The oil system

Badly distributed wealth

If one observes the distribution of hydrocarbons in the world, it is quite clear that it is not uniform all over the planet, but there are areas in which hydrocarbons are much more abundant and others that are totally devoid: the imbalance between the quantity of hydrocarbons contained in the reserves of the different world oil-yielding provinces is very clear. What conditions and determines the distribution of natural gas and oil in the subsoil?

Geology helps us to understand

The factors that determine the quantity of hydrocarbons present in a region are manifold and all of a geological nature: to understand why one region is richer than another and to evaluate the potential of an oil-yielding province it is necessary to know its geology very well, both in terms of the different types of rock you can find and in terms of its geological history. This knowledge, that is not always easy to obtain, is very important to be able to implement a preliminary evaluation on areas that have not yet been explored as far as hydrocarbon research is concerned and to determine their productive potential. It is a fundamental step when an exploration is being carried out.

The oil system

The set of all the characteristics that lead to the formation of an oil field make up the so-called ‘oil system’. This system is made up of the following fundamental elements that will be dealt with in detail in the subsequent paragraphs:

- the presence of a mother rock (source rock);
- the presence of a reservoir rock;
- the presence of a cap rock (seal);
- the formation of traps with a suitable structure.

The necessary processes comprise:

- the generation of hydrocarbons (conditions to reach the ‘oil window’);
- the expulsion and migration of the hydrocarbons from the mother rock to the reservoir rock;
- the accumulation of hydrocarbons in a reservoir rock within a trap.

The areas that produce the most hydrocarbons are divided into ‘oil fields’ according to their geological and structural characteristics; these in turn are subdivided into smaller provinces characterized by a uniform geological situation and by similar characteristics of the reservoir rocks and of the structure of the traps. The task of the person who is engaged in exploring for hydrocarbons is to locate the areas that have the above-mentioned geological characteristics, those that are the most favourable to the formation of important reserves.

The mother rock

Hydrocarbons are formed due to the transformation of organic material scattered in rocks. Organic substances provide the two elements essential to the constitution of hydrocarbons: carbon and hydrogen. For the formation of a significant quantity of hydrocarbons, the source rock must contain more than 0.5% of its weight in organic carbon. Hence, the first prerequisite condition for the formation of an important oil field is the presence of rocks that are rich in organic substances.

Organic substances derive from animal and plant organisms that, when dead, accumulate in sediments and detritus that deposit at the bottom of sedimentation basins. Accumulation can take place in both a marine or a continental

environment and in both cases the organic substances are generally decomposed rapidly and only a small part (about one per thousand) avoids the attack of bacteria and the oxidation processes. Organic substances can therefore accumulate in great quantities only in sedimentary rocks that form in basins that have been stable for a long time.
The accumulation of organic material also depends on the production rate of the same, that is conditioned by environmental factors such as the availability of food and nutritious substances, light intensity and temperature. The sites that are more favourable to a high accumulation of organic material (remains of marine and land organisms) are warm, relatively shallow seas and those off the coast. In deep sea environments organic material is less, due to a scarce supply, while on land it decomposes very rapidly. The first places to look for hydrocarbons are therefore those areas in which shallow water marine sediments that are rich in organic material are present: the 'mother rocks' from which hydrocarbons originate.
It is also necessary that the organic substances should be preserved and protected from the decomposition processes as much as possible. This can be accomplished in regions of quick sedimentation, where the material is rapidly buried or in environments deprived of oxygen. Anoxic conditions can be found in closed basins with limited or no water circulation, as in lakes or lagoons with scarce communication with the open sea, in relatively shallow seas within emersed lands or in very deep oceanic basins. Anoxic basins are so tightly connected to the presence of noteworthy hydrocarbon deposits that they are considered among the most important generators of mother rocks and are therefore the object of exhaustive studies by those working on gas and oil exploration.
Mother rocks formed in closed anoxic basins have been identified in all the main oil yielding provinces: Venezuela, Colombia, Gulf of Mexico, Saudi Arabia and Alaska, while mother rocks that have formed due to rapid sedimentation have been found in the oil-yielding provinces of Argentina, West Africa, the North Sea, USA and Italy (the Po basin).

Transformation of organic material

The sediments that are progressively deposited bury the ones below, that are therefore covered by growing layers of material that accumulate in time. As they are pushed deeper and deeper in the Earth's crust, the sediments slowly loose the water that they contained originally, become denser and more compact and are subjected to growing temperature and pressure. The 'oil window' is defined as the set of particular pressure and temperature conditions that are required for the transformation of organic material into hydrocarbons. For an important oil-yielding province to be formed, it is also necessary that the mother rock should reach the conditions of an 'oil window'.
The transformation can take place at low temperatures but over a long lapse of time (as in older rocks) or in a short time but with higher temperatures (as in younger rocks): the age of the mother rock is not a determining factor in the production of hydrocarbons but the temperature it reaches is. The initial characteristics of the organic substance in addition to the conditions and the time required to reach the 'oil window' can be decisive to determine a greater production of gas rather than oil. The researchers carry out a series of tests on the possible mother rocks to establish whether these have reached the conditions that are necessary for transformation, or not, by checking some specific 'indices': the reflecting power of vitrinite (an organic substance that increases, reflecting the higher the temperature to which it is subjected) and the colour of pollen spores (that become darker as the temperature rises).

