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Petroleum in the South Atlantic*

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Résumé — Le pétrole de l'Atlantique Sud — La richesse pétrolière de l'Atlantique Sud s'explique par le biais du concept contemporain de système pétrolier.

Ces réserves d'hydrocarbures (7 % des réserves mondiales), qui s'égrainent le long des côtes de l'ouest africain et de l'est du continent sud-américain, résultent d'une situation géologique favorable, essentiellement la même pour les deux côtés de l'océan. Leur mise en place est décrite ici dans le cadre général de l'ouverture de l'océan sud-Atlantique, qui a commencé il y a plus de 140 Ma avec la déchirure du protocontinent Pangée. On soulignera l'importance de ces concepts pour l'exploration des réserves offshore profondes et ultraprofondes des marges occidentale de l'Afrique et orientale du Brésil.

***Abstract* — *Petroleum in the South Atlantic* —** *The petroleum deposits in the South Atlantic are considered in terms of the contemporary understanding of the formation of petroleum and of the petroleum system concept.*

These hydrocarbon reserves (7% of the global reserves), contained in the sedimentary rims along the coasts of West Africa and of the Eastern seaboard of South America, result from a favourable geological setting that is essentially the same on both sides of the ocean, giving rise to an almost symmetrical pattern. Their history is described within the general framework of the opening of the South Atlantic Ocean, which began over 140 Ma ago with the breaking up of the proto-continent Pangea. The importance of these concepts for the opening up of deep and ultra-deep offshore prospects in West Africa and Brazil is underlined.

INTRODUCTION

The South Atlantic accounts for around 7% of the world's hydrocarbon reserves. They are contained in a belt of deposits along the coasts of West Africa and on eastern seaboard of the South American continent. The rich resources described in this article result from a favourable geological setting that is essentially the same on both continental shelves, giving rise to an almost symmetrical pattern on either side of the ocean. In fact, the prolific petroleum systems at the origin of these deposits share a common history, including the oil and gas accumulations off the coasts of Angola, Congo, Nigeria and Gabon, on one side, and Brazil on the other. They were emplaced within the general framework of the opening of the South Atlantic Ocean, which began over 140 Ma ago (beginning of the Cretaceous) with the breaking up of a proto-continent (Pangea). The moving apart of the South American and African continents began at that time and is continuing today at a rate of a few centimetres per year.

In this region, the discovery and exploitation of oil fields goes back to the 1950s and has continued ever since without interruption. Since then, the major oil companies have made spectacular advances in drilling techniques in deep waters (from hundreds to thousands of metres), leading to important offshore discoveries in West Africa and Brazil that have opened up previously unreachable prospects.

The history of petroleum operations in the South Atlantic has widely benefited from the contemporary development of concepts linked to the formation of petroleum as well as the emergence of the notion of "petroleum system" (Hunt, 1995; Magoon and Dow, 1994; Tissot and Welte, 1984). Therefore, this regional presentation will be introduced with a brief reminder of this body of knowledge that has revolutionised petroleum exploration over the last few decades.

1 WHAT IS A PETROLEUM SYSTEM?

Sedimentary basins correspond to depressions in the upper parts of the Earth's crust generally occupied by a sea or an ocean. These depressions are initiated by geodynamic phenomena often associated with the displacement of lithosphere plates. The "basement" of the sedimentary basins is formed of crust made up of igneous rocks (granite on the continents and basalt in the oceans). Sedimentary rocks such as clays, sandstones, carbonates or massive salt have accumulated in these basins over geological time. Sedimentation generally involves a process extending over tens of millions of years, at a rate of several millimetres per year on average. Chiefly due to the weight of the deposits, the ongoing geodynamic processes and the accumulation of sediments lead to deformation and progressive sinking of the underlying crust. This accentuates the initial depression, giving rise to a sedimentary filling that is often many kilometres thick. This deepening of the basin, which is known as subsidence, results from the combined effects of tectonic movements and sedimentary overburden. In extreme cases, subsidence can reach as much as 20 km. The Paris Basin is an example of a sedimentary basin with a thickness of filling that attains a maximum of 3000 m; it overlies a crystalline basement that crops out in the Armorican Massif, the Vosges and the Massif Central. Hydrocarbons can be formed and entrapped within such sedimentary basins.

However, not all sedimentary basins satisfy the necessary conditions for them to become oil-bearing. And this is where the concept of a petroleum system comes in. *A petroleum system is a sedimentary basin, or more often a portion of a sedimentary basin, where we find all the essential geological and physico-chemical "ingredients": source rock, reservoir rock, cap rock and trap, combined with progressive burial of the source rock and appropriate migration and trapping of the hydrocarbons (Fig. 1).*

1.1 Elements of a Petroleum System (Source Rocks, Reservoir Rocks, Cap-Rocks, Traps)

• ***The source rock***, which is a clayey or carbonate sediment containing a large quantity of organic debris accumulated at the same time as the mineral constituents. This organic material corresponds to the accumulation of more or less well preserved remains of organic tissues derived from populations of organisms living very close to the site of deposition of the source rock.

