http://journal.uir.ac.id/index.php/JGEET

E-ISSN : 2541-5794
P-ISSN : 2503-216X

Journal of Geoscience,
Engineering, Environment, and Technology
Vol 11 No 1 2026

RESEARCH ARTICLE

Evaluation Of The Oil Potential, Kerogen Type And Degree Of Maturation Of The Kipala Shales (Kwilu Province,Democratic Republic of Congo) Based On Rock-Eval Parameters

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Received: Nov 22, 2025; Accepted: Mar 13, 2026.
DOI: 10.25299/jgeet.2026.11.1.25680

Abstract

This note aims to contribute to the assessment (still rudimentary at this stage) of the oil potential, kerogen type and degree of maturation of the Kipala shales, using Rock Eval parameters (TOC or COT: Total Organic Carbon; Tmax: Maximum Temperature; Peaks S1, S2, S3; IO: Oxygen Index; HI: Hydrogen Index; PI: Production Index; PP: Production Potential; RC: Residual Carbon; MINC: Mineral Carbon), as well as the associated geochemical diagrams, based on ten samples of these shales analysed by Rock Eval Pyrolysis at the PETROCCI laboratory in Côte d'Ivoire. The main results of this assessment can be summarised as follows: (i) based on the criteria established by Espitalié et al. (1977), the high TOC content (6 to 15%) of these Kipala rocks classifies them as excellent hydrocarbon source rocks; (ii) the kerogen in the shales studied is 'Type I'; (iii) the evolution of their organic matter is at the 'Immature-Mature' limit; with the exception of two samples which, with their relatively high Tmax (435°C < Tmax > 455°C), are classified as mature rocks; i.e. rocks that have reached 'oil window' conditions; (iv) almost all of the Kipala shales are classified as source rocks producing good quality oil; (v) the very high PP values of these shales classify them as rocks with very good to excellent potential, suggesting that they can generate hydrocarbons; (vi) IP values < 0.1 for most of the shale samples analysed, coupled with their low Tmax values (< 435°C), suggest that the organic matter in these shales is "immature" or even "early mature", as evidenced by the presence of traces of bitumen in some of the shale samples.

Keywords: Shales, Hydrocarbon source rock, Kerogen, Oil potential, Rock Eval parameters, Oil window, Degree of maturation.

1. Introduction

The Congo Basin is a large intracontinental sedimentary basin that forms the central basin of the DRC (Democratic Republic of Congo) and continues to be the subject of numerous geological studies, particularly regarding the presence and potential of oil. With this in mind, any oil exploration of even the smallest part of this basin contributes to the pre-exploratory work on this large basin. The shales under study belong to the Cretaceous Kipala Formation in the Kwilu province of the DRC (Fig. 1), which belongs to the Kwango Group located near the top of the stratigraphic column of the sedimentary basin of the central basin of the DRC (Lepersonne, 1977; Cahen, 1983; Daly et al., 1992; Linol et al., 2015) (Fig. 2). The Kipala Formation has been of interest to the oil industry since 1990, following the discovery of bituminous claystones by the CTCPM (Cellule Technique de Coordination et de Planification Minière) Subsequently, the work of Makuku and Inkiba (2005) identified, through four conventional geochemical analyses, good source rock potential for these shales, with a Total Organic Carbon (TOC) percentage of around 6.7 to 8.7%. Kadima (2007) analysed two samples of these Kipala rocks using Rock Eval pyrolysis, the results of which were taken up by Delvaux and Fernandez-Alonso (2015), who concluded, based on the use of the van Krevelen diagram, that these Kipala formations constitute an 'immature' source rock, with Type I kerogen, but above all that they are very limited in extent. Motivated by these interesting but very preliminary results, Munene et al. (2023) and Munene (2025) conducted a more exhaustive geological survey covering a larger area of the region and subjected some twenty samples collected from outcrops of these Kipala shales to petrographic and geochemical analysis.Their work resulted in the identification of two subfacies in these shales: a black subfacies, oily to the touch and showing under the microscope constituents bound by a clay-siliceous cement invaded by bitumen; the second, grey-brown in colour, with constituent elements bound by a clayey cement, and without bitumen. The two subfacies also differ geochemically: the black oil shales are richer in TOC (11% on average) and silica (SiO_2: 49-62%) than the grey-brown shales (TOC: 8% on average; SiO_2: 30-42%). Conversely, the latter are richer in alumina and iron (Al_2O_3: 2-52%; Fe_2O_3: 7-12%) than the black oil shales (Al_2O_3: 0.2-0.7%; Fe_2O_3: 0.4-1.1%). However, in all cases, the two subfacies of Kipala shales are classified, according to the criteria established by Espitalié et al. (1977), as excellent hydrocarbon source rocks (for details on this subject, see Munene et al., 2023; Munene, 2025).

