(Geo 209)
Petrophysics

Second Year Engineering and Environmental Geology Program

By:

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Petrophysics course outline

Course contents:

1- Introduction to petrophysics and rocks
2- Introduction to petroleum geology
3- Porosity and Permeability
4- Formation evaluation and well logging
5- Nuclear Magnetic Resonance (NMR): Petrophysical Properties
6- Nuclear/Radioactive Properties
7- Elastic Properties
8- Geomechanical Properties
9- Electrical Properties
10- Thermal Properties
11- Magnetic properties

Textbooks:

1- Tiab, D. and Donaldson, E. C. (2016): Petrophysics. 4th edition. Elsevier Inc., USA.
2- Schön, J. (2015): Physical Properties of Rocks: Fundamentals and Principles of Petrophysics, 2nd Edition. Elsevier Inc., USA.
3- Darling T. (2005): Well logging and Formation Evaluation. Elsevier Inc.m USA. https://doi.org/10.1016/B978-0-7506-7883-4.X5000-1

Introduction

What is petrophysics?

Petrophysics is the study of physical and chemical rock properties and their interactions with fluids.

Why we study petrophysics?

1. Petrophysics can be used in studying reservoirs for the hydrocarbon industry:
    a. identify and evaluate hydrocarbon reservoirs
    b. understand the rock properties of the reservoir,
    c. Accurate knowledge different rock properties that contain important fluids (gas and oil), is required for efficient development, management and prediction of future performance of the oilfield.

2- Petrophysics can be also used to estimate important useful parameters for engineering applications such as design dams, roads, foundations for buildings, and many other large construction projects.

3- Interpretation of geophysical data used for exploration.

Aspects of petrophysics:

Petrophysics is intrinsically bound to mineralogy and geology because the majority of the world's petroleum occurs in porous sedimentary rocks. The sedimentary rocks are composed of fragments of other rocks derived from mechanical and chemical deterioration of igneous, metamorphic and other sedimentary rocks, which is constantly occurring.

Rocks – overview:

Rocks are naturally occurring aggregates of one or more minerals. In the case of porosity or fracturing, they also contain fluid phases. With respect to their geological genesis and processes, rocks are divided into three major groups:

1. Igneous rocks (magmatites),
2. Metamorphic rocks (metamorphites), and

3. Sedimentary rocks (sediments).

Igneous rocks are formed by crystallization from a molten magma. Metamorphic rocks are the result of metamorphism. Metamorphism is the solid-state conversion of igneous and sedimentary rocks under the pressure–temperature regime of the crust

Sedimentary rocks are highly important for hydrocarbon exploration; most commercial reservoirs occur in this rock type characterized by its porosity and permeability. Sedimentary rocks cover more than 50% of the earth's surface and are therefore also of fundamental importance in many aspects of our lives, from agriculture to the foundations of buildings, and from groundwater resources to the whole environment.

Sedimentary rocks are formed by a sequence of physical, chemical, and biological processes:

1- Magmatic, sedimentary, and metamorphic source rocks are disaggregated by weathering to:
   – resistant residual particles (e.g. silicate minerals, lithic fragments),
   – secondary minerals (e.g. clays),
   – water-soluble ions of calcium, sodium, potassium, silica, etc.
2- Weathered material is transported via water, ice, or wind to sites and deposited:
   – mineral grains drop to the depositional surface,
   – dissolved matter precipitates either inorganically, where sufficiently concentrated, or by organic processes,
   – decaying plant and animal residues may also be introduced into the depositional environment.
3- Lithification (consolidation) occurs when the sedimentary material becomes compacted; aqueous pore solutions interact with the deposited particles to form new, cementing diagenetic (authigenic) minerals (Best, 1995).

There are three major rock classes of sedimentary rocks:

(1) clastic: broken from a pre-existing rock (e.g. sandstone),

(2) chemical: formed by chemical precipitation as carbonates (limestone, dolomite) or as evaporates (e.g. gypsum, anhydrite, salt), and

(3) organic: formed by biological precipitation and by accumulation of organic material (peat, coal, limestone, diatomite).

Sandstones and carbonates are the most common reservoir rocks.

1- Clastic Rocks:

Clastic rocks are formed by:

a) Erosion, reworking, and transportation of rock components,
b) Deposition and sedimentation of the material, and
c) Compaction and diagenetic processes.

Typical members of this important group of rocks are conglomerate, sandstone, siltstone, shale, and claystone.

The nomenclature of clastic sedimentary rock is given by the following rules:

– Sandstone is composed of >50% sand-sized particles. The mineral composition is dominated by quartz and feldspar.
– Siltstone is composed of >50% silt-sized particles; they are generally less rich in quartz than is sandstone.
– Claystone is composed of >50% clay-sized particles; they are generally formed by clay minerals.
– The term “shale” describes a sedimentary rock type which is a mixture of - clay-size particles (mainly clay minerals), silt-size particles (quartz, feldspar, calcite), and perhaps some sand-size particles as, for example, quartz, occasionally feldspar, calcite.

The physical properties of clastic sediments are strongly controlled by:

a) textural properties (particle dimensions, size, shape, spatial orientation), and
b) mineral composition, mainly the presence and effect of clay minerals.

A- Textural Properties:

The term texture encompasses particle or grain size and size distribution, shape, and packing of the solid particles in clastic sediments. The elements of rock texture include:

– Grain size is the classifying and defining parameter for clastic rocks.

