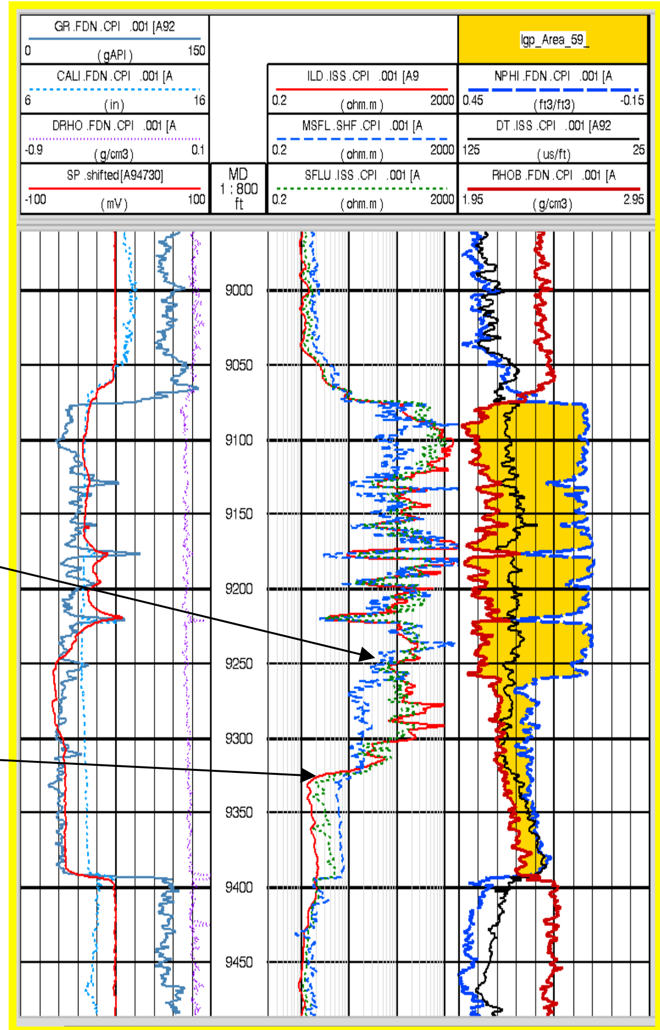
- rate of Penetration (ROP),
- drilling parameters,
- lithological description of cuttings,
- chemical composition and calcimetry,
- gas curves,
- mud data,
- drilling operation (i.e. coring, etc.)
- others.

# Pressure Measurements

Localization of fluid contacts within the reservoir



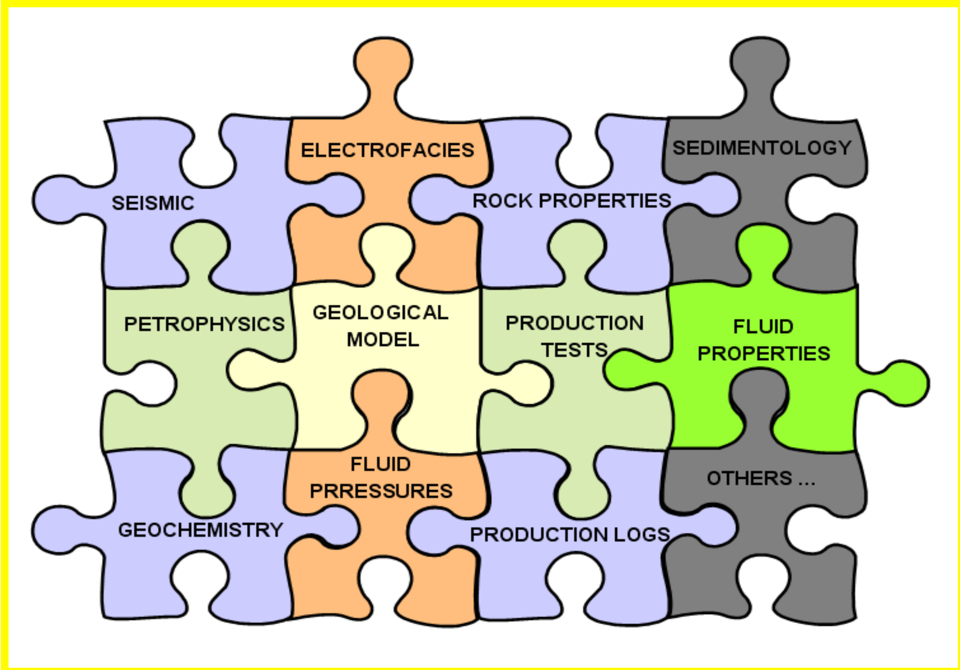



# Well logging applications

**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.



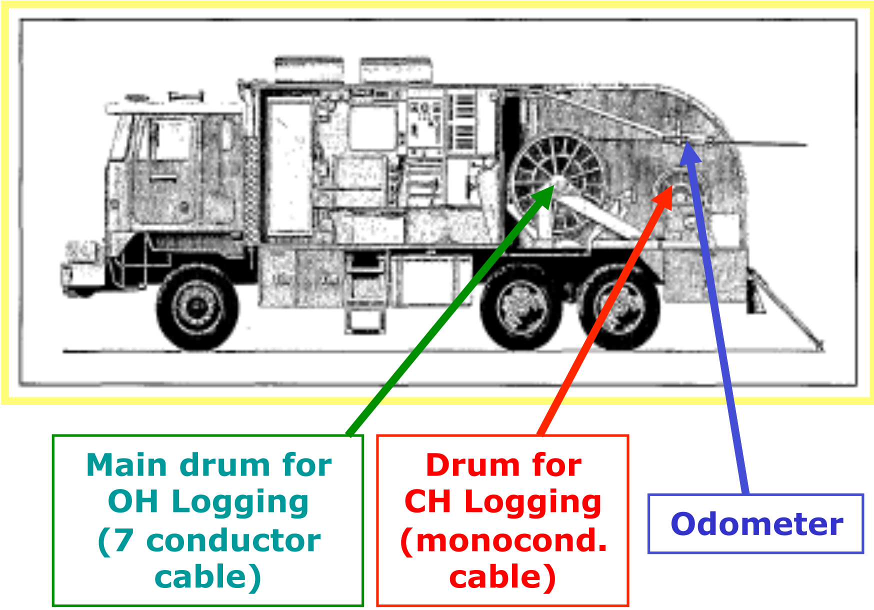
# The most important log measurement: depth!

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.

