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Françoise Behar, Vincent Delhay-prat, Sylvain Garel. Detrital input quantification in lacustrine petroleum systems: An example of the pre-salt source rocks from the lower Congo Basin (Congo). Depositional Record, 2020, <10.1002/dep2.131>. <hal-03048913>

HAL Id: hal-03048913

<https://hal.science/hal-03048913v1>

Submitted on 9 Dec 2020

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DETRITAL INPUT QUANTIFICATION IN LACUSTRINE PETROLEUM SYSTEMS: AN EXAMPLE OF THE PRE-SALT SOURCE ROCKS FROM THE LOWER CONGO BASIN (CONGO)

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ABSTRACT

This study describes an integrated workflow designed to quantify detrital input into lacustrine deposits in terms of regional extent and total organic carbon content. This workflow includes (1) organic geochemical data such as Rock Eval and palynofacies and (2) palaeogeographical maps. This workflow was applied to the immature Barremian source rocks from the Lower Congo Basin because of a large available dataset describing a complex sedimentary record. From palynofacies analysis, it was demonstrated that lacustrine organic matter corresponds to a hydrogen index higher than 600 mg/g C whereas detrital input corresponds to a hydrogen index lower than 300 mg/g C. The range seen in the hydrogen index of between 300 and 600 mg/g C corresponds to mixtures of organic matter. The correlation between the hydrogen index and detrital content was then applied to 50 wells which allowed the extent of detrital input to be mapped at local and

This article has been accepted for publication and undergone full peer review but has not been through the copyediting, typesetting, pagination and proofreading process, which may lead to differences between this version and the [Version of Record](#). Please cite this article as [doi: 10.1002/DEP2.131](#)

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regional scales. The geochemical data were plotted on high resolution palaeogeographic maps for four stratigraphic intervals, BA2, BA2-BA3, BA3-PN and BA3-PI. Results confirm the periodic presence of lacustrine turbiditic systems allowing strong detrital inputs into the palaeolake under the tropical palaeoclimate, especially in the BA2-BA3 and BA3-PI intervals. These inputs of continental derived organic material degrade the quality and richness of the lacustrine source rock leading to a decrease of the initial hydrogen index values. These detrital influxes were related to coastal rivers whereas, in the deepest parts of the basin, the autochthonous organic matter is well preserved and not diluted. This allowed the deposition of exceptional source-rocks especially during the BA2 and BA2-BA3 intervals. All of these geochemical diagnostics are consistent with available palaeogeographic maps. This demonstrated the importance of integrating geochemical data into the palaeo-reconstruction of the source rock depositional environment. It enables palaeogeographic maps to be constrained in terms of both detrital input and preservation at both regional and local scales for a given source rock.

Keywords: Lower Congo Basin, pre-salt lacustrine source rocks, palaeogeography, detrital inputs, Rock-Eval, organofacies **INTRODUCTION**

Source rocks are deposited in lacustrine, marine and terrestrial environments, each being associated with specific organic matter (OM) characteristics (Tissot and Welte, 1984). For instance, in lacustrine and marine environments, fossil OM is mainly composed of lipids whereas in terrestrial OM, lignin is dominant with a small contribution of cellulose. During sediment burial, temperature increases leading to fossil OM decomposition into oil and gas, the relative proportions of which depends on the original OM source. Lacustrine and marine source rocks are dominantly oil prone whereas the terrestrial source is dominantly gas prone.

When a mass of sediments is transferred from the continent, the OM originally deposited into a lacustrine or marine environment could be significantly mixed with a gas prone source increasing the likelihood of gas and directly impacting exploration project economics. Consequently, it is crucial to develop a specific workflow to map the transport efficiency at both regional and local scales in order to anticipate possible variability in terms of volume and quality of accumulated fluid in the petroleum reservoir.

In the oil industry, recognition of reservoir rocks is also fundamental to the prediction of possible oil and/or accumulation. A precise description of potential reservoirs in terms of geographical

distribution and mineral composition helps to build palaeographic maps in order to better understand the dynamics of mineral transport from the continent and the extent of detrital sediments, as well as conditions for source rock occurrence in terms of richness and quality. The existence of such palaeogeographic maps allows data regarding source rock existence and quality to be supported with a more quantitative approach developed in organic geochemistry such as palynofacies and Rock Eval pyrolysis.

From optical analyses, it is possible to determine the nature of fossil OM components as well as maturity. Palynofacies, a concept first introduced by Combaz (1964), is the study of the total assemblage of particulate OM under an optical microscope following removal of the sediment matrix by HCl and HF. It is one of the most discriminating techniques for explaining organofacies patterns (Tyson, 1995). Palynofacies data can give insights regarding the OM source, preservation and depositional environment. The use of palynofacies analysis is a key step to validate the occurrence of source rock with a pure autochthonous source or, conversely, establish a terrestrial contribution.

Rock Eval pyrolysis is a rapid method to determine the initial hydrocarbon potential (HI mg/g C) for a given source rock and the corresponding organic carbon content (TOC wt %) (Espitalié *et al.*, 1977; Lafargue *et al.*, 1998; Behar *et al.*, 2001). Four main types of OM were defined (Tissot and Welte, 1978): the first group (Type I) with a very high HI above 750 mg/g C, a second group (Type II) with a HI between 500 and 600 mg/g C, a third group (Type III) with a HI between 150 and 250 mg/g C and a fourth group (Type IV) with a HI below 100 mg/g C. It is generally agreed that a HI above 750 mg/g C corresponds mainly to lacustrine source rocks, a HI below 250 mg/g C corresponds to terrestrial material whereas HI indices around 500 – 600 mg/g C correspond to mainly marine samples. However, the correlation between HI values and depositional environmental is very simplified since very well-preserved marine source rocks may exhibit a HI higher than 700 mg/g C or poorly preserved lacustrine source rocks may have a HI lower than 700 mg/g C. Consequently, using only the Rock Eval data, it is not possible to determine the OM source or the quantitative contribution of detrital input. Indeed, HI values are related to the chemical composition of immature OM and are not directly related to the depositional environmental in terms of autochthonous source.

Previously, there have been attempts to correlate geochemical types of kerogen based on pyrolysis devices (i.e. Type I to III) and maceral content or palynofacies to propose more or less exhaustive organofacies classifications defined by their HI (or H/C ratios) and the dominant OM (Gutjahr, 1983; Jones, 1984; 1987). For instance, Jones (1987) defined seven organofacies based on the amorphous OM and phytoclasts proportions, and the fluorescence intensity, and compared these parameters with TOC, HI values and kerogen type. However, this classification was established for idealised marine siliciclastic facies and only shows generalised relative trends that cannot be fully applied to a complex lacustrine system like the pre-rift Congo Basin. Furthermore, if previous studies on lacustrine OM combined both bulk geochemistry and palynofacies (Martín-Closas *et al.*, 2005; Silva *et al.*, 2014), they do not correct the mineral matrix effect that may affect HI values (Espitalié *et al.*, 1980) nor define different classes of lacustrine amorphous OM that would reflect the state of preservation. It has therefore been necessary to build a new classification scheme based on the observations and results reported here.

The combination of palaeogeographic maps, the presence or absence of terrestrial OM determined by optical analysis and the overall hydrocarbon potential of the regional source rocks should enable us to:

- Determine a correlation between the amount of detrital input and the bulk TOC and bulk hydrocarbon potential.
- Compare this correlation with the available palaeogeographic maps.

This workflow was applied to the immature pre-salt source rocks from the Lower Congo Basin, and more specifically to the Barremian ones, because of its efficient tropical palaeoclimate in terms of detrital fluxes from the continent to the deepest part of the offshore basin.

The aim of this study is to determine transport directions for sediments at both local and regional scales based on organic geochemistry techniques and to verify that the prediction in terms of direction and efficiency fits palaeogeographic maps. The global trends in terms of proportion of detrital input thus defined will result in a better understanding of both direction and efficiency of mass transport from the continent to offshore basins. It is a pragmatic approach to screen a geographical area by anticipating both organic carbon distribution (TOC) and organic facies variability at regional and local scales. The key factor to support such a global approach is to have access to a very large patrimonial data base in terms of number of wells and samples, as well as

regional representability. Therefore, the present study represents a statistical approach to constrain palaeogeographic models through geological time. The conjunction of quantitative analytical tools (e.g. Rock Eval pyrolysis), palynofacies assessment and access to the patrimonial database constitutes the original approach of the proposed workflow. This methodology, however, implies some simplifications which will be discussed below.

GEOLOGICAL SETTING

GEOLOGICAL CONTEXT

The sedimentary series detailed in the present study were deposited in the Lower Congo Basin located along the margin of the South Atlantic Ocean and within the borders of the Republic of Congo. Well selection and main structural elements are displayed on Figure 1.

The Lower Congo Basin is characterized by the existence of an Aptian evaporitic (halite, anhydrite, other salts) ductile series known principally in Gabon (Ezanga Formation), Congo (Loémé Formation) and Angola (Loémé Formation). The evaporites divide the sedimentary record into two megasequences, the pre-salt and post-salt megasequences (De Ruiter, 1979; Nombomakaya & Han, 2009). The pre-salt series are related to the rift phase between Africa and South America between Neocomian and Aptian times while the post-salt series correspond to a subsequent passive margin or drift phase (De Ruiter, 1979; Bidiet *et al.*, 1988; Teisserenc & Villemin, 1990; Seranne & Anka, 2005; Chaboureaud *et al.*, 2013). This paper is focused on the pre-salt series and more particularly on the Barremian deposits as they record major changes in terms of facies, sedimentary processes and palaeoenvironments, together with high variations of organic content through space and time. A comparison of the records of the Barremian systems of the Lower Congo Basin proved particularly interesting in terms of the sedimentary systems and OM deposition/preservation observed.

GENERALITIES ON THE PRE-SALT SERIES OF THE LOWER CONGO BASIN (CONGO SEGMENT)

The pre-salt series of the West African Margin were investigated almost exclusively in subsurface studies related to hydrocarbon exploration (Bidiet *et al.*, 1988; Huc, 2004), this is especially true for the Congo acreage. The drilling campaigns allowed the lithostratigraphy of the pre-salt series

to be defined, with the major formations listed from oldest to youngest as the Vandji, Sialivakou, Djéno, Pointe-Noire, Pointe Indienne and Chéla formations (Figure 2).

The sandy deposits of the Neocomian Vandji Formation constitute the first sedimentary record preserved onto the Proterozoic basement of the Congo Coastal Basin (Bidiet *et al.*, 1988). This kind of deposit is commonly known as the Basal Sandstone facies (Brownfield and Charpentier, 2006). When entirely preserved, the Vandji Formation does not display any abrupt changes in thickness, such as those observed for the subsequent synrift formations, and can reach up to 500 m. However, subtle thickness changes point to possible early fault activity and thus the beginning of extension before the main extension phase. Moreover, the areas which seem to have subsided more have the same orientation and approximately the same location as the future synrift depocenters of Emeraude and Louvessi. This is why the interval represented by the Vandji Formation is sometimes interpreted as an “initial rifting” (Bidiet *et al.*, 1988) or a “proto-rift”. The sandstones of the Vandji Formation display the typically planar and oblique laminations of braided river systems and alluvial fans (Bidiet *et al.*, 1988). However, in wells drilled more recently, the palaeoenvironment seems to be more diversified as highlighted by the presence of aeolian and subaqueous lacustrine deposits.

The Neocomian Sialivakou Formation (Bidiet *et al.*, 1988; Baudouy and Legorjus, 1991) marks the development of perennial lacustrine conditions characterized by a typical organic-rich shale to marl facies. The good preservation of OM is interpreted as resulting from water stratification in a relatively deep lake with very low sand input (starvation). The Sialivakou Formation is essentially known as a source rock but displays different depositional environments along the palaeoshoreline of the Neocomian lake, as observed in Kouakouala-1, for example. In this well, the Sialivakou Formation is characterized by the deposition of a fan delta/alluvial fan but fluvial activity was probably not sufficient to provide large amounts of sand to the distal part of the lake.

The Neocomian to Barremian Djéno Formation (Bidiet *et al.*, 1988; Baudouy and Legorjus, 1991) is bounded by two source rock deposits: the Neocomian Sialivakou facies and the Marnes de Pointe-Noire. The top of the Djéno Formation corresponds to a major unconformity (Harris, 2000b). The Djéno Formation is characterized by very active clastic systems with large volumes of sediment recorded as gravity driven, subaqueous lacustrine deposits, typical of the synrift times. The main facies consist of micaceous and shaly fine grained sandstones interfingering with

siltstone beds and grey organic-rich lacustrine muds (Bidiet *et al.*, 1988). Many facies are characteristic of slope deposits (mud-clast debris flow, bypass erosional features, etc). At the end of the Djéno Formation, a sediment starvation event was recorded which resulted in the deposition of the “Marnes Noires” , a source-rock (SR) facies, just below the top Djéno unconformity. In the first wells drilled on the Congo acreage (e.g. PI-2bis, PN-1), the source-rock facies located below and above the top Djéno unconformity was termed the “Marnes Noires” facies. However, the mineralogical suite is quite different before and after the unconformity:

- A chlorite dominated clay association with almost no carbonate below the unconformity.
- A sharp increase in carbonate content with almost no chlorite above the unconformity.