These organisms are essentially planktonic algae, higher plants and bacteria that together make up the major part of our planet's biomass. It should be noted that this kind of rock, rich in organic sedimentary matter (for it to be called a "source rock", the organic matter should account for at least 2% of the rock by weight), is far from common and requires very special conditions. To allow significant quantities of organic matter to accumulate in a sediment, the depositional environment must be associated with an eco-system that produces a large amount of biomass (high biological productivity) (Pedersen and Calvert, 1990). This should be combined with a good preservation of the organic matter after the death of the organisms as well as during its incorporation into the sediment. This last condition assumes a short transport time from the site of biological production to the site of sedimentation, so that the degradation of the organic material and its dispersal is minimised. Moreover, the sedimentary environment must be devoid of oxygen (anoxic), to prevent decomposition of the organic matter by aerobic bacteria and consumption by benthic organisms (Demaison and Moore, 1980). Benthic animals (crustaceans, worms, gastropods, bivalves, etc.) can live on the seabed if the water contains sufficient dissolved oxygen. Anoxia develops in confined basins when the circulation of water

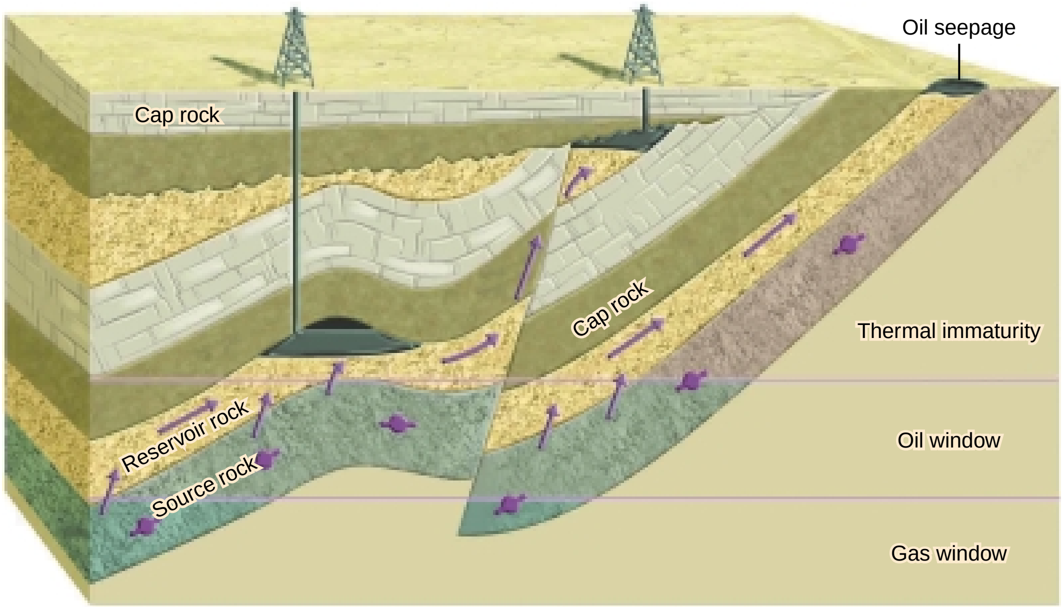

Figure 1

A petroleum system corresponds to a sedimentary basin, or most frequently some part of a basin, which combines all the essential structural and sedimentary ingredients: source rock, reservoir rock, cap rock and trap. In addition, it brings together the geological processes necessary for the formation and accumulation of oil and gas in deposits: thermal history of the source rock associated with its progressive burial and the appropriate migration of hydrocarbons and their entrapment.

masses is hindered, or in any case becomes insufficient, to ensure the renewal of oxygen to the environment (the sole source of oxygen being atmospheric oxygen).

Rocks rich in organic matter are most often clayey or marly (mixture of clay and limestone), being fine-grained with a low porosity and permeability. These properties result from their sedimentation in a low-energy environment, going hand in hand with the weak circulation of water and anoxic conditions (Huc, 1988).

The source rock is an essential element in the petroleum system since, in a way, it acts as a "petroleum and gas factory". Hydrocarbons are formed by thermal decomposition of the "fossilised" organic matter contained within the rock. In any case, sedimentary basins which lack sedimentary intervals with sufficient quantities of organic matter cannot develop oil-bearing deposits.

We should point out here that not all source rocks are the same. In fact, they differ in their organic matter content, their volume (thickness and regional extension) and according to the nature of the fossilised organic constituents. Sedimentary organic matter is classically divided into three "types" (Tissot and Welte, 1984).

– Type I is mainly formed from the remains of bacterial membranes and unicellular algae living in lakes. Although this type is not very widespread, it corresponds to organic matter of excellent quality since 70 to 80% of its initial weight can be transformed into hydrocarbons if the rock undergoes an appropriate thermal history (see below). The best-known examples are the early Cretaceous lake deposits on the western margins of the African continent and the eastern margins of South America, (see below), as well as the lake deposits of the Tertiary in South-East Asia and certain Chinese intracontinental basins.
– Type II, by far the most common, is mainly composed of the remains of planktonic marine algae. The source rocks in the North Sea, Venezuela and Saudi Arabia represent well-known examples containing Type-II organic matter. Whilst being very prolific in terms of oil-bearing potential (40-60% of the organic material transformable into hydrocarbons), Type II is nevertheless of a lower quality than Type I.
– Finally, Type III corresponds to the source rocks found for instance in fossil deltas. The organic precursors are essentially made up of the remains of higher terrestrial plants. In this respect coal represents a particular example of this Type III. While the oil-bearing potential of this type is relatively low (10-30% of the material transformable into hydrocarbons), this is often compensated by the very great thickness (up to several thousand metres) of the sediments containing the organic matter.

• A system of drains, generally made up of porous and permeable rocks, which are also referred to as "***reservoir rocks***". These rocks have porosity (void space separating the mineral grains) ranging from 5 to 25%, and even up to 30%, of the rock volume. The hydrocarbons formed within the source rock are later expelled towards the reservoir. Due to their buoyancy, the hydrocarbons migrate towards the surface of the basin along sedimentary beds (in almost all cases, petroleum products have a lower density than the water completely impregnating the sedimentary rocks). Sets of fractures or faults can also act as drains for the hydrocarbons. These drains can also be considered as the "plumbing" of the petroleum system.

• A ***cap rock*** must be situated above the drains. Because of its impermeable character, the cap rock will confine the hydrocarbons to the porous and permeable system within which they are migrating. For example, the cap can be a clayey rock or massive salt (evaporites). The absence of cap rocks results in the dispersal of the hydrocarbons in the sedimentary basin and their escape towards the surface, where they are destroyed by chemical (oxidation) or biological (biodegradation) mechanisms, in the same way as occurs during accidental oil pollution.