As can be seen, the assessment of the oil potential, kerogen type and maturation state of the Kipala shales was previously rudimentary, based solely on the few results presented above. However, the Rock Eval parameters and the number of samples analysed are very important for a rigorous assessment. To remedy this shortcoming, ten samples (three for the grey-brown subfacies and seven for the black oil-rich subfacies) were selected based on the results of petrographic and conventional geochemical analyses obtained from numerous samples of these shales and previously published by Munene et al. (2023). The selected samples were sent to the PETROCCI laboratory in Côte d'Ivoire for analysis by Rock Eval pyrolysis.This study therefore aims to contribute to a more rigorous assessment of this oil potential and the degree of maturation of the Kipala shales, based on new Rock Eval parameter data, which has now become essential for this purpose, according to the work of numerous authors (Espitalié et al., 1985; Behar et al., 1989 & 2001; Nunez-betelu & Baceta, 1994; Baroud, 2017; Laouali Ibrahim Sarki & Moussa Harouna, 2021; Kouamé Kouasi et al., 2022).

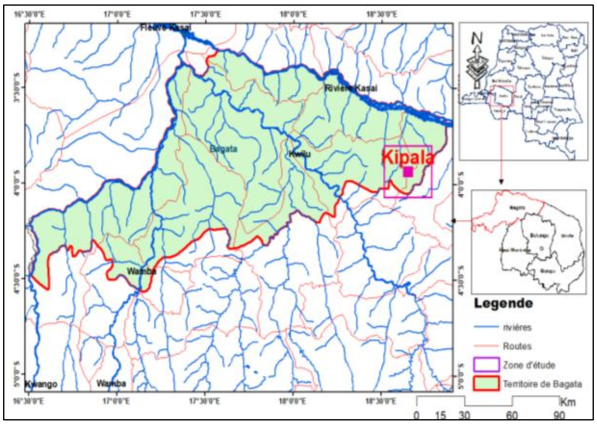

Fig. 1. Location map of the study area (Kipala outlined in purple) in the Bagata Territory (Kwilu Province)

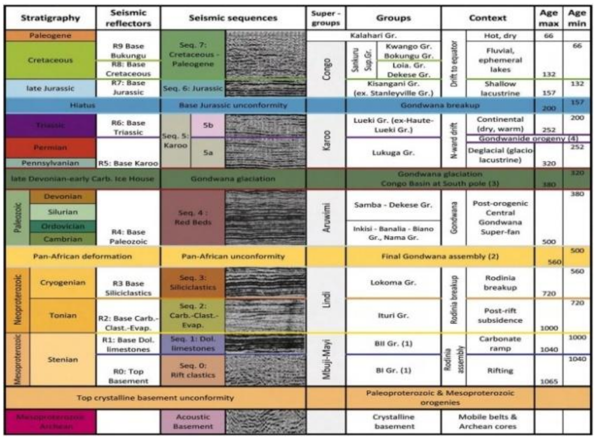

Fig. 2: Seismostratigraphic model integrating data from wells, outcrops and seismic reflection profiles,age estimates of the sedimentary basin of the Central Basin of the DRC. The thick coloured lines refer to the boundaries of the sequences interpreted from seismic profiles (Delvaux et al., 2021).

2. Methods and Equipment

To achieve its objectives, this work went through the stages inherent in any geological investigation, namely: documentation, fieldwork, laboratory work and, finally, discussion and interpretation of the results.

2.1. Documentation stage

This stage involved reviewing the writings of previous authors (various books, doctoral theses and scientific articles) in order to gather, after critical analysis, relevant data related to the subject. The aim was to select the methods, techniques and resources to be used to achieve the study's objectives.