- Grain shape (sphericity) describes how nearly a particular grain approaches the shape of a sphere. In general, particles are of non-spherical shape.
- Grain roundness (angularity) measures the sharpness of edges and corners.
- Grain packing is a measure of the density of the grain aggregates.

In terms of physical properties, the spatial arrangement of the individual particles can be defined as internal structure—it controls, for example, anisotropy properties.

B- Clays:

Clay minerals are aluminosilicates with a sheet structure. The principal building elements are two types of sheets or units:

(1) a tetrahedral unit of a central Si atom and surrounding O atoms, and

(2) an octahedral unit of O atoms and OH groups around a central Al atom.2

Clay minerals (kaolinite, illite, montmorillonite, and chlorite) are characterized by different stacking combinations or "architecture" of the two building elements. In the tetrahedral sheet, silica (Si^{4+}) is sometimes partly replaced by aluminum (Al^{3+}); in the octahedral sheet, aluminum (Al^{3+}) can be replaced by magnesium (Mg^{2+}) or other atoms (e.g. iron). Such a replacement by atoms of lower positive valence results in an excess of negative charge. This excess is compensated for by adsorption of cations (Na, Ca, Mg) from the adjacent water and an electric double layer is formed. The compensating cations on the layer surface can exchange with other cations. This property plays a leading role in the electrical conduction of shales and shaly sands.

2- Carbonate Rocks

The non-clastic carbonate rocks are formed mainly by chemical and biochemical precipitation in special environments (typically warm, shallow, clear marine water in low latitudes). In carbonates, the major sources of porosity are fracturing, solution, and chemical replacement.

Carbonates have autochthonous origin (formed very close to the depositional site), whereas clastics sandstone and shale are formed of transported sedimentary particles mostly from sources outside the depositional site. The most abundant carbonate minerals are calcite ($CaCO_3$) and dolomite ($CaMg(CO_3)_2$). Secondary minerals are anhydrite, chert, and quartz. Accessory minerals are phosphates, glauconite, ankerite, siderite, feldspars, clay minerals, pyrite, etc., depending on the environment of deposition and diagenetic history.

The two main rock types are:

(1) Limestone: composed of more than 50% carbonates, of which more than half is calcite.

(2) Dolomite: composed of more than 50% carbonates, of which more than half is dolomite. Dolomite can precipitate directly from a solution containing Mg, Ca, and carbonate ions or by chemical alteration of limestone or calcareous mud (dolomitization). Dolomite frequently forms larger crystals than the calcite it replaces and forms good reservoir properties.

Carbonates are modified by various post-depositional processes such as dissolution, cementation, recrystallization, dolomitization, and replacement by other minerals. Dolomitization is associated with an increase of porosity. The interaction with meteoric pore fluids can result in a leaching of grains and can influence reservoir quality in both directions (new pore space, cementation).

Fracturing as a result of stress is diagenetic process in carbonates; it can create high-permeability zones and permeability barriers or baffles.

Physical rock properties:

Rocks in most cases are heterogeneous composites as they composed of a wide range of different minerals; only monomineralic rocks like rock salt or anhydrite contain only one mineral type. Heterogeneity becomes more contrasted if pores and fractures, filled with fluids, are present. Mineral composition, porosity/fracturing, and internal rock structure therefore influence the physical rock properties. This leads to a classification of rock properties into the following main groups or types: conventional petrophysical properties, and rock mechanical properties.

1- Conventional petrophysical properties

a) ***Lithology:*** A description of the rock's physical characteristics, such as grain size, composition and texture.
b) ***Porosity:*** The percentage of a given volume of rock that is pore space and can therefore contain fluids; symbolized as φ.
c) ***Fluid saturation:*** The fraction of the pore space occupied by a fluid.

d) ***Permeability:*** The quantity of fluid (usually hydrocarbon) that can flow through a rock as a function of time and pressure, related to how interconnected the pores are.
e) ***Thickness*** of rock with enough permeability to deliver fluids to a well bore.

2- Rock mechanical properties

The compressional (P) wave velocity of sound through the rock is measured as well as the shear (S) wave velocity and use these with the density of the rock to compute the rocks' *compressive strength*, which is the compressive stress that causes a rock to fail, and the rocks' *flexibility*, which is the relationship between stress and deformation for a rock. These measurements are useful to design programs to drill wells that produce oil and gas. The measurements are also used to design dams, roads, foundations for buildings, and many other large construction projects. They can also be used to help interpret seismic signals from the Earth, either man-made seismic signals or those from earthquakes.

Measurements of the physical rock properties

Physical rock properties could be measured as a scalar property (given as one value for the property, no directional dependence of the property) or a tensorial property (given as a tensor with directional dependence). Examples of scalar properties are porosity and fluid saturation. Tensorial character is relevant for rocks with an anisotropy (originated by lamination, preferred direction of fractures, grain axis or mineral orientation, etc.). The terms isotropy and anisotropy refer to the directional dependence of considered (tensorial) properties. Isotropic expresses that a vectorial property has at any point the same magnitude for all directions, if the magnitude shows a directional dependence, then the material is anisotropic.
Empirical fundamentals of rock physics are generated from measurements of rock samples under defined conditions (pressure and temperature). Laboratory measurements determine physical properties (for example pore spaces, or electrical, elastic, thermal properties) for different groups of rocks.

Physical rock properties could be measured by two methods: core analysis, and well logging.

Core analysis:

Core analysis is a special discipline of experimental rock evaluation. It is based on the direct determination of rock properties on samples.