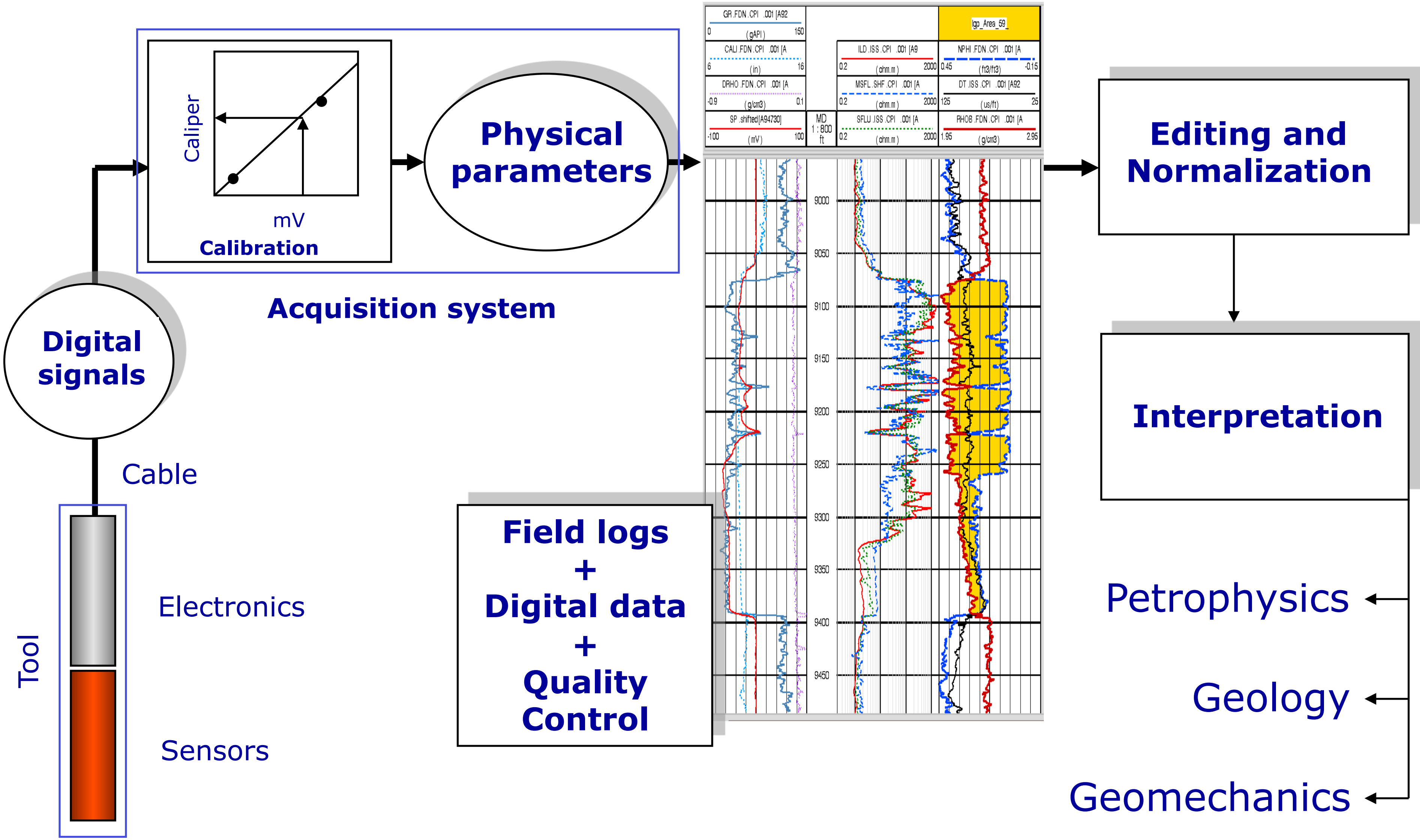
Depth control is of very high importance for the success of any log operation aimed exploration, completion and production of hydrocarbons.

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

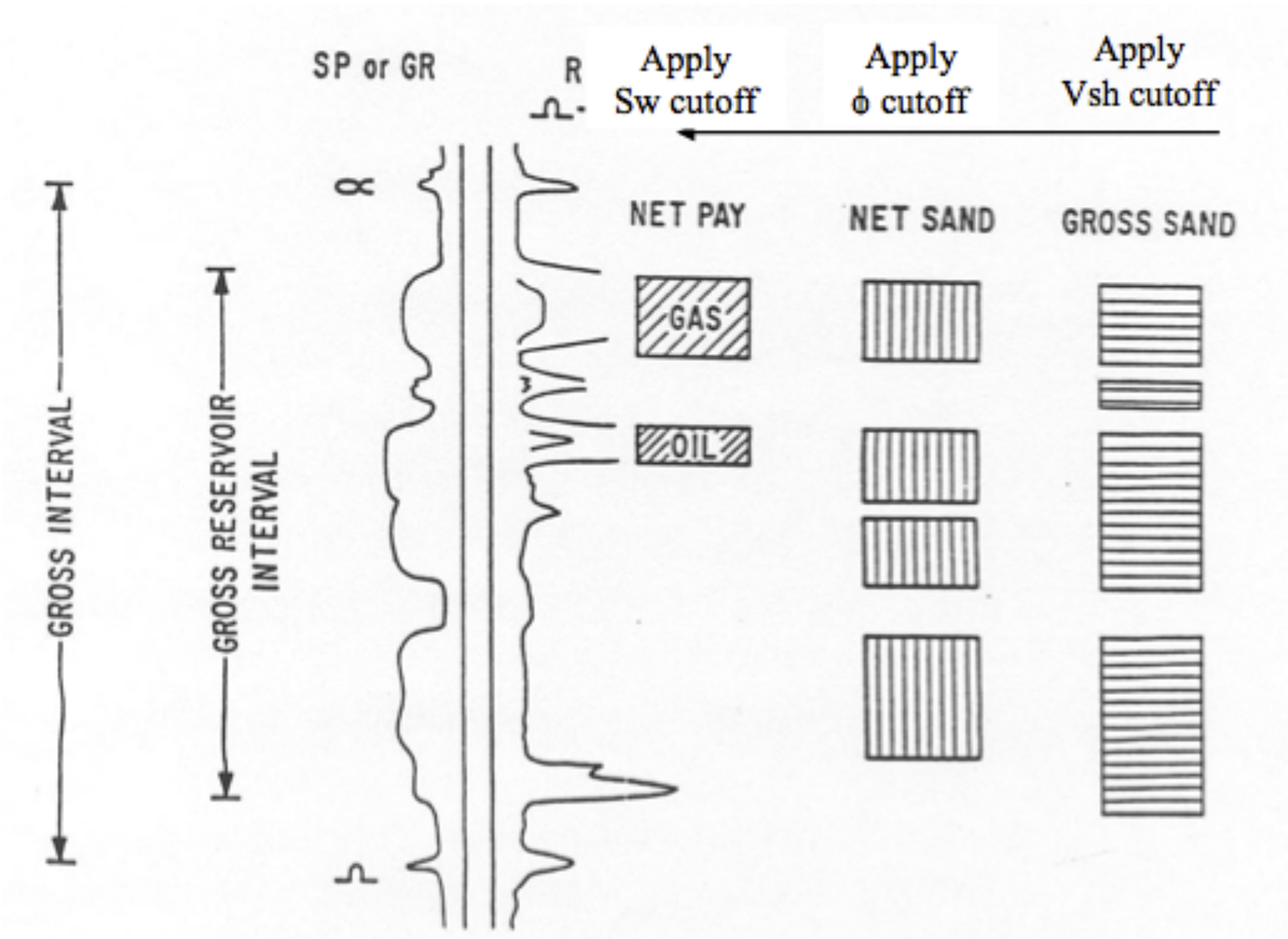
Main petrophysical parameters evaluated by means of well log interpretation are:

- porosity ($\Phi$),
- water saturation (Sw),
- permeability (K)