• ***Traps***. During their migration towards the surface, hydrocarbons can encounter flaws in the "plumbing". These may take the form of closures around high points, for example due to the fold geometry of an anticline, the presence of impermeable barriers (breaks in continuity of the drains caused by offsets in the sedimentary succession due to faults) or a deterioration in the drain quality (loss of permeability). These situations create zones of accumulation of hydrocarbon-bearing fluids that correspond to the deposits from which oil operators can extract crude oils and gases. These traps are called "structural" or "stratigraphic" according to whether their main cause is the deformation of the porous layers (folding or faulting) or lateral variations of porosity and permeability in the sediments.

1.2 Evolution of a Petroleum System

Apart from containing these essential ingredients, the petroleum system should be seen as a whole entity functioning in a dynamic framework.

Over the course of geological time (generally some tens of millions of years) the source rock in a subsiding basin (see above) will become buried and its temperature will rise. The increase of temperature with depth, which is well known to miners, is partly explained by the contribution of fossil thermal energy and its progressive dissipation over time. This contribution accounts for about a half of the heat flow, originating from the time of the Earth's formation during the accretion of planetesimals around 4.5 Ga ago. The remaining contribution comes from the thermal energy released due to the continual decay of radioactive elements naturally present in the Earth's crust. This thermal flux from the Earth is manifested by a progressive increase of temperature with depth in the sediments of about 30°C/km (known as the geothermal gradient). It should be noted that the value of this geothermal gradient is not constant and varies across a wide range according to local geological conditions.

This increase in temperature during the subsidence of the source rock prompts the transformation of part of the organic matter that is present into petroleum and gas *(Fig. 1)*. It is described as entering the "oil window" and then the "gas window". This involves a phenomenon of "cracking" which, activated by thermal energy, leads to the breaking of chemical bonds and the production of chemical species of lower and lower molecular weight. The "large molecules" characterising the initial "solid" organic matter are split up into smaller molecules that make up a liquid called petroleum. Then, with rising temperature, these molecules are themselves reduced in size, thus forming a gas. This corresponds to a kinetic phenomenon that depends on both temperature and time. For petroleum to be formed, a thermal history is required that involves progressive heating up of the source rocks. For example, to be effective the Tertiary source rock of the Californian oils was brought to around 115°C in 20 Ma and the Jurassic source rock of the Paris Basin to around 100°C in 100 Ma.

The hydrocarbons formed in this way are expelled from the source rock ("primary" migration "per ascensum" or "per descensum"). In fact, this displacement is governed by the difference in pressure between the source rock and the drains, a difference due to the greater compressibility of the former. This is just what happens when a sponge (source rock) is pressed between two porous bricks (surrounding reservoir rocks)!

After expulsion from the source rock, the hydrocarbons migrate towards the surface of the basin along the drains ("secondary" migration), until they eventually encounter a trap where they can accumulate.

Hydrocarbons will eventually find their way to the surface if they are not held back by the traps or if the cover forms an inadequate seal. Alternatively, the integrity of the cover may become modified thorough the course of geological history. In such cases, hydrocarbons will occur as the natural localised emanations of oil or gas (seepage, shows). These seepages can be found in most of the petroleum provinces which are currently active. They were exploited throughout Antiquity as a source of bitumen, as well as by the early explorationists who used them to locate oil deposits. The analysis of seepages, when they exist, still forms part of the panoply of modern-day oil explorationists. In some cases, this arrival of oil at shallow depth leads to the formation of enormous superficial accumulations impregnating the exposed rocks. This is the case with the bituminous sands of Alberta in Canada or the Orinoco bituminous belt in Venezuela. Oils reaching the surface in this way, or which accumulate at shallow depths, are altered by bacteria, that render the oils very viscous (Connan, 1984; Head *et al.*, 2003). This is not a marginal phenomenon, since these oils —which are qualified as "heavy" or "extra heavy"—make up almost half of the world's oil reserves. There is a strong increase in the exploitation of these heavy oils.

We should note that the detailed molecular composition of the hydrocarbons derived from a given source rock actually represents a “fingerprint”. By the simple analysis of a petroleum sample, we can thus identify the source rock in which the sample was formed. This type of detective work, which is called “oil-source rock correlation”, is based upon methods of chemical analysis such as gas phase chromatography coupled with molecular or isotopic mass spectrometry (Peters and Moldowan, 1993). This kind of information proves very useful when the exploration geologist is confronted with multiple petroleum systems, as in the case of the Atlantic margins as described below.

The body of knowledge brought together over recent years has not only led to an improved understanding of petroleum systems but has also quantified the geological, physical and chemical phenomena involved. Moreover, these phenomena have been formalised by means of equations (for example, kinetic-chemical equations for the formation of hydrocarbons). On this basis, it has been possible to develop the algorithms lying at the very heart of numerical basin models, which provide veritable simulations of petroleum systems (Burrus, 1997; Schneider *et al.*, 2000; Ungerer *et al.*, 1992; Welte *et al.*, 1997). We can use these simulators to reconstruct the history of the geometry and sedimentary filling of a basin through geological time. Using geological cross-sections or three-dimensional volumes, we can represent the thermal history of the sediments (particularly the source rock), the formation of hydrocarbons, their migration within the basin and their accumulation in traps. Under favourable conditions, these simulations can suggest the nature of the hydrocarbons contained in the deposit (oil or gas) and even propose a more detailed chemical composition.

At present, these models serve to integrate data at the level of a sedimentary basin. They allow the testing of geological hypotheses and, when they are sufficiently constrained by the available information (in the case of extensively explored basins), they can be used, with prudence and experience, as a means of prediction.

