

# Geochemical Analysis of Albian-Maastrichtian Formations in the Offshore Basin of the Abidjan Margin: Rock-Eval Pyrolysis Study

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## Abstract

The Albian-Maastrichtian interval of the Ivorian sedimentary basin has been the subject of numerous sedimentological, biostratigraphic, and geophysical studies. However, its geochemical characteristics remain relatively unexplored. This study aims to determine the oil potential and the nature of the organic matter it contains. It focuses on the geochemical analysis (physicochemical method) of two oil wells located in the offshore sedimentary basin of Côte d'Ivoire, specifically in the Abidjan margin. A total of 154 cuttings samples from wells TMH-1X and TMH-2X were analyzed to determine their oil potential and the nature of the organic matter (OM) they contain. The analyses were performed using Rock-Eval pyrolysis, a method that characterizes the amount of hydrocarbons generated by the organic matter present in the rocks. The key parameters measured include Total Organic Carbon (TOC), Hydrogen Index (HI), oil potential (S<sub>2</sub>), and maximum pyrolysis temperature (T<sub>max</sub>). These parameters are used to assess the amount of organic matter, its thermal maturity, and its potential to generate hydrocarbons in the studied wells. The results show significant variations between different stratigraphic levels. In well TMH-1X, the Cenomanian and Campanian intervals stand out with very good quantities of organic matter (OM) with good oil potential, although often immature. In contrast, other stages such as the Albian and Turonian contain organic matter in moderate to low quantities, often immature and of continental type, which limits their capacity to generate hydrocarbons. In well TMH-2X, a similar trend is observed. Despite an abundance of organic mat-

ter, the oil potential remains low in most of the studied stages. The organic matter is primarily of type III (continental origin) and thermally immature, indicating a low potential for hydrocarbon generation. The study reveals that, although some intervals exhibit high-quality organic matter, the majority of the samples show insufficient maturity for effective hydrocarbon production. Wells TMH-1X and TMH-2X offer limited oil potential, requiring more advanced maturation conditions to fully exploit the hydrocarbon resources.

## Keywords

Geochemistry, Rock-Eval Pyrolysis, Upper Senonian, Petroleum Potential, Côte d'Ivoire

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## 1. Introduction

The West African coast has recently emerged as a significant hub of activity in the field of oil and gas exploration, with major discoveries of deposits in the offshore basin of the Abidjan margin. These recent advances have sparked increased interest in the geological understanding of this crucial part of the Ivorian basin, revealing promising prospects for the energy industry.

The Abidjan margin, located off the coast of Côte d'Ivoire, has been the site of significant hydrocarbon reserve discoveries in recent years. These deposits, spanning a range from the Albian to the Maastrichtian, open up new economic prospects and reinforce the status of this margin as a premier oil exploration zone in the Ivorian basin [1]-[4].

Previous studies have provided crucial information on the regional geology [5]-[10], but a thorough geological understanding of this part of the Ivorian basin is essential to contextualize these discoveries [11]-[15]. This study aims to characterize the source rocks of the Albian-Maastrichtian interval from wells TMH-1X and TMH-2X. It will: 1) evaluate the oil potential; 2) characterize the organic matter; 3) identify zones conducive to hydrocarbon generation, all coupled with their level of maturity, based on geochemical analysis results obtained from Rock-Eval 6.

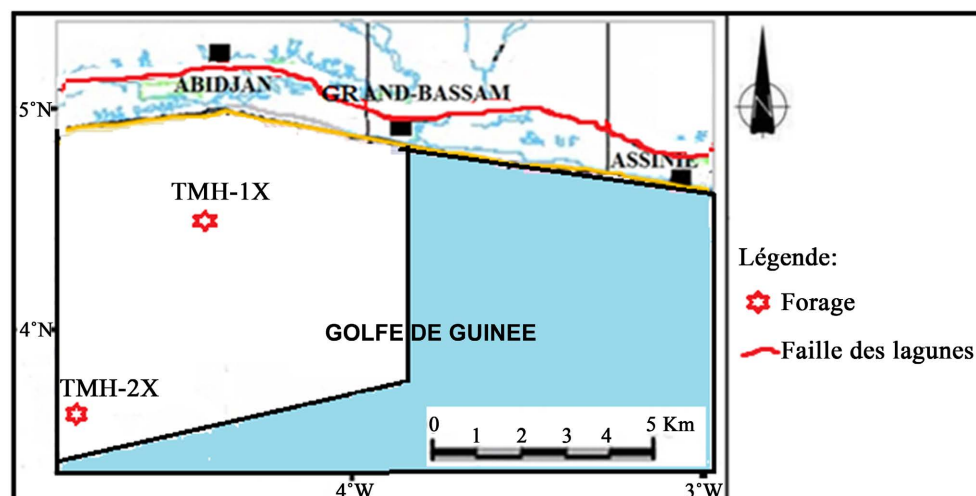
## 2. Presentation of the Study Area

In this work, the studied drillings are located in the submerged part of the sedimentary basin, specifically in the Abidjan margin (**