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

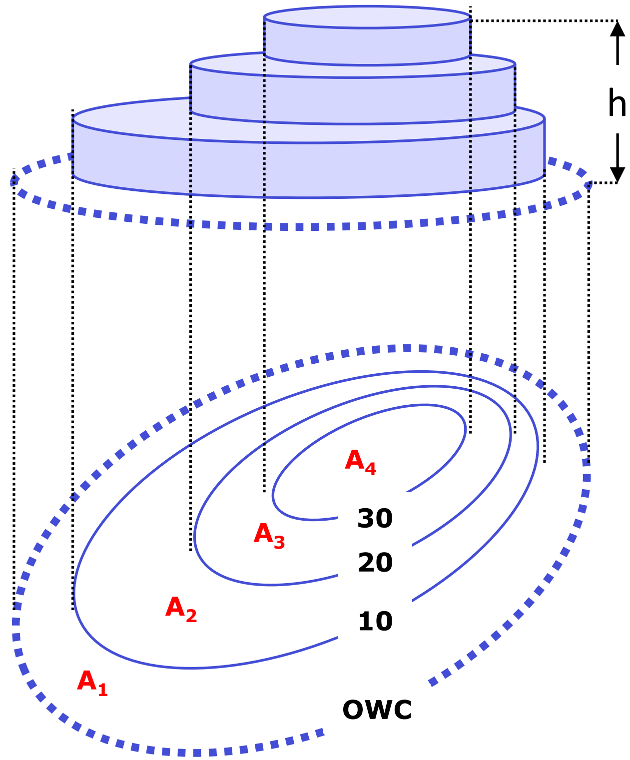
- gross pay,
- net sand,
- net reservoir,
- net pay and net to gross.

# Petrophysical parameters



# 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.




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

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

# 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 ($\Phi_t$) while the effective porosity ($\Phi_e$) is evaluated, in clastic sequences, by means of empirical relationships between $\Phi_t$, $\Phi_e$ and Volume of shale (Vsh), according to the distribution of the shales.

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

# 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. |

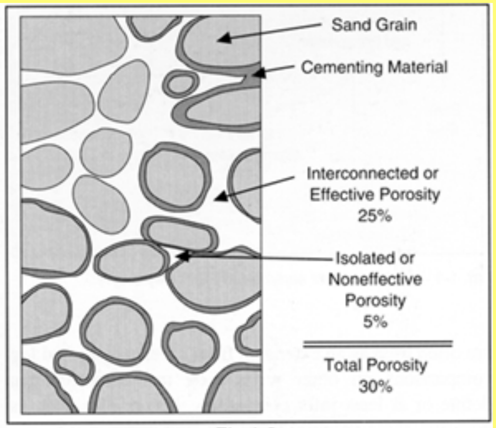


Fig 1-2
Graphic depiction of effective, noneffective, and total porosity

# 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**

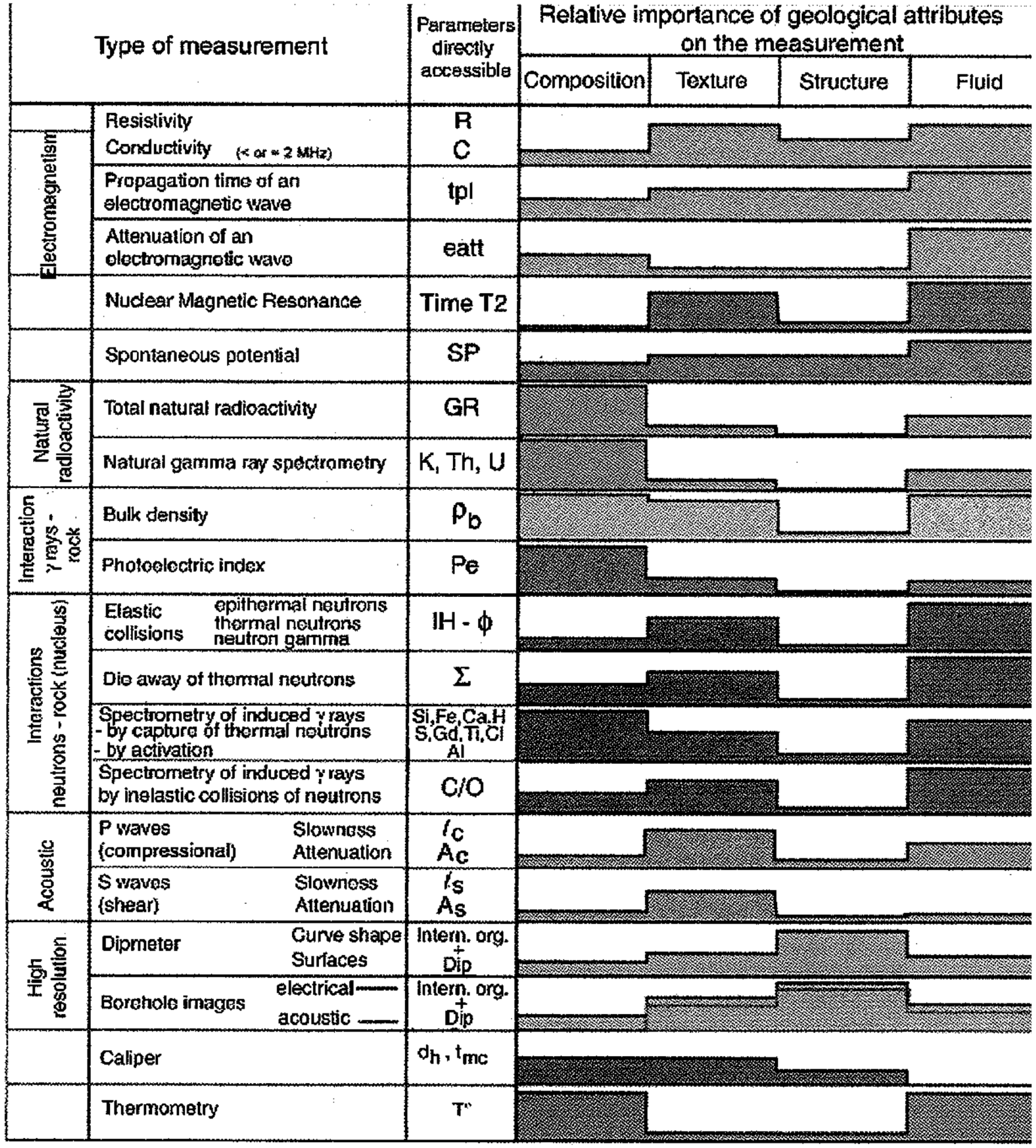
pores formed after the deposition of the sediment:

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

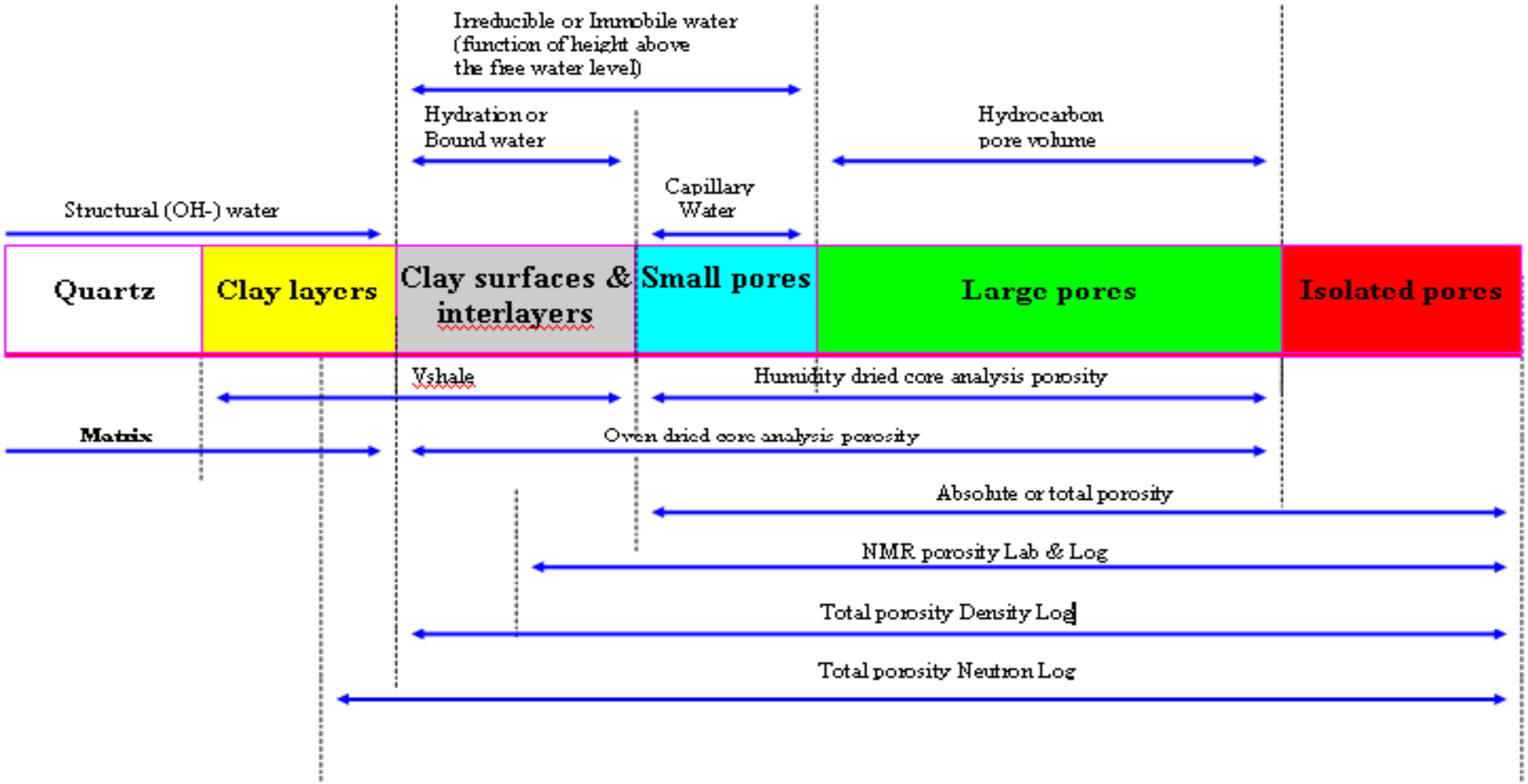
# Laboratory petrophysical measurements

| 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<br>- Fluid distribution with depth<br>- Amount of filtrate invasion |
| Grain density | Grain densities for calibration of density logs |
| Permeability | - Flow capacity, distribution and profile<br>- Transmissivity – stress sensitivity<br>- Zonation of reservoir units |
| Electrical properties<br>- Formation factor / m<br>- 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<br>- Centrifuge / Porous plate<br>- High pressure Hg intrusion | - Pore throat geometry and size distribution<br>- Rock typing, texture, lithology<br>- Residual wetting/non wetting phase saturation<br>- Fluid distribution with height<br>- Differentiation of pay from non-pay zones |
| NMR properties<br>- T2 distribution curve | - T2 cut-off for NMR log calibration<br>- Permeability estimator<br>- Initial saturation<br>- Porosity |
| Acoustic properties | - Lithology and porosity log-calibration<br>- In-situ stress computation for sand control, fracture mechanics, selection of appropriate confining stresses<br>- Seismic amplitude calibration and interpretation |
| Relative permeability | - Rock-fluid interactions<br>- Reservoir performance prediction, recovery factors |