2 THE CASE OF THE SOUTH ATLANTIC

About 140 Ma ago, at the beginning of the Cretaceous, a huge continental mass (Pangea) was split up giving rise to the two continents that we now know as South America and Africa. This separation process was initiated by the thinning and dislocation of a mainly granitic continental crust. The thinning was caused by the local uprise of partially melted igneous rocks coming from the underlying asthenosphere *(Fig. 2)*. The geographical setting of this break-up zone, corresponding to what geologists call the “rifting” phase, is very similar to that observed today along the East African Rift Valley: a long corridor with a series of successive shifted faulted troughs occupied by large lakes *(Fig. 3)*. Thick sedimentary layers rich in Type-I organic matter were accumulated in these lakes, interbedded with sandy and carbonate-bearing sediments that can exhibit the properties of a reservoir rock *(Fig. 4)*. The rifting phase can be followed, as in the case of the South Atlantic, by a spreading apart of the continental domains, which become separate blocks, and the creation of a sedimentary basin that widens as it grows *(Fig. 3)*. In the course of this opening, the remains of syn-rift lake basins are preserved on the margins of both the African and American continents. Within these basins, we find the most prolific source rocks in the South Atlantic region. These rocks are responsible for a large part of the enormous oil reserves in Angola, Congo, Gabon and Brazil. The drifting apart of the two continents allows the periodic incursion of oceanic waters into the newly formed basins. The phases of filling of these basins alternate with periods of isolation, during which the seawaters are not replenished and evaporation gives rise to thick layers of salt (evaporites). These layers, dated at around 120 Ma, cover the previously formed lake basins. The confinement of the environment at that time also leads to the regional deposition of rocks rich in organic matter able to act as source rocks, as has been demonstrated in certain Brazilian deposits. The opening of the South Atlantic then continues with the formation of an oceanic crust made up of basaltic volcanic rocks that are erupted at the mid-ocean ridge formed at the site of the initial rift. With the widening separation and establishment of communication with the rest of the world’s oceans, the marine sedimentary environment becomes permanent. The accumulation of salt is interrupted to make way for limestones and marls (marls are rocks made up of a mixture of limestone and clay), and sometimes sandy sedimentation. These limestones correspond to the excellent reservoir rocks along the African and American margins. However, this new ocean remains somewhat isolated from the open marine circulation and thus maintains its confined character. This situation is favourable for the establishment of anoxic conditions, which leads to the intermittent deposition of new source rocks, this time belonging to Type II. At the end of the Cretaceous, that is around 80 Ma ago, the oceanic basin become sufficiently wide so it is ventilated by the circulation of marine waters containing dissolved oxygen. In this way, the conditions for preservation of the source rocks are no longer satisfied. It is not until the end of the Cretaceous and particularly the Tertiary, around 50 Ma ago, that we see the extensive development of detrital deposits, notably deltas. These deposits are formed at the outlets of major drainage basins accumulating material eroded from the continents, making up the thick clayey-sandy successions as observed, for example, in the Niger delta. This depositional regime is favoured by the cooling of the now old oceanic crust associated with the continental margins. This cooling increases the density, and hence the weight, of the oceanic crust, which results in subsidence and a tendency towards