There are two types of core acquisition from wells:

(1) conventional (or rotary) cores, and

(2) sidewall core (percussion and rotary sidewall coring).

A full-diameter core is approximately 4.5–13.5 cm in diameter. For standard laboratory measurements, the core is dissected into multiple plugs about 1 in. in diameter and 3 in. long.

Well logging:

Well Logging is used as a relatively inexpensive method to obtain petrophysical properties downhole. Measurement tools are conveyed downhole using either wireline or LWD method.

Introduction to Petroleum Geology

Introduction:

Petroleum geology is the study of origin, occurrence, movement, accumulation, and exploration of hydrocarbon fuels. It refers to the specific set of geological disciplines that are applied to the search for hydrocarbons (oil exploration). There are five geological requirements for the formation of a conventional hydrocarbon reservoir:

A) Source Rock
B) Migration Path
C) Cap Rock or seal
D) Reservoir Rock
E) Trap

These geological requirements are illustrated in **Figure 1,** below.

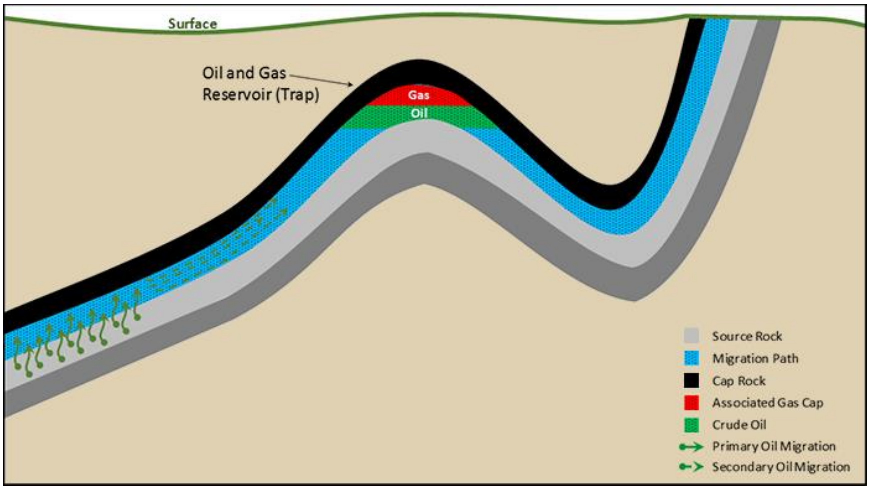

Figure 1: Typical Oil and Gas Reservoir Showing the Requirements for Conventional Crude Oil and Natural Gas Reservoirs

*A- **Source rock:***

A source rock is the rock in which the original organic material is converted into hydrocarbons. As we can see from this figure, the hydrocarbons do not necessarily originate in the hydrocarbon reservoir itself but are generated away from the reservoir in rocks that are conducive to hydrocarbon generation.

B- <u>Migration pathways:</u>

Since the hydrocarbons are generated away from the reservoir, there must be a pathway for the hydrocarbons to migrate from the source to the reservoir. This pathway is the Migration Path in the hydrocarbon system.

C- <u>Cape rock or seal:</u>

A cap rock is an impermeable rock layer that overlies the reservoir rock and where the oil stops to flow and migrate further.

D- <u>Reservoir rock:</u>

The reservoir rock is a subsurface rock where the oil migrates and accumulates. The most common reservoir rocks are sedimentary rocks; however, naturally fractured igneous and metamorphic rocks can also form hydrocarbon reservoirs. The two requirements for a commercial crude oil or natural gas reservoir are high porosity and high permeability. Oil and natural gas exist in the pore-space between the grains of the sedimentary rocks. permeability is defined as the ease in which fluids flow through porous media. A high permeability formation implies greater oil and gas production rates and more economically attractive production wells.

E- <u>Oil trap:</u>

A trap or trapping mechanism is a change in the stratigraphy or a structural deformation that is capable of stopping the migration process and keeping the oil and gas in place over geologic time.

In the following sections, we will explain in more detail the processes that formed all the above elements of petroleum geology.

Petroleum occurrences:

Sedimentary basins:

Sedimentary basins are areas that have undergone subsidence with respect to the surrounding land mass and represent accumulations of clastic and evaporite materials in a geologically depressed area. They have thick sedimentary layers in the center that thin toward the edges. The layers represent successive sedimentary episodes.

The sediments are accumulated in sedimentary basins during transgressive-regressive cycles:

A) A transgressive phase occurs when the sea level is rising, or the basin is subsiding. During this period, subsidence generally increases and hence the depth of the sea increases. As the sea advances over the land surface, the depositional facies also migrate inland creating a shallow, low energy, environment along the shore that tends to accumulate fine grained particles. The fine-grained sediments have low permeability and are potential petroleum source rocks rather than reservoirs.

B) During a regressive phase in the formation of a basin, the basin is becoming shallower. The sediments accumulating during the regressive phase tend to be coarse grained. The rocks of this sequence therefore have relatively high permeabilities and are potential reservoirs layed down on top of potential source rocks deposited during the transgressive phase.

Hydrocarbon traps:

Hydrocarbon traps are porous, permeable, layers that are enclosed between impermeable rocks. In most cases the hydrocarbon trap is not filled completely with oil. It may contain a gas cap if the oil contains light hydrocarbons. The lithology of the individual traps may vary from sands to limestone and dolomite. Hydrocarbon traps are generally classified as either structural or stratigraphic, depending on their origin.