Moreover, above the unconformity (Figure 2), the electrofacies display much higher readings for the resistivity and neutron values, together with very low densities. Such higher readings are related to a higher OM content for the SR facies.

As previously stated, the Djéno Formation ends with an unconformity (Bidiet *et al.*, 1988; Harris, 2000b; Brownfield and Charpentier, 2006) highlighted by truncations observable on seismic, especially on top of large-scale tilted blocks, and sharp dip changes observable on electric logging. This unconformity is sealed by the Marnes de Pointe-Noire and marks a sharp change of structural style between the smooth resulting surface and the intra Djéno Formation deformation characterised by a synrift tilted series (figure 7 from Bidiet *et al.*, 1988).

The Barremian Pointe-Noire Formation, equivalent to the Upper Melania (Gabon; Brownfield and Charpentier, 2006) and Organic Bucomazi Formation (Cabinda; Burwood *et al.*, 1995; Braccini *et al.*, 1997; Brownfield and Charpentier, 2006), can reach up to 500 m and includes two members (Bidiet *et al.*, 1988): “Marnes de Pointe-Noire” and “TOCA” (for TOp CARbonate). The first facies to be deposited above the unconformity corresponds to the early Marnes de Pointe-Noire onlapping on a residual palaeotopography. This facies is mainly made of organic-rich shales, grey to black pyritic with interstratified sandy to silty micaceous beds. During a second depositional phase, carbonate production starts along the shoreline of the lake, mostly organized as stacked bioclastic dominated platforms (at least three, according to Harris, 2000a) clinging to palaeohighs such the Loussima-Likouala High and feeding carbonate gravity flows to the basin (Harris *et al.*, 1994; Harris, 2000a). These carbonates are laterally equivalent to the Marnes de Pointe-Noire

Member, a very rich source rock and diachronous facies. They display diversified facies and have experienced a complex, spatially varied diagenetic history (See Harris *et al.*, 1994; Harris, 2000a).

The transition between the Pointe-Noire and the Pointe Indienne formations is gradual and is typically recorded by an upward colour change from black to green shales, with a grey transition interval. This change is associated with a sharp decrease in TOC and is interpreted as the onset of more oxic conditions, in other words a deconfinement of the lake in the Upper Barremian.

The Upper Barremian Pointe Indienne Formation can be very thick (up to 2,000 m) and includes four different members (Bidiet *et al.*, 1988; Tchikaya, 1994):

- “Grès de Mengo”
- “Argiles vertes de Pointe Indienne”
- “Grès and calcaires intra Pointe Indienne”
- “Grès de Tchibota”.

This formation is characterised by a large volume of greenish silty shales, the Pointe Indienne facies. The other members are intercalated in the greenish shales. The “Grès de Mengo” sandstone, is located in the lower part of the formation and corresponds to a large lacustrine fan delta with the subaqueous part of the fan on the Congo acreage. The Mengo system was confined in a shallow depression between the Loussima-Likouala High to the west and the basin border to the east (Figure 1). Carbonate production stalled during the early stages of deposition of the Pointe Indienne Formation but once the Mengo depression filled up, new occurrences of bioclastic carbonates were recorded. Finally, a thick (>400 m) sandy package, the Tchibota sandstone, was deposited in the latest stage of the Barremian to the north-west of the basin. The “Grès de Tchibota” sandstones are characterised by high frequency alternation with greenish shales. The facies and architecture of the Tchibota sandstone is typical of lacustrine deltas. The Pointe Indienne Formation is originally defined in the proximal domain, between the basin margin and the Loussima-Likouala High, and is a lateral equivalent of the Dentale Formation deposited in a western external sub-basin (Bidiet *et al.*, 1988; Baudouy and Legorjus, 1991).

The Pointe Indienne Formation is deeply truncated by a regional unconformity which marks the base of the Chéla Formation (Bidiet *et al.*, 1988; Brownfield and Charpentier, 2006).

The Aptian Chéla Formation is the thinnest pre-salt unit (10 to 60 m) typically constituted of a succession of three units (Bidiet *et al.*, 1988), from base to top:

- Basal polygenic conglomerates or very coarse sands.
- Homolithic fine sandstones with common dolomitic cement.
- A dolomitic shale, pyritic and often bituminous with rare traces of anhydrite.

This architecture may be more complex as quite diverse depositional environments have been described from incised valley fills rediscovered during recent roadworks (Fulgraf *et al.*, 2015; Kebi-Tsoumou *et al.*, 2017). Most of the time, the sandstones have very good reservoir properties and are now slanted towards the basin margin due to the tilt recorded between the late Oligocene to Middle Miocene. This unit acts then as a thief zone for the migrating hydrocarbons below the salt and often provides oil and gas shows. The last shale unit is just below the first halite beds of the Loémé Formation, with a similar facies and position to the Vembo Member from Gabon.

MATERIAL

The present study was focused on the following intervals: intra BA2, BA2-BA3, BA3 Pointe-Noire and BA3 Pointe Indienne. The corresponding wells are displayed on Figure 1.

From the TOTAL patrimonial geochemical database, 65 wells are available covering the four selected intervals and including approximately 900 geochemical analyses (Table 1). However, quantification of detrital input should be done only on immature samples in order to avoid any bias on the measured HI due to maturity. For that purpose, maturity assessment indicated that below a regional palaeoburial of 2,700 – 2,800 m, source rocks are not in the oil window zone. Therefore, deeper samples were systematically excluded. The two intervals BA3 Pointe-Noire / Pointe Indienne and BA2/BA3 are well represented whereas only three wells contain samples for BA2.

METHODS

PALAEOGEOGRAPHIC MAPS

Hydrocarbon exploration in the Republic of Congo started in the 1920's and originally focused on the onshore bitumen (Babet, 1929). A first stratigraphic well was drilled in 1945 and the first true exploration well was drilled in 1957 with the first discovery of Pointe Indienne, a field still producing today. Since then hundreds of exploration wells have been drilled and more than 60

fields discovered. The Congo acreage is therefore a very mature area now and it is necessary to synthesise all available data at higher resolution both in time and space in order to assess the remaining prospectivity of this basin. More specifically, accurate palaeogeographic maps are key documents that give access to the spatial and temporal distribution of depositional environments, in other words the integrated understanding of reservoirs, seals and source-rocks for play delineation.

However, there are very few publications on the sedimentary series of the Republic of Congo, with even fewer providing palaeogeographic maps. Data availability may partially explain this situation since, as in many countries, seismic data are not accessible in the public domain even after a number of years. The rare, pre-salt maps that are available (Bidiet *et al.*, 1988; Harris, 2000a) are at a very broad scale and generally deal with a specific formation. Fortunately, the Lower Congo Basin benefits from almost five decades of biostratigraphic studies performed by TOTAL's specialists. The standards for the biozone descriptions on the West African Margin were mostly defined by palaeontologists from TOTAL (Grosdidier *et al.*, 1996; Braccini *et al.*, 1997). For the pre-salt series, they are based on ostracods (As biozones) and pollens (C biozones). The combination of the two disciplines results in the composite biozones: NE for Neocomian, BA for Barremian and AP for Aptian with further subdivisions (e.g. BA1, BA2, BA3, BA4, AP3) (Grosdidier *et al.*, 1996; Poropat and Colin, 2012). As the pre-salt series are mainly continental, associated biozones are not calibrated against standard biozones derived from marine settings and are therefore not accurate in terms of chronostratigraphy (as discussed in Chaboureaux *et al.*, 2013). Nevertheless, this biostratigraphic scheme has been applied by the same specialists and with the same criteria to a great number of exploration wells from Gabon, Congo and Angola providing, therefore, a robust stratigraphic framework all along the West African Margin (Poropat and Colin, 2012).

The biostratigraphic data were systematically incorporated in the well composites to constrain log pattern interpretation at relatively high resolution for pre-salt deposits, thus providing a much more detailed evolution through time with many maps per stage compared to previous works with only one map per stage (Chaboureaux *et al.*, 2013) or per formation (Bidiet *et al.*, 1988). This approach, together with the control from seismic regional picking (at a lower stratigraphic resolution), resulted in high consistency correlations at a regional scale despite the continental setting of the Congo pre-salt series.

Correlations were then performed using a standardised set of logs, a lithofacies column and biozones. Three kinds of surface were propagated:

- Lacustrine sequence boundaries, identified by the abrupt record of sharp based massive and blocky sandstones onto fine-grained facies.
- Lacustrine transgressive surface, positioned at the base of an overall fining-up trend with more and more shaly intervals preserved upward.
- Lacustrine starvation event (no to very low sand input in the lake as seen on cuttings, wireline logs and facies distribution maps), identified by organic-rich shales (high sonic readings with high resistivity) for which nuclear tool values are close to a coal bed response (very low density, high HI values) and associated with high TOC content (calibrated on wells with good logs and geochemical data).

Unconformities are a fourth kind of surface also recorded in the pre-salt series for the Congo Coastal Basin. They are identified by significant missing intervals on regional highs (e.g. Loussima-Likouala and Kaba highs on Figure 1), toplaps observable on seismic and sharp dip changes when imagery log data are available. Two major unconformities are recorded respectively during the top BA1/Base BA2 (top Djéno Formation) and AP2 (base Chéla Formation) biozones (Figure 2). A third, more subtle one, is possibly identified within the BA4 at the base of the “Grès de Tchibota” Member within the uppermost section of the Pointe Indienne Formation. The reference surfaces thus defined result in a depositional architecture at relatively high resolution for the pre-salt lacustrine series. Indeed, 15 palaeogeographic maps were computed for the intervals in between selected reference surfaces only for the Barremian (four composite biozones). The previous in-house reports generally proposed a single map for one composite biozone or even for a whole formation. From this high-resolution scheme, four Barremian intervals were selected for the present study, listed from oldest to youngest: intra BA2, the transition BA2-BA3, BA3 Pointe-Noire and BA3 Pointe Indienne. This is the first time that detailed pre-salt palaeogeographic maps have been proposed for the Congo acreage.

Correlations give access to spatial distribution of both thickness and lithofacies for each stratigraphic unit. The combined analysis of facies distribution and isopach maps is the key step to define the location of depocenters, fluvial source-points, bypassed/eroded areas which constitute the basic elements of palaeolandscapes or palaeogeography. All the pre-salt palaeogeographic

maps built for the Lower Congo Basin were refined taking into account palaeoenvironments and sedimentary processes identified in cores to better constrain lithofacies distribution according to the depositional model defined for each time interval.

A typical pre-salt landscape can be derived from the palaeogeographic maps reconstructed for the Barremian series of the Congo, with the following characteristics:

- A large, connected lake, large enough for wave action to be recorded.
- Fluvial entry points anchored at the basin margin in relation with basement structural elements (transverse fault system).
- Fluvial systems feeding alluvial fans/fan deltas in the proximal domain and gravity driven complexes in the distal domain captured by active depocenters (high syn-sedimentary subsidence).
- Highs of regional scale which are periodically rejuvenated and expressed as palaeo-islands.
- Carbonate production away from clastic input and deposited in a wave dominated shoreline (basin margin and/or islands) where both oxygenation and light are appropriate for the carbonate producing organisms (gastropods, pelecypods, ostracods) as well as the organisms they are feeding on.

This generic palaeolandscape is modulated through space and time in relation with local characteristics (e.g. basement morphology, fault rejuvenation, etc), possible variations in climate (inferred from salinity variations, OM type and preservation and clay mineralogy, etc) but more importantly by major geodynamic events.

A summary of the intervals identified during both the Aptian and Barremian are listed in Table 2 together with their main characteristics in terms of source rock occurrence, dynamics of clastic transport and OM preservation. As mentioned earlier, the present study was focused on four intervals: intra BA2, BA2-BA3, BA3 Pointe-Noire and BA3 Pointe Indienne.

The contrasting properties of the source rocks and the clastic dynamics of the four intervals represent an excellent case study to test the correlation between TOC richness, organofacies distribution and available palaeogeographic maps.

KEROGEN ISOLATION

Two kerogen isolation procedures were performed using HCl and HF following standard protocol (Durand and Nicaise, 1980). The first one was carried at ambient air on crushed samples for palynofacies analyses. The second one was performed on powdered samples under a nitrogen atmosphere in order to prevent oxidation of the isolated organic fraction for Rock-Eval analyses. The total OM was extracted under reflux in dichloromethane for 1 hour and filtered to recover the kerogen which is dried at 50 °C and stored in a closed bottle under argon.

PALYNOFACIES OBSERVATIONS

For this study, 53 samples from six wells and outcrops were prepared for palynofacies observations. Since there was not always sufficient material available for Barremian source-rocks, eight Aptian samples were also chosen to provide a wide range of HI values. Four of these samples were collected from Djéno BA1-BA2, 18 from Pointe-Noire BA2, two from Pointe-Noire BA2-BA3, 16 from Pointe-Noire BA3, four from Pointe Indienne BA3, one from Pointe Indienne BA4 and eight from Chéla AP3 (Table 3). After kerogen preparation, the samples were rinsed 3 times with demineralized water and the obtained kerogens mounted on slides. Observations were carried out on all samples with an Axioplan2 Imaging Zeiss microscope under transmitted light and under UV excitation (Zeiss HBO 100 Microscope Illuminating System, mercury short-arc lamp) with a magnification of 630x. In order to obtain semi-quantitative results (i.e. a relative percentage for each organofacies), surface counting was performed for each sample. To be statistically relevant, at least 2,000 surface units and 500 particles were counted per sample.