2.2. Fieldwork stage

Two exhaustive geological survey campaigns, each lasting three weeks, were carried out using basic geologist's equipment (compass with clinometer, hammer, GPS, notebook, a 1:50,000 topographic map of the investigation area, etc.), from July to August 2018 and from February to March 2021 in the Kipala region. During these surveys, a large number of samples of two shale subfacies were collected, which were subjected to petrographic and conventional geochemical analyses, the results of which were published by Munene et al. (2023). However, around ten of these samples were selected for analysis by Rock Eval Pyrolysis, the results of which are presented in this note.

2.3. Laboratory studies

Currently, no petroleum interest in a source rock can be rigorously assessed without resorting to Rock Eval Pyrolysis analysis, as recommended by the French Petroleum Institute (IFP) in 1973 and by numerous authors (Behar et al., 1989 & 2001; Nunez-betelu & Baceta, 1994; Baroud, 2017; Laouali Ibrahim Sarki & Moussa Harouna, 2021; Kouame Kouasi et al., 2022). Pyrolysis is the thermal decomposition of organic matter in the absence of oxygen or in an oxygen-poor atmosphere. It uses two techniques to establish the kinetic model of oil generation, namely (Bordenave et al., 1993; Samira Saifi, 2012): (1) open pyrolysis, which is carried out in an inert atmosphere and allows the hydrocarbon products generated by the source rock to be characterised and quantified; (2) Closed-environment pyrolysis, a technique used to simulate the thermal evolution of kerogens and asphaltenes in the laboratory, equivalent to the evolution of source rock that has never generated oil. In this study, the first alternative was used. It is based on the principle of heating a 100 mg sample of source rock at an average rate of 25°C/minute for 20 minutes in an inert atmosphere (helium) in order to quantitatively and selectively determine:

- Free hydrocarbons: gas or oil contained in the sample submitted for analysis;
- Hydrocarbon and oxygenated compounds expelled during the cracking and oxidation of non-extractable organic matter from the source rock (kerogen).

To do this, around ten samples of Kipala shale (three from the grey-brown subfacies and seven from the black oil shale subfacies) were selected after examination under a petrographic microscope and sent to PETROCI Laboratory (Côte d'Ivoire) to determine the main Rock Eval parameters such as Tmax (maximum temperature), OI (oxygen index), HI (hydrogen index), S1, S2 and S3 peaks, which are essential for assessing the petroleum potential (PP) and the degree of maturation of the rocks studied as potential source rocks for hydrocarbons, but also for estimating, using the van Krevelen diagram, the type of kerogen that may be produced during this maturation.

3. Results And Discussions

The results of the Rock Eval pyrolysis analysis of the Kipala shale samples are summarised in the table below, and they enable us to:

3.1. Examination of oil potential and quantity of hydrocarbons produced.

Three Rock Eval parameters must be taken into consideration for this examination, namely:

- S1: which corresponds to the quantity of free hydrocarbons (HC) present in the rock sample and released at a temperature of 300°C (without kerogen cracking), expressed in mg of HC/g of rock. The constraints for this parameter are such that if S1 > 1mg HC/g of rock, the quantity of hydrocarbons (HC) in the rock is considered significant and worthy of interest (Makhous & Galushkin, 2005). Given this constraint, only the black fatty subfacies of Kipala shales, with S1 between 1.15 and 1.63 mg HC/g of rock, is worthy of interest.

- S2: reflects the rock's potential to produce hydrocarbons after maturation; i.e. the quantity of hydrocarbons obtained after cracking kerogen between 300°C and 600°C. For the shales studied, the S2 values are greater than 10 mg HC/g of rock (S2: 2.09 – 58.89 vs S2: 63.98 – 84.74 mg HC/g of rock, respectively for grey-brown shales and black oil shales); these values rank these rocks among the very good source rocks, except for sample KP11, which, with an S2 value of 2.09, stands apart from the group. This oil potential is confirmed by the TOC vs. S2 diagram (Fig. 3), which defines, according to Behar et al. (1989), the quality of hydrocarbon source rocks; when plotted on this diagram, the samples from the two groups of Kipala shales occupy the typical range of excellent source rocks, with the exception of sample KP11, which falls within the range of poor-quality source rocks.

- PP: corresponds to the sum of S1+S2 (expressed in mg HC/g rock) and reflects the capacity of a source rock to generate hydrocarbons (Negrovi, 1988). For the shales studied, PP values range from 2.97 to 59.75 for grey-brown sub-facies, and from 65.13 to 86.24 for black geasy facies; these values are all above 20 and classify the Kipala shales as a source rocks with very good to excellent petroleum potential; with the exception of the KP11 sample of grey-brown shale, which, with a PP value of 2.97, indicates low petroleum potential (Negrovi, 1988).