A- *Structural traps:*

Structural traps were formed by tectonic processes acting on sedimentary beds after their deposition. They may generally be considered as distinct geological structures formed by folding and faulting of sedimentary beds. Structural traps may be classified as:

(1) fold traps formed by either compression or compaction anticlines (**Figure 2**),

(2) fault traps formed by displacement of blocks of rocks due to unequal tectonic pressure,

(3) diapiric traps produced by intrusion of salt or mud diapirs (**Figure 3**).

B- *Stratigraphic traps:*

Stratigraphic traps are produced by facies changes around the porous, permeable, formation such as pinchouts (**Figure 3 a**) and lenticular sand bodies surrounded by impermeable shales. Many hydrocarbon accumulations are associated with unconformities. An unconformity forms when a site of sedimentation is uplifted, eroded, and buried again under a new layer of sediment (**Figure 4**). The rocks immediately below an unconformity are likely to be porous and permeable because an unconformity is a zone of erosion that is on the top of a weathering zone where water is percolating through the rocks causing solution of some minerals and precipitation of others as cementing agents.

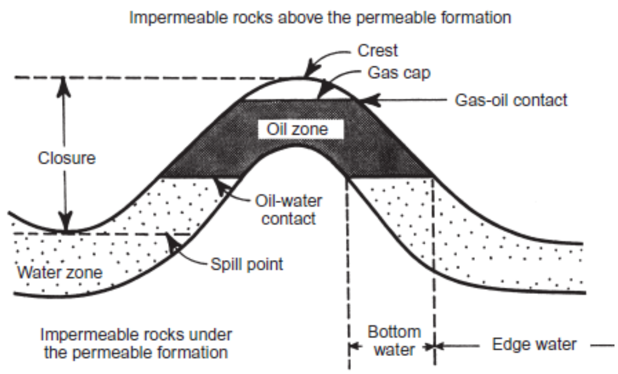

FIGURE 2: Idealized cross-section through an anticlinal trap formed by a porous, permeable, formation surrounded by impermeable rocks. Oil and gas are trapped at the top of the anticline.

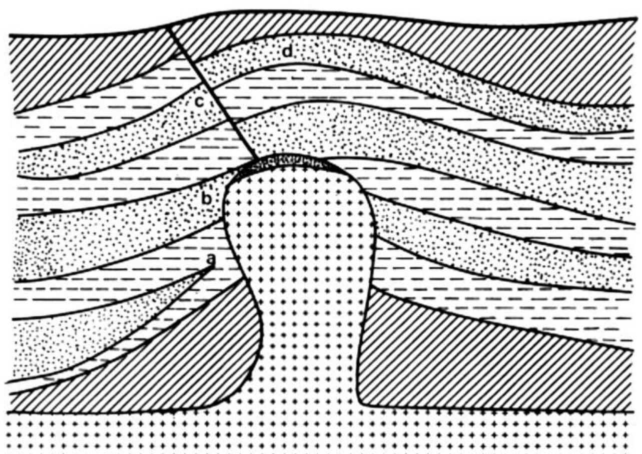

FIGURE 3: Illustration of several types of traps: (a) stratigraphic pinch-out trap, (b) trap sealed by the salt dome, (c) trap formed by a normal fault, (d) domal trap.

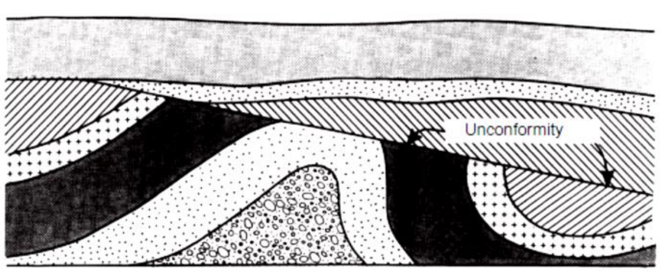

FIGURE 4: Unconformity, showing the uplifted, eroded strata overlain unconformably by younger sediments.

Pore space properties: 1- Porosity

The void space created throughout the beds between grains, called pore space or voids or interstice, is occupied by fluids (liquids and/or gases). The measure of the void space is defined as the porosity of the rock, and the measure of the ability of the rock to transmit fluids is called the permeability. Knowledge of these two properties is essential for petrophysical studies.

Definition of porosity:

The porosity of a rock is defined as that fraction of a given volume of rock that is pore space to the total bulk volume of the rock. This can be expressed in mathematical form as:

$$\emptyset = \frac{V_p}{V_b}$$

Where, Φ=porosity, fraction; V_b=bulk volume of the rock; V_p=pore volume

Factors governing the porosity:

(a) Uniformity of grain size: Uniformity is the gradation of grains. If small particles of silt or clay is mixed with larger sand grains, the porosity will be considerably reduced as shown in Figure 1. These reservoirs are referred to as dirty or shaly. In the other hand, poorly sorted sediments with grains of different sizes (not clay minerals), have higher porosity than well-sorted sediments.

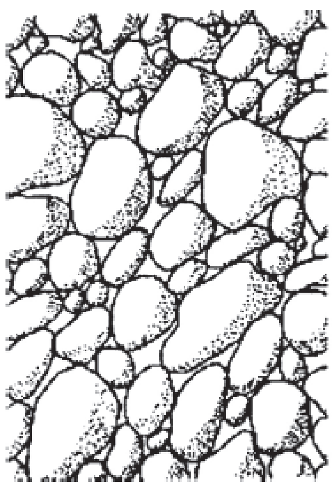

Figure 1: Collection of different sized and shaped sand grains.