ROCK EVAL PYROLYSIS

Before Rock Eval analysis, the source rocks were systematically crushed into powder. The Rock-Eval pyrolysis method has been extensively used for oil and gas exploration in sedimentary basins worldwide (Espitalié *et al.*, 1977; Lafargue *et al.*, 1998; Behar *et al.*, 2001). This open system pyrolysis enabled quantification of the hydrocarbon potential (S2 mg/g) and the total organic content (TOC %). The hydrocarbon potential is defined as the S2 divided by the TOC and is expressed in mg/g C.

When clays were present in the initial rock, a mineral matrix effect was observed for samples with TOC lower than 3% (Espitalié *et al.*, 1980; 1984; Peters, 1986) due to the catalytical effect of clay minerals. Above 250-300°C, water from the clays was removed and swept away from the pyrolysis chamber. Once dehydrated, clays were very reactive on kerogen thermal cracking reactions. It was observed that for lean source rocks with TOC below 3-4%, the HI values are dramatically reduced compared to the HI measured on corresponding isolated kerogens (Espitalié *et al.*, 1977; Dembicki, 1992; Dahl *et al.*, 2004). Consequently, the key issue is to be able to correct the observed HI for lean source rocks. Dahl *et al.* (2004) carried out a detailed experimental procedure to build correlation between TOC and S2 for a marine kerogen mixed with illite. However, as the mineral matrix effect depends on the chemical composition of the minerals present in the source rock, it is not possible to determine a universal law for correcting the S2 peak of lean source rocks. In order to overcome this problem, it is proposed in the present study to build a specific correlation for lacustrine source rocks from the Lower Congo Basin by selecting a subset of samples with TOC between 1 and 10% and measure the HI on both initial rock (HI)_{SR} and corresponding isolated OM (HI)_{OM} (Durand and Nicaise, 1980). The correlation between TOC and ratio (HI)_{OM}/(HI)_{SR} is shown on Figure 3. The discrepancy between (HI)_{OM} and (HI)_{SR} is maximum for TOC < 2% and is equal to 1 for TOC > 4%. The results obtained in the present study clearly show a much lower impact of the mineral matrix effect on HI estimation compared to that obtained by Dahl *et al.* (2004). The correction of the mineral matrix is necessary for lacustrine source rocks with TOC lower than 4% corresponding to a S2 equal to 32 mg/g considering a HI value of 800 mg/g C. This value is much lower than that observed at 60 mg/g by Dahl *et al.* (2004). This confirms that it is necessary to build a specific abacus for each case study to correct the mineral matrix effect.

Examples of mineral matrix correction are given in Figure 3. In case A, observed HI values between 440 and 640 mg/g C with TOC < 3% were corrected to a single value of 800 mg/g C. In case B, HI values between 200 and 250 mg/g C with TOC at 2% were corrected to 350 mg/g C whereas HI values for TOC > 4% were not modified. In case C, all HI values below TOC at 2% were corrected to 250 mg/g C. Finally, in case D, values with TOC between 2 and 3% were corrected to 800 mg/g C and those with TOC between 3.5 and 5% were not modified.

It is worth noting that after mineral matrix removal, HI in the range 200 – 500 mg/g C are still observed for some kerogens contrasting with HI values > 700 – 800 mg/g C normally expected for

in situ lacustrine OM (Table 4). This proves that variable HI are present at a regional scale and support the assumption that they are related to the depositional conditions and not to a mineral matrix artefact.

RESULTS

PALYNOFACIES ANALYSIS

Palynofacies observations revealed the presence of five main OM groups (Figure 4):

- Fluorescent amorphous OM (AOM): a structureless brown to yellow OM that shows a very intense heterogenous yellow fluorescence under UV (Figure 4A).
- Diffuse AOM: diffuse flakes of yellow to brown OM that displays a yellow-green fluorescence under UV with a dull to moderate intensity (Figure 4B).
- Orange OM: mainly a yellow-orange AOM sometimes with phytoclast-like shapes (Figure 4D) that displays a medium heterogenous orange fluorescence under UV (Figure 4C, D).
- Gelified OM and phytoclasts. Phytoclasts are rather well-preserved plant debris that can be cuticles, charcoal or tracheids (Batten, 1996). Gelified OM either corresponds to amorphous particles or phytoclasts with an orange to brown gelified outlook displaying no or very low fluorescence under UV (Figure 4E).
- Greyish OM: an assemblage of degraded plant debris within a grey to brown matrix that displays no fluorescence under UV (Figure 4F).

Furthermore, palynomorphs, either spores and pollen or unidentified palynomorph fragments (*Incertae sedis*) were also observed.

In the present study, a sample is considered to be purely dominated by an OM group when the concerned group represents more than 80 % of the total assemblage of OM. If this not the case, the sample is considered to be a mixture of different organic particles. The number of samples per dominant OM group or mixture is presented in Table 1. The fluorescent AOM clearly dominates 16 samples, all belonging to the Pointe-Noire Formation (i.e. BA2 and BA3 intervals). Diffuse AOM dominates seven samples from BA2 to BA4 intervals (i.e. Pointe-Noire and Pointe Indienne formations), which represents 80 % of the samples from Pointe Indienne BA3 and BA4. The

orange OM was found in 13 samples and dominates seven, all belonging to BA2 and BA3 intervals of the Pointe-Noire Formation. Gelified OM and phytoclasts dominate 11 samples from all studied biozones except Pointe Indienne BA3 and BA4, and is the only group found in every sample with phytoclasts. Greyish OM is only found in Aptian AP3 samples and its concentration is always below 55 %. Nine Barremian samples are marked by an OM mixture: four by a mixture of diffuse and fluorescent AOM in Pointe-Noire BA2 and BA3 intervals; and five by gelified, diffuse, orange and fluorescent OM in BA1 to BA3 samples. Finally, three Aptian AP3 samples are characterised by a mixture of gelified OM, greyish OM and phytoclasts. All data are reported in Table 5.

Spores and pollen are only present in 13 samples including all Chéla (AP3) ones. They never represent more than 3% of the total OM assemblage and only five Chéla samples display relative proportions above 1%. The *Incertae sedis* subgroup never represents more than 0.8% and is only present in seven samples including six Chéla (AP3) ones. As the origin of this very minor subgroup is unknown, it will not be discussed further.

Organic matter origin and preservation

Table 6 synthesises the OM source and preservation for each group of OM described below. The fluorescent AOM is characterised by a very high fluorescence intensity under UV light corresponding to a fluorescence scale point of 5 to 6 (Tyson, 1995). This kind of AOM generally originates from bacteria and/or phytoplankton and often occurs in true ‘oil shale’ facies (Tyson, 1995). Furthermore, such fluorescence intensity indicates very good preservation of OM unique to anoxic environments (Tyson, 1995). Here, since the pre-salt Congo Basin corresponded to a lake environment, the fluorescent AOM can be attributed to well-preserved, autochthonous lacustrine OM. Thus, this AOM constitutes the lacustrine end member.

The diffuse AOM shows a similar appearance under transmitted light to that of fluorescent AOM. The main difference between these organic particles is the fluorescence intensity that is moderate for diffuse AOM (i.e. scale point of 4 to 5; Tyson, 1995). This lower intensity, along with the immature state of the samples, suggests that diffuse AOM also originates from phytoplankton and/or bacteria but has been degraded within the water column prior to deposition (Tyson, 1995; Paction *et al.*, 2011). Thus, here the diffuse AOM corresponds to degraded lacustrine OM.

Orange OM corresponds mostly to an AOM displaying an orange fluorescence with a moderate to high intensity (i.e. scale point of 4 to 5; Tyson, 1995). Sometimes, it can also represent phytoclast-like particles colonised by bacteria (i.e. round orange spots on the phytoclast in Figure 4D). A fluorescence colour that shifts towards the red (i.e. green → yellow → orange → brown → red) is either linked to an increase in maturity (Robert, 1988; Tyson, 1995) or with an anoxic environment where bacteria-induced degradation caused the aromatization of compounds (Pacton *et al.*, 2011). As indicated by vitrinite reflectance values, our samples are immature. Thus, the orange OM likely corresponds to an autochthonous lacustrine OM degraded by bacteria in a stable anoxic environment. This is confirmed by the fact that all samples containing significant orange OM (> 20 %) correspond to the black shale layers of the Pointe-Noire Formation. Finally, the orange OM and the diffuse AOM can be combined to constitute the lacustrine altered end member.

Gelified OM has a gelified aspect under transmitted light and generally shows no or a dull red-orange fluorescence (i.e. just visible above background) corresponding to a scale point of 2b to 3 (Tyson, 1995). This OM corresponds to plant particles that have suffered from bacterial degradation in an aqueous suboxic to anoxic environment (Batten, 1996; Pacton *et al.*, 2011). Thus, in this study, gelified OM is the main representative of the allochthonous OM and constitutes the terrestrial end member with phytoclasts and spores and pollen.

Greyish OM is an assemblage of degraded phytoclasts and palynomorphs within a grey and diffuse amorphous matrix that shows no fluorescence (scale point of 1; Tyson, 1995). This type of OM has a terrestrial origin, suffered from degradation in a relatively well oxygenated environment and is often associated with the inertinite maceral (Tyson, 1995; Batten, 1996). Thus, the greyish OM corresponds to a degraded plant OM and constitutes the inertinite end member.

Relation between OM type and HI values

In the Congo Basin pre-salt formations, samples can be sorted into six kinds of organofacies: three characterised by the dominance of the main OM groups (i.e. well preserved lacustrine, altered lacustrine and terrestrial); one representing a mixture of lacustrine OM, one being a mixture of lacustrine and terrestrial OM; and the last one corresponding to a mixture of two kinds of terrestrial OM. The distribution of the HI values of these organofacies is presented in Figure 5. It clearly shows that well preserved lacustrine OM dominates samples with the highest HI values, above 750 mg/g C. Below this threshold, samples dominated by altered lacustrine OM display a

range of HI values between 600 and 730 mg/g C. Mixtures of lacustrine OM are characterised by a narrow range of HI values between 725 and 747 mg/g C.

Moreover, mixtures of lacustrine and terrestrial OM show HI values between 530 and 680 mg/g C. These rather high values for mixtures of different organofacies can be explained by the fact that such samples are all dominated (minimum of 64%) by autochthonous lacustrine OM (i.e. preserved and altered lacustrine OM).

Terrestrial OM displays a specific distribution into two distinct populations. The first is represented by four samples with HI values between 480 and 520 mg/g C and dominated by gelified cuticles with a weak red fluorescence indicative of bacterial degradation in anoxic settings (Pacton *et al.*, 2011). Cuticles consist of cutinite, a maceral displaying H/C ratios close to those of standard Type II OM (i.e. 1.5; Waples, 1985), and thus higher HI values than the regular Type III. As these cuticles were confined to a limited number of Pointe-Noire Formation samples from one well, gelified cuticles were not defined as a specific end member.

The second population of terrestrial OM is dominated by non-fluorescent gelified particles and display HI values below 315 mg/g C, typical of a regular Type III. Finally, mixtures of plant material (i.e. standard terrestrial and inertinite) display very low HI values, below 200 mg/g C, with an anticorrelation between the proportions of refractory lignocellulosic material (i.e. inertinite; Tyson, 1995) and the HI values: the sample with the highest inertinite proportion displaying the lowest HI value.

Thus, it appears that four main endmembers can be established using both palynofacies and Rock-Eval data: (i) a standard lacustrine one with HI values above 750 mg/g C; (ii) a lacustrine altered one with HI values between 600 and 750 mg/g C; (iii) a standard terrestrial gas-prone with HI values between 100 and 300 mg/g C and (iv) an inertinite end member with HI values below 100 mg/g C.

In conclusion, a comparison between organic geochemistry data and palynofacies observations allows assemblages of mixed and/or degraded OM to be linked with HI variations. If we combine such data with precise information on the geological context, one can propose very accurate palaeoenvironmental reconstructions.

QUANTIFICATION OF DETRITAL INPUT BY ROCK EVAL PYROLYSIS

Methodology

The following points were demonstrated from palynofacies analyses:

- Presence of well preserved lacustrine OM with HI values above 750 mg/g C up to more than 950 mg/g C.
- Presence of altered lacustrine OM with HI ranging between 600 and 750 mg/g C.
- Detrital OM with HI below 300 mg/g C.
- Altered detrital OM with HI below 100 mg/g C.

Consequently, it is possible to assign a HI range for these four organofacies. The observed HI of lacustrine source rocks were split into three ranges: exceptional with a HI between 850 and 950 mg/g C, standard with a HI between 750 and 850 mg/g C and altered for a HI between 650-750 mg/g C. This classification enables the quality of the maps generated using lacustrine source rock data to be compared with the palaeogeographic maps.

Terrestrial particles are classified into three classes. The first contains original particles which were not altered during transport such as gas prone OM with a maximum HI between 150 – 250 mg/g C. However, in few wells, samples exhibit a HI between 50 and 100 mg/g C. They are considered to be altered terrestrial OM and labelled as “inertinite” according to palynofacies analysis. Some source rocks have no hydrocarbon potential with HI below 2 – 10 mg/g C. Their OM source corresponds to forest fire organic debris called “fusinite”.