# Relative influence of geological attributes on well logs

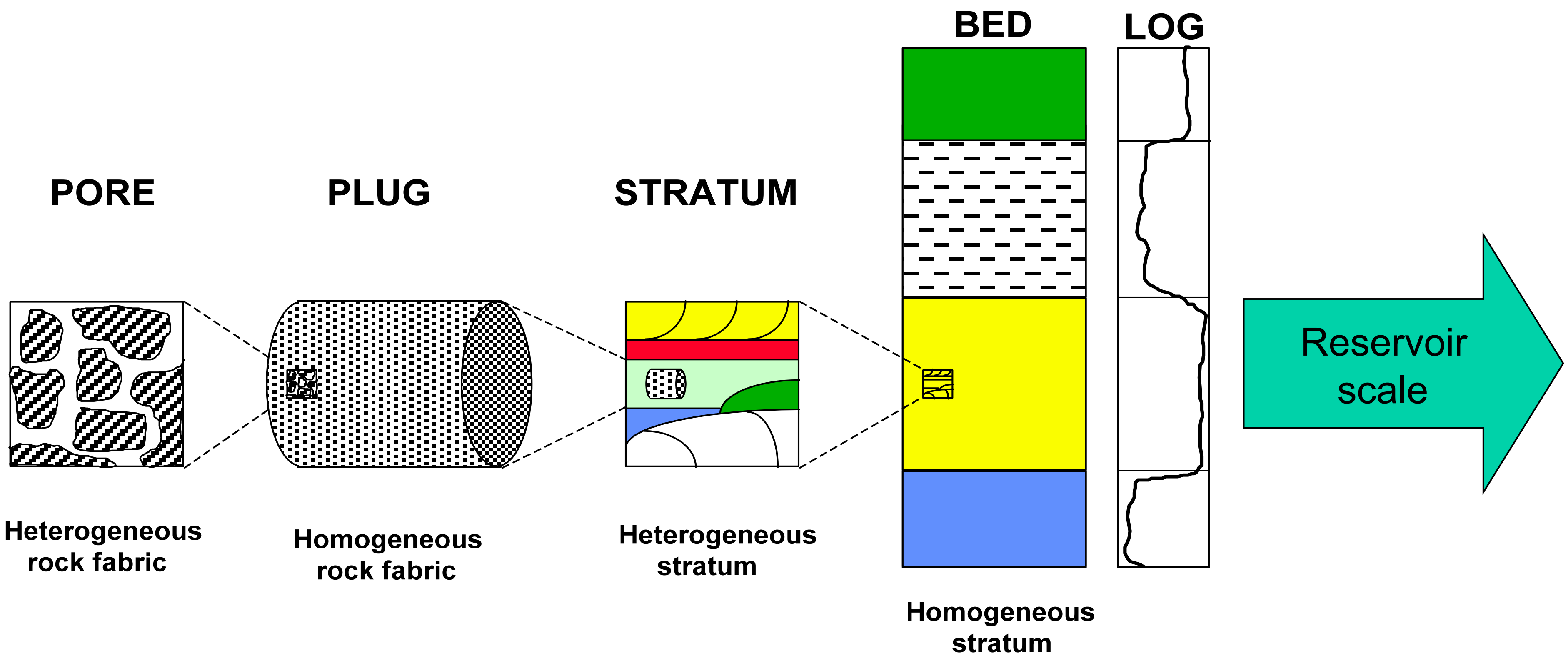


# Porosity measurements



Porosity definitions for hydrocarbon reservoirs

# The problem of different scales of the measurements



# Porosity distribution in sedimentary rocks

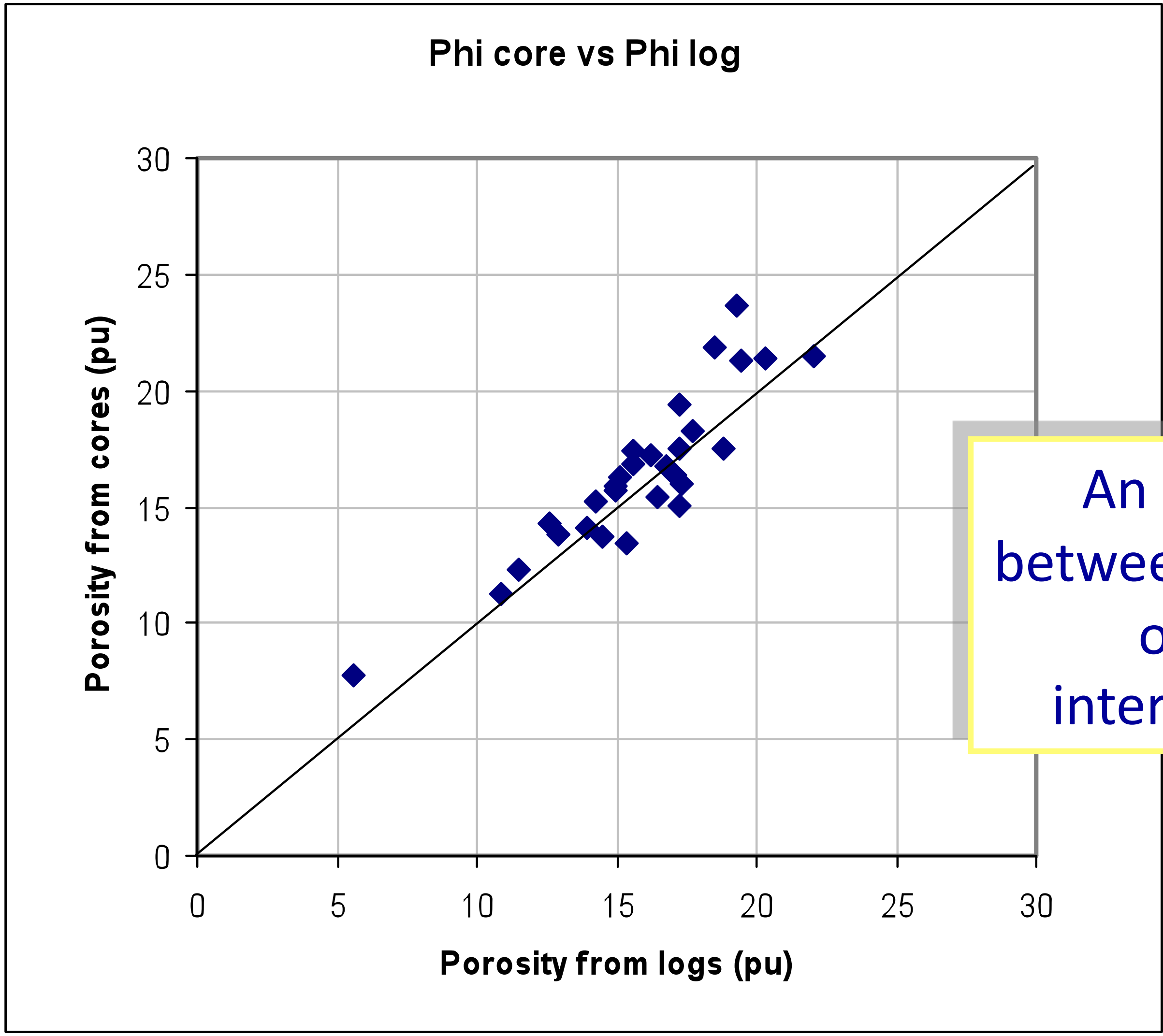
Porosities of subsurface formation can vary widely:

- 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 measurements 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

ARCHIE'S LAW

TOTAL SATURATION

$\rho = a\Phi^{-m} \rho_w$

or, in general:

$\rho = F \rho_w = (a\Phi^{-m} S^{-k}) \rho_w$

Where $\Phi$=porosity, S= saturation(from 0.1 to 1), a=tortuosity, m=cementation, k=2 (if $H_2O > H_2O_{min}$, otherwise up to5)

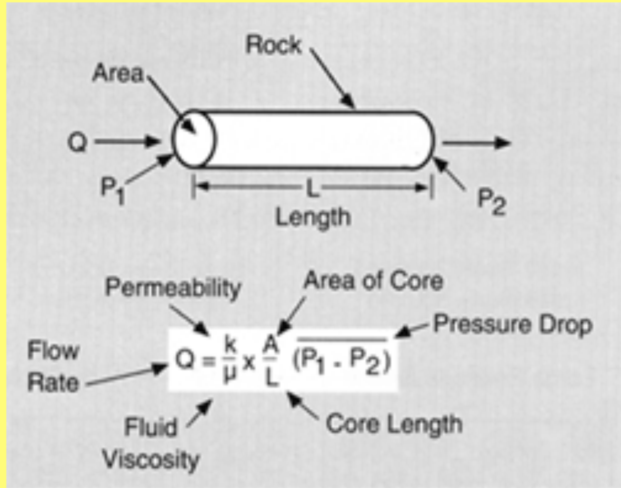
# Petrophysical parameters: Water Saturation

| 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

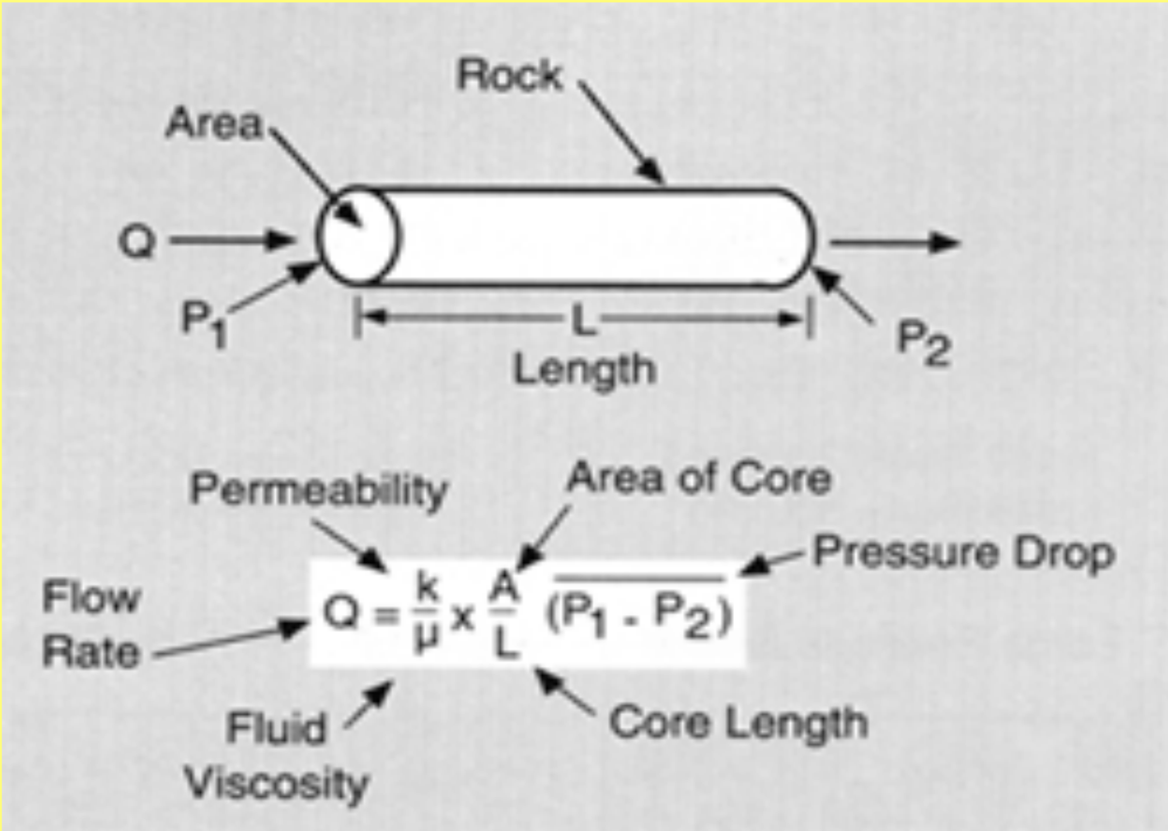
# Petrophysical parameters: Permeability

