THE PETROLEUM UPSTREAM INDUSTRY: HYDROCARBONS EXPLORATION AND PRODUCTION

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Summary

The oil industry deals with the global processes of exploration, production, transportation, refining and marketing of natural hydrocarbons (crude oil and natural gas). Hydrocarbons, besides being the basic raw materials of the chemical industry (plastics, textiles, dyes, medicines, solvents, fertilizers, pesticides, etc.) represent the largest source of energy on the planet. Over 60% of primary energy needed in the world

today comes from crude oil and natural gas (more than 80% from fossil fuels) and thus it is critical to many nations in terms of economic, geopolitical and national security. The oil industry (exploration, production, transportation, refining and marketing of crude oil and natural gas) is the single largest industry in terms of monetary value in the world. It is usually divided into three main areas: the upstream sector (exploration and production), midstream sector (transport) and the downstream sector (refining and marketing). The midstream sector is often included in the upstream. The main subject of this paper is a brief description of the upstream industry.

1. Oil and Gas Reserves

Crude oil ("oil" in the petroleum industry jargon) is a fossil fuel, like coal and natural gas. Fossil fuels originated from the remains of plants and animals that died hundreds of millions of years ago, when man had not yet appeared on Earth. Those plants and animals, just like today, have accumulated energy from the Sun and, after their death, were buried for millions of years to turn into oil, gas and coal. Prehistoric plants and animals give back to us the solar energy accumulated in the past. All existing hydrocarbon molecules are composed of two types of atoms, carbon and hydrogen. Depending on the amount of carbon in the molecule, there are gaseous hydrocarbons (up to 4 atoms), liquid (5 to 16 atoms) and solids (more than 16 atoms). Hydrocarbons are a broad category of substances, as carbon has many opportunities to bond with other carbon and hydrogen atoms in open chains (linear or branched), closed (ring) or mixed structures. There are thousands of hydrocarbons with different molecular structures, but the same chemical composition. There are hydrocarbons with single bonds (alkanes or saturated hydrocarbons such as methane, or natural gas), double bonds (alkenes, such as propylene) or triple bonds (alkynes such as acetylene).

Coal was the first fossil fuel utilized by man, since the Industrial Revolution of the XVII Century, and then it was partially substituted by crude oil at the end of the XIX Century. Natural gas became an important source of energy only after the 1950s, and since then natural gas importance in the energetic mix increased at fast rate. For more than a century, when the gas was discovered at sites away from end users, it was preferred to burn it on site or release it into the atmosphere, as the construction of gas pipelines to carry the gas hundreds of miles away was not economical. The situation changed in the last forty years and now natural gas is at the third place in the world's consumption of fossil fuels and the energy source with the best growth prospects.

The natural environments more favorable to the formation of natural hydrocarbons are the slow sinking sedimentary basins and continuous supply of debris from the rivers. These areas are normally subsiding as a result of natural geological processes. Here live a large number of micro- and macro-organisms (phytoplankton, zooplankton, algae, bacteria, as well as multicellular organisms) that after death settle on the bottom and are buried by sediments (gravel, sand, silt, clay, carbonate sediments, etc.). The sediments rich in organic matter (source rock) slowly sink due to the burden of new sediments. At a certain depth and temperature inside the Earth's crust, the organic matter "mature", turning first into kerogen (around 1000 m depth and 50°C) and then into hydrocarbons. When heated to the right temperature in the Earth's crust, some types of kerogen release crude oil or natural gas. When such kerogens are present in high concentration, such as in shales, they form possible source rocks. Shales rich in kerogens that have not been heated to the temperature necessary to produce hydrocarbons may form oil shale deposits. The duration of the hydrocarbon generation process varies from 10 to 100 million years, depending on temperature and pressure. The natural hydrocarbons (crude oil and natural gas) are thus generated within the pores of sedimentary rock, and can accumulate in the porosity or micro-fractures within particular geologic formations known as "reservoir rocks".