Observed values between 250 and 650 mg/g C are considered to be a mixture of lacustrine (A) and terrestrial end members (B); the relative proportions of which are calculated according to the following equation:

$$HI_{\text{observed}} = \alpha \times (HI_{\text{initial}})_A + (1-\alpha) \times (HI_{\text{initial}})_B$$
 α being the proportion of the lacustrine end member. Examples are given on Figure 6.

The choice of the HI ranges used for both lacustrine and terrestrial end members is determined from observed data. In a few wells, all HI values are higher than 850 mg/g C meaning that the corresponding source rocks are “pure lacustrine”. In other wells, HI values are between 750 and 850 mg/g C with no values above 850 mg/g C. Consequently, in this situation the HI of the lacustrine end member would be the average value, i.e. 800 mg/g C. This value is chosen to

compute the proportion of lacustrine and detrital input for HI values observed between 200 and 800 mg/g C. Examples of calculations are given in Figure 6.

For terrestrial end members, the geochemical data clearly show that most of the HI are around 200 mg/g C for the four selected intervals. The presence of either inertinite fusinite is restricted to two onshore wells for the four selected intervals. Therefore, the HI for terrestrial end members was fixed at 200 mg/g C in all calculations.

The same procedure is applied to calculate the relative proportions of fusinite and inertinite (i.e. all inertinite macerals except for fusinite) within the terrestrial input. For example, a sediment with an average HI of 150 mg/g C is a mixture of 60% terrestrial end member and 40% inertinite. When the average HI is 50 mg/g C, it is a mixture of 64% inertinite and 36% fusinite.

The number of lacustrine and terrestrial end members is listed on Figure 7. It must be kept in mind that in such calculations, the end members are considered to be pure OM. This means that source rocks with HI values higher than 650 mg/g C are 100% lacustrine, those with a HI ranging from 150 to 250 mg/g C are 100% terrestrial gas prone, those with a HI between 50 and 100 mg/g C are considered as inertinite and those with a HI < 50 mg/g C are fusinite. This type of calculation assumes no lacustrine input into a source rock with a HI equal to 150 mg/g C or a terrestrial input into a source rock with a HI equal to 650 mg/g C. As explained in the introduction, the aim of the present study is to relate the dominant OM source to regional palaeogeographic maps. Consequently, the proposed approach is a simplified version of the real geochemical variability.

The final geochemical diagnostic consists of the relative proportions of the three different lacustrine end members and the relative proportions of gas prone end member, inertinite without fusinite and fusinite, as shown on Figure 7.

The final step is to assign the relative proportions of the different end members according to the number of samples counted for each observed HI.

End member distribution

The distribution of the overall HI values for the four selected intervals are displayed on Figure 8. Depth was first converted into palaeoburial, including the erosion occurring during the end of the Oligocene (derived from seismic interpretation), for a direct comparison between intervals and

individual wells. Most of the source rocks from the four composite biozones are buried below 2,000 and 2,900 m. In both the BA2-BA3 and BA3 PN intervals, HI values as high as 800 to 850 mg/g C are observed at palaeoburial equal to 2,700 – 2,800 m, meaning that all source rocks between 2,800 and 0 m are immature source rocks in this database. Due to a lack of samples below 2,800 m palaeoburial, it is impossible to precisely determine the top depth of the oil window all over the basin.

Significant changes occur through geological times. The intra BA2 interval is dominated by very high TOC (up to 25%) and high HI values between 600 and 900 mg/g C meaning that source rocks are mainly lacustrine with low detrital transport. In contrast, various HI from less than 50 up to 950 mg/g C are observed in the BA2-BA3 interval suggesting that active transport of allochthonous terrestrial OM has occurred during this geological period. The BA3-Pointe-Noire interval (BA3-PN) seems to be similar to BA2 with lacustrine source rocks but lower TOC. The BA3-Pointe Indienne (BA3-PI) exhibits very low TOC and most of the HI values need to be corrected for the mineral matrix effect.

When looking at a HI profile in a subset of individual wells (Figure 9), only few samples are present for the BA2 interval but values observed in W-12 well clearly indicate a low contribution of terrestrial OM.

Contrasting observations are observed for the BA2-BA3 intervals in individual wells as shown on Figure 9. In W-4 and W-17 wells, only lacustrine source rocks are present (HI between 650 and 850 mg/g C) with a very limited input of terrestrial OM. In W-2, W-7 and W-11 wells, HI values range from 300 to 900 mg/g C indicating the co-existence of both lacustrine autochthonous and allochthonous terrestrial particles. The maximum terrestrial input is observed in both W-20 and W-26 with a HI below 600 mg/g C and 400 mg/g C, respectively.

The BA3-Pointe-Noire exhibits the same range in HI values as BA2-BA3, either almost lacustrine dominated in the W-12 well or significantly mixed with detrital OM in the W-4 well. In W-2 and W-4 wells, BA3-Pointe Indienne is well represented in terms of sampling and reflects what was observed in the overall interval with low TOC and a HI ranging from 200 to 800 mg/g C.

DISCUSSION

The different proportions of lacustrine, terrestrial, inertinite and fusinite are represented on palaeogeographic maps for each selected interval. The percentage of samples with less than 1% TOC is also represented because they are usually considered to be non-source rocks. Three legends are systematically displayed (Figure 10): palaeoenvironmental conditions, end member proportions and TOC distribution between 0 and more than 25%.

Intra BA2 interval

The BA2 map corresponds to the interval deposited just after the top Djéno regional unconformity (Harris, 2000b). The palaeolandscape (Figure 11) is characterised by extremely low clastic input with widespread organic-rich black shales, the Marnes de Pointe-Noire Formation, also known as the Middle (Organic) Bucomazi in Angola (Braccini *et al.*, 1997; Harris *et al.*, 2004) or Upper Melania in Gabon (Teisserenc and Villemin, 1990).

The widespread distribution of the Marnes de Pointe-Noire on this map points to a large and well-connected lake. This is confirmed by the presence of organic-rich levels with exceptionally high organic carbon content within the BA2 Marnes de Pointe-Noire that can be correlated across the basin. The Marnes de Pointe-Noire Formation is a world class source-rock related to a very specific depositional setting. The well data analysis has shown much less sandstone in this formation compared to the previous deposits of the Djéno Formation (Delhaye-Prat, TOTAL in-house report). The lower clastic input implies a low palaeo-topography and/or the drowning of most of the palaeo-reliefs (i.e. a high lake level), but also low to no OM dilution by terrestrial input in the lake and no to poor mixing (see Katz, 1990). These conditions associated with high productivity (as demonstrated by Harris *et al.*, 2005) have contributed to an optimum environment for both concentration and preservation of the OM in the lake. There is no evidence of emersion nor any record of wave action, despite the fact that the lake was very large and therefore had enough fetch for waves to form. Such observations imply that the Marnes de Pointe-Noires have been deposited in relatively deep palaeobathymetries, at least below storm wave base. Furthermore, there is absolutely no evidence of bioturbation, so anoxic to dysoxic conditions have contributed to the preservation of OM in the black shale (Harris *et al.*, 1994; Harris *et al.* 2004), in addition to the probable absence to low level of mixing previously mentioned.

A narrow coastal margin is fed by limited clastic input derived from the Mayombe basement. No subaerial part of lacustrine deltas nor fan deltas have been identified in any well, so the existence

of possible clastic source-points along the margin is inferred from the few most proximal wells recording some silt to sand interbeds.

Carbonate facies are absent either along the margin or around the Kaba and Loussima-Likouala palaeo-islands. The absence of carbonate at this stage may be the result of unfavourable living conditions for the organisms producing limestone related to the high lake level, together with the prevailing anoxic to dysoxic conditions for this time interval all over the basin.

The BA2 deposits are not completely preserved in the core of the palaeo-islands due to the AP2 unconformity so the deposition of small carbonate patches cannot be completely ruled out in these zones.

In terms of geochemical data sets, only two wells contain BA2 source rocks and these are located near the Likouala palaeo-island. As explained, clastic input on a regional scale is low. Therefore, the minor detrital input observed in the two wells is probably related to detrital input coming from the palaeo-island. The nearest well to the palaeo-island consistently exhibits a higher detrital input with lower TOC. However, the proportion of terrestrial OM does not exceed 20% meaning that detrital transport is not sufficient to dilute significantly the autochthonous OM. In terms of preservation, very good TOC are observed with values between 2 and 25% in the W-14 well and remain excellent in the W-12 well with values up to 10%. However, in these two wells, a large part of the lacustrine quality is classified as “altered”. This can be explained by the wave action expected near the palaeo-island and resulting disturbance of water stratification leading to alteration of the lacustrine OM in the shallower lake water. This alteration is limited since as soon as the distance to the palaeo-island increases, higher TOC and good lacustrine source rocks are observed as in W-14. These results show consistency between palaeogeographic characteristics and geochemical data. Consequently, in the other parts of the basin where a regional regime of “starved organic-rich lacustrine muds” is described, the occurrence of very good source rocks with high TOC and very minor detrital input is expected. It is worth noting that, although terrestrial input is observed as well as degradation of the hydrocarbon potential for the lacustrine OM, source rocks keep a very high potential with S₂ higher than 50 mg/g in the W-12 well and more than 100 mg/g for the W-14 wells.

BA2-BA3 interval

This interval is characterised by much higher clastic input in a large well-connected lake with two major source points and their related gravity driven subaqueous fans (Figure 12). The lacustrine coastal plain is poorly developed while submarine fans are quite extensive. This highlights a rapid transition from the shallow proximal domain to the distal part of the lake and therefore rather steep slope conditions. The distal part of the lake is still dominated by the same organic-rich deposits seen in the previous interval. However, the organic-rich facies disappear in the areas characterised by strong clastic input, a clear example of OM dilution by clastic dominated input.

Large carbonate platforms, dominated by coquina facies, are also present. The coquina beds of the TOCA member are mainly made of stacked disarticulated to broken freshwater mollusc shells (l.c. figure 19 of Tchikaya, 1994) sometimes organized as coarsening-up cycles, both observations being consistent with wave dominated lacustrine coastal complexes. Away from the platform, there is no record of in situ carbonate production within the black shales. However, carbonates can be mixed with black shales as gravity flows (Harris *et al.*, 1994; Harris, 2000a). As with the clastic dominated area, the presence of such gravity flows implies a relatively steep slope and thus points to a relatively deep bathymetry for the organic-rich shales. The most important carbonate platform is located all around the Likouala High. The integration of the most recently drilled wells documents a larger carbonate platform than previously published (Harris, 2000a) and a palaeo-island setting, as hypothesised by Harris *et al.* (1994), is confirmed. The Loussima-Likouala palaeo-island is now documented over at least 50 km along its long axis and extends even further into the Cabinda (McHargue, 1990; Bracken, 1994; Braccini *et al.*, 1997). The proposed landscape corresponds therefore to a very large connected lake. The Kaba High constituted another palaeo-island with carbonate developments. Such carbonate factories are clearly away from clastic source-points with a striking example around the Noubi Nose:

- Absence of carbonates east of the Noubi Nose where clastic input is observed.
- Presence of carbonates west of the Noubi Nose where no clastic input is recorded.

Clastic input at the outflow of the coastal river systems has locally resulted in much more turbid water stalling the development of carbonate producing organisms, water turbidity being one of the main controls on organic productivity (Katz, 1990). Second, as mentioned by Harris (2000a), maximum carbonate production occurs around palaeohighs, *i.e* in a shallow water setting. Many carbonate facies recorded in the TOCA member are typical of high energy shallow platforms

(Harris, 2000a) and are laterally equivalent to the Marnes de Pointe-Noire member, a very rich source rock facies. The OM in the Marnes de Pointe-Noire was preserved due to anoxic to dysoxic conditions (Harris *et al.*, 1994; Harris *et al.*, 2005). The only area with acceptable living conditions for the carbonate producing organisms (gastropods and molluscs) was in the shallow waters around the palaeo-highs where wave action agitated and oxygenated the water (Katz, 1990). Moreover, such areas were also favorable in term of light penetration into the lake waters, another parameter controlling organic production (Katz, 1990).

The BA2-BA3 palaeo-landscape seems then to be characterized by very different palaeo-environmental conditions with three competing end members: TOCA carbonates in proximal settings (margin or islands) with rather oxygenated shallow waters, Marnes de Pointe-Noire in more distal settings under more anoxic conditions, and gravity driven carbonates or sandstones. The latter end-member is not mentioned in previous publications on the TOCA Formation (Harris *et al.*, 1994; Harris, 2000a) because they were based on a limited set of wells close to the Likouala High without any calibration in the Louvessi Trough or in the very proximal zone of the basin.

The hypothesis of having the Marne de Pointe-Noire Member deposited again in a rather deep lake is favoured here for the following reasons:

- No palaeosoils and no extensive evaporitic deposits.
- Absence of widespread sand sheets related to high frequency basin-ward facies downward shifts as generally observed on shallow lakes (e.g. Lake Albert, Uganda; Bez *et al.*, 2016).
- As many carbonate beds are characterised by wave action, organic-rich shales recorded away from the carbonate platforms are deposited at least below storm wave base, i.e a deeper water setting.
- Clastics are mainly gravity driven systems which are deposited downslope. Considering the size of the lake, such a slope will result in relatively deep bathymetry 10 or 20 km away from the lake shore (bathymetry on the order of 100-300 m).