- 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

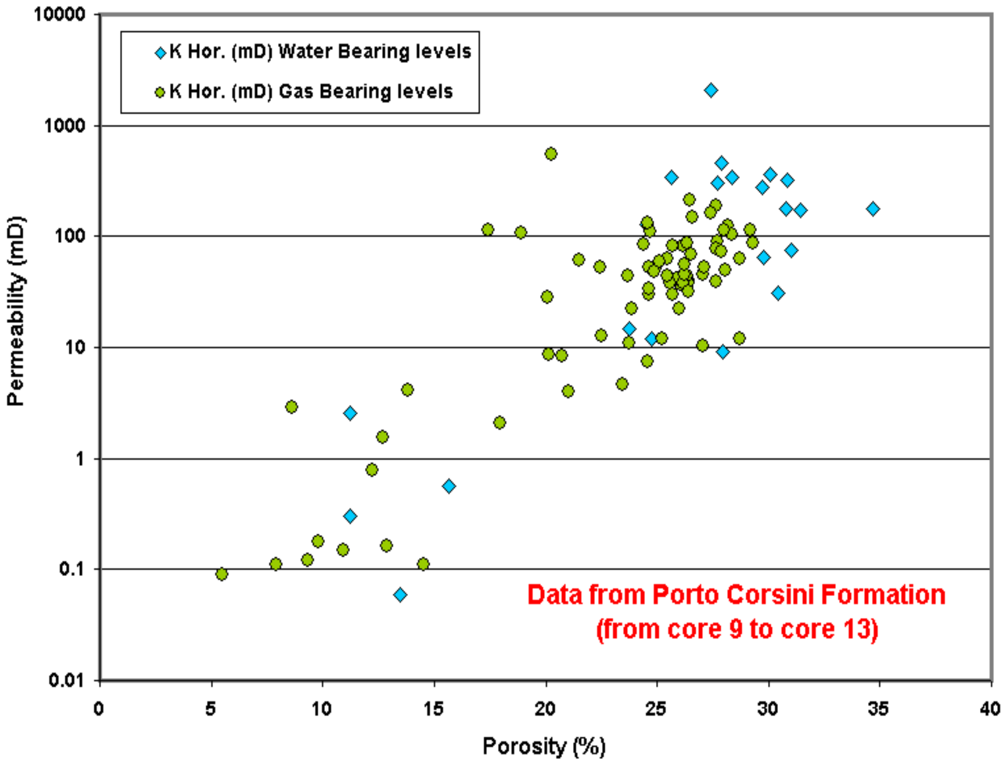



Permeability determination from core

# 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.



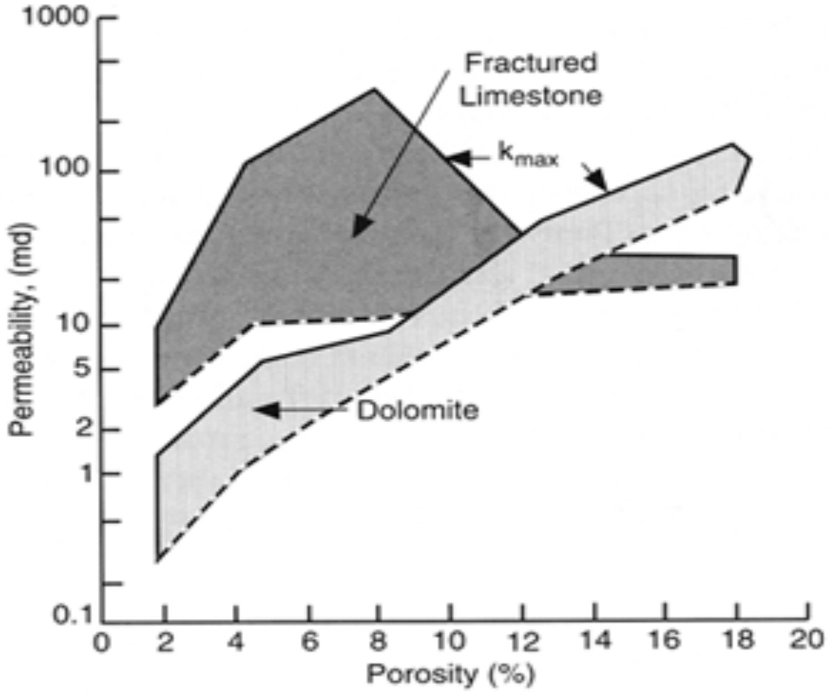




Fig 1-8
Reservoir rocks demonstrate a wide range of permeability that may not follow porosity trends.

# 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 than 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**

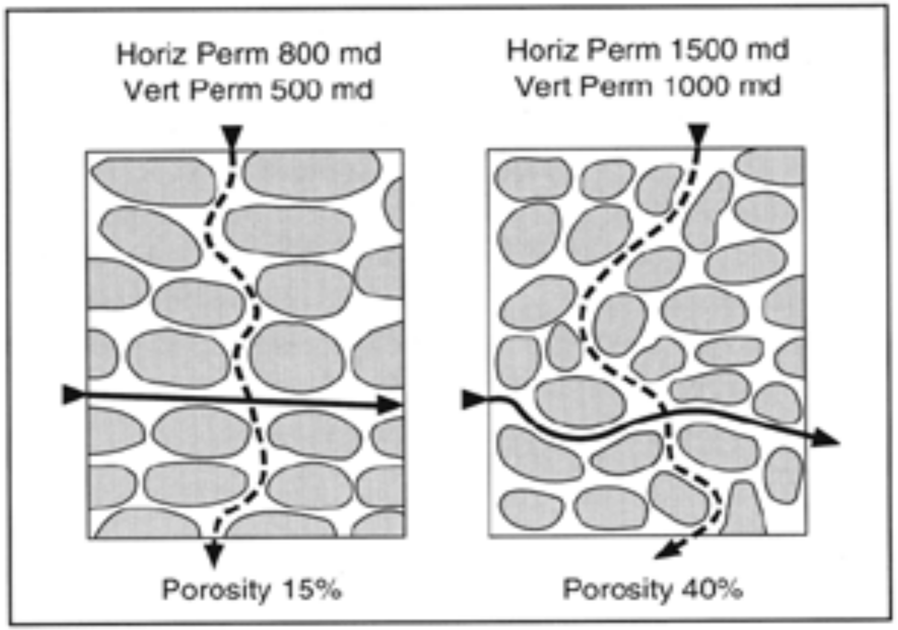
| | | |
|---|---|---|
| Krw | = Kw / K | K rel. to water |
| Kro | = Ko / K | K rel. to oil |
| Krg | = Kg / K | K rel. to gas |