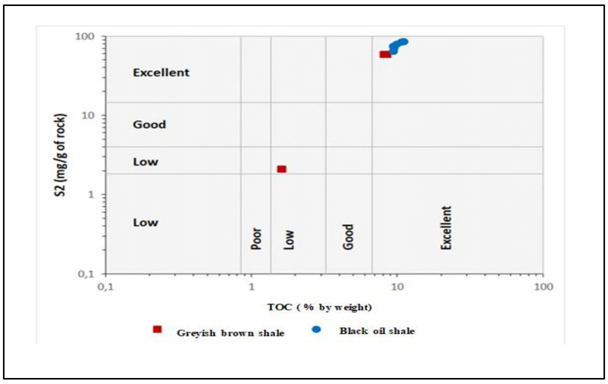

Fig. 3. Position of the Kipala shales in the TOC vs. S2 diagram (Behar et al., 1989)

Table 1. Rock-Eval pyrolysis analysis results for Kipala source rock samples

Subgroup	Echantillons	S1	S2	S3	Tmax(°C)	HI	IO	PI	PP	TOC(%)	RC	MINC
Grey-brown shales	KP1a	0,86	58,89	1,72	436	696	20	0,01	59,75	8,47	3,4	0,36
	KP3	0,97	58,34	1,26	432	711	15	0,02	59,31	8,2	3,2	0,29
	KP11	0,88	2,09	1,32	431	128	81	0,3	2,97	1,63	1,35	0,18
Black oil shales	KP2	1,48	83,33	1,17	434	775	11	0,02	84,81	10,76	3,63	0,36
	KP4b	1,37	70,51	1,25	430	741	13	0,06	71,88	9,51	2,76	0,27
	KP6	1,39	74,31	1,23	428	784	13	0,06	75,7	9,48	2,66	0,17
	KP7	1,63	84,50	1,18	434	762	11	0,09	86,13	11,09	1,34	0,19
	KP8	1,38	78,04	1,11	432	780	11	0,08	79,42	10,00	1,33	0,26
	KP16	1,5	84,74	1,84	435	761	17	0,09	86,24	11,14	3,85	0,27

3.2. Origin of organic matter in the rocks under study

In sedimentary rocks, organic matter can be either autochthonous, i.e. formed in situ in the basin, or allochthonous, in which case it comes from outside the basin. The autochthonous or allochthonous origin of the organic matter in sedimentary rocks is established using a diagram with TOC (by weight %) on the x-axis and Peak S1 (in mg HC/g of rock) on the y-axis (Behar et al., 1989). Plotted on this diagram (Fig. 4), the Kipala shales reveal that their organic carbon is essentially autochthonous, with the exception of sample KP11, which is thought to be allochthonous in origin.

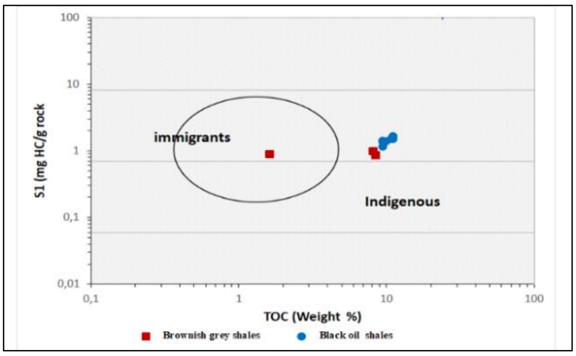

Fig. 4. Position of Kipala shale samples in the TOC vs. S1 diagram (Behar et al., 1989).

3.3. The type and degree of maturation of organic matter.

The type of kerogen present in rocks is defined using the Van Krevelen diagram (Epistalié et al., 1985b; Vandenbroucke, 2003) with the hydrogen index (HI) on the y-axis and the oxygen index (OI) on the x-axis. Plotted on this diagram (Fig. 5), the shales studied show early maturation and produce a kerogen located at the Type I-Type II boundary, which produces oil; only sample KP11 is overmature and stands out by occupying the domain reserved for Type III kerogen, which produces gas.