Such observations point to relatively deep water, on the order of a few hundred metres, for the distal part of the lake.

The BA2-BA3 landscape has all the characteristics of the balanced-fill type of lake from Carroll and Bohacs, 1999.

In contrast to the BA2 interval, extensive geochemical data covering the whole area are available. As described above, three distinct environments are present: a carbonate platform surrounding the two palaeo-islands (Likouala and Kaba), a large area of starved organic-rich lacustrine muds and subaqueous turbidite fans.

Surprisingly, in the carbonate environment, source rocks exhibit a limited terrestrial input and a very good to excellent TOC of 15 to 20%. As explained above, carbonates developed in areas unsuitable for good OM preservation because of the shallow water depth and relatively oxygenated waters. This apparent paradox can be explained by a bias related to the thickness of the studied intervals. High frequency alternations can occur and the mapping of a dominant facies within a given interval may hide heterogeneities with the occurrence of thin interbeds characterised by very different facies. This is typically the case in the BA2-BA3 organic poor, carbonate/sandstone dominated facies where thin shale interbeds are recorded, giving rather high TOC and HI Rock-Eval values in an unexpected zone considering the global palaeolandscape.

For the two wells located at the eastern part of the Likouala palaeo-island (W-4, W-17), two wells (W-21, W-28) located near the Banio Trough and near the Kaba palaeo-island, detrital inputs are below 20 % with fair to excellent TOC (2 to 15%). This means that the transport dynamic from the palaeo-islands and from the northern shore of the Banio Trough was limited, thus leading to deposition of source rocks with an excellent petroleum potential (i.e. S₂ ranging from 50 to more than 100 mg/g). In contrast, three wells offshore Northern Likouala palaeo-island (W-11, W-25 and W-22) are clearly impacted by detrital input. They display an increase in the terrestrial proportion from the distal realm to the palaeo-island shore. Another increase is observed from W-25 to the palaeo-Kouilou lacustrine gravity driven deposits which suggests that the detrital transport from the palaeo-island is efficient in this zone and is enhanced by the input from the lacustrine gravity driven deposit for offshore wells. These detrital inputs caused the dilution of the OM within sediments and thus lowers TOC values. However, the contribution of terrestrial OM does not exceed 30 – 40% and the TOC values can reach 10%. This means that source rocks still have a very high petroleum potential with an average S₂ of 25 mg/g assuming a 5% TOC for the lacustrine part.

Wells drilled within the lacustrine gravity driven deposits (Palaeo-Kouilou and Mengo systems) display, as expected, relatively high detrital proportions, even though autochthonous OM is still

observed. Due to the tropical palaeoclimate, a lot of terrestrial debris is brought by active onshore rivers into the lake. The detrital portion depends on the position of the wells within the lacustrine fans. When they are located on the transport dynamic axis (along the axis of the yellow fans in Figure 12), terrestrial OM largely dominates, such as in W-13 where significantly lower TOC values (between 1 to 5%) are observed. The three wells (W-19, W-20 and W-21) located on the current axis of the Mengo system also exhibit very high proportions of detrital particles with contrasting TOC from low values at 1% up to 20%.

This is a particularly interesting observation as the landscape derived from well and seismic data does not display a significant development of gravity driven sandstones in this specific area. However, the facies predicted is composed of muds together with silts and organic-poor mud, interpreted as the fringe of a clastic depocenter. According to the geochemical results, the lacustrine fan should probably be extended to these three wells, even if the sand thickness and net to gross is not as high as at the Mengo depocenter.

The same observation can be made for the W-3 and W-5 wells. Geochemical data suggest that terrestrial inputs are much higher in these wells than initially deduced from palaeomaps only. This means that a subaqueous fan with no obvious thickness signature and rather fine-grained deposits has been missed. It could be the distal fringe of a fan parallel to the palaeo Mengo system captured in the Emeraude depocenter.

Finally, the wells located on the north-western flank of the Loussima-Likouala High display a higher proportion of terrestrial material which can be explained by the dispersion of sediment derived from the emergent part of the high. The dispersal process is most probably related to wave action during the high lake level of high frequency cycles as there is no clear evidence of riverine clastic export from the palaeo-island (but this could be a resolution issue if the related rip-up channels are of limited extension).

BA3 PN interval

This interval is similar to the previous one but with much lower clastic input (Figure 13). A careful screening reveals also a slight backstep of the carbonate platform, especially along the shore of the Loussima-Likouala palaeo-island. Conversely, the organic-rich shales have greater extent. Such observations point to a higher lake level and partial drowning of the most proximal settings. This

illustrates the fluctuating nature of the lake level during TOCA deposition with successive carbonate platforms (TOCA1, 2 & 3 of Harris *et al.*, 1994; Harris, 2000a) more or less stacked depending on the local accommodation space (low close to the shore of the palaeo-island and high towards the basin centre).

In contrast to the BA2-BA3 composite biozone, the lacustrine fans have now almost completely disappeared except for a small portion in the eastern part of the lake (Figure 13). Consequently, the proportion of terrestrial OM has significantly decreased although it is still present in three wells with values up to 25%. In terms of preservation, all TOC values are relatively low with values not exceeding 5% and, in most wells, samples with TOC lower than 1% dominate. Offshore of western Likouala palaeo-island, all TOC values are below 2% and display no terrestrial input. The results from these selected wells, all corresponding to a carbonate platform environment, could indicate that source rocks were deposited during a period unfavourable for OM preservation. However, the low organic content may also be related to dilution by mineral sedimentation (carbonates) as pointed out by Harris *et al.*, 2005. This could be a very good example of a different dilution process by autochthonous (mineralogical) input in contrast to the allochthonous contribution of clastics by coastal rivers. In other parts of the lake where starved organic-rich lacustrine muds occur, it is likely that good to excellent source rocks were deposited. Unfortunately, no geochemical data are available to confirm this assumption.

BA3-PI interval

A drastic change is recorded when compared to the previous interval (Figure 14). The organic-rich deposits as well as the carbonates have disappeared. Two major clastic systems are recorded. The first is a lacustrine delta perpendicular to the shore and localised to the east of the Noubi Nose. The second, known as the “Mengo Sandstone”, is parallel to the shore, close to the Cabinda border, and corresponds to the subaqueous part of a major fan delta deposited in a subtle depression within the lake. Both systems pass laterally to silty green shales known as “Argiles Vertes de Pointe Indienne”. The uppermost BA3 landscape displays a larger lacustrine coastal plain. Moreover, these are the thickest deposits of the pre-salt in the proximal part of the Congo acreage with a very thick sequence of shale, silt and sands recorded for example in the W-26 well or in the Viodo area as mentioned by Harris *et al.*, 2004. Organic shales disappeared at the same time as larger volumes of sediment were funnelled to the lacustrine basin together with fresh

water, another striking illustration of OM dilution by the input of clastic dominated material. Since carbonate producing organisms are sensitive to clastic input, the almost complete disappearance of carbonates is most probably also linked to the high sedimentation rate of this interval and the correlative turbidity detrimental to carbonate producing organisms.

Once the Mengo depression filled up, the basin was mainly characterised by the aggradation of a thick pile of silty green shales or “Argiles Vertes de Pointe Indienne”. Areas with clastic entry points such as the delta close to the Noubi Nose were then characterised by marked progradations built with stacked high frequency coarsening-up cycles. The occurrence of a delta within the Argiles Vertes Formation of this area was already recognised by Karner *et al.* (1997).

The presence of two clastic systems brought into the lake a massive quantity of sediments mixed with some terrestrial OM. The very low TOC recorded in almost all wells, with values below 1%, demonstrate that these sediment inputs have dramatically diluted the organic carbon content in the autochthonous source rocks. Therefore, not only is the source rock very lean but terrestrial OM is dominant in wells located within the clastic systems. However, when wells (W-10, W-14 and W-17) are located far away from the Mengo clastic system (Figure 14) characterised by detrital OM, some lacustrine source rocks seem to be better preserved with higher TOC values ranging between 5 to 10%.

CONCLUSIONS

The integrated statistical and geochemical approach on the pre-salt lacustrine sediments of the Congo Basin provide new insights into the dynamics of detrital input and their link with palaeogeography, source-rock richness and potential. Here, the focus is on four intervals of the Barremian: BA2, BA2-BA3, BA3-PN and BA3-PI, and their corresponding detailed palaeogeographic maps based on seismic and well data. For the first time a large geochemical database was processed in combination with palynofacies observations. For this kind of study, it should be noted that:

- The organofacies assessment was only done for immature samples since HI values are impacted by maturity.
- The HI values of samples with TOC < 3% were corrected for the mineral matrix effect that underestimates the hydrocarbon potential.

- Samples with various HI values were selected for palynofacies observations in order to identify every organofacies and their specific HI ranges, and to calculate the relative proportion of terrestrial OM for mixed organofacies.

The comparison of palynofacies results with geochemical data allowed the determination of six organofacies characterised by specific HI ranges: exceptional (> 850 mg/g C), standard (between 750 and 850 mg/g C) and altered lacustrine (between 650 and 850 mg/g C); and gas prone terrestrial (between 150 and 250 mg/g C), inertinite (between 50 and 100 mg/g C) and fusinite (< 5 mg/g C). Mixtures of terrestrial and lacustrine OM displayed HI values between 300 and 650 mg/g C and the relative quantity of each type of OM was calculated using a simple equation. Then, for every studied interval and well, the proportion of each organofacies was calculated and mapped together with the initial TOC distribution.

These maps reveal, for every studied interval, a close relationship between the palaeogeographic context and TOC content and organofacies distribution. For the BA2 interval, data from two wells revealed significant proportions of terrestrial OM (up to 20 %), which are linked with detrital fluxes from the Likouala palaeo-island. However, these inputs were not sufficient to dilute or prevent the deposition of lacustrine OM as proven by both high TOC and HI values.

The BA2-BA3 interval is characterised by the development of deep lacustrine fans that clearly influence the preservation and concentration of lacustrine organofacies. These fans and their surroundings are generally associated with higher terrestrial organofacies proportions (>50 %) and lower TOC values compared to the rest of the basin. Moreover, geochemical data revealed the presence of significant concentrations of terrestrial organofacies even outside of lacustrine fan systems, suggesting that they were larger than previously expected. Therefore, in contrast to the BA2 interval, the distribution of source rocks with a dominant lacustrine endmember is controlled by the real extension of the lacustrine fans. This interval is also notable for areas around the palaeo-islands. When there were favourable conditions, carbonate platforms developed, preventing the accumulation and preservation of large amounts of lacustrine OM. However, these periods alternated, at a high frequency, with phases of organic-rich shale deposition dominated by lacustrine organofacies.

The BA3-PN interval shows the disappearance of lacustrine fan systems, normally associated with the development of rich lacustrine source-rocks. However, low TOC source-rocks are observed in

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this interval only within carbonate platforms and were thus possibly impacted by carbonate dilution. Finally, the development of the Mengo fan-delta during BA3-PI increased dramatically the detrital fluxes into the lake. These huge detrital inputs caused the dilution of both terrestrial and lacustrine OM leading to the deposition of source-rocks with lean TOC and reduced hydrocarbon potential. The data used in this paper highlight that dilution by terrestrial input is a key driver for variations in source-rock properties within the Barremian interval of the Congo acreage. Carbonate dilution is possibly observed in the BA3 PN interval, but in general is not well captured. Carbonate dilution most probably occurred locally, especially in the core of the carbonate platforms observed along the palaeo-islands. Both the terrestrial and carbonate dilution were probably occurring simultaneously, the two effects being recorded with a different relative importance depending on the palaeogeographic location considered.

This study demonstrates the importance of integrating geochemical data and palynofacies observations into a palaeoenvironmental scheme. It proved crucial for constraining palaeogeographic maps in terms of detrital input, OM quality, and source-rock quality at both local and regional scale.

ACKNOWLEDGMENTS

We thank Prof. N. Harris and an anonymous reviewer for their constructive comments. We also thank Françoise Champion, Robert Le Van Loi, Gaelle Grundman and Yolaine Rupert (Total S.A.) and IFP Geochemical Laboratories for technical support. Sylvain Garel thanks Total S.A. for a postdoctoral grant. Finally, we thank Greta Swart for her corrections.

DATA AVAILABILITY STATEMENT

Research data are not shared.