(b) Degree of cementation or consolidation: The highly cemented sandstones have low porosities, whereas the soft, unconsolidated rocks have high porosities. Cementation takes place both at the time of lithification and during rock alteration by circulating groundwater. The process is essentially that of filling void spaces with mineral material, which reduce porosity. Cementing materials include calcium carbonate, magnesium carbonate, iron carbonate, iron sulfides, limonite, hematite, dolomite calcium sulfate, clays, and many other materials including any combination of these materials.

(c) Amount of compaction during and after deposition: Compaction tends to lose voids and squeeze fluid out to bring the mineral particles close together, especially the finer-grained sedimentary rocks. Generally, porosity is lower in deeper, older rocks. Many carbonate rocks show little evidence of physical compaction.

Classifications of porosity:

A- Engineering classification of porosity:

During sedimentation and lithification, some of the pore spaces initially developed became isolated from the other pore spaces by various diagenetic processes such as cementation and compaction. Thus, many of the pores will be interconnected, whereas others will be completely isolated. This leads to two distinct categories of porosity:

1- Total (absolute) porosity:

Absolute porosity is the ratio of the total void space in the sample to the bulk volume of that sample, regardless of whether or not those void spaces are interconnected. A rock may have considerable absolute porosity and yet have no fluid conductivity for lack of pore interconnections. Examples of this are lava, pumice stone.

2- Effective porosity:

Effective porosity is the volume of the interconnected pores which are mostly filled by fluids. Effective porosity is affected by a number of lithological factors including the type, content, and hydration of the clays present in the rock; the heterogeneity of grain sizes; the packing and cementation of the grains; and any weathering that may affect the rock.

In order to recover oil and gas from reservoirs, the hydrocarbons must flow several hundred feet through the pore channels in the rock before they reach the producing wellbore. Therefore, effective porosity is the value used in all reservoir engineering calculations.

B- Geological classification of porosity:

This classification of porosity is based on the time of origin, mode of origin, and distribution relationships of pores spaces.

1- Primary (or matrix) porosity:

This is the porosity where the pore spaces in the rock formed at the time when it was deposited. This porosity includes four types (all are shown in Figure 2):

A- Intercrystalline porosity (or microsporosity):

It is the porosity found between cleavage planes of crystals, voids between individual crystals, and voids in crystal lattices.

B- Intergranular or interparticle porosity:

It is the porosity found between grains, i.e., interstitial voids of all kinds in all types of rocks.

C- Bedding planes porosity:

It is the porosity where voids of many varieties are concentrated parallel to bedding planes.

D- Miscellaneous sedimentary voids:

This porosity formed by:

a. Voids resulting from the accumulation of detrital fragments of fossils,
b. vuggy and cavernous voids of irregular and variable sizes formed at the time of deposition, and
c. voids created by living organisms at the time of deposition.

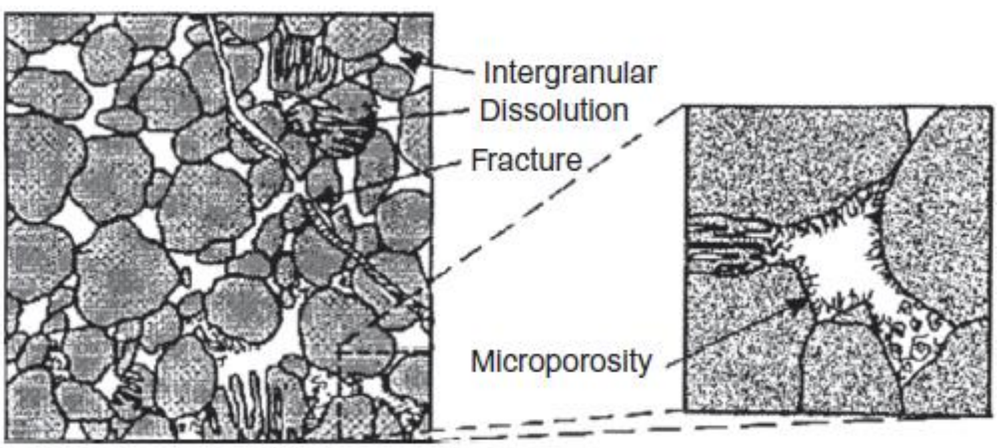

Figure 2: Types of porosity found in sandstone reservoirs.

2- Secondary (or induced) porosity:

Secondary porosity is the result of geological processes (diagenesis) after the deposition of sediment. Induced porosity can be subdivided into four groups based on the most dominant geological process:

a. Solution porosity:

Includes:

- Channels due to the solution of rocks by circulating warm or hot solutions;
- openings caused by weathering, such as enlarged joints and solution caverns;
- and voids caused by organisms and later enlarged by solution.

b. Dolomitization:

A process by which limestone is transformed into dolomite according to the following chemical reaction:

$$\underset{\text{Limestone}}{2CaCO_3+Mg^{2+}} \longrightarrow \underset{\text{Dolomite}}{CaMg(CO_3)+Ca^{2+}}$$

Some carbonates are almost pure limestones, and if the circulating pore water contains significant amounts of magnesium cation, the calcium in the rock can be exchanged for magnesium in the solution. Because the ionic volume of magnesium is considerably smaller than that of the calcium, which it replaces, the resulting dolomite will have greater porosity. Complete replacement of calcium by magnesium can result in a 12-13% increase in porosity.

c. Fracture porosity:

Openings created by structural failure of the reservoir rocks under tension caused by tectonic activities such as folding and faulting. These openings include joints, fissures, and fractures. Fracture types can be classified into two groups related to their mode of formation:

1. Shear fractures, originated from shear stress parallel to the created fracture. On a big scale, this type corresponds to faults as result of tectonic events.
2. Tension fractures (extension fractures) originated from tension stress perpendicular to the created fracture. On a big scale, this type corresponds to joints.