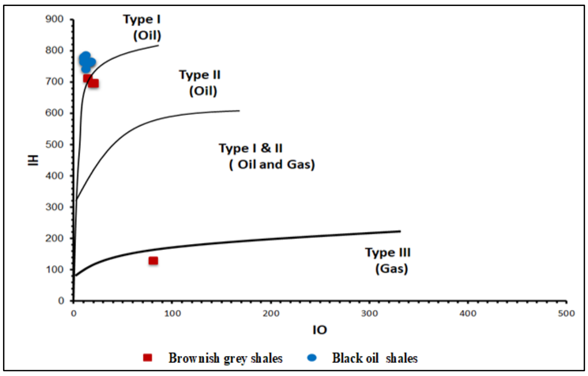

Fig. 5: General IH vs. IO diagram of Position of the Kipala shales in Van Krevelen's IH vs. IO diagram (Tissot and Welte, 1978; Espitalié et al., 1985b).

However, in the diagram by Epistalié et al. (1985a) taking into account TOC as a function of S2 (Fig. 6), some of the samples from the Kipala shales fall into Type II kerogen, others are located at the Type I-Type II boundary, with the exception of sample KP11, which falls into Type III.

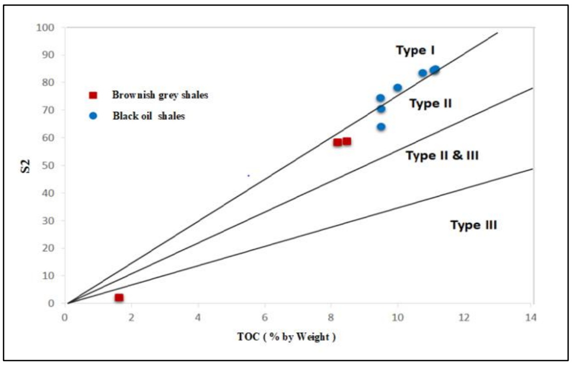

Fig. 6: Position of the shales studied in the S2 versus TOC diagram (Epistalié et al., 1985a)

3.4. Thermal maturation (Tmax) of organic matter contained in rocks

With regard to the thermal maturation of organic matter, the work of Nuñez-betelu & Baceta (1994) stipulates that Tmax values below 435ºC indicate immature organic matter, those between 435ºC and 455ºC indicate an 'oil window' condition (mature organic matter), while values between 455 and 470ºC are considered transitional. A Tmax above 470º C corresponds to the wet gas zone and overmature organic matter. The degree of thermal maturation of petroleum-prone Type I kerogens is often higher than that of other types of kerogens (Tissot & Welte, 1978; Peters, 1986). Taking the above considerations into account, only samples KP1a and KP16, with a Tmax in the range 435°C – 455°C, are mature, i.e. they have reached the 'oil window' conditions; all other samples analysed, with a Tmax below 435°C, are immature.

Still on the subject of thermal maturation, Espitalié et al. (1985b) proposed a diagram taking into account the hydrogen index (HI) on the y-axis and Tmax on the x-axis, which shows the variations in the transformation rate of three main types of organic matter as a function of Tmax (Fig. 7). Plotted on this diagram, the shales studied reveal early maturation; this means that they are located at the "immature-mature" boundary, with Type I kerogen.

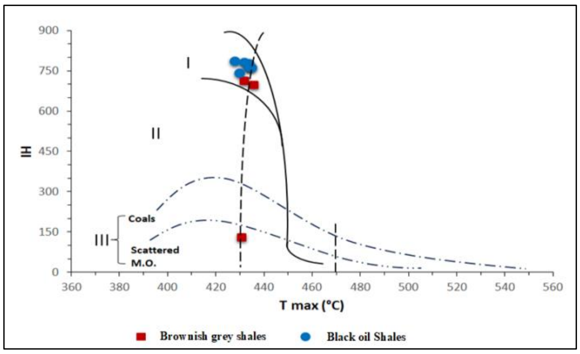

Fig. 7: Position of Kipala shales in the IH versus Tmax diagram (Espitalié et al., 1986)

3.5. Evaluation of the capacity of the studied source rocks to generate hydrocarbons based on their TOC.

It is important to note from the outset that TOC is a parameter that provides information on the richness of organic matter in rock. It reveals the sum of organic carbon present in the rock and is associated with free hydrocarbons (HC) and kerogen. The minimum value required for a rock to be classified as "mature" is 1 (Epistalié et al., 1986). Based on this parameter, the two sub-groups of Kipala shales, with TOC values above 1%, can be classified as excellent source rocks.