**Horizontal Permeability (Kh) and vertical permeability (Kv)**

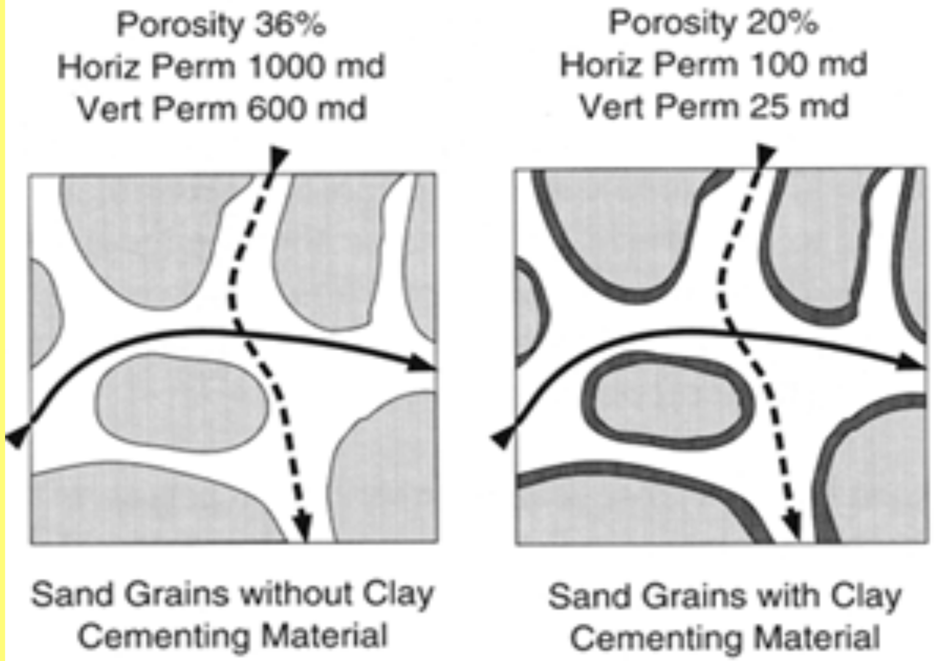
Permeability is a tensorial property which depends on the direction of the measurements;

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.