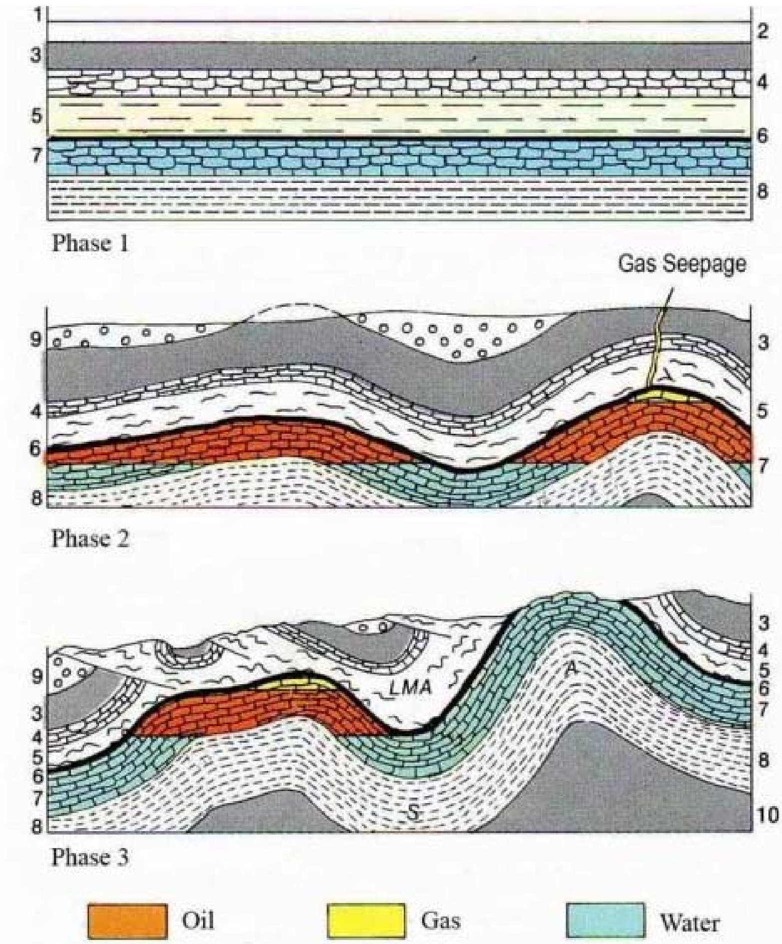

Figure 1. Formation of hydrocarbon reservoirs. Phase 1 (top). The sediments, saturated with water, sink to the sea bottom and subside within the Earth's crust under the burden of sediments. Phase 2 (center). Sediments undergo stress, strain and bending due to tectonic movements, with the formation of anticlines and accumulation of oil and gas. The cap rock on the right anticline is faulted and the gas seeps to the surface through the fault plane. Phase 3 (bottom). The new folding and uplift of the layers caused the surface erosion of the anticline on the right, whose hydrocarbons were lost in the atmosphere in geologic times; the anticline on the left was preserved as an oil field with gas cap. 1, sea level, 2, sea, 3, sandstone, 4, limestone, 5, marl and evaporitic rocks, 6, anhydrite (cap rock), 7, limestone reservoir rock, 8, clay, 9, conglomerates, 10, crystalline basement, A, anticline; S, syncline; LMA, maximum level of accumulation. (Picture courtesy of the Authors)

In order to generate and preserve a deposit of hydrocarbons until its commercial discovery (an hydrocarbon reservoir if it can be economically exploited), four conditions must occur simultaneously: a) the presence of a source rock not too far away from the reservoir, b) the transformation of the organic matter contained in the source rock into oil and gas (hydrocarbon generation), and relocation of these fluids into adjacent porous and permeable formations (hydrocarbon migration), c) the existence of porous and permeable layers with a geometric configuration that allows the entrapment and accumulation of hydrocarbon fluids in favorable subsoil structures (reservoir rock with a geological trap), d) the presence, above the reservoir rock, of a layer of impermeable rock (cap rock) that blocks the vertical migration of oil and gas; if migration continues, hydrocarbons may reach the surface, creating oil and gas seepage, and disperse in the atmosphere. The conditions listed above are shown schematically in Figure 1.