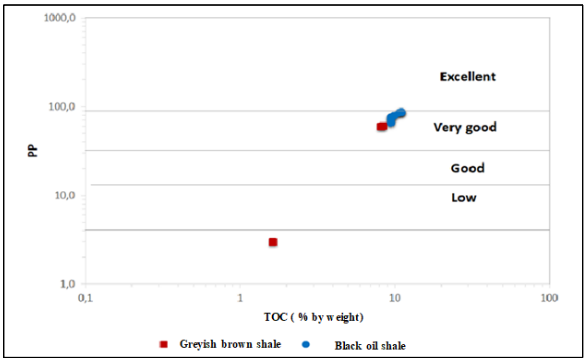

Fig. 8. Position of Kipala shales in the PP versus TOC diagram (Laouali Ibrahim Sarki and Moussa Harouna, 2021)

As for assessing the potential of source rocks to generate hydrocarbons, based on their TOC content, this is done using a diagram with the Production Potential (PP) (equivalent to the sum of S1+S2; Negrovi, 1988) on the y-axis and TOC on the x-axis (Fig. 8). The work of Laouali Ibrahim Sarki and Moussa Harouna (2021) suggests that PP values relative to TOC between 0.37 and 10 indicate poor, low and good oil potential for generating hydrocarbons; while PP values relative to TOC greater than 10 correspond to very good and excellent source rocks capable of generating hydrocarbons. Plotted on this diagram, the Kipala shales occupy the range of rocks that are very good for generating hydrocarbons and can therefore be considered to have very good oil potential.

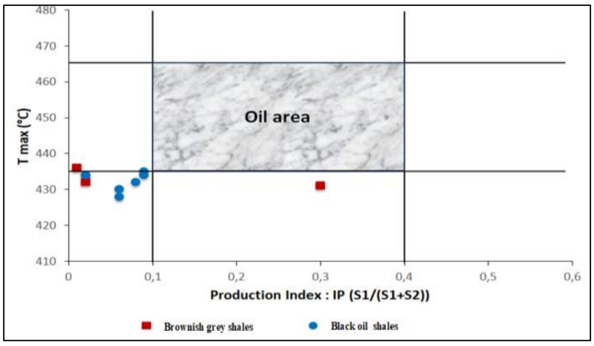

Fig. 9: Position of Kipala shales in the Tmax vs. IP diagram (Lafargue et al., 1998)

3.6. Production Index (PI)

PI values range from 0.01 to 0.3 for grey-brown shales, and from 0.02 to 0.09 for black oil shales. In all cases, they are below 0.1, and given the Tmax values below or close to 435°C, the organic matter in the Kipala rocks is considered "immature" but "early" in maturation, as suggested above by the Tmax diagram based on the hydrogen index (Fig. 6) (Espitalié et al., 1986). This early maturation is further confirmed by the presence of traces of bitumen observed in these shales by Munene et al. (2023), which prove that the shales under study were in the process of generating hydrocarbons (early maturation), as also attested by the Tmax versus IP diagram by Lafargue et al. (1998) (Fig. 9).

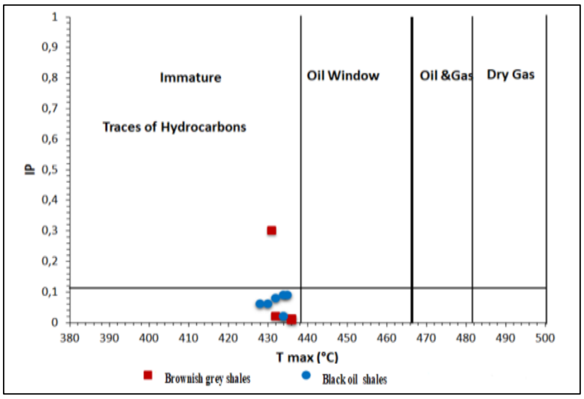

Fig. 10: Position of the Kipala shales in the IP versus Tmax diagram determining the depth of hydrocarbon formation (Espitalié et al., 1985b).