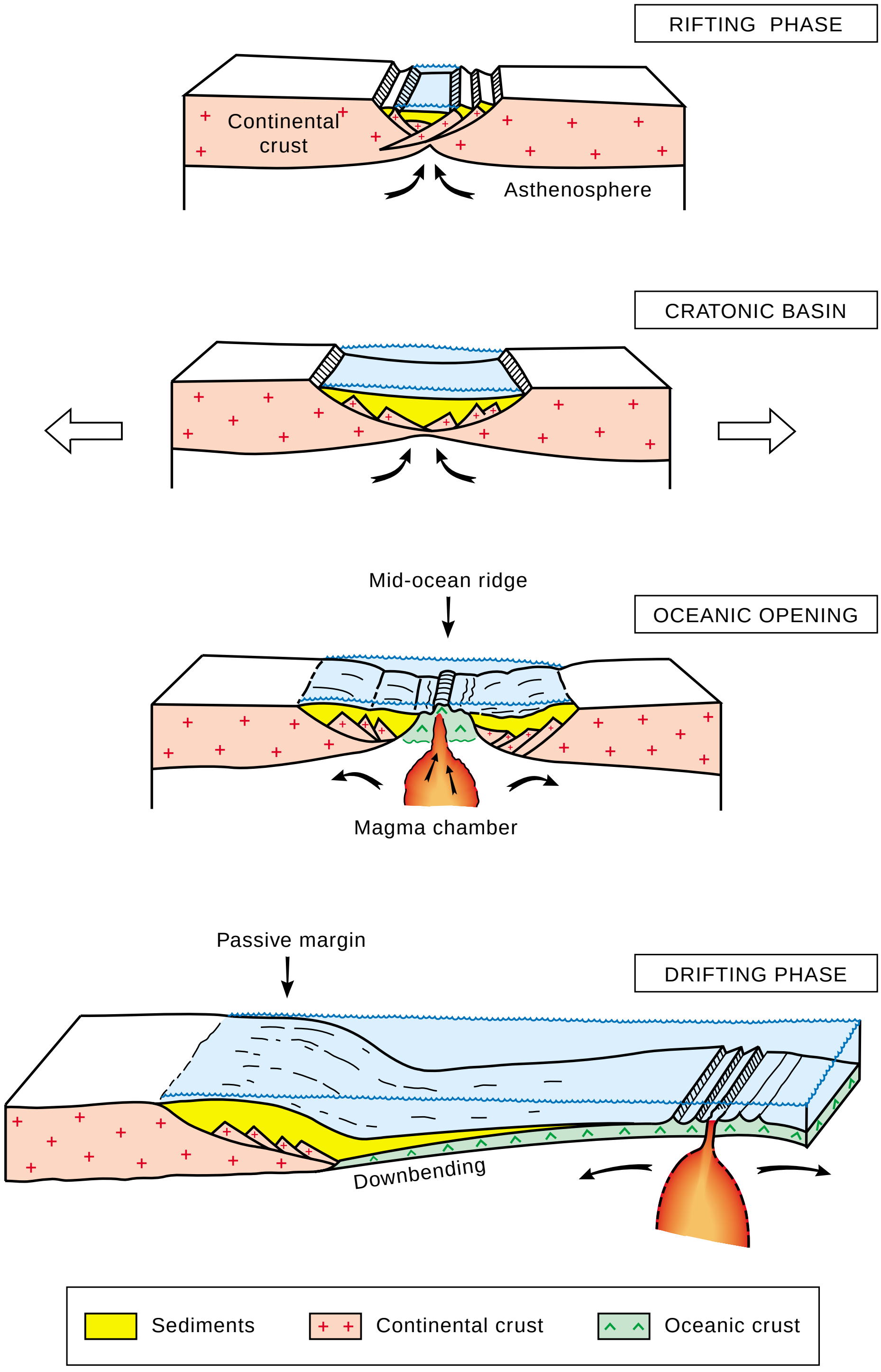

Figure 2

Stages in the opening of the South Atlantic.

The opening is initiated by the break up ("rifting" phase) of an initial continental mass (Pangea), caused by a regional phenomenon of magma ascent along a line foreshadowing the future mid-oceanic ridge. The resulting fault troughs (or rifts) are occupied by large lakes such as those observed today in the East African Rift. The initial corridor widens progressively giving rise to a marine basin, a "cratonic basin" still underlain by continental crust. The asthenospheric magma then begins to be emplaced at the level of the mid-oceanic ridge, where it generates a basaltic oceanic crust making up the floor of the ocean being formed. This is the "drift" phase. As the ocean basin continues to open, the oldest parts of the oceanic crust, situated nearest to the continental margins, become progressively colder and their density increases, which leads to warping under the effect of their own weight. This corresponds to the phenomenon of "downbending" or "flexure". Thick terrigenous sedimentary sequences are accumulated in the space thus created at the end of the Cretaceous, but especially during the Tertiary.

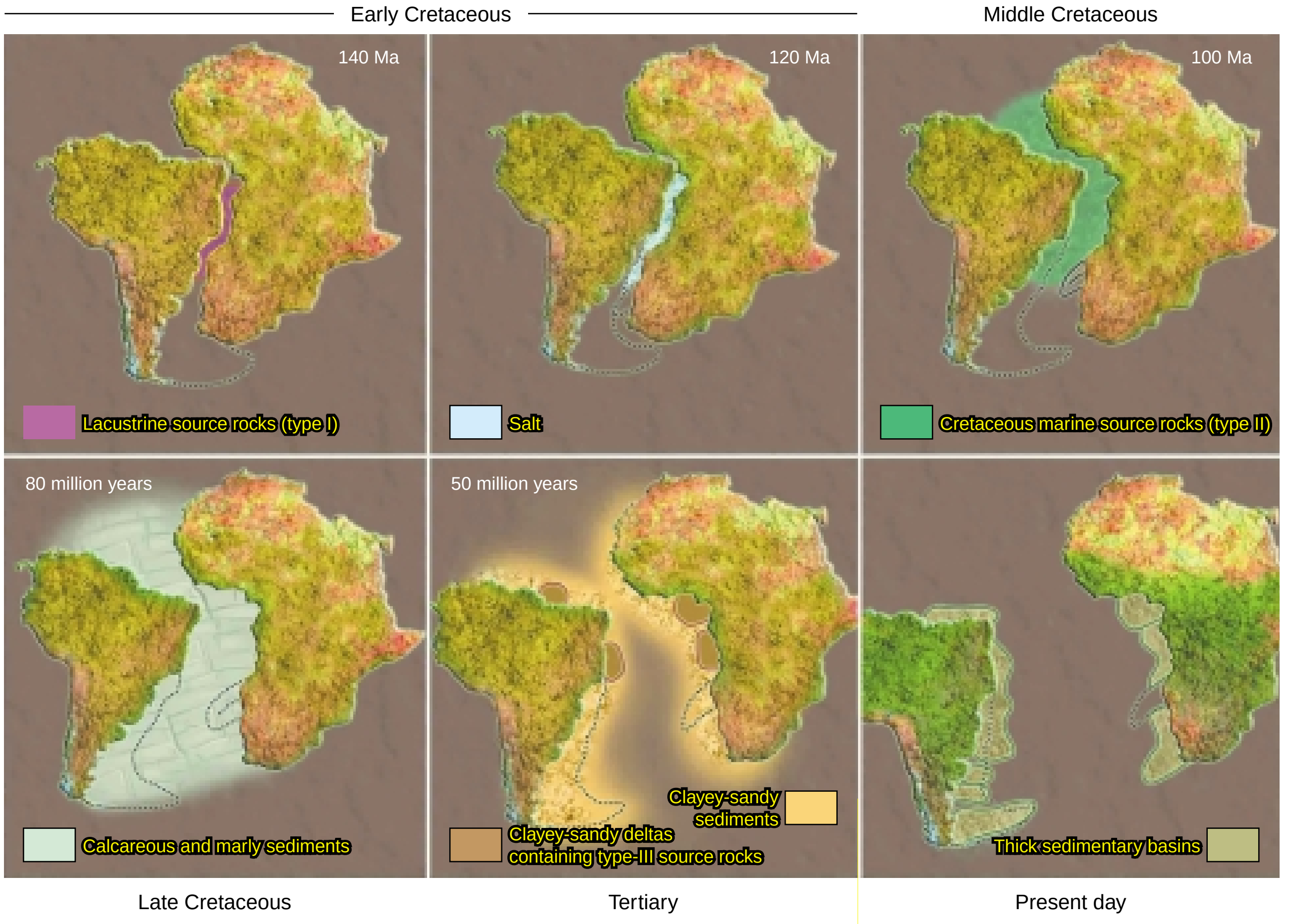

Figure 3

Evolution of the sedimentation regime during the opening of the South Atlantic and deposition of the principal source rocks. During the rifting phase, the depressions caused by continental break up are occupied by lakes, in which Type-I source rocks are accumulated. During the Aptian, the initial "corridor" gives way to an oceanic basin of irregular depth and still only of moderate width. This basin, 3500 km from North to South and 600 km at its widest (southern part), is periodically isolated from the worldwide ocean: it then becomes the site of evaporation phenomena resulting in the accumulation of large quantities of salt and the regional deposition of sediments rich in Type-II organic matter. The basin widens progressively, but its communication with the world ocean remains limited, notably because of physiographic barriers such as the Walvis ridge and the Falkland plateau. This confinement hinders the circulation as well as the oxygenation of water masses, which favours the accumulation of organic matter and the formation of Type-II source rocks. During the Late Cretaceous, as the opening continues, the ocean becomes ventilated, thus interrupting the conditions favourable for the accumulation of source rocks. The sediments are now essentially composed of marls. Right at the end of the Cretaceous, and more particularly in the Tertiary, thick layers of terrigenous sediment fill the available space produced by the "downbending" of the margin. The sedimentary deposits are thicker on the African side, because of erosion of greater intensity due to the uplift of the continent in response to its collision with the European continent. Type-III source rocks can be locally deposited at this stage.

"downbending" (or flexure) of the margin. In this way, space is created to accommodate the detrital sediments from the continent. These sedimentary detrital complexes can contain levels rich in Type-III organic matter derived from continental plants, as well as reservoirs made up of sandy channels interspersed within clays that act as cap-rock.

The South Atlantic is characterised by several notable features (Mello and Katz, 2000) *(Figs. 5 and 6)*:

– The existence of several families of source rock having different ages and quality.
– The availability of multiple reservoir levels within the main sedimentary sequences, *i.e.*: pre-salt lacustrine deposits, post-salt marine carbonates and Tertiary clayey sands.
– The presence of efficient drains often corresponding to faults classically associated with basins resulting from tectonic opening, as seen in the case of the South Atlantic, and from faults characteristic of rapidly growing deltas (Niger Delta). When they exist, these drains allow the vertical migration of hydrocarbons formed in the source

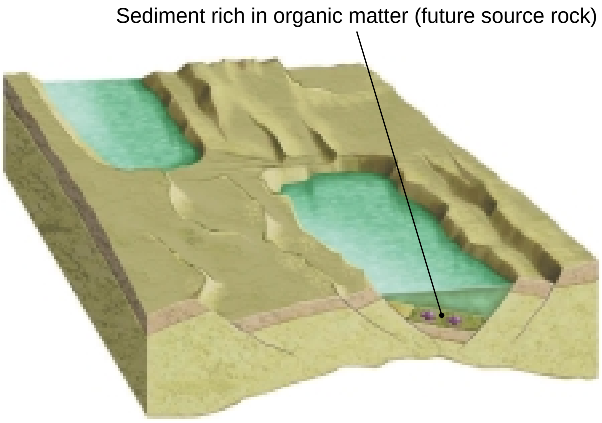

Figure 4

The "rifting" phase is characterised by the establishment of a corridor several thousand kilometres long, which contains a series of troughs offset from each other and occupied by large lakes. Thick sedimentary layers rich in Type-I organic matter (future source rock) are deposited in these lakes, interspersed with sandy and carbonate-bearing sediments that can exhibit reservoir properties.

rocks towards reservoirs situated at a higher level in the sedimentary pile.

– The occurrence of good quality cap rocks. The salt-bearing interval is particularly impermeable to hydrocarbons, so where this lithology is continuously present, it plays a major role by confining the hydrocarbons formed in the underlying lacustrine deposits. These hydrocarbons can reach the post-salt reservoirs only in places where salt is absent or discontinuous. This discontinuity shows up notably at more distal locations away from the shoreline, where the salt is deformed under the action of gravity. The salt makes up veritable rafts isolated from each other. In fact, salt has the property of exhibiting a ductile behaviour and thus creating decollement surfaces over which the other sediments can easily slide. The flowage of the salt, which is one of the consequences of the downbending of the margins, causes the reactivation of faults in the post-salt succession. These faults have an important role in the migration of hydrocarbons.

– The existence of a geometry favourable for the development of a wide variety of traps. These comprise structures formed by salt rafts, as well as major anticlines in the Tertiary succession (resulting from gravitational deformation above the preferential decollement level, *i.e.* salt) and stratigraphic traps (Duval *et al.*, 1992).

Thus, the wealth of oil in the South Atlantic can be explained by the multiplicity of the petroleum systems. The activation of these systems, that is to say, the thermal maturity of the different source rocks, is mainly controlled by the thickness of the sedimentary deposits covering them. The regional sedimentation regimes and geodynamic evolution of

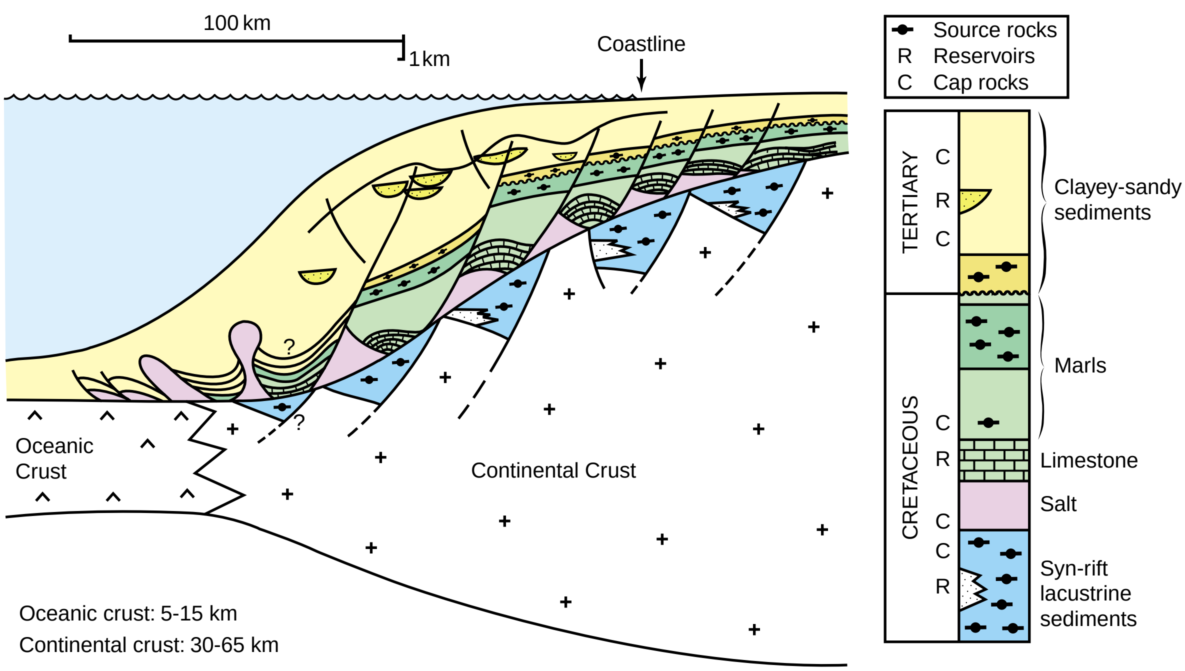

Figure 5

Schematic geological cross-section of a typical South Atlantic margin. The example chosen is based on the situation in offshore Gabon, Congo and Angola. The horizontal scale bar does not apply to the thickness of the continental and oceanic crusts.

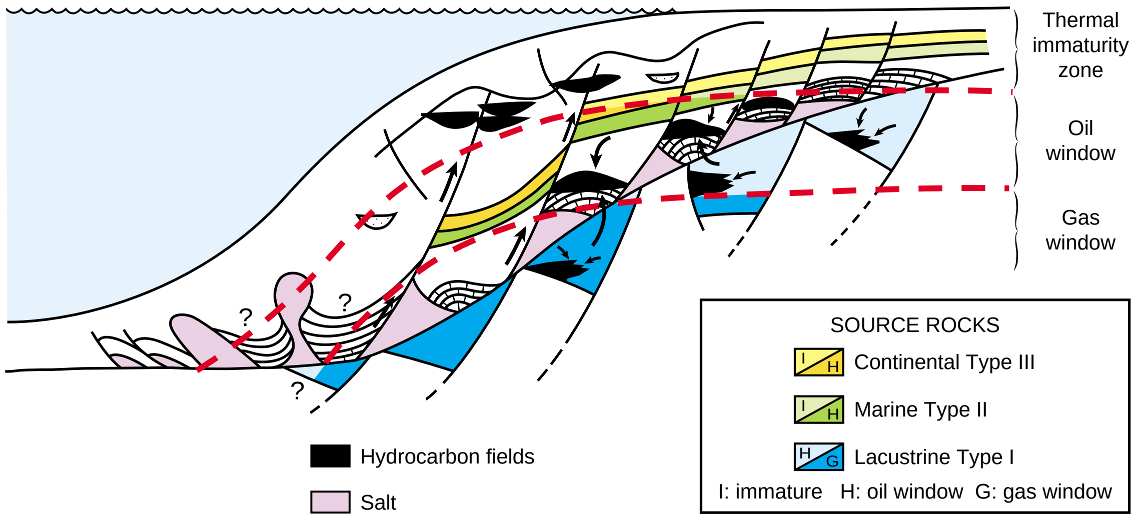

Figure 6

Formation and migration of hydrocarbons in the petroleum systems on the African margin of the South Atlantic. A similar situation is found on the South American side, but with a smaller thickness of terrigenous Tertiary sedimentary filling.

the margins are therefore determining factors. As an example, the Campos Basin in offshore Brazil and the Lower Congo Basin both contain lacustrine source rocks (Type I) emplaced during the rifting phase as well as more recent Cretaceous marine source rocks (Type II). The higher rates of sedimentation characterising the African margin often allow the production of hydrocarbons at both levels of the source rocks, while only the lacustrine source rocks have reached the "oil window" in the Campos Basin. This difference in sedimentation rate results from the collision between the continents of Africa and Europe. In fact, one of the consequences of this collision was the uplift of the African continent, which favoured the erosion and transport of large volumes of terrigenous sediments accumulating on the African margin since the end of the Cretaceous.

The enormous quantities of sediments deposited at the mouth of the Niger River during the Tertiary (the thickness of the delta can reach up to 11 km) has resulted in the thermal maturation of the source rocks contained within the sedimentary succession (mainly of Type III). This organic matter is at the origin of almost all the colossal oil reserves in the delta, which place Nigeria in twelfth place among the world's oil producers.

3 DEEP OFFSHORE

For a long time, the technological limitations of drilling did not allow oil companies to venture into offshore zones where the water depths exceeded 200 m. The considerable technological advances in recent years have ensured that the deepwater domains (from 500 to several thousand metres deep) are accessible to the major operators. *Total* and *Petrobras* have been world leaders in this race to the ocean depths, carrying out their operations on the African and Brazilian margins, respectively. Beyond the mere technical achievement involved, this seaward movement of the zones of interest has raised new conceptual challenges in the geosciences. Without casting doubt on the body of knowledge acquired on "conventional" petroleum systems over the last few decades (as outlined above), we need to take into account a geological reality that is modified with increasing distance from the coastline.

In this way, the sedimentary thickness tends to increase farther offshore, chiefly because of the greater input of Tertiary clayey sands that actually modify the conditions of source rock maturity (Schoellkoepf and Patterson, 2000). The lacustrine source rocks that were producing oil in the proximal zone are buried more deeply in the distal zone, and are likely to produce gas. As a result, although the post-salt source rocks (Cretaceous and Tertiary) are immature in the proximal zone, they can become oil generating in the distal zone *(Fig. 6)*.

The ability to predict the nature of the expected fluid —whether oil or gas—depends on the implementation of properly applied numerical modelling, which therefore takes on a real strategic importance. For many years, the difficulties involved in transporting gas has meant that this fluid used to be largely ignored by prospectors in certain geographical contexts. However, the policies for developing gas in many countries has now given it a growing economic role. On the one hand, for local use, gas can be re-injected into fields to increase the oil recovery yield, and can also provide a suitable energy source for the production of electricity. On the other hand, once transformed into liquefied natural gas (LNG) in processing plants, it can be exported by sea to the user countries.

The Tertiary reservoirs often correspond to channels and sandy lobes deposited at the foot of slopes. Up to quite recently, the sedimentology of these bodies (distribution, architecture and internal structure) was poorly understood, and they remain the object of very active research work (Navarre *et al.*, 2002). Some of these reservoirs may only be buried at relatively shallow depth and, consequently, they are made up of poorly consolidated sands. This represents a real source of problems linking to their behaviour during production. For similar reasons, the cap rocks associated with these reservoirs can be of mediocre quality and, if they are poorly indurated, they may allow escape of the hydrocarbons. In this situation, the shallow burial can also lead to oil fields having a low enough temperature to allow the development of bacteria. When this occurs, the microbial activity transforms, by biodegradation, the petroleum into a high-density viscous fluid called “heavy oil”. This latter is difficult to produce and has a low marketing value. Given the investments involved, this means that certain prospects are rendered of little or no economic interest.

We should remember that explorationists have very elaborate geophysical methods at their disposal that enables them to not only define the geometry of the traps but also identify the potential reservoirs more “directly”. In some favourable cases, these tools can even detect the fluids present. Some of these techniques, which might be compared to medical echography, are based on the generation of surface waves (for example, airguns are used at sea) and then analysing the waves reflected off geological objects situated within the sedimentary pile. However, this method entails certain uncertainties regarding the precision and geological reality of the images obtained, so the last word, of course, always belongs to the drilling results.

4 ULTRA-DEEP OFFSHORE

Finally, the pursuit of oil exploration into even more distal and deeper domains poses an acute problem concerning the evolution of petroleum systems.

Beyond a certain distance offshore, the sedimentary thickness begins to decrease. This eventually results in the rise of lacustrine source rocks back into the oil window, whereas, as described in an earlier paragraph, the same rocks would be situated in the gas window in domains nearer the coastline. Similarly the Tertiary and then Upper Cretaceous source rocks would come back into the immaturity zone, while they did reach the oil window in sectors nearer the coast exhibiting a thicker sedimentary pile. Insufficient burial of the whole set of source rocks can result in their thermal immaturity and a consequent lack of hydrocarbons *(Fig. 6)*.

This point concerning the thermal history becomes even more crucial as the heat flux at the base of the sediments decreases. This tendency can be attributed, on the one hand, to the reduced thickness of the continental crust containing radioactive elements that decay to produce heat. On the other hand, the continental crust is replaced by oceanic crust that does not contain such heat-producing elements, so, accordingly, it is “colder”. By acting together, these two phenomena will define the extreme limits of viability of present-day petroleum systems. The numerical modelling mentioned above is an extremely valuable tool because it enables us to simulate the local thermal conditions that the source rocks have undergone. However, these models can be made even more precise if they are supplied with high-quality geological and geophysical data that are used to build the “simulator” and constrain its results. We have seen the economic impact of such simulations.

The fundamental constituents of petroleum systems are no longer guaranteed to be present in ultra-deep zones, so the very existence of such systems is also a central concern in oil exploration.

In fact, we have little or no understanding of the maximum extension and quality of source rocks and reservoirs in deep offshore zones (Stow *et al.*, 2001).

Exploration is rendered even more problematic because the most distal parts of these sedimentary basins, situated at the greatest water depths, exhibit very complex geometries due to the compressive tectonics, linked mainly to the gravitational movements mentioned previously (Jackson and Cramez, 1998). The tectonic style is characterised by the thrusting of sedimentary blocks and the presence of salt domes *(Fig. 5)*. “Imaging” of the subsurface by geophysical tools is made very difficult by the steep dips within the sedimentary blocks as well as the presence of salt, and requires the implementation of highly sophisticated processing of the received signals.

CONCLUSION

The South Atlantic, along with the Gulf of Mexico, is currently one of the principal theatres in the adventure of deep and ultra-deep offshore petroleum. This endeavour can only be carried out with very heavy drilling costs, so it is imperative to achieve a high rate of success. For reasons of economic profitability, the hydrocarbon discoveries made under such conditions will demand fields of very large size (several hundred Mbbl) with a very high productivity for each well: around 8000 to 10000 bbl/d (1 bbl corresponds to around 159 l). This inescapable constraint means that the operators must possess an increasingly powerful capacity for understanding and predicting petroleum systems, as well as an ever-increasing mastery of the visualisation of geological structures and reservoirs using geophysical tools. In this respect, the successes recorded in these “frontier” regions, as well as the hopes of future discoveries, reflect the ability of the petroleum industry and researchers in the earth sciences to push back the technological limits ever further and develop innovative geological concepts.

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