1.1. Origin and Migration of Petroleum Fluids

It is widely accepted today that oil and natural gas originate from microbial and/or thermal degradation of organisms (plants and animals) deposited together with inorganic clastic (clay and sand) or chemical (limestone) sediments on the bottom of the oceans, lagoons or lakes. The amount of these organisms per unit volume of rock depends on environmental conditions existing at the time of sedimentation. The highest concentrations of organic matter occurs in shallow, calm and warm waters, that is, in general, along the continental slope, a short distance from the shore. In these conditions clayey clastic sediments are predominant: consequently, the source rocks are very often composed almost entirely of clay.

Only a small part of the organic matter present in the surface water can reach the bottom and be included in the sediments. Most of it is destroyed by bacterial action already on its way to the bottom. The action of the bacteria continues within the sediments, allowing the bacterial hydrocarbon generation. As the deposition of new sediments continues over time, the sea bottom sinks (subsidence) due to the geostatic load of the overlying sediments, and thus the organic matter incorporated in the clay is subjected to increasing temperature and pressure. Due to the geothermal gradient, temperature increases of about 33 °C per 1000 m depth, while pore pressure of clayey rock increases of about 2.2 MPa per 100 m depth. The action of temperature, combined with the catalytic action exerted by the clay minerals, continues for geologic time, and causes the thermal degradation (cracking) of organic matter, initially with the formation of heavy hydrocarbon (bitumen, heavy oil), then lighter oil and gas up to the full thermal degradation of hydrocarbons into methane. The evolution is a function of the maximum depth (and therefore time after deposition and temperature) of sediment containing organic matter, as represented in Figure 2.

As the oldest and deepest are the sediments that compose the source rock, the more likely is the formation of light oils, or even only natural gas. This is why, historically, oil exploration has usually found deeper reserves of natural gas or light oil. The pressure exerted by the overlying sediments causes compaction and reduction of pore volume. Part of the fluids (water and hydrocarbons) contained in the pores of the source rock is squeezed out and lighter fluids migrate upwards to porous and permeable formations (primary migration). As for gaseous hydrocarbon it is fairly certain that the migration takes place in the form of water solution; as for liquid ones is not yet clear whether the migration occurs by means of micro-emulsion in water or solution. Once the hydrocarbon fluids reach the permeable layers (sand, sandstone, limestone and dolomite) in contact with the source rock, oil and water move inside the same, in the direction of the local gradient of the hydraulic potential (secondary migration). Hydrocarbons, lighter than water, separate by gravity inside the porous and permeable layers and, in presence of particular geometric conditions, they can form oil or gas fields (Figure 1). In absence of geological traps, the hydrocarbons migrate slowly toward the Earth's surface and disperse into the atmosphere or the hydrosphere.