Fractures are not only caused by external stress—processes like dolomitization result in volume reduction and create fractures and pore space in the rock. Thermal effects can also create fracturing.

d. Miscellaneous secondary voids:

(1) Saddle reefs, which are openings at the crests of closely folded narrow anticlines,

(2) pitches and flats, which are openings formed by the parting of beds under gentle slumping, and

(3) voids caused by submarine slide breccias and conglomerates resulting from gravity movement of seafloor material after partial lithification.

2- Fluid Saturation

Fluid saturation is the proportion of the pore space occupied by fluid (oil, gas and water). It is expressed as the fraction, or percent, of the total pore volume occupied by the oil, gas, or water. Thus, for instance, the oil saturation S_o is equal to:

$$S_o = \text{Volume of oil in the rock, } V_o \text{ / Total pore volume of the rock, } V_p$$

Because of the difference in fluid densities, a petroleum reservoir is formed in such a way that, from top to bottom of the sand bed there will be gas, oil, and water, as shown in Figure 3.

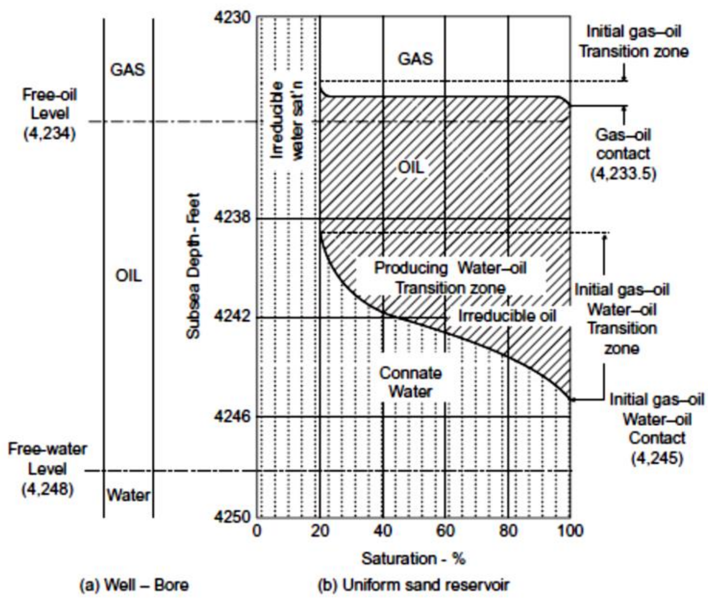

Figure 3: Distribution of fluids in reservoirs.

The water that occurred in the reservoirs is the seawater trapped in porous spaces of the sediments during their deposition and lithification, long before the oil migrated into the reservoir rock. It is called connate water. In case of groundwater, the pore spaces in the rock will be occupied only by water. The rock in this case, is called aquifer, to differentiate it from the petroleum-bearing rocks (reservoirs).

3- Permeability

- Permeability is the rock's ability to conduct fluids. This indicates that nonporous rocks have no permeability.
- Permeability is a tensorial property and exhibits, in many cases, anisotropy. Anisotropy greatly affects fluid flow characteristics of the rock. The difference in permeability measured parallel and vertical to the bedding plane is the consequence of the origin of the sediment, because grains settle in the water with their longest and flattest sides in a horizontal position.
- The permeability of a rock depends on its effective porosity, consequently, it is affected by the rock grain size, grain shape, grain size distribution (sorting), grain packing, and the degree of consolidation and cementation.
- The type of clay or cementing material between sand grains also affects permeability, especially where fresh water is present. Some clays, particularly smectites (bentonites) and montmorillonites swell in fresh water and have tendency to partially or completely block the pore spaces.

Classification of permeability:

A- Engineering classification of permeability:

Due to that permeability is anisotropic, the permeability in the horizontal direction will be different from that at the vertical direction. Accordingly, there are two types of permeability:

1. **Horizontal permeability (K_H):**

   This is the permeability in the horizontal direction parallel to the bedding plane. It is formed at the deposition, as the grains arranged themselves with their longitudinal axis parallel to the bedding plane. Thus, it is always greater than the vertical permeability.

2- Vertical permeability (K_V):

It is the permeability in the direction normal to the bedding plane. It generally results from fracturing or solution channels that cut across bedding.

B- Geological Classification of permeability:

Permeability can be classified as:

1- Primary permeability:

Formed at the time of the rock deposition

2- Secondary permeability:

formed after the rock was deposited and resulted from the alteration of the rock matrix by compaction, cementation, fracturing, and solution. Whereas compaction and cementation generally reduce the permeability, fracturing and solution tend to increase it. In some reservoir rocks, particularly low-porosity carbonates, secondary permeability provides the main flow conduit for fluid migration.