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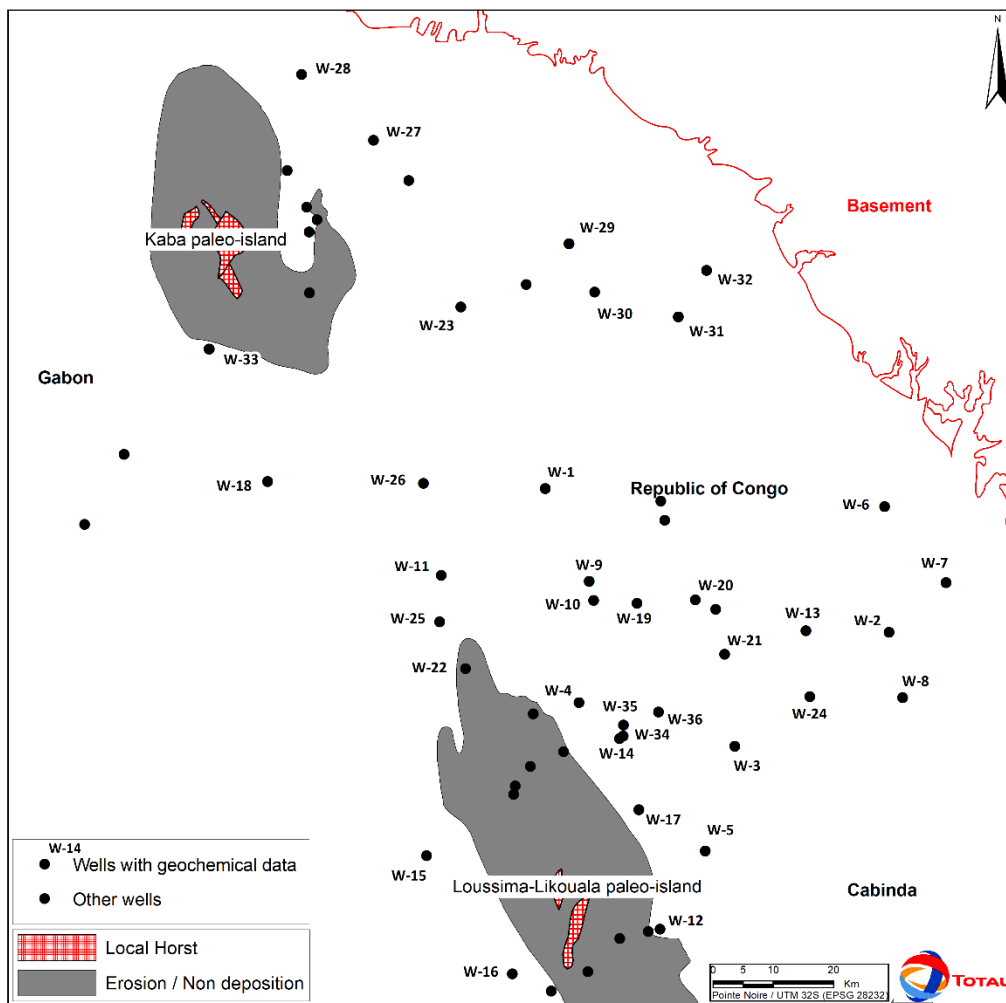


Fig. 1: Well repartition and main structural elements.

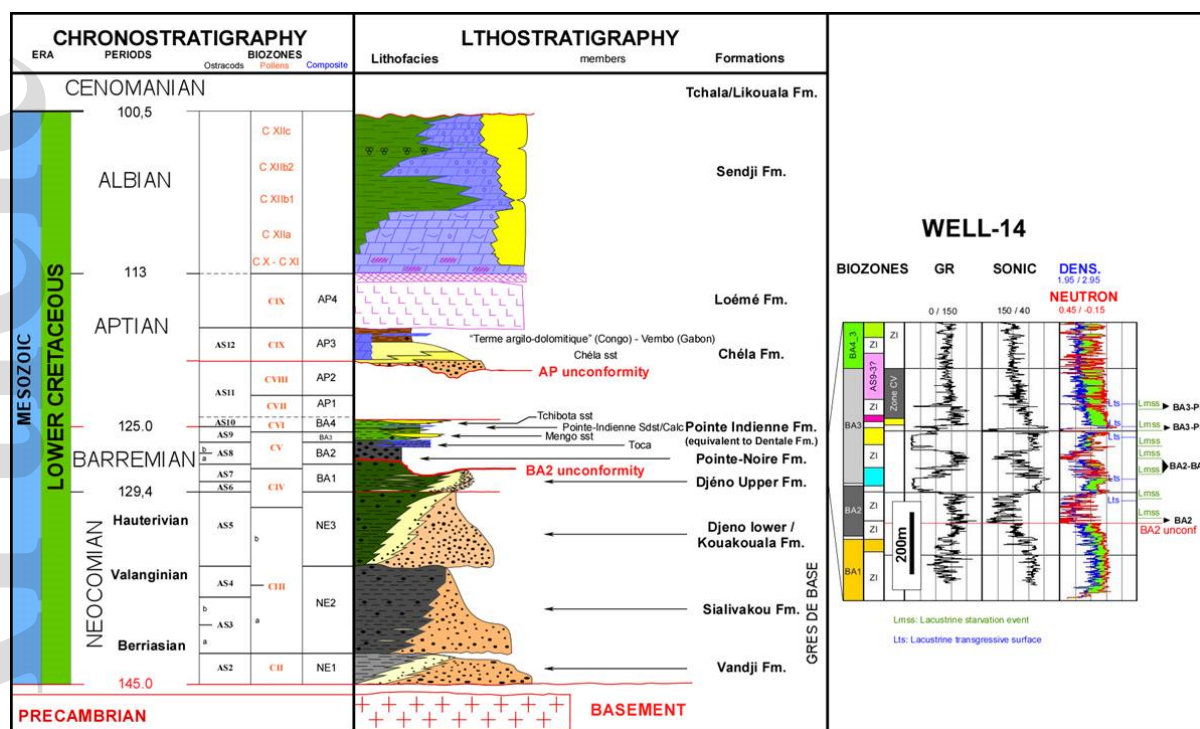
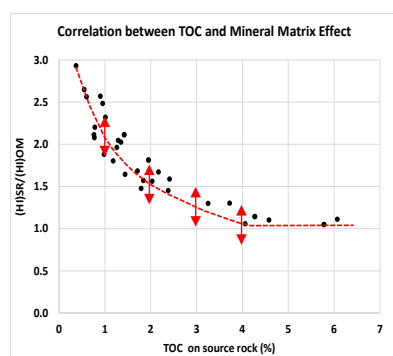


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TOC = 1% → 1.9 < ratio < 2.3
 TOC = 2% → 1.4 < ratio < 1.7
 TOC = 3% → 1.0 < ratio < 1.5
 TOC = 4% → ratio = 1

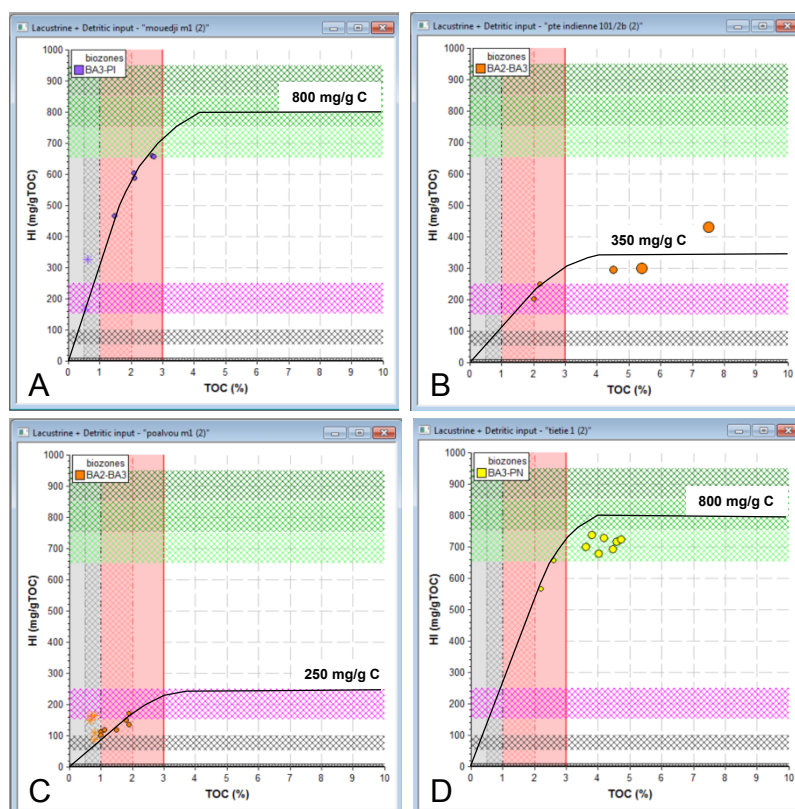


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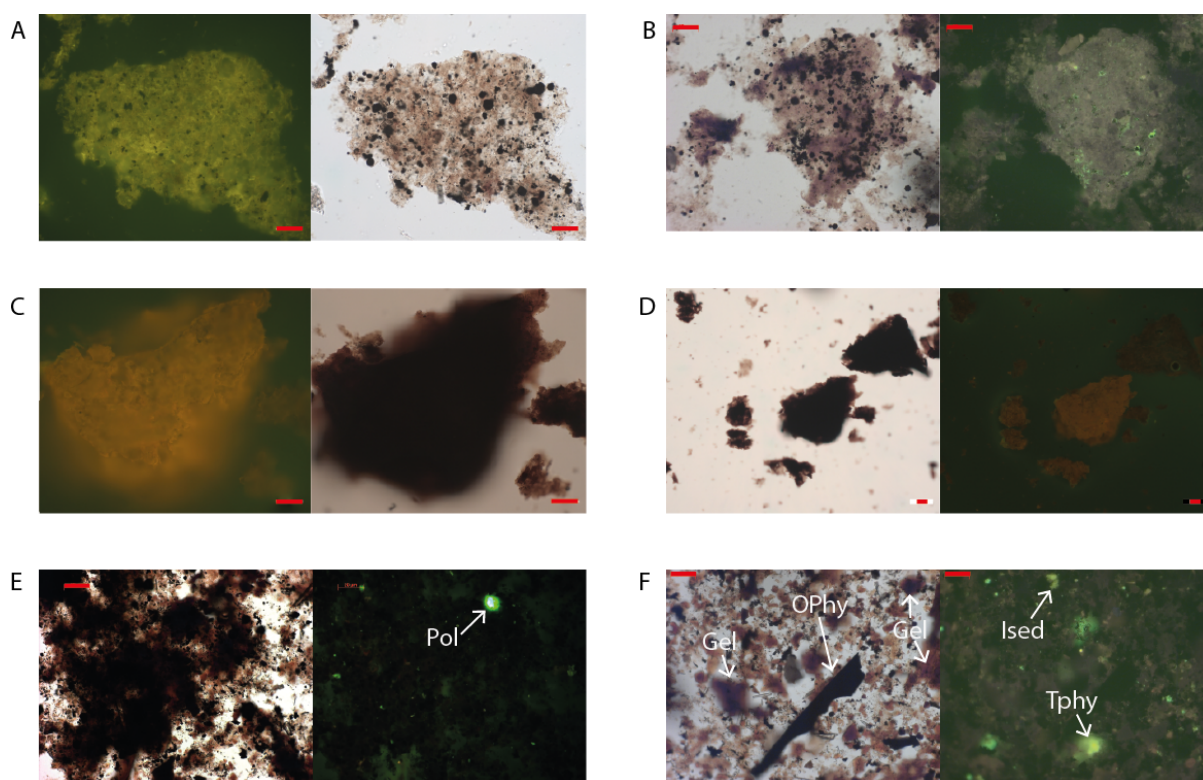


Fig.4. Main palynofacies particles observed in the Congo basin in transmitted light and under UV. A: fluorescent AOM; B: diffuse AOM, green sparks under UV are undetermined palynomorphs debris (*incertae sedis*); C and D: orange OM; E: gelified OM; F: gelified particles and phytoclasts. Note that, all fluorescent photos have been taken with the same exposure time (75 ms) and RGB parameters. Pol: pollen grain Gel: gelified particle; Ophy: opaque phytoclast; Tphy: translucid phytoclast; Ised: *Incertae sedis*.

