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# CONTRIBUTION OF SEISMIC AND GEOTHERMAL DATA ANALYSIS TO THE ASSESSMENT OF THE HYDROCARBON POTENTIAL OF THE CENTRAL BASIN OF THE D.R. CONGO

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## ABSTRACT

This paper presents an evaluation of the hydrocarbon potential of the Cuvette Centrale basin in the Democratic Republic of Congo (DRC) using an integrated approach that combines seismic and geothermal data. The envelope attribute of seismic data was used to identify different rocks of the petroleum system, including potential gas-prone zones. The interpretation of seismic profiles helped to delineate geological units and determine their lithology. Isobath maps based on seismic data revealed the presence of grabens and anticlines, which are favorable geological structures for hydrocarbon accumulation. Analysis of the geothermal gradient and temperature evolution in the formations allowed us to establish source rock maturity maps, highlighting two distinct zones: an overmature zone favorable for gas and a mature zone favorable for oil. These results suggest a strong hydrocarbon potential in the Cuvette Centrale basin.

**Keywords:** seismic data, envelope attribute, isobaths, geothermal gradient, source rock maturity.

## INTRODUCTION

Exploration of the Cuvette Centrale since the 50s has been based on Geological, geochemical, and geophysical studies, along with their respective interpretations, were conducted by various foreign companies and organizations, including the Brussels laboratories of TERVUREN, CGG, and the Belgian firm REMNA. Field work was also carried out by the Secrétariat Général des Hydrocarbures [23, 25] has confirmed that there are indeed surface showings at several sites, as well as reconnaissance of potential source rocks, reservoir rocks and blankets.

The results of previous work have enabled us to divide the Cuvette Centrale into sub-basins and oil blocks. This sedimentary basin is made up of seven sub-basins: Lokoro, Busira, Bushimay, Kwango, Lindien, Ouest-Congolien and Lomami. Of these sub-basins, only three (Lokoro, Busira and Lomami) have been the subject of geological, geophysical and well studies [25].

This study aims to characterize the Cuvette Centrale petroleum system using a multidisciplinary approach to identify areas favorable for hydrocarbon accumulation in the Cuvette Centrale Basin. The results of this study will help guide future oil and gas exploration in the region.

## GEOLOGICAL SETTING

The Cuvette Centrale (Figure 1) covers ±1,000,000 km$^2$ of the national territory of the Democratic Republic of Congo and, with a sediment thickness of 9 km, remains the greatest hope for oil prospects. The optimum conditions for hydrocarbon formation are to be found in this regional basin with a large radius of curvature, formed by thermal subsidence after the Pan-African stretching episode. Structural analysis confirms seven sub-basin compartments, including: Busira, Lokoro, Lomami, Bushimay, Kwango, Lindien and West Congolian.

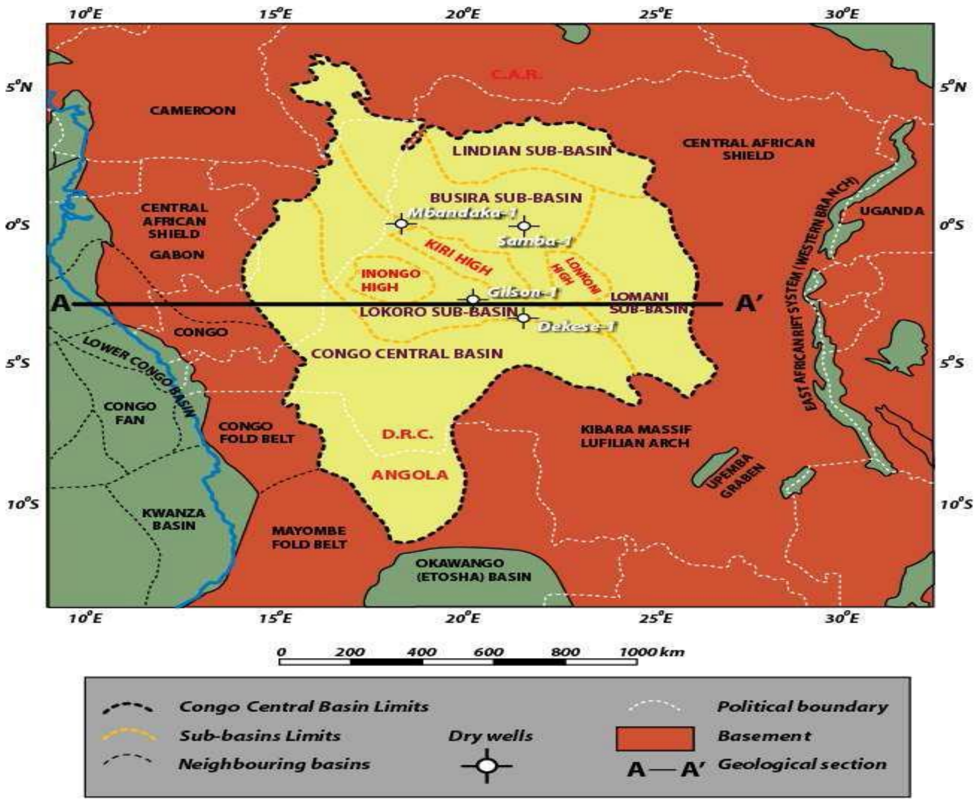


***Fig.1***. *Map of the Cuvette Centrale sub-basins* [2]

At several levels of the geological and/or stratigraphic assemblages, sedimentation provides opportunities for the genesis of mature source rocks, reservoirs and potential coverings. Confirmation of the seepage along the Lukenie River and Lake Maï-Ndombe as a surface indication by the Brazilian firm HRT in 2007 means that one or even more petroleum systems may exist in this sedimentary basin.

The geological structures of the Cuvette Centrale (Figure 2) are configured in steps that slope slightly from east to west. The Cuvette Centrale was formed in several stages, depending on the geological period. Today's structures are the superimposition of different crustal movements. The geological history of the DRC can be divided into two main periods. Firstly, there are the Precambrian bedrock formations, with their complex tectonics (numerous folds and faults). These formations are more or less metamorphic and, regionally, very granitized. The Phanerozoic overburden, dating from the Upper Carboniferous to the Holocene, lies unconformably on top of these ancient layers. Generally speaking, this subdivision corresponds to a distinct geographical distribution. The bedrock formations outcrop mainly at the edge of the Cuvette Centrale, which in turn is made up of most of the overburden. The latter also appear in the coastal zone between the Atlantic Ocean and the Cristal Mountains, and cover part of the Kasai Basin. Finally, recent formations of various facies are found above the two main subdivisions. Let's take a closer look at how the country's subsoil was formed [26].

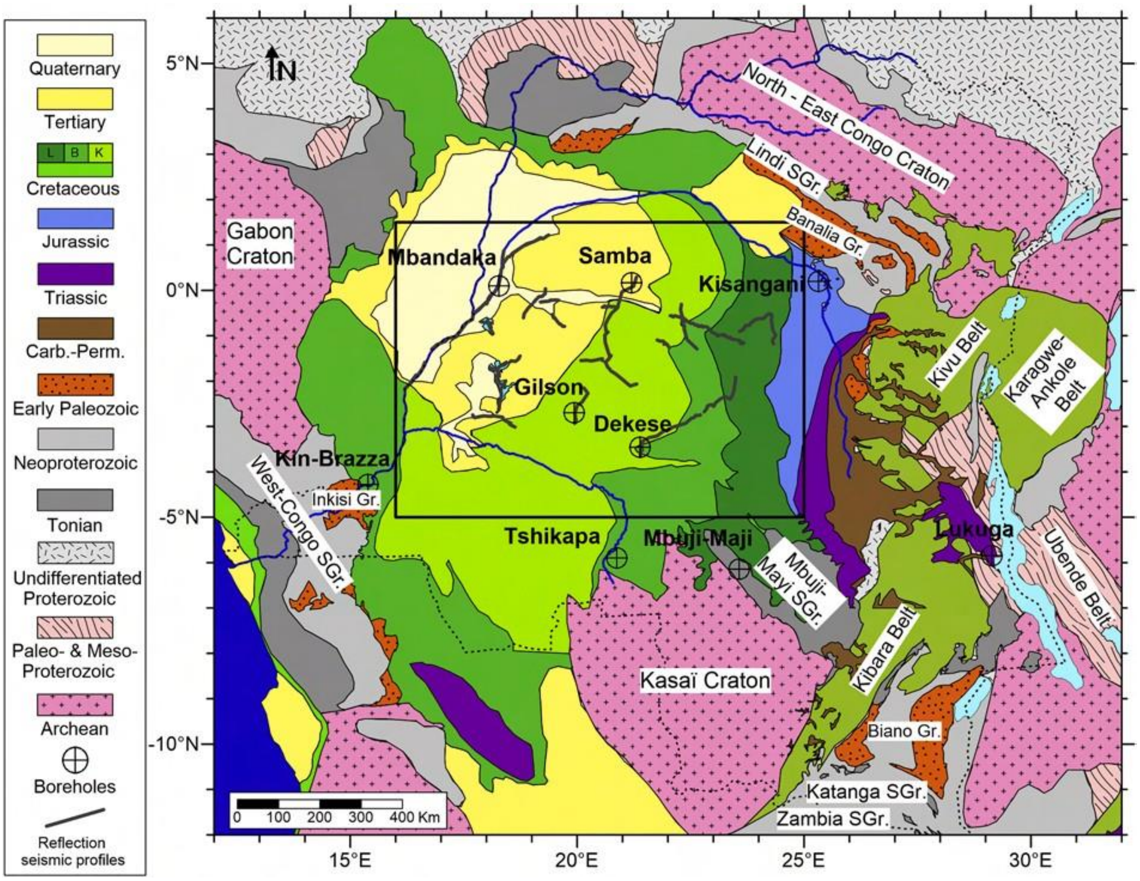


*Fig.2. Geological map of the Congo Basin [3]. The figure includes deep wells (Dekese, Gilson, Mbandaka, and Samba) and areas of shallow wells (Kisangani, Mbuji-Mayi, Tshikapa, Lukuga, and Kinshasa-Brazzavile) in the periphery. The broken lines represent reflection seismic lines, and the black rectangle indicates the study area.*

The bedrock formations are subdivided into two distinct units: the older Katangian formations and the Ante-Katangian formations. The Ante-Katangian formations (absolute age prior to around 1300 Ma).

At present, it is proposed to subdivide these training courses into three groups:

- First, there are the oldest rocks in the Democratic Republic of Congo, thought to predate 2,700 Ma, with the oldest absolute age at around 3,400 Ma (essentially gneissic rocks from the Upper Luanyi in Kasai and the Bomu Basin);

- Then there is a series of formations that outcrop regionally but have no geographical continuity. They are therefore referred to by regional names. These are a series of metasediments, generally poor in limestone, which are regionally very granitized. They occur in western, north-western and north-eastern Congo, as well as in Kivu-Maniema, southern Shaba and the Kwango-Kasai-Lomami region;

- The Kibaran chain continues into Maniema and Kivu, where it is referred to as the Burundian, but its stratigraphy is still poorly understood [26].

The Katangian complex, as the name clearly indicates, is found in Katanga, where it occupies the central and southern part, to the south-east of the Kibaran chain. In this region, the Katangian strata rest on top of the Kibaran strata in a markedly unconformable manner. They are therefore younger than the Kibaran, and expressed in absolute age, they represent the final period of the Precambrian, between 1,300 Ma and 645 Ma. From top to bottom, the Katangian formation comprises the Kundelungu, the Grand Conglomerat-Mwashya and the Roan.

A wide variety of rocks can be found here, including dolomites, limestones and kimberlite intrusions [26].

Outside Katanga, there are several groups that are also part of the Katangian and bear regional names. In the north of the country, we find the Lindian (Aruwimi-Lokoma-Ituri basins). Continuing with the Lindian, the Ubangian outcrops (Aruwimi-Lokoma basins). Their lithological composition is identical to that of the Katangian in Katanga .

In Central Kongo, the Katangian occupies an important place in the geology and is called West-Congolian. It outcrops to the east of the older formations of the Luozi-Ngungu region. Moving from west to east, it becomes subhorizontal as it folds. The West Congolian contains a series of schistosandstone rocks unconformably underlain by clay-limestone. At the base are tillites (glacial conglomerates). These tillites are interbedded with basaltic and andesitic lavas, tuffs and dolerites. The latter rock is also reported outside the tillite domain. [26].

Boreholes drilled in the Cuvette Centrale have encountered rocks at great depth that are attributed to either the Lindian or Katangian of Central Kongo. Subhorizontal layers of red sandstone and rare outcrops of 1 carbonate rocks in Maniema are related either to the Lindian of the type region, or to the bedrock of the Cuvette Centrale. There would therefore appear to be fairly good continuity between the three isolated regions where the Katangian is well represented (Katanga, Central Kongo and the north of the country) [26].

## SEDIMENTATION THE CENTRAL BASIN

Towards the end of the Katangian, the continental influence begins to become increasingly apparent. Indeed, the Katangian represents the Late Precambrian, whereas the geological history of the overburden deposits begins in the Late Carboniferous. The overburden deposits often contain fossils that allow them to be assigned a definite geological age. [26].

The first group dates from the Upper Carboniferous and Permian periods and comprises shales, mudstones, psammites, sandstones and poudingues. The latter are often of glacial or periglacial origin. This ensemble outcrops in the Lukuga basin, on the slopes of Lake Tanganyika, in the Luena basin, in Maniema and in the Irumu region. It has been drilled through in the Cuvette. It contains no effusive or intrusive rocks [26]. The Mesozoic contains important formations of different varieties of sandstone and argillite. Limestone, marl and shale are also present. Regionally (e.g. in the Kasai), the Mesozoic complex is crossed by kimberlites. Mesozoic strata outcrop around the perimeter of the Cuvette Centrale and have been identified at depth by drilling in the Cuvette itself.

The Tertiary begins with a thick formation (up to 80 m thick) of soft sands and sandstones (polymorphous sandstone series), followed by an equally thick deposit (almost 120 m thick) of sands and silts (ochre sand series). The two series are often grouped together under the name "Kalahari system" and outcrop in the southern part of the country (including the Kwango and Kwilu basins) [26]. Alluvium (recent and ancient), slope and plateau deposits (including laterites), travertines and cave deposits are formed throughout the interior of the country during the 2nd half of the Tertiary and during the Quaternary. Regionally, these deposits can reach significant horizontal extent, as in the Cuvette Centrale, for example, which is covered by lacustrine and fluvial deposits. Quaternary deposits in and around the basin are poor in fossils. Fortunately, artefacts are frequently found, making it possible to define age based on prehistoric industries. It should be noted that during the Tertiary and Pleistocene periods, many of the deposits were formed under arid to sub-arid climatic conditions, in contrast to today's humid tropical and equatorial climate [26]. In short, the geological formations of the Cuvette Centrale are underlain by a basement of crystallophyll metamorphic rocks (granites, quartz, feldspar, mica and schists). This basement is Precambrian in age and was covered by sediments rich in sand, sandstone, clay, limestone and other minerals.

## STRATIGRAPHY

The Cuvette Centrale basin boasts a rich geological history reflected in its sedimentary layers. These layers, reaching depths of up to 12 kilometers, record periods of uplift (horsts) and subsidence (ditches) [24]. The basin's stratigraphy can be broadly categorized from oldest to youngest:

- Cenozoic Era: Polymorphous sandstones and ochre sands deposited by rivers and wind;
- Upper Paleozoic Era: Carboniferous and Permian formations ;
- Late Proterozoic to Paleozoic Era (Devonian): Three distinct groups:
    - Proterozoic: Marginal marine sediments;

- Cambrian: Alluvial deposits (Bobwamboi arkoses) and shales (Mamung and Koé) formed in deltaic environments;
- Ordovician, Silurian, and Devonian: Gaamboge quartzites (marine dunes), Alolo shales (fluvial), and Banalia arkoses (deltaic).

Understanding the basin's stratigraphy (Figure 3) is an ongoing process aided by continuous exploration efforts [23].

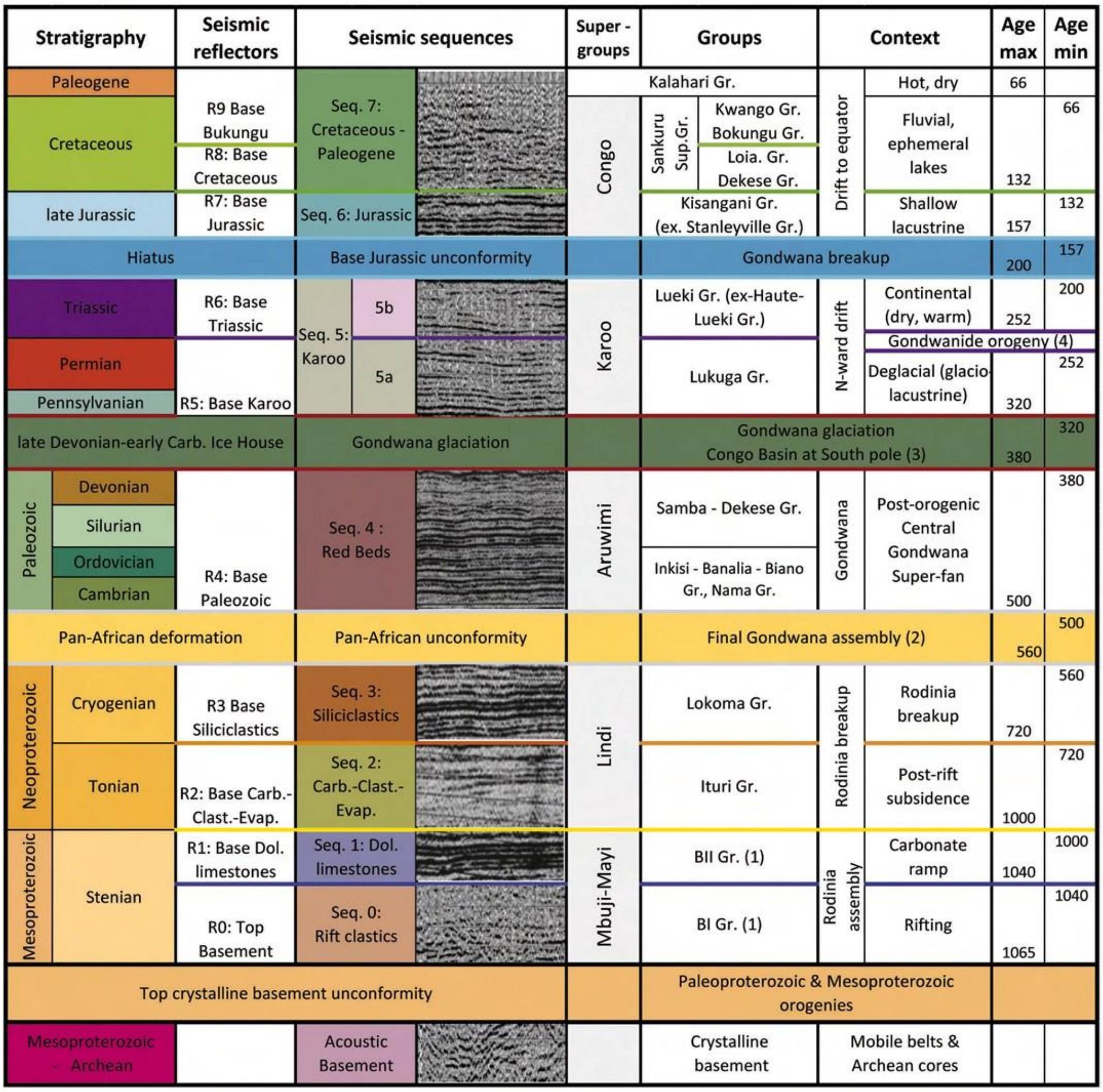


***Fig.3.*** *Illustrating a combined seismostratigraphic model incorporating data from wells, outcrops, and seismic reflection profiles* [3,4,5,6,7,8,9,10,11,12 and 13]. *Age estimations are based on various sources* [11,12,14,15,16,17,18,19,20 and 21].

## SEISMIC DATA PROCESSING

In this article, we will use the envelope filter to highlight the different rocks in the petroleum system.

## ENVELOPE

The attribute of the envelope or reflection intensity shows acoustically strong (bright) events both in negative and positive events. This is the most commonly used trace attribute. It is calculated from the complex trace of the seismic signal to highlight the main seismic features. The envelope represents the immediate energy of the signal, and its magnitude is proportional to the reflection coefficient. The envelope is useful for emphasizing discontinuities, changes in lithology, faults, variations in deposition, tuning effects, and sequence boundaries [1].

Important bright spots in this attribute can indicate the presence of gas, especially in relatively young clastic sediments. The advantage of using this attribute instead of the original seismic trace values is that it is not affected by the phase or polarity of the seismic data, which can affect the apparent brightness of a reflection. Bright spots likely correspond to channel bodies or sand layers due to differences in acoustic impedance. Faults in the envelope attribute are typically characterized by abrupt and discontinuous features. However, it can be challenging to observe the seismic attribute.

## INTERPRETATION OF SEISMIC PROFILES

The seismic profiles shown in the Figures 4, 5, 6 and 7, presented below are interpreted as follows:

- Unit U1 is essentially clayey with a good proportion of carbonate and lies on the bedrock and could correspond to the Ituri clay-limestone formation;
- Unit U2 is essentially sandstone and should correspond to the Bokwamboli sandstone formation. It would be a good reservoir rock;
- Unit U3 is essentially clay with carbonate layers. Based on the stratigraphic scale of the Cuvette Centrale, it would correspond to the Mamungi Shale;
- Unit U4 would be the Galambodge sandstone, in which we find a significant portion of carbonate;
- Unit U5 is deposited in unconformity (Pan-African unconformity) on the basement to the SW and Unit U4 (Galambodge Sandstone) to the NE. This sequence may correspond to the Alolo Shale;
- Unit U6 is made up of carbonate, shown here with low acoustic impedance contrast and bright spots indicating the presence of coarse-grained rocks. The formation is thought to be the Lukuga sandstone carbonate.

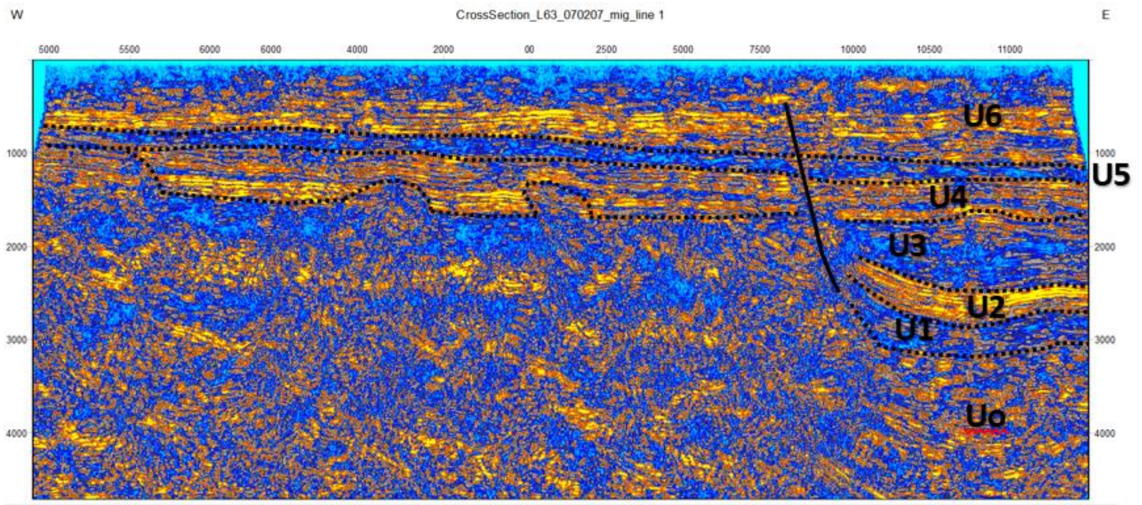


*Fig.4*. Profil L63

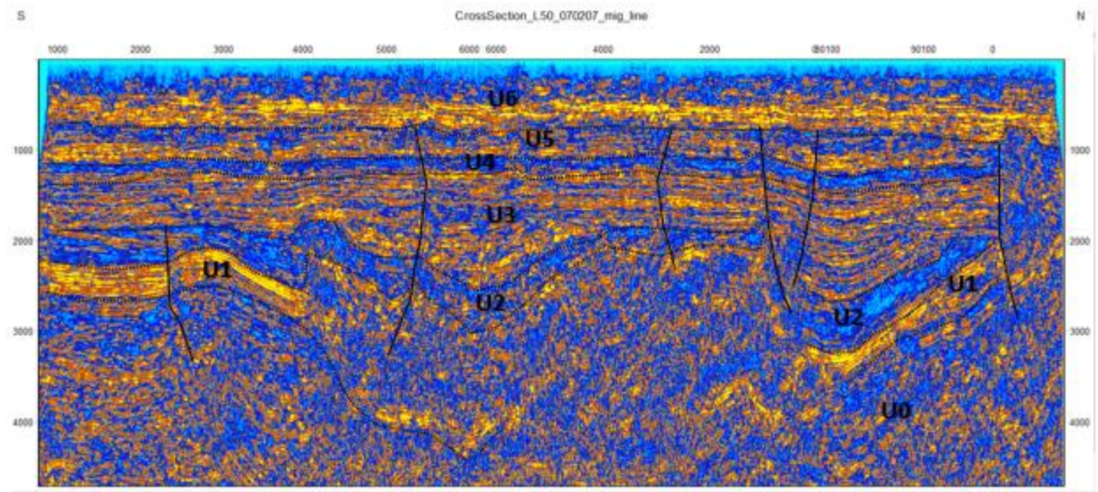


*Fig.5*. Profil L50

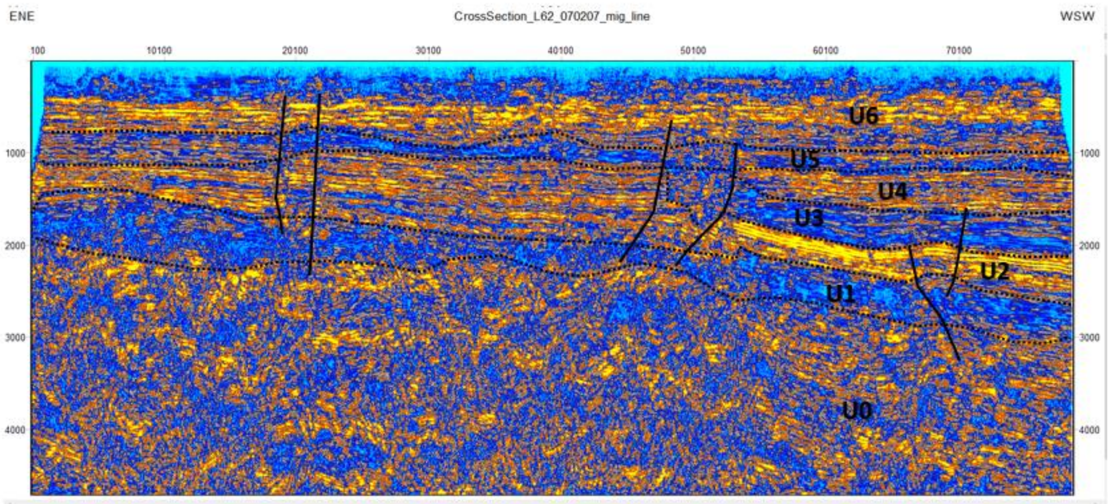


*Fig.6*. Profile L50

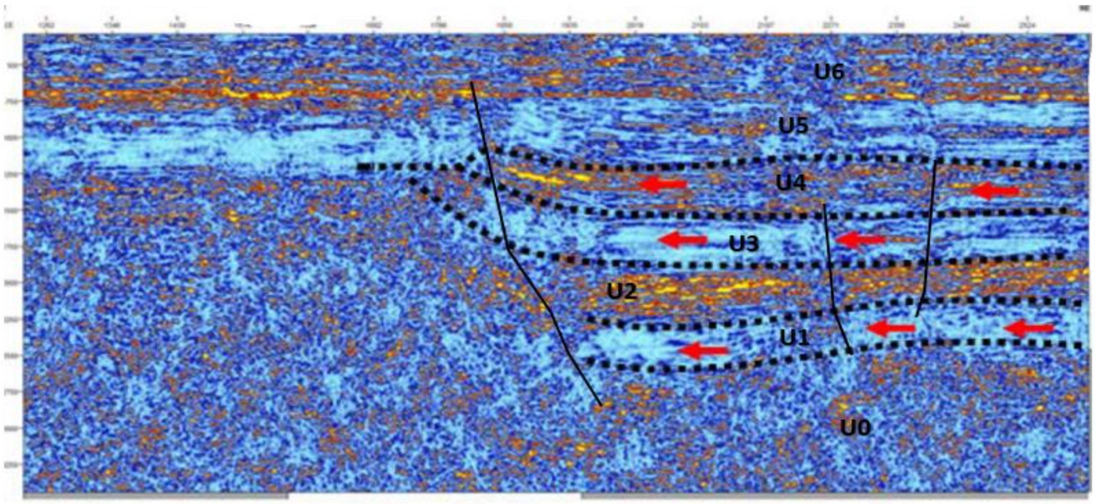


***Fig.7**. Profil R5*

## ISOBATH ANALYSIS OF SEISMIC DATA

The isobath data (Figure 8) come from seismic profiles of the Cuvette Centrale. To obtain depth data for the seismic horizons, we proceeded by limiting the horizons in the seismic profile according to geological age period, including Carboniferous, Cambrian and Top Vendéen. Having identified the seismic horizons, we then chose a few points with an equidistance of 5 Km on the different seismic profiles to obtain coordinates with two variables. These are distance and depth (D, h). To draw up the interpolation maps for these horizons, we used ArcMap to identify the longitude and latitude values for each distance drawn from the seismic profiles, so as to have at least three parameters (Longitude, Latitude and Depth). The table 1 shows a few samples of the data found.

***Table 1**. Depth data for selected seismic horizons*

| ***Carboniferous base*** | | | ***Top Cambrian*** | | | ***Top Vendéen*** | | |
|---|---|---|---|---|---|---|---|---|
| *X* | *Y* | *Z* | *X* | *Y* | *Z* | *X* | *Y* | *Z* |
| 841733.86 | 10146164.5 | -1100 | 976360.15 | 10122011 | -2200 | 744992.066 | 9736635.77 | -1600 |
| 808837.007 | 10137705.6 | -1100 | 1022567.36 | 10120497.3 | -2200 | 745069.836 | 9790882.26 | -1600 |
| 779943.967 | 10116878.1 | -1100 | 911021.551 | 10161456.7 | -2400 | 725828.119 | 9810049.36 | -1600 |
| 755042.249 | 10087646.7 | -1100 | 947702.467 | 101115643.4 | -2400 | 683034.147 | 9821786.84 | -1600 |
| 753056.319 | 10072297.1 | -1100 | 1000286.27 | 10099885.5 | -2400 | 661653.834 | 9851572.81 | -1600 |
| 887136.684 | 10133337.7 | -1100 | 1079955.49 | 10125345.3 | -2400 | 652045.00 | 9897294.29 | -1600 |
| 908118.286 | 10111552.5 | -1100 | 888746.065 | 10159840.1 | -2600 | 816568.187 | 9682230.6 | -1800 |
| 940564.374 | 10107127.3 | -1100 | 933389.197 | 10101390.1 | -2600 | 809190.464 | 9732263.19 | -1800 |
| 969523.975 | 10105177.9 | -1100 | 989155.683 | 10079296.9 | -2600 | 786843.032 | 9811039.73 | -1800 |
| 1001985.77 | 10106707.7 | -1100 | 1052893.75 | 10093618 | -2600 | 757977.239 | 9846179.84 | -1800 |
| 1025462.67 | 10110214.4 | -1100 | 1105502.12 | 10112710.7 | -2600 | 713024.683 | 9853664.35 | -1800 |
| 1045944.88 | 10115209.8 | -1100 | 866479.535 | 10155064.9 | -2800 | 680938.041 | 9889839.04 | -1800 |
| 1067929.15 | 10121701.8 | -1100 | 904723.125 | 10112428.5 | -2800 | 664905.78 | 9960018.61 | -1800 |
| 1076420.08 | 10126684 | -1100 | 946157.072 | 10069766.1 | -2800 | 906419.929 | 9662803.82 | -2000 |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| 729148.194 | 10015357 | -1100 | 1011479.53 | 10061904.4 | -2800 | 864769.695 | 9697006.23 | -2000 |
| 722668.241 | 9974269.42 | -1100 | 1073642.59 | 10079384.9 | -2800 | 840221.766 | 9726874.39 | -2000 |
| 722661.445 | 9944072.96 | -1100 | 1124673.08 | 10100058.3 | -2800 | 834953.893 | 9767331.68 | -2000 |
| 728128.938 | 9909418.48 | -1100 | 837846.409 | 10156606.5 | -3000 | 812534.33 | 9806747.11 | -2000 |

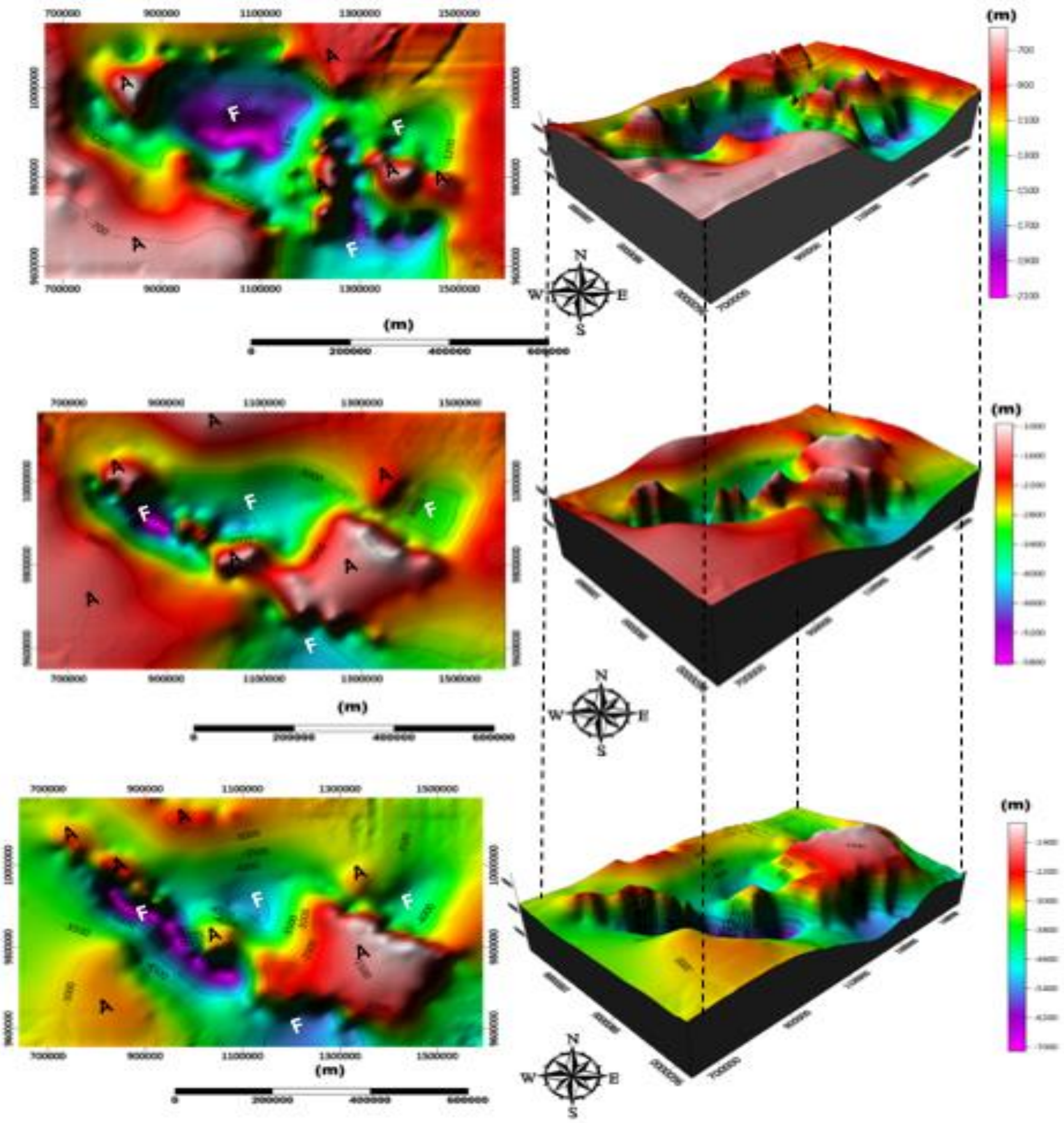

***Fig.8***. *Isobaths of geological formations (a: Carboniferous; b: Cambrian and c: Vendéen Top) A: Symbolizes the anticline and F: Collapse ditch*

– Carboniferous wall isobath: the Carboniferous wall isobath map reveals two large collapse trenches, one in the central part of the wall, running north and north-east, and the other in the south-east. There is also a small collapse ditch to the east. The maximum depth of these collapse ditches reaches 2200m. In terms of hydrocarbon migration structures, we have highlighted faults with a preferential north-westerly direction towards the south-east, and others that run perpendicular to the first (Figure 8).

- Cambrian formation wall isobath: the map below shows the depth distribution of the Cambrian geological formation wall in 2D and 3D models. We observe a few structures or anomaly shapes that can tell us about the presence of anticlines. There are also deep zones located in the center, moving west, east and south. The depth of the Cambrian Wall geological formation varies from 1,000 to 5,800 m (Figure 8).
- Isobath at the top of the Vendéen formation: the isobath map at the top of the Vendéen varies in depth from 1400 to 7000m. The depth is greatest in the center, moving northwest and southeast, south and north. Based on the shape of the isobaths and the color scale, we can highlight the zones that constitute the collapse traps and ditches (Figure 8).

## EVOLUTION OF THE GEOTHERMAL GRADIENT IN THE CENTRAL BASIN

With a geothermal gradient of 25°C, i.e. a temperature variation of 25°C every 1 km below ground, we were able to reconstruct the different degrees of maturation of the petroleum source rocks in the Central Cuvette of the DRC. For the Cuvette Centrale, according to JNOC:

- 0°C to 80°C (3 km) immaturity zone
- 80°C to 110°C (4.2 km): early maturity => oil
- 110°C to 130°C (5 km): mid-maturity => oil (petroleum)
- From 130°C to 155°C (6 km): lead maturity => Gas.

The aim of source rock identification is to assess the degree of maturity reached in the region under study and the quantity of hydrocarbons released during maturation. Based on the evolution of the geothermal gradient in the Cuvette Centrale, we drew up maps showing the evolution of the geothermal gradient in different horizons.

- Temperature trends in the Carboniferous formations: The geothermal gradient in the Carboniferous Roof formations ranges from 14.2687 to 52.8301°C (Figure 9). The parts of the Central Cuvette containing high temperatures ranging from 25 to 50°C are therefore located in the center, moving towards the south-east and east (on the map they are symbolized by the colors blue, green and yellow). Temperatures below 25°C are identified on the map by the color purple. If we look at the variations in the geothermal gradient in the Carboniferous formations of the DRC's Central Cuvette, we can see that this variation in temperature does not allow us to reach the oil window;
- Temperature evolution in the Cambrian formations: The evolution of the geothermal gradient in the Central Basin, based on the Cambrian formations, we noted varied from 23 to 146°C (Figure 9). In terms of location, the geothermal gradients of the Cambrian formations are distributed as follows:

– In the central part, heading west, east and south, temperatures range from 50° to 146°C. On the map, they are represented by the colors blue, green and yellow; the remaining parts are therefore dominated by temperatures below 50°C.

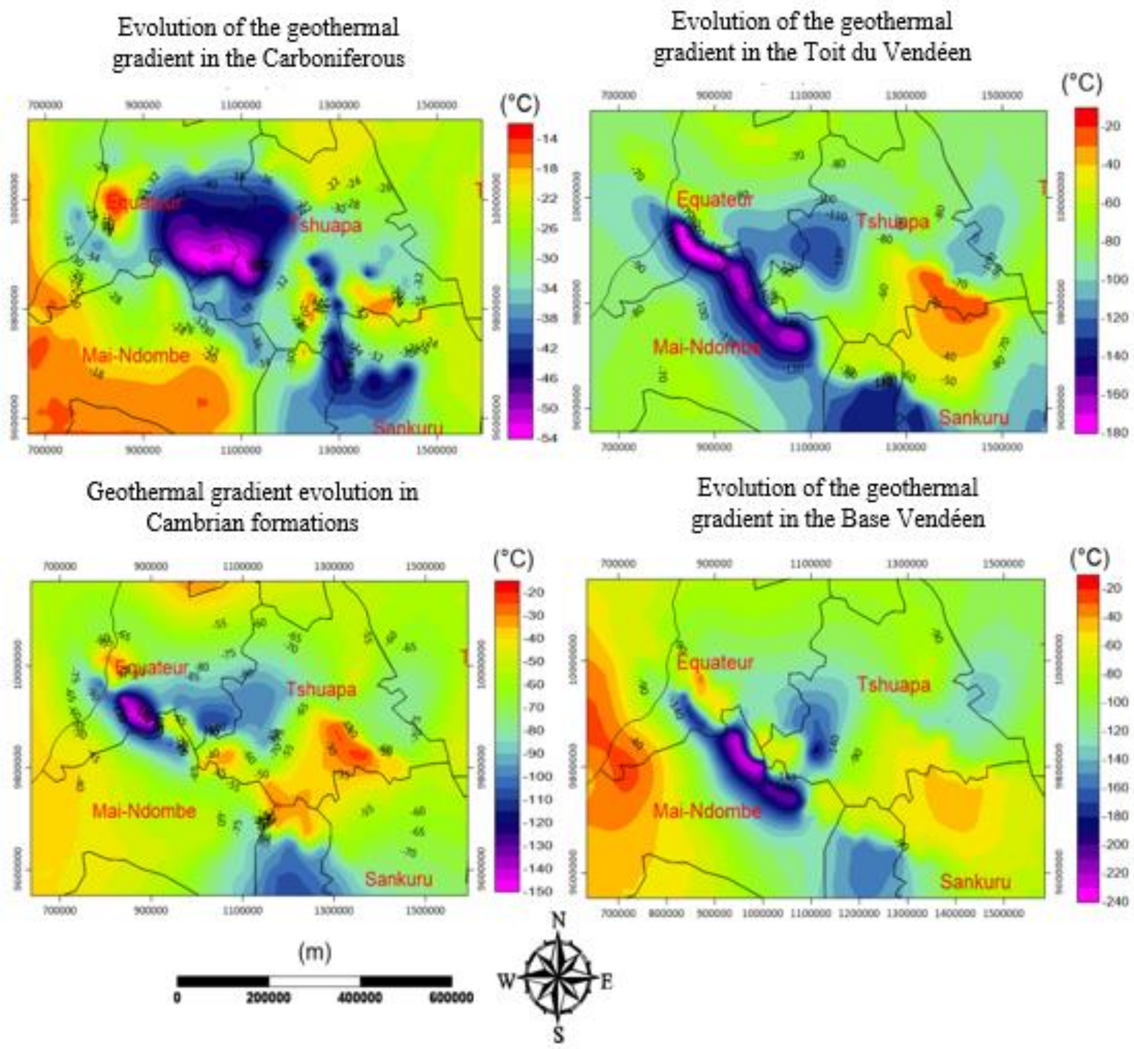


***Fig.9***. *Evolution of the geothermal gradient in the formations (a: Carboniferous; b: Cambrian and c: Top Vendéen)*

A close look at the evolution of the geothermal gradient in the Cambrian formations, which in some areas reaches a temperature of 146°C, and the fact that the oil window in the Central Cuvette is between 110 and 130°C and 130 to 155°C for gas, as highlighted in the previous pages, show that the oil and gas formation stage has already been reached.

Temperature trends in the Vendéen roof formations: The map showing temperature trends in the Vendéen Top formations illustrated in Figure 9 shows temperature variations ranging from 22.1669 to 177.789°C. Temperatures are highest in the blue-green zone. Based on this temperature variation in this basin of the Central Cuvette, the oil and gas window has already been reached towards the blue and green colored parts.

The vertical evolution of temperature in the Central Cuvette of the DRC, showed according to the variation of temperature which stipulates that 25°C corresponds each 1 Km in the basin of the Central Cuvette made it possible to highlight 3 Zones (Figure 10) having allowed the evolution of organic matter in the source rock namely:

- The Mature Over Zone: located more to the northeast, moving towards the center, west and southwest. It is a gas formation zone;
- The fully mature zone: this zone corresponds to the formation of oil and is located in the north-eastern, central and south-eastern parts of the Cuvette Centrale basin;
- Immature zone: occupies all areas outside the two above-mentioned zones.

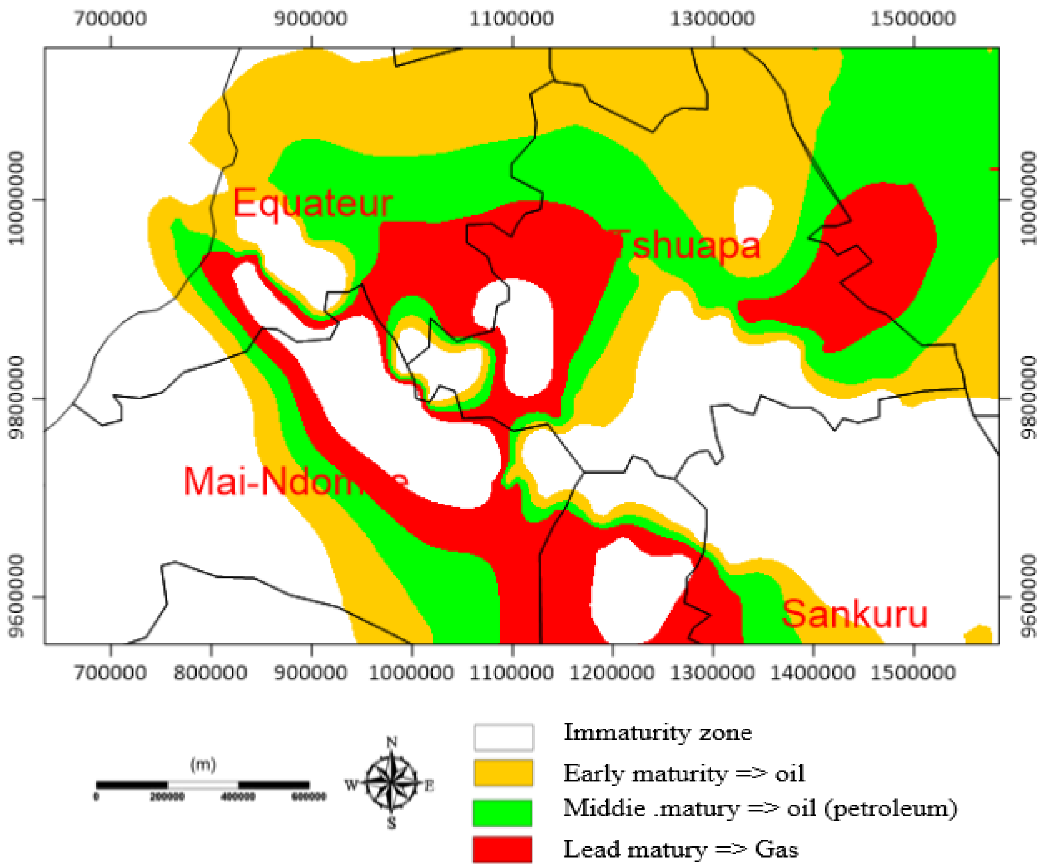


***Fig.10**. Location of the Hydrocarbon Maturation Zone*

## CONCLUSIONS

The study of the Cuvette Centrale basin highlighted the following elements:

- *Presence of different petroleum system rocks:*

The envelope attribute of the seismic data was used to identify the different rocks of the petroleum system, including potential gas zones.

The seismic profiles were used to delineate the geological units and interpret their lithology.

- *Geological structures favourable to hydrocarbon accumulation:*

Isobath maps revealed the presence of collapse troughs and anticlines, which are geological structures favorable to hydrocarbon accumulation.

- *Degree of maturity of source rocks:*

Analysis of the geothermal gradient and temperature trends in the formations has enabled us to determine the degree of maturation of the petroleum source rocks.

Two maturation zones were identified: an over-mature zone (gas) and a fully mature zone (oil).

These results indicate that the Cuvette Centrale basin has significant potential for hydrocarbon production.

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