Factors affecting permeability:

(a) Shape and size of sand grains:

- If the rock is composed of large and flat grains uniformly arranged with the longest dimension horizontal, as illustrated in Figure 4 (A), its horizontal permeability will be very high, whereas vertical permeability will be medium-to-large.
- If the rock is composed of mostly large and rounded grains, its permeability will be considerably high in both directions, as shown in Figure 4 (B).
- When the grains are small and of irregular shape, permeability becomes generally low, especially in the vertical direction (Figure 4 C).

(b) Lamination (the presence of clay minerals):

- Platy minerals such as muscovite, and shale laminations, act as barriers to vertical permeability.
- Vertical permeability increased due to fractures or vertical jointing and vertical solution channels, but when these fractures and joints filled with clay minerals, horizontal permeability is reduced.

(c) Cementation:

– Cementation reduces permeability.

(d) Fracturing and solution:

– Fractures and solution increase permeability.

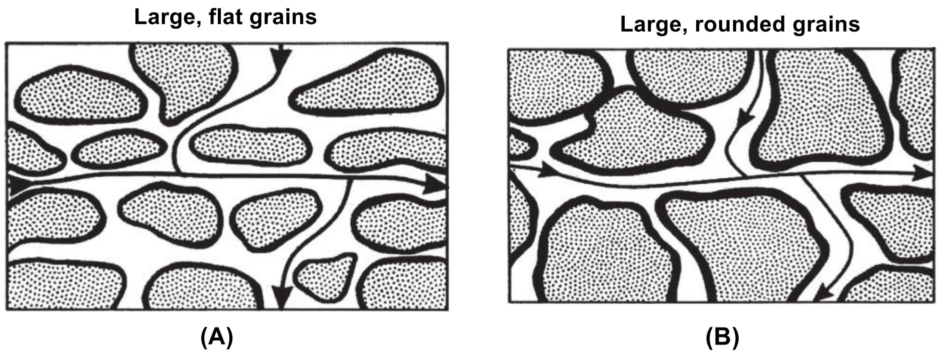

Figure 4: (A) Effects of large flat grains on permeability, (B) Effects of large rounded grains on permeability.

Formation Evaluation and Well Logging

Formation evaluation:

Formation evaluation can be generally defined as the practice of determining both the physical and chemical properties of rocks and the fluids they contain. The objective of formation evaluation is to locate, define, and produce from a given reservoir by drilling as few wells as possible. To this end, oil companies utilize a variety of formation evaluation methods, some of which are outlined in the following table.

Phase	Activity	Evaluation method
Exploration	Define Structure	Seismic, gravity mapping, magnetic mapping
Drilling	Drill well	Mud logging, whole coring
Logging	Log well	Open hole logs
Primary Evaluation	Log analysis	Sidewall cores, vertical seismic profile
Analysis	Core analysis	Laboratory studies
Feedback	Refinement of seismic model and log analysis	Log calibration via core analysis results, seismic calibration from log analysis results
Exploration	Producing hydrocarbons	
Secondary recovery	Water or gas injection and production logging	Production log analysis, micro-rock property analysis
Abandonment	Economic decisions	

Well logging:

Wireline logging or well logging is one of the many different sources of data used in formation evaluation. However, due to accurate depth determination and near proximity of receiver to formation, wireline logs occupy an important position in formation evaluation. Logging is a very small, but very important, piece of the larger puzzle. The decision to plug or complete a well is often based upon the logs response and hence a proper and accurate acquisition and analysis of these data is a must.

Well logging refers to the process of recording and analyzing measurements collected discretely or continually within wellbores. Borehole measurements are made by lowering a probe into the borehole on the end of an electric cable. The probe, generally 2.5–10.0 cm in diameter and 0.5–10.0 m in length, typically encloses sources, sensors, and the electronics necessary for transmitting and recording signals. The well log measurements can be compared with each other and with direct measurements (such as from core samples) to develop site-specific petrophysical relationships.

Well logging is performed to:

1- Identify the rock lithology of the reservoir rock and the properties of this rock.
2- Identify the type of the fluid included withing the reservoir rocks (gas, oil or water or all of them).
3- Measuring the reservoir rock porosity and permeability to define the amount of hydrocarbons

Types of well logging:

1- Logging while drilling (LWD):

In this type, the acquisition of log data is performed by tools placed in the actual drilling assembly. These tools may transmit data to the surface on a real-time basis or store the data in a downhole memory from which it may be downloaded when the assembly is brought back to the surface. LWD is done to:

– Real-time information is required for operational reasons, such as steering a well (e.g., a horizontal trajectory) in a particular formation or picking of formation tops, coring points, and/or casing setting depths.
– Acquiring data prior to the hole washing out or invasion occurring
– Safeguarding information if there is a risk of losing the hole.

LWD data that may typically be acquired include the following:

– GR: natural gamma ray emission from the formation
– Density: formation density as measured by gamma ray Compton scattering via a radioactive source and gamma ray detectors. This may also include a photoelectric effect (Pe) measurement.