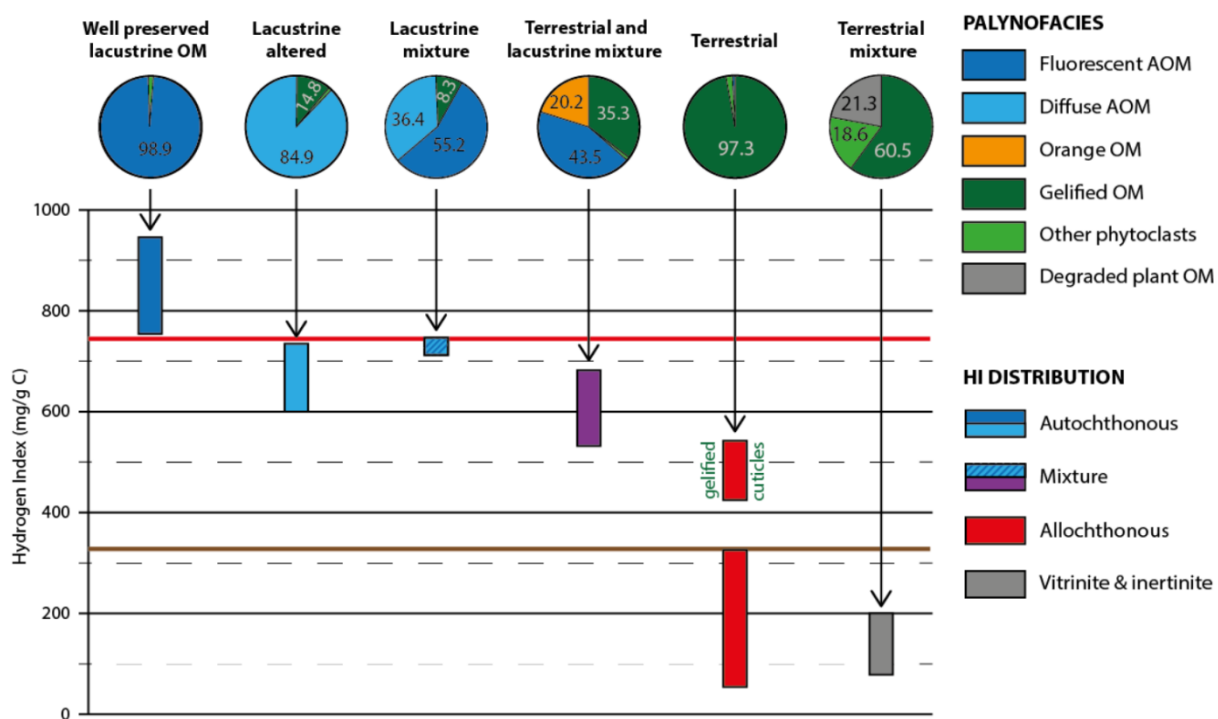


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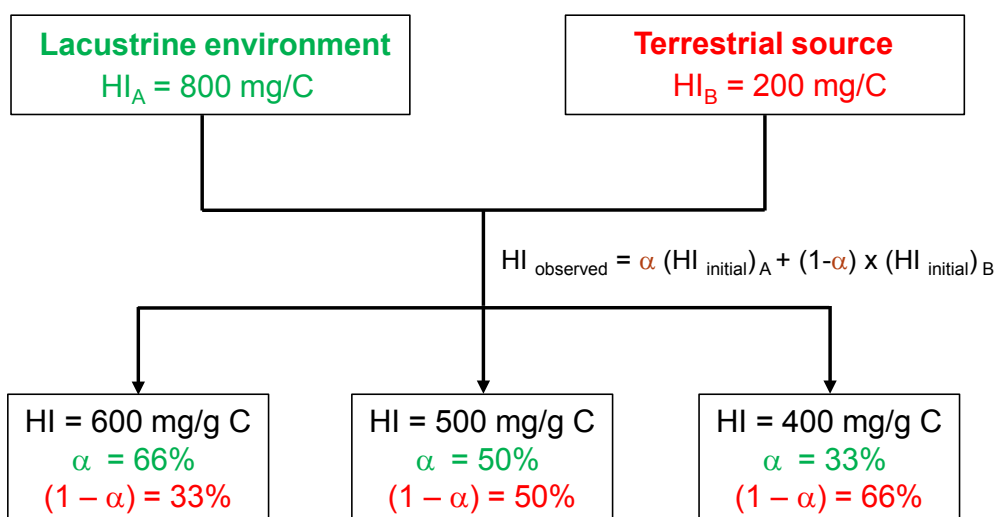


Fig.6: Example of relative proportion of lacustrine end member with mixed with terrestrial organic matter.

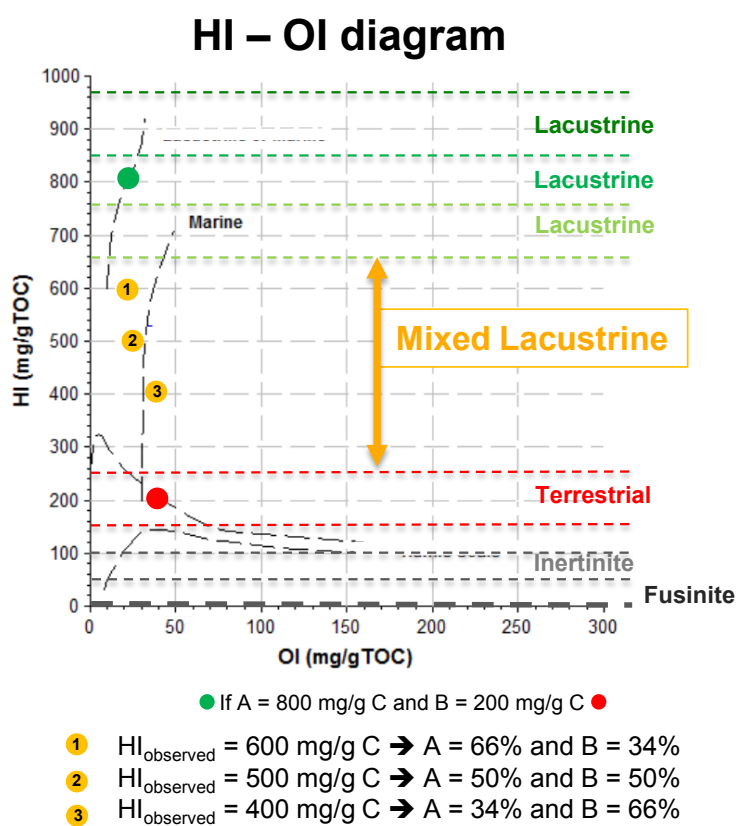


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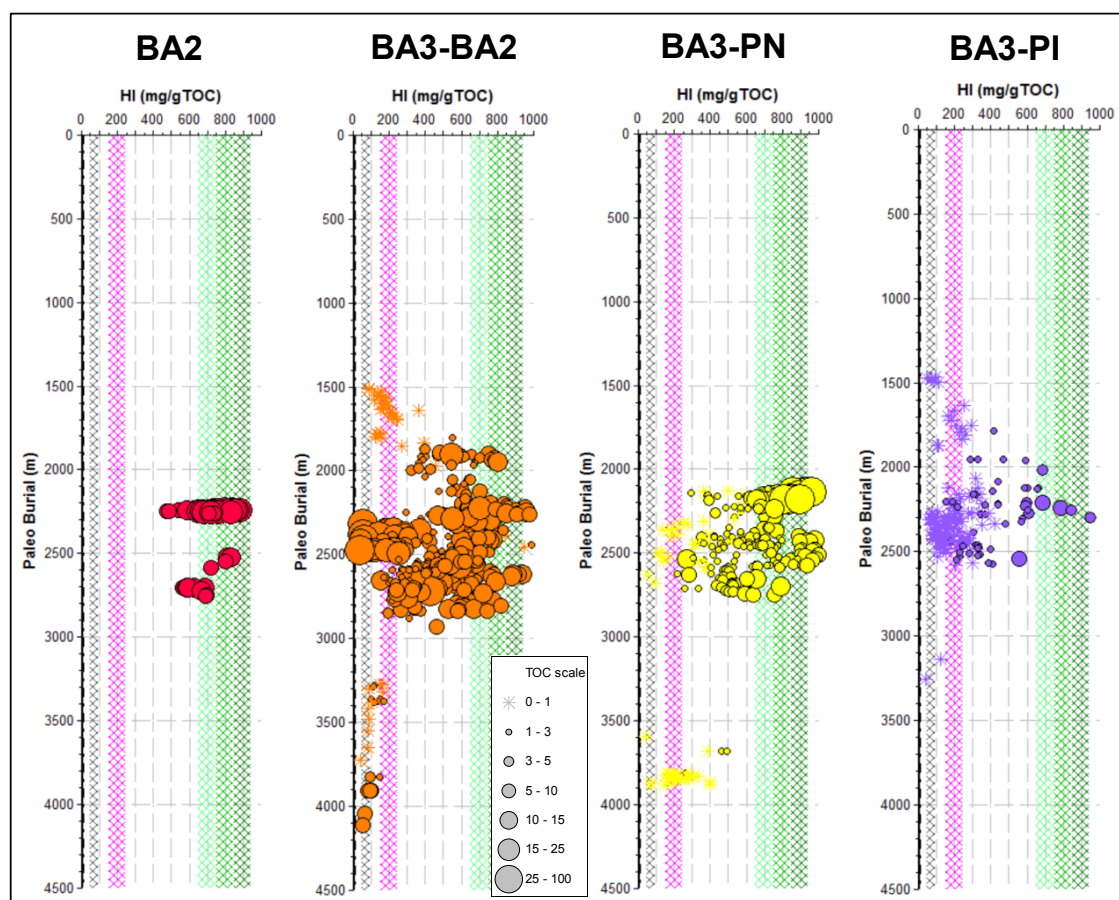


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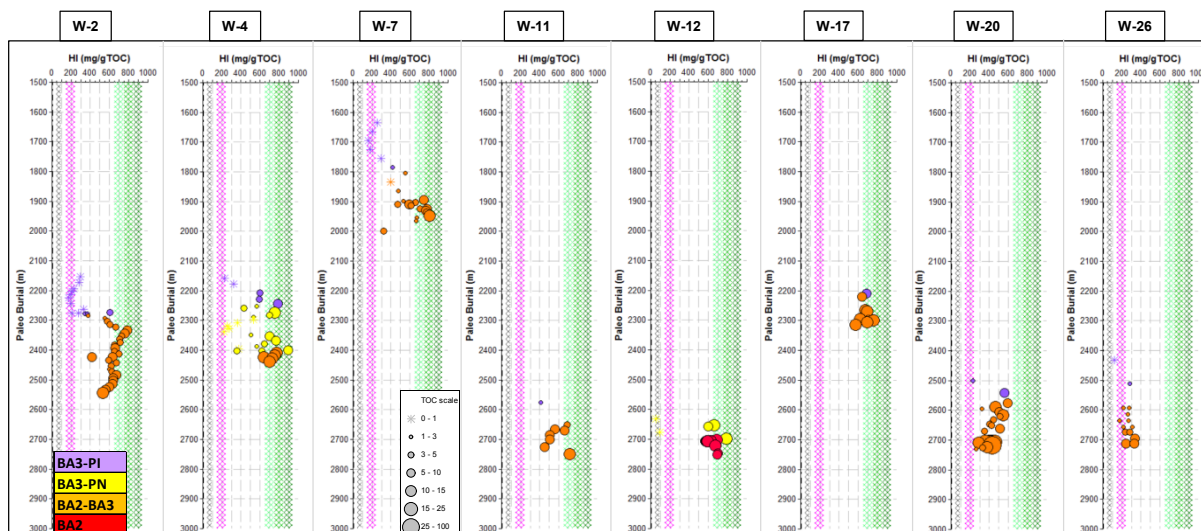


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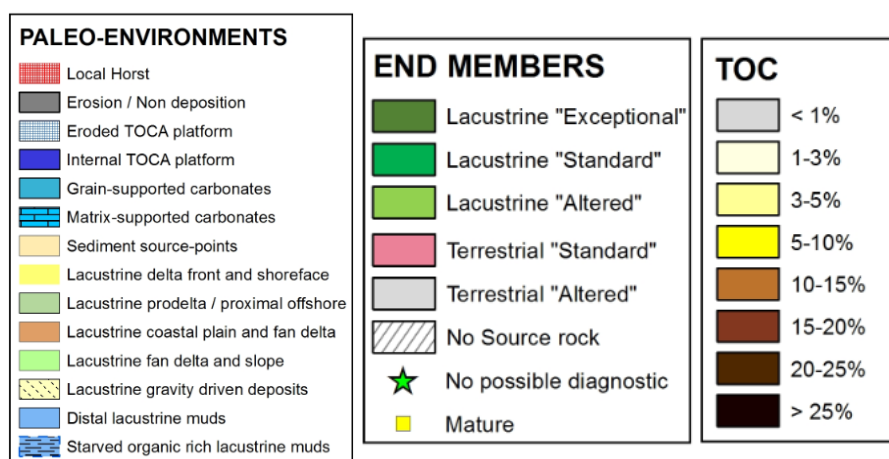


Fig.10: Palaeoenvironmental conditions, colour palette for lacustrine/terrestrial organic matter source and initial TOC distribution (%).

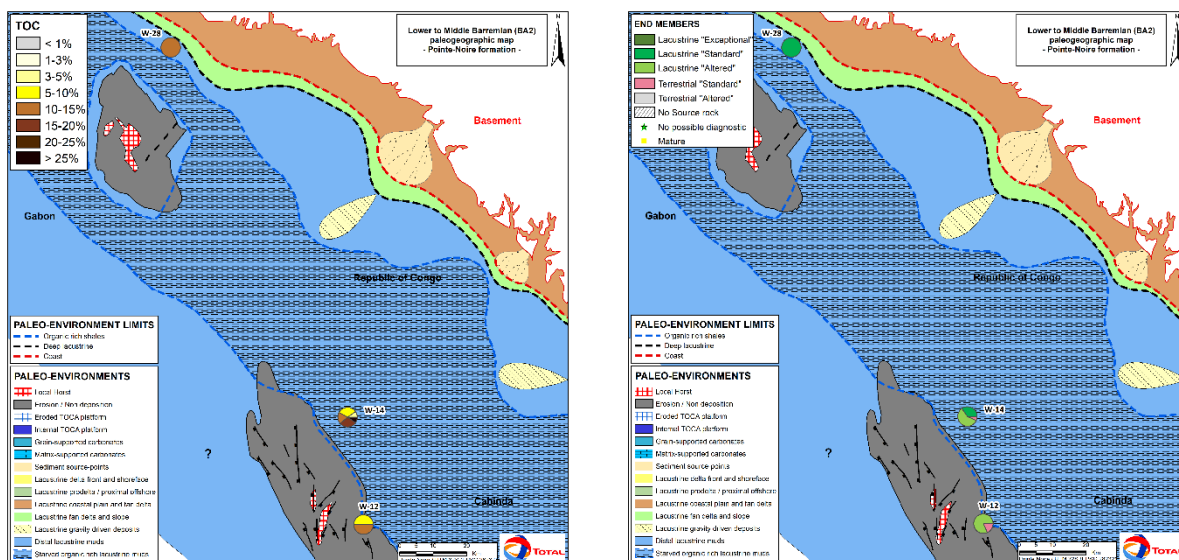


Fig. 11: Initial TOC and end-members distribution on the BA2 palaeogeographic map.