The migration of hydrocarbons

The hydrocarbons that form within the mother rock are generally scattered in the sediments and must have the possibility of migrating and concentrating to build up economically significant deposits. It has been calculated that only 5% of the hydrocarbons that form accumulate in oil fields of a certain importance.
Migration takes place in two phases. **Primary migration** allows the expulsion of hydrocarbons from the mother rock with a mechanism similar to the one that provokes the alienation of the water originally present in the sediments due to the growing pressure to which they are subjected.
Oil and gas are lighter and less dense than water so during secondary migration they tend to rise through pores and fractures in the rock.

For migration to take place, it is necessary that the surrounding rocks should be permeable, i.e. that they should have pores and fractures wide enough to allow the passage of oil drops and gas bubbles. The higher the permeability of the surrounding rocks, the higher the possibility that a great quantity of hydrocarbons can accumulate. Permeability depends on the geological history of the region and is conditioned by two important factors:

- **initial permeability** depends on the kind of rock and on the conditions of its formation; it is very high in gravel and sand, lower in sandstone and very low in limestone and in igneous and metamorphic rock;
- **secondary permeability** is created by fractures and faults that form in the rock as a result of tectonic deformations or hollows that develop as a consequence of karstification processes.

The more productive oil-yielding provinces must therefore be sought for in places where the geological history has increased the probability of finding rocks with the characteristics of mother rocks surrounded by permeable rocks. Less permeable rocks, such as clay, act as an impermeable barrier that stops hydrocarbon migration and forms the 'cap rock'.

Elements that form an oil field

Hydrocarbons, being light and not very dense, tend to rise while they migrate. If they do not find obstacles on their ideal pathway, they scatter in the overlying rocks until they reach the surface and give rise to spontaneous evidence: the so-called oil seepage that remains on the surface. In short, for an important oil field to form it is necessary that the rock formations that surround the mother rocks should be able to trap and accumulate hydrocarbons within, and require three indispensable conditions:

- the presence of a rock that can contain the hydrocarbons, the so-called reservoir;
- the reservoir rock must be bounded by an impermeable rock, called 'cap rock', capable of stopping the migration of fluids and of confining them within the reservoir;
- the disposition and configuration of the reservoir and cap rocks must be such that they form a rather capacious container with a shape suited to hold the maximum amount of hydrocarbons and constitute the so-called 'trap'.

Capacious reservoirs

Reservoir rocks must have an elevated porosity and permeability: the higher these values are, the greater the quantity of hydrocarbons that the reservoir rock can contain and the easier it will be to extract oil and gas. Naturally, the greater the volume of the reservoir rock, the greater the volume of the oil field.
The most efficient reservoir rocks are the 'silicoclastic' ones, made up of granules and fragments of pre-existent rocks (sand, sandstone, conglomerate). These rocks are characterized by an elevated porosity and form high quality basins. It has been calculated that 60% of the oil fields discovered up to now are contained in rocks of this type.
Even carbonate rocks (calcareous and dolomite) are good reservoir rocks when they are intensely fractured or of organic origin (such as coastal calcareous rocks), when karst processes are active and create big underground void spaces. A little less than 40% of the world oil fields is contained in rocks of this kind.
All other kinds of rocks make good reservoirs only when they are intensely fractured: generally, they contain very small oil fields that are therefore practically irrelevant, Important fields in fractured granite rock can only be found in the area between Kansas and Texas (Anadark basin), in the Egyptian field of Ashrafi, in the Gulf of Suez and in the off-shore field of Bach-Ho, in Vietnam.

A suitable 'cap'

For the hydrocarbons to remain confined within the reservoir rock it is necessary that it should be surrounded by rocks that prevent the hydrocarbons from moving away. Cap rocks must therefore have characteristics that are in contrast to those necessary for a rock to be a good reservoir: in fact, they have to be as impermeable as possible. Usually they are made up of fine-grained sedimentary rock (such as clay, marl, clayey limestone) or of evaporite rocks (such as gypsum and halite) and must not be very fractured. 95% of the cap rocks of the world's main oil fields is made up of clays or evaporites.

Efficient traps

The above-mentioned characteristics of reservoir and cap rocks are conditions that are necessary but not sufficient for the formation of noteworthy oil fields. A decisive factor is the shape of the 'trap' that imprisons the hydrocarbons because it determines the shape and volume of the reservoir and the magnitude of the reserves that the latter can contain. Traps can be either structural or stratigraphic.

Structural traps are caused by tectonic deformations that have fractured and folded the rocks. The conformation that is most favourable is that of rocks deformed in anticline folds with the layers upwardly convex. These structures are therefore the most suitable to contain fluids that tend to flow upwards because they are less dense.

Even evaporite rocks can originate excellent traps: salt deposits, being lighter than the surrounding rocks, tend to flow upwards and curve the layers above forming structures called 'diapirs' that are favourable for the accumulation of hydrocarbons. Very many oil fields in the world are associated to the presence of salt diapers. (for example, in Central Europe).

Even tectonic structures, where fault systems create an alternation of low-lying basins and protruding areas (Horst and Graben), can constitute efficient trap systems like in the North Sea Basin and in the Rhine Trench between France and Germany.

Structural traps are the easiest to identify with geophysical surveys which explains why the majority of the world oil fields are contained in structures of this type.

Stratigraphic traps, instead, are formed due to sedimentary causes, when there are sudden changes in the permeability and porosity of the rock, such as in river and relatively shallow sea environments. Even though stratigraphic traps are very numerous, they contain only 15% of the world oil fields, not because they are less efficient than structural traps but because their identification with geophysical survey methods is much more problematic.

Within a trap, due to the difference in density of the various components, we find: at the top the lightest gas, below this, hydrocarbons and lastly, water. The surface that separates oil from water marks the lower limit of the oil field and its identification is fundamental to calculate the volume of hydrocarbons contained in the field.