- Neutron porosity: formation porosity derived from the hydrogen index (HI) as measured by the gamma rays emitted when injected thermal or epithermal neutrons from a source in the string are captured in the formation
- Sonic: the transit time of compressional sound waves in the formation
- Resistivity: the formation resistivity for multiple depths of investigation as measured by an induction-type wave resistivity tool

2- Wireline Openhole Logging

In this type, the well logginig measurements is done after the well drilling is completed. Wireline versions of the LWD tools described above are available, and the following additional tools may be run:

- Gamma ray: This tool measures the strength of the natural radioactivity present in the formation. It is particularly useful in distinguishing sands from shales in siliciclastic environments.
- Natural gamma ray spectroscopy: This tool works on the same principal as the gamma ray, although it separates the gamma ray counts into three energy windows to determine the relative contributions arising from (1) uranium, (2) potassium, and (3) thorium in the formation. These data may be used to determine the relative proportions of certain minerals in the formation.
- Spontaneous potential (SP): This tool measures the potential difference naturally occurring when mud filtrate of a certain salinity invades the formation containing water of a different salinity. It may be used to estimate the extent of invasion and in some cases the formation water salinity.
- Caliper: This tool measures the geometry of the hole using either two or four arms. It returns the diameter seen by the tool over either the major or both the major and minor axes.
- Density: The wireline version of this tool will typically have a much stronger source than its LWD counterpart and also include a Pe curve, useful in complex lithology evaluation.
- Neutron porosity: The “standard” neutron most commonly run is a thermal neutron device. However, newer-generation devices often use epithermal neutrons (having the advantage

of less salinity dependence) and rely on minitron-type neutron generators rather than chemical sources.

– Full-waveform sonic: In addition to the basic compressional velocity (Vp) of the formation, advanced tools may measure the shear velocity, Stonely velocity, and various other sound modes in the borehole, borehole/formation interface, and formation.
– Resistivity: These tools fall into two main categories: laterolog and induction type. Laterolog tools use low-frequency currents (hence requiring water-based mud [WBM]) to measure the potential caused by a current source over an array of detectors. Induction-type tools use primary coils to induce eddy currents in the formation and then a secondary array of coils to measure the magnetic fields caused by these currents. Since they operate at high frequencies, they can be used in oil-based mud (OBM) systems. Tools are designed to see a range of depths of investigation into the formation. The shallower readings have a better vertical resolution than the deep readings.
– Microresistivity: These tools are designed to measure the formation resistivity in the invaded zone close to the borehole wall. They operate using low-frequency current, so are not suitable for OBM. They are used to estimate the invaded-zone saturation and to pick up bedding features too small to be resolved by the deeper reading tools.
– Imaging tools: These work either on an acoustic or a resistivity principle and are designed to provide an image of the borehole wall that maybe used for establishing the stratigraphic or sedimentary dip and/or presence of fractures/vugs.
– Formation pressure/sampling: Unlike the above tools, which all "log" an interval of the formation, formation-testing tools are designed to measure the formation pressure and/or acquire formation samples at a discrete point in the formation. When in probe mode, such tools press a probe through the mudcake and into the wall of the formation. By opening chambers in the tool and analyzing the fluids and pressures while the chambers are filled, it is possible to determine the true pressure of the formation (as distinct from the mud pressure). If only pressures are required (pretest mode), the chambers are small and the samples are not retained. For formation sampling, larger chambers are used (typically 23/4 or 6 gallons), and the chambers are sealed for analysis at the surface. For some tools, a packer arrangement is used to enable testing of a discrete interval of the formation (as

opposed to a probe measurement), and various additional modules are available to make measurements of the fluid being sampled downhole.

- Sidewall sampling: This is an explosive-type device that shoots a sampling bullet into the borehole wall, which may be retrieved by a cable linking the gun with the bullet. Typically this tool, consisting of up to 52 shots per gun, is run to acquire samples for geological analysis.
- Sidewall coring: This is an advanced version of the sidewall sampling tool. Instead of firing a bullet into the formation, an assembly is used to drill a sample from the borehole wall, thereby helping to preserve the rock structure for future geological or petrophysical analyses.
- NMR: These tools measure the T1 and T2 relaxation times of the formation.
- Vertical seismic profiling (VSP): This tool fires a seismic source at the surface and measures the sound arrivals in the borehole at certain depths using either a hydrophone or anchored three-axis geophone. The data may be used to build a localized high-resolution seismic picture around the borehole. If only the first arrivals are measured, the survey is typically called a well shoot test (WST) or checkshot survey. VSPs or WSTs may also be performed in cased hole.

3- Wireline Cased Hole Logging

When a hole has been cased and a completion string run to produce the well, certain additional types of logging tools may be used for monitoring purposes. These include:

- Thermal decay tool (TDT): This neutron tool works on the same principle as the neutron porosity tool, that is, measuring gamma ray counts when thermal neutrons are captured by the formation. However, instead of measuring the HI, they are specifically designed to measure the neutron capture cross-section, which principally depends on the amount of chlorine present as formation brine. Therefore, if the formation water salinity is accurately known, together with the porosity, Sw may be determined. The tool is particularly useful when run in time-lapse mode to monitor changes in saturation, since many unknowns arising from the borehole and formation properties may be eliminated.
- Gamma ray spectroscopy tool (GST): This tool works on the same principal as the density tool, except that by measuring the contributions arising in various energy windows of the gamma rays arriving at the detectors, the relative proportions of various elements may be

determined. In particular, by measuring the relative amounts of carbon and oxygen a (salinity independent), measurement of Sw may be made.

- Production logging: This tool, which operates using a spinner, does not measure any properties of the formation but is capable of determining the flow contributions from various intervals in the formation.
- Cement bond log: This tool is run to evaluate the quality of the cement bond between the casing and the formation. It may also be run in a circumferential mode, where the quality around the borehole is imaged. The quality of the cement bond may affect the quality of other production logging tools, such as TDT or GST.
- Casing collar locator (CCL): This tool is run in order to identify the positions of casing collars and perforated intervals in a well. It produces a trace that gives a “pip” where changes occur in the thickness of the steel.

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