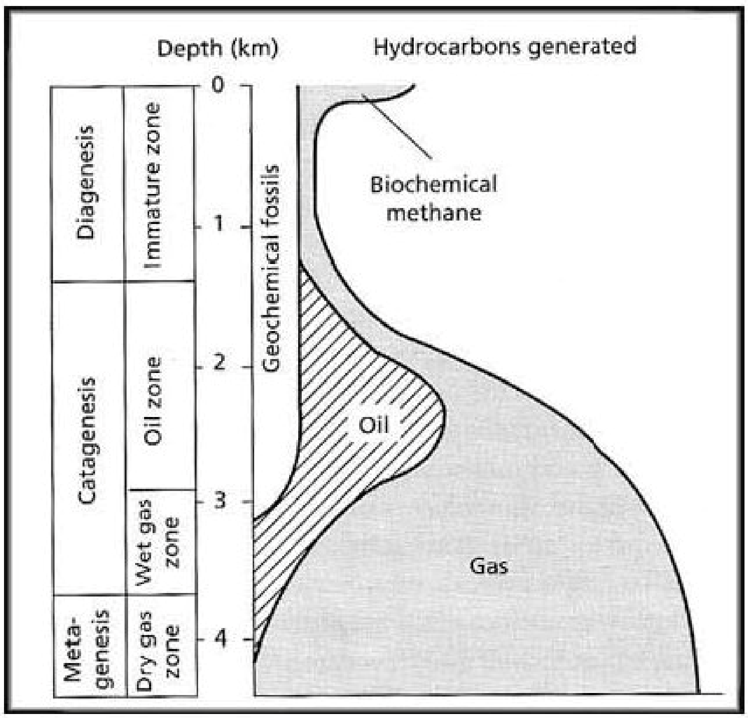

Figure 2. Formation of different types of hydrocarbons as a function of temperature and maximum depth of source rocks. Natural gas is formed by microbial action at shallow depth and, after the formation of oil (oil window), by thermal degradation at higher depth. Picture courtesy of http://www.columbia.edu/~mls2125/oil.html

1.2. Geological Traps

The term trap means any subsurface geometric situation, stratigraphic or structural in origin, able to collect and contain a volume of fluids, including hydrocarbons. The concept of geologic trap involves the presence of at least one layer of continuous cap rock impermeable to oil and gas. This layer, commonly composed of clay or evaporitic rocks, acts as the upper limit of the porous and permeable rock in which there was hydrocarbons accumulation (reservoir rock). The inexistence or not perfect impermeability of the cap rock (also due to fractures generated after sedimentation) is one of the most common causes of unsuccessful oil and gas exploration. The traps can be divided into three types, namely structural traps (or tectonic), stratigraphic and mixed.

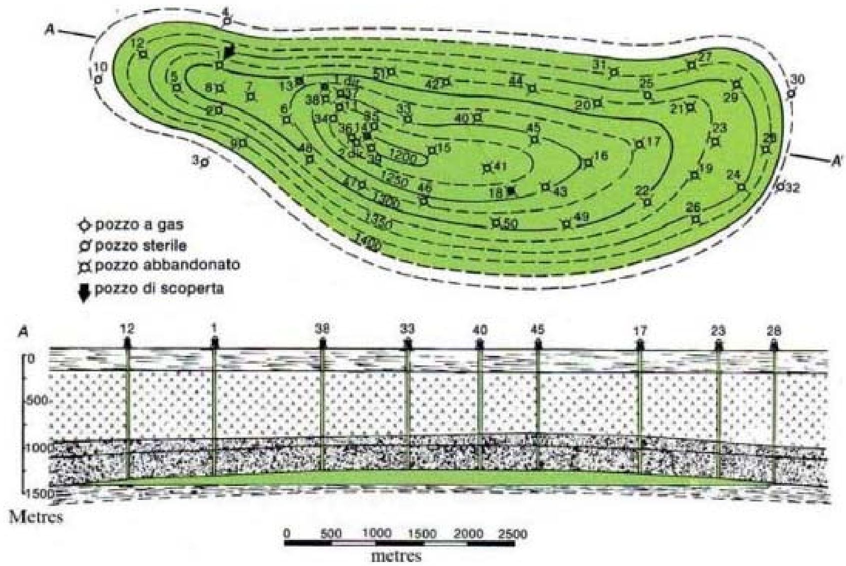

Figure 3. Hydrocarbon reservoir contained in a structural trap (anticline). The gas (green) is in contact with a bottom aquifer. (Caviaga gas field, Italy). (Picture courtesy of the Authors)