# Horizontal vs vertical permeability

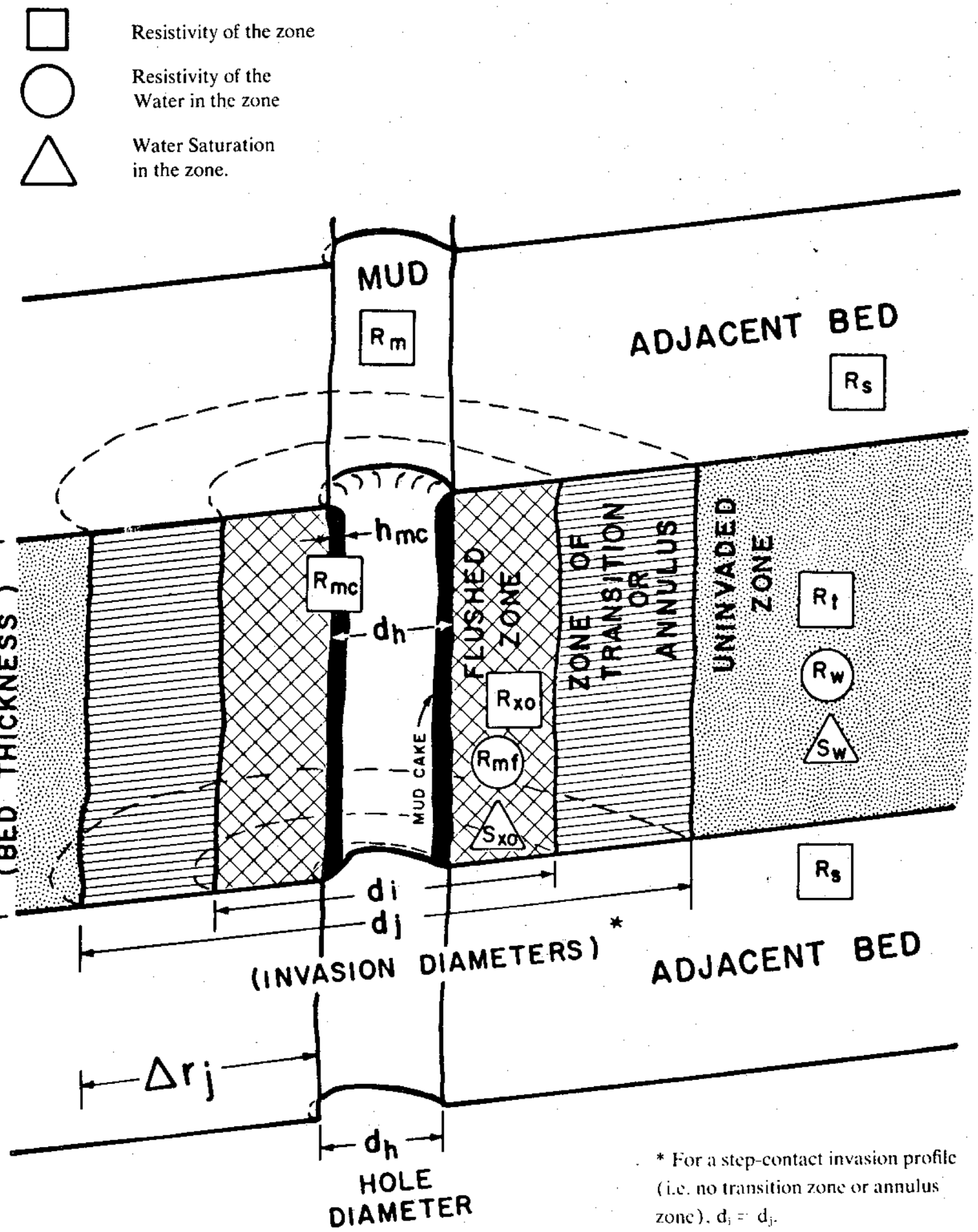



Arrangement of sand grains and pore structure affects permeability

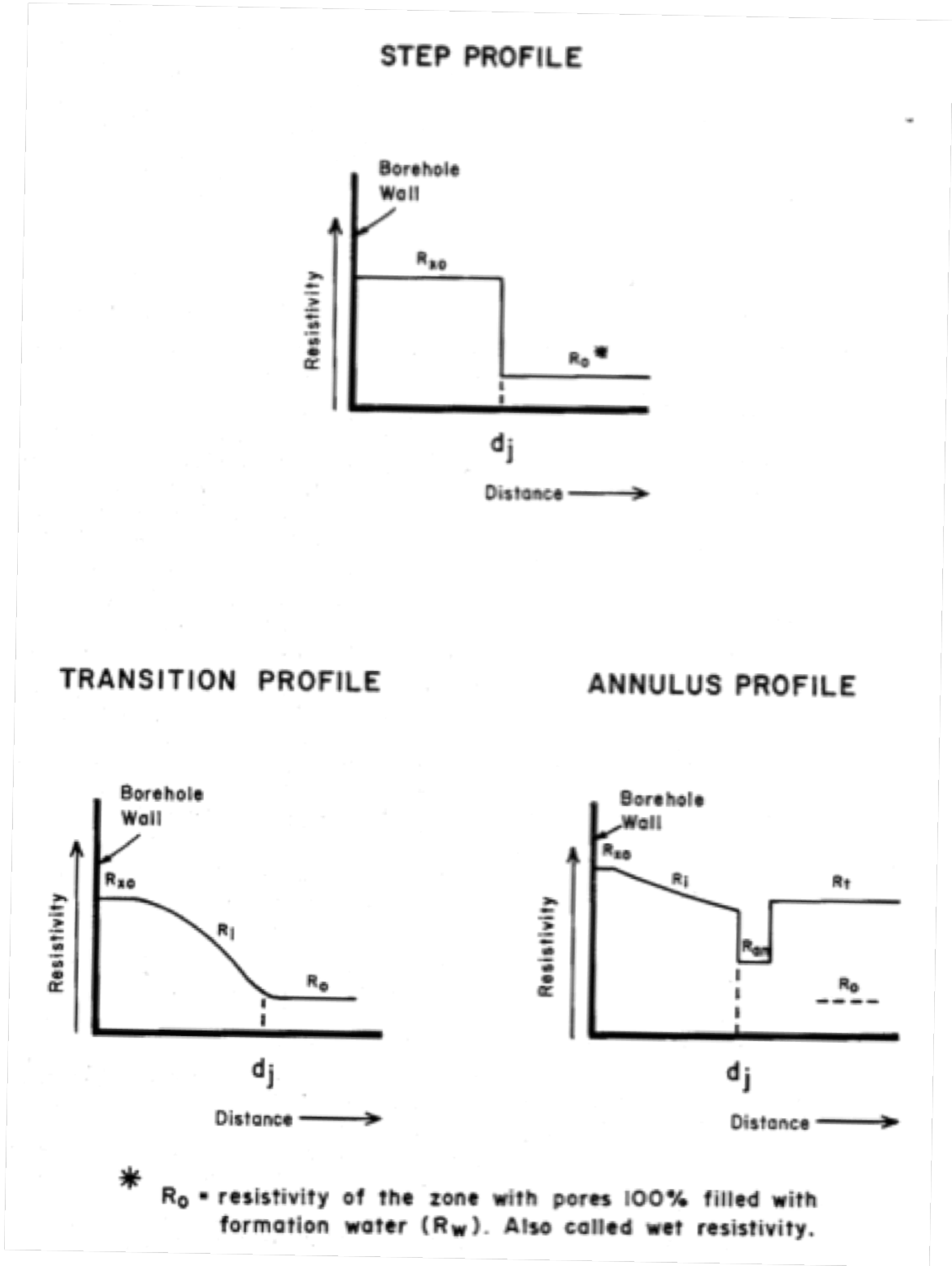



Clay cement can affect porosity and permeability

# The borehole environment



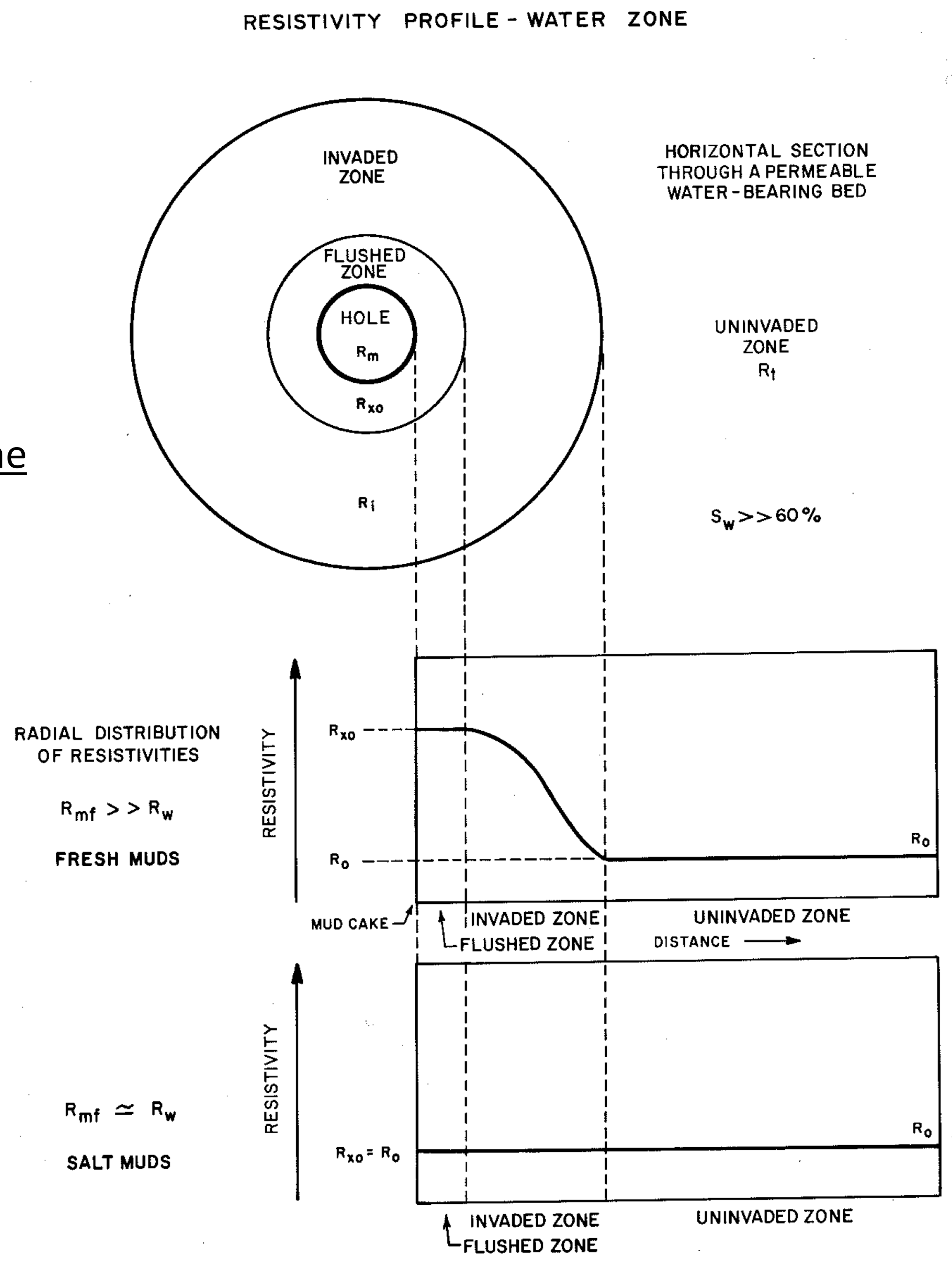
# The borehole environment



# The borehole environment

Resistivity profile, hydrocarbon zone

Sw of uninvaded zone >> 60%



# The borehole environment

Resistivity profile, hydrocarbon zone

Sw in uninvaded zone <<60%