3.7. Depth of hydrocarbon production

The production index represents hydrocarbons produced by the source rock during its evolution, but in the absence of migration. It increases with depth and thus makes it possible to identify the areas where hydrocarbons are formed (Espitalié et al., 1985b) (Figs. 9 and 10). Thus, we can distinguish between:

- Gas formation zone: 0.05 ≤ IP ≤ 0.10
- Oil formation zone: 0.30 ≤ IP ≤ 0.40

In view of the above constraints and the position of the Kipala shales in Figure 10, it appears that the rocks studied are outside the 'oil window', with the exception of a few samples that are almost at the limit of this zone.

3.8. Quality of the oil produced

Numerous authors (e.g. Espitalié et al., 1985a; Makhous and Galushkin, 2005) have proposed a diagram that takes into account the hydrogen index (HI) and total organic carbon (TOC) to assess the quality of the oil produced by a source rock.

When plotted on this diagram, almost all of the Kipala shales fall, as illustrated in Figure 11, among the source rocks producing good quality oil, thus demonstrating their significant petroleum potential. Except for one sample (Sample KP11) which stands apart from the group and occupies the gas + oil production field.

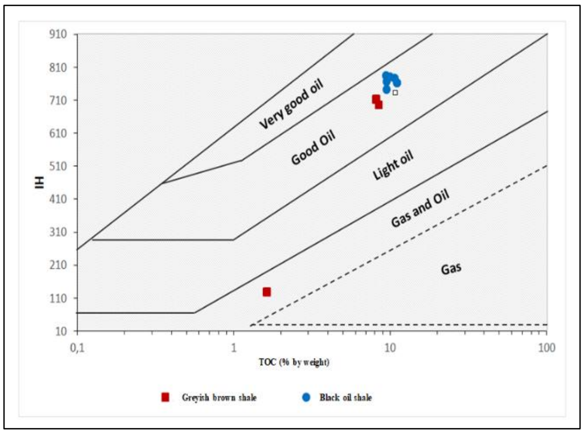

Fig. 11: Position of Kipala shales in the COT vs IH diagram (Makhous and Galushkin, 2005).

4. Conclusion

Following this study on the use of Rock-Eval parameters to assess the oil potential and degree of maturation of the Kipala shales in Kwilu Province, DR Congo, the following key points can be noted:

Shales, the only lithofacies of petroleum interest in the area, are subdivided into two subfacies: one black in colour, oily to the touch, whose microscopic constituents are bound together by a clay-siliceous cement and invaded by black organic matter (bitumen); the second is grey-brown in colour, with constituent elements bound together by clay cement and no bitumen;

The differences between these two shale subfacies are maintained at the classical geochemical level, as demonstrated in our previous publication (Munene et al., 2023);

The various Rock Eval parameters and associated geochemical diagrams used to assess the oil potential and degree of maturation of the organic matter in these two groups of shales lead to the following main findings: (1) The total organic carbon (TOC) content is higher on average for black oil shales (average TOC: 11.5% compared to 6.3% for the grey-brown subfacies). (2) However, this latter parameter classifies both subfacies as excellent source rocks, based on the criteria established for this purpose and confirmed by the TOC vs S2 diagram (Fig. 3); (3) The kerogen in these rocks is Type I, and the evolution of their organic matter is at the 'immature-mature' limit, as supported by the van Krevelen diagram (Fig. 4) and their Tmax values below 435°C; with the exception of two samples of black oil shales (KP1b and KP16) which have a Tmax between 435 and 455°C, classifying them as mature rocks (i.e. having reached "oil window" conditions);(4) The very high Production Potential (PP) values of the Kipala shales classify them as rocks with very good to excellent potential, suggesting that they can generate hydrocarbons. (5) The Production Index (PI) values of most of the shale samples analysed are below 0.1, coupled with their low Tmax values (< 435°C), suggesting that the organic matter in these shales is "immature" or even "early mature", as corroborated by Figures 4 and 7 and the presence of traces of bitumen in these rocks; (6) almost all of the Kipala shales are classified as source rocks producing good quality oil, as shown in Figure 10.

Acknowledgement

The authors would like to express their sincere gratitude to Professor Fori Yao Paul Assalé of Félix Houphouët Boigny University in Côte d'Ivoire for facilitating the analysis of the 10 shale samples studied, using Rock Eval pyrolysis at the Petroci laboratory in Côte d'Ivoire.

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