Structural trap are originated by rock deformation (originally horizontal), and can be classified into folds and anticlines traps, fault traps and fracture traps. Typical are the anticlines folds (Figure 3), a classic structural target of oil exploration. Fault traps are originated by strong tectonic actions, which cause the vertical displacement of large blocks of rock, resulting in a side contact of porous and permeable layers with impermeable ones (Figure 4). The fault interrupts the lateral continuity of the porous layers, with possible entrapment of hydrocarbons during secondary migration. If the tectonic actions crush large portions of an originally impermeable rock, a fracture trap is created. In fact, if an overlying (intact) cap rock exists, hydrocarbons can accumulate in the secondary porosity and permeability originated by tectonic fracturing.

A stratigraphic trap is originated by a local variation of the deposition mechanism (permeable layers in contact with impermeable ones) or a change in stratigraphy. These are formed when different strata seal a reservoir or when the permeability changes within the reservoir rock (facies change). Stratigraphic traps are divided into primary and secondary ones. Typical primary traps are the sandy lenses incorporated in clay formations. The formation of such lenses can occur by means of different mechanisms: river deposition in lakes or oceans (burial of riverbeds, fan-shaped distribution of deltaic sediments, formation of coastal bars, etc.). Other stratigraphic traps are those of chemical origin, due to precipitation of calcium carbonate from saturated water, with possible subsequent dolomitization. In other cases the formation of carbonatic rocks is due to the action of living organisms (algae, corals, etc.), with growth of a central core, as in the case of coral reefs. The secondary stratigraphic traps are those arising from stratigraphic unconformities and lateral facies changes, with possible permeability reduction. Other traps are salt domes. It is known that salt (sodium chloride) has a density significantly lower than that of carbonate and clastic sediments and behaves, in geological time, as a high viscosity fluid. Salt layers undergo buoyancy and therefore tend to pierce the overlying layers to form salt domes that deform the top and lateral layers, disrupting continuity, thus creating geological traps along the edges of the dome itself (Fig. 5).

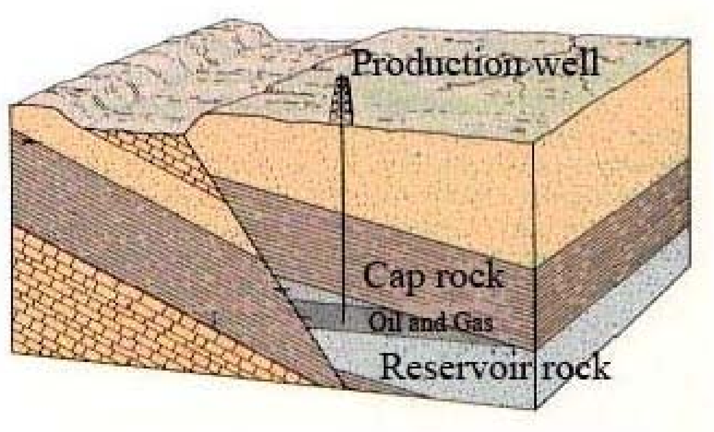

Figure 4. Reverse fault trap. (Picture courtesy of the Authors)

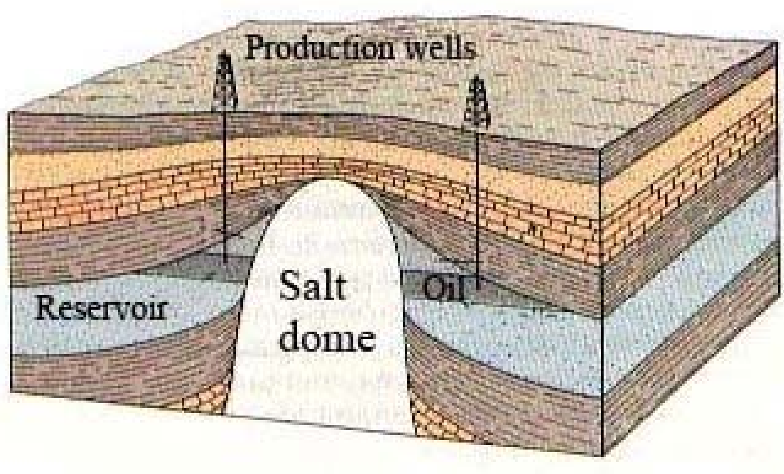

Figure 5. The intrusion of a salt dome, interrupting the continuity of the pierced strata, paves the way for the formation of geological traps. (Picture courtesy of the Authors)

1.3. Reservoir Rock

A reservoir rock is a body of rock having sufficient porosity and permeability to store and transmit fluids, respectively. Sedimentary rocks are the most common reservoir rocks because they have more porosity than most igneous and metamorphic rocks. A reservoir rock can be considered as a natural porous medium with an adequate porosity and permeability.

As far as fluids distribution in a reservoir is concerned, one must recall that after migration from source rocks, hydrocarbons tend to accumulate below the cap rocks of geological or stratigraphic traps. Here, fluid density plays a major role in determining the vertical distribution of the fluid saturating the reservoir rock. Practically all hydrocarbon reservoirs have a bottom aquifer, or water zone. Oil and gas accumulate above the water-oil contact (water table), and the gaseous phase accumulates above the oil zone, forming the gas cap. The transition between oil and gas is called oil-gas contact. Both the water table and the oil-gas contact are not well defined geometrical planes separating immiscible fluids in a reservoir, as it happens in closed containers. In fact, due to the porous nature of reservoir rocks, the transition between immiscible fluids is governed by capillary phenomena, and thus above the water table a transition zone exists, where water saturation decreases upward until it attains the irreducible water saturation, that marks the beginning of the oil zone. The same happens above the oil-gas contact.

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Biographical Sketches

Paolo Macini is Associate Professor of Petroleum Engineering at the University of Bologna (Italy). Prof. Macini holds a M.S. Degree in Mining and Petroleum Engineering from the University of Bologna. He is a Registered Professional Engineer in Italy. Before joining the University, he worked for a Service Company supplying tools and services to the oil and gas industry, with experiences in Italy, North Sea, Africa and USA. He joined the University of Bologna in 1992, and his present appointment is Associate Professor at the Civil, Environmental and materials Engineering Department. Prof. Macini has taught a number of classes at the University of Bologna. Principal among them are Underground Fluid Mechanics, Drilling Engineering, Reservoir Engineering and Petroleum Production, which are also the main areas of his research activity. He has authored or co-authored more than 100 papers and three books. Prof. Macini is a member of the Society of Petroleum Engineers (SPE), where he served for more than 15 years in the Board of the Italian Section and as Chairman of the Ravenna Subsection, of the American Society of Mechanical Engineers (ASME), of the Russian Academy of Natural Sciences (US Section) and of the Italian Society of Mining Engineers (ANIM).

Ezio Mesini is Full Professor of Petroleum Engineering at the University of Bologna (Italy), and he holds a M.S. Degree in Mining and Petroleum Engineering from the same University. The main areas of his research activity are in the fields of Environment and energy, Subsidence phenomena due to underground fluid withdrawals, Laboratory investigations on porous media, Drilling and production technologies and Well logging. He is author or co-author of about 150 papers and publications in the above topics
During his teaching activity at the University of Bologna, Prof. Mesini covered almost all the classes offered to Petroleum Engineering students at the College of Engineering.
He is member of the following scientific and professional associations: Italian Society of Mining Engineers (ANIM), Society of Petroleum Engineers (SPE), Pi Epsilon Tau (National Petroleum Engineering Honor Society, University of Southern California); International Hall of Fame (IHF Los Angeles); Russian Academy of Natural Sciences. In addition, he is member of the Editorial Board of the Journal of Petroleum Science and Engineering, Elsevier, Amsterdam.