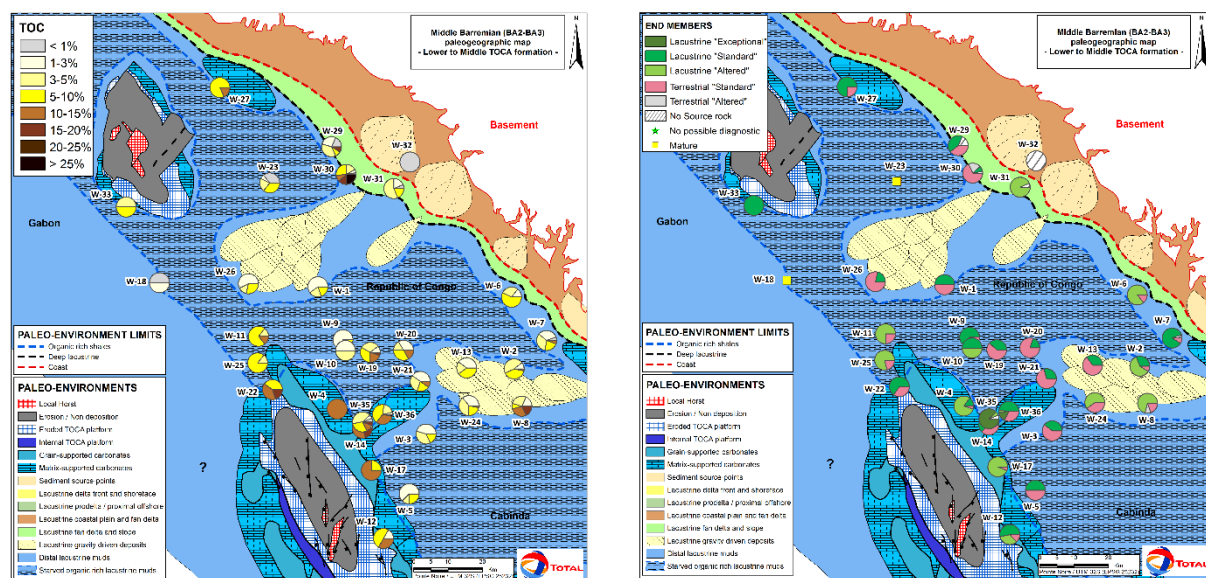


Fig. 12: Initial TOC and end-members distribution on the BA2-BA3 palaeogeographic map.

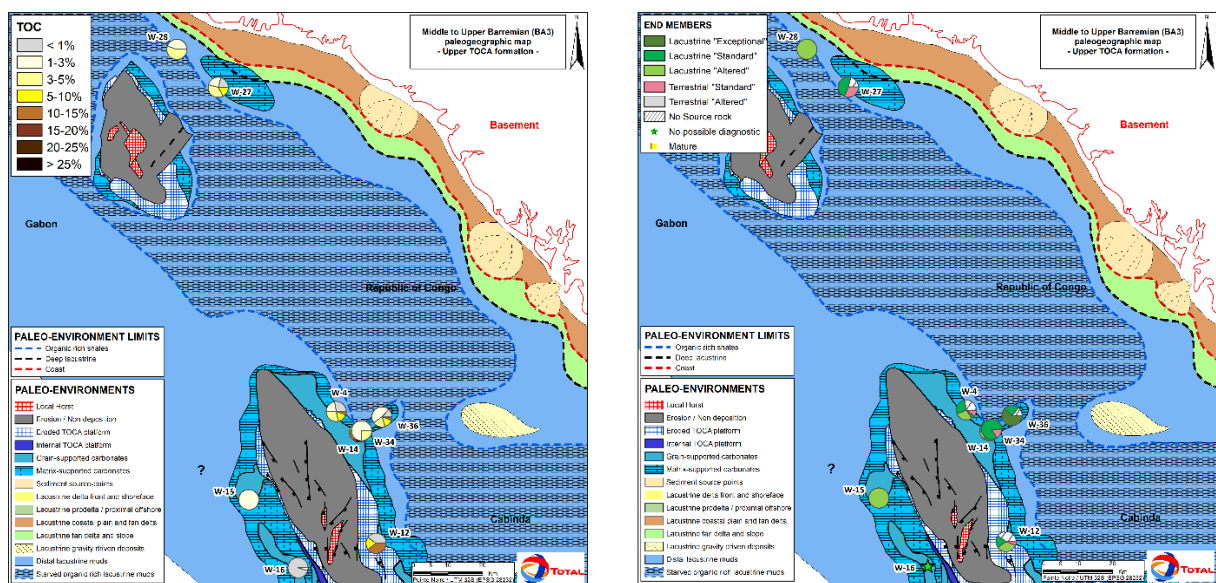


Fig. 13: Initial TOC and end-members distribution on the BA3-PN palaeogeographic map.

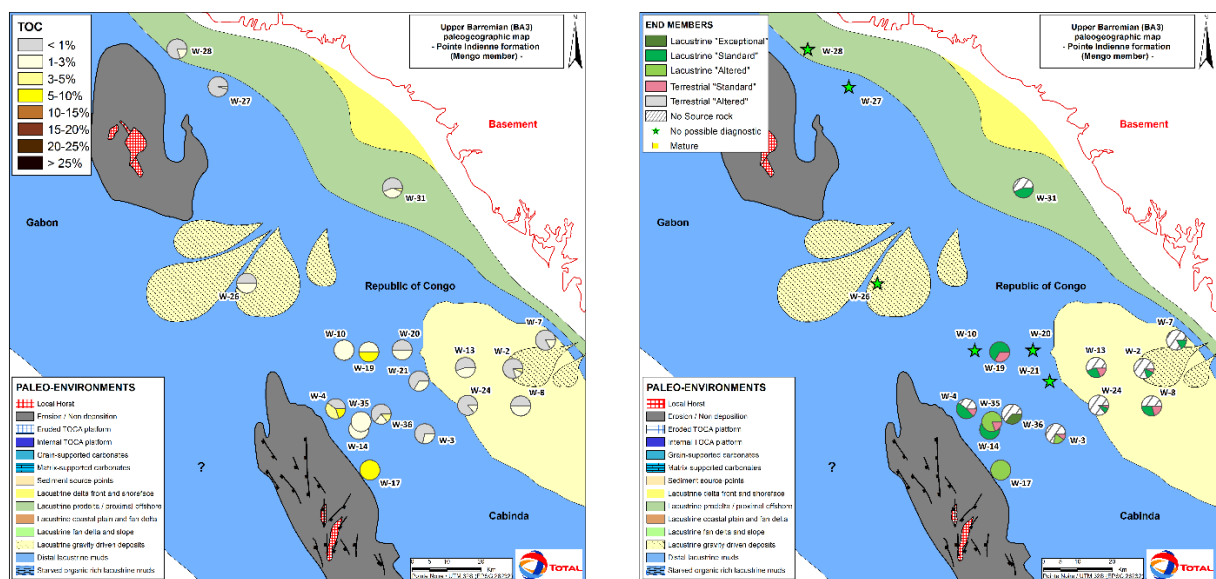


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Table 6: Source and preservation of each OM group and their corresponding end member.

Age	Composite biozone	wells	Samples		
			Total	TOC < 1%	TOC > 1%
Barremian	BA3-Pointe Indienne	10	235	52	183
	BA3-Pointe-Noire	20	187	137	50
	BA2-BA3	32	400	50	350
	BA2	3	41	0	41
TOTAL		65	863	239	624

Table 1: Well repartition for the 4 selected intervals and corresponding number of available geochemical data.

Formation	Members and/or Facies	Ostracod biozone	Pollen Biozone	Composite Biozone	Studied intervals	Sedimentological context
Loémé		-	C-IX	AP4		Stacked evaporitic cycles starting with shales then halite and then Carnallite (eventually Bischofite)
Chéla	Grès de Chéla, Terme argilo-dolomitique (Vembo)	AS12	C-IX	AP3		Fluvio-lacustrine deposits ending with shales and dolomites, more rarely anhydrite
<i>not deposited in Congo</i>		AS11 AS10/AS11	C-VIII C-VII	AP2 AP1		
Uppermost Pointe Indienne	Tchibota, Argiles Vertes	AS9/AS10	C-VI	BA4		Prograding lacustrine fan-deltas/deltas in an oxygenated lacustrine basin with a rather large coastal plain
Middle Pointe Indienne	Grès/Calcaire de Pointe Indienne, Argiles Vertes	AS9	C-V	BA3		
Lower Pointe Indienne	Grès de Mengo, Argiles Vertes	AS9	C-V	BA3	BA3 PI	Large clastic input, oxygenated clays (grey to green), absence of carbonates
Upper Pointe-Noire	TOCA, Marnes de Pointe-Noire	AS9	C-V	BA3	BA3 PN	Anoxic to suboxic black shales, decrease of clastic input, carbonates along palaeohighs
Middle Pointe-Noire	TOCA, Marnes de Pointe-Noire	AS8/AS9	C-V	BA2/BA3	BA3-BA2	Anoxic to suboxic black shale and clastic input in depocenters, carbonates along palaeohighs
Lower Pointe-Noire	Marnes de Pointe-Noire	AS8	C-V	BA2	intra BA2	Black shale, very low clastic input, no carbonates
Uppermost Djéno	Marnes noires	AS7/AS8	C-V	BA2		Condensed interval, very low clastic input

Upper Djéno	Grès de Djéno, Marnes noires	AS6/AS7	C-IV/C-V	BA1		Huge clastic input, large lacustrine subaqueous fans
Lower Djéno/Kouakouala	Grès de Djéno, Grès de Kouakouala	AS5	C-III/C-IV	NE3		
Sialivakou	Marnes de Sialivakou, Grès (unnamed)	AS3/AS4	C-III	NE2		Lacustrine systems with black shales, clastic discharge close to margin
Vandji	Grès de Vandji	AS2	C-II	NE1		Fluvial and lacustrine systems, eolian sands in places

Table 2: Summary of the main intervals for the pre-salt Aptian and Barremian source rocks with their main characteristics. Highlighted in yellow are the main intervals discussed in the present study.

Composite Biozones	HI distribution (mg/g C)				
	< 150	150-300	300-650	> 650	Total
AP3	8	0	0	0	8
BA4	0	0	1	0	1
BA3 PI	0	0	2	2	4
BA3 PN	0	0	2	14	16
BA2-BA3	0	0	2	0	2
BA2	0	0	3	15	18
BA1-BA2	0	1	3	0	4
Total	8	1	13	31	53

Table 3: Number of samples selected for palynofacies analysis and corresponding HI ranges measured on bulk rocks.

well name	Biozone composite	palaeo burial	Initial bulk rock			isolated kerogen		
			TOC	HI	OI	TOC	HI	OI

		m	%	mg/g C		%	mg/g C	
W-4	BA2-BA3	2428	10.29	707	15	79.52	720	3
W-7	BA2-BA3	1924.37	4.74	684	21	65.59	787	8
W-12	BA3	2575.5	1.37	266	116	34.08	527	10
W-12	BA2-BA3	2650.5	4.63	522	26	62.83	672	5
W-12	BA2	2702	13.91	662	13	72.86	770	9
W-12	BA2	2737	11.44	649	17	72.56	748	7
W-12	BA2	2752	8.27	670	15	71.63	753	7
W-24	BA3	2477.34	2.25	283	25	47.09	469	6
W-24	BA2-BA3	2507.34	2.55	384	20	58.34	526	4
W-24	BA2-BA3	2602.34	3.82	360	24	70.51	392	2
W-24	BA2-BA3	2732.34	4.81	226	25	73.2	246	4
W-26	BA3	2824	1.18	216	36	37.92	361	4
W-26	BA2-BA3	2902	4.23	355	15	63.74	465	10
W-26	BA2-BA3	2905	2.03	287	30	50.32	398	5

Table 4: Comparison of the HI (mg/g C) between bulk rocks and corresponding isolated kerogens.

Composite Biozones	number of samples per dominant OM group/mixture							Total
	fluorescent AOM	diffuse AOM	orange OM	fluorescent & diffuse/orange AOM mixture	other OM mixture	gelified OM & phytoclasts	gelified & greyish OM mixture	
AP3	0	0	0	0	0	5	3	8
BA4	0	1	0	0	0	0	0	1
BA3 PI	0	3	0	0	1	0	0	4
BA3 PN	9	1	3	1	1	1	0	16
BA2-BA3	0	1	0	0	1	0	0	2

BA2	7	1	4	3	0	3	0	18
BA1-BA2	0	0	0	0	2	2	0	4
Total	16	7	7	4	5	11	3	53

Table 5: Palynofacies assessment for the 4 selected intervals.

OM group	OM source	Preservation	End member
fluorescent AOM	Algae-bacteria	excellent preservation	lacustrine
diffuse AOM	Algae-bacteria	altered in the water column	altered
orange OM	Algae-bacteria	altered under anoxic conditions	lacustrine
gelified OM	Terrestrial plants	altered under suboxic/anoxic conditions	terrestrial
greyish OM	Terrestrial plants	altered under rather oxic conditions	inertinite

Table 6: Source and preservation of each OM group and their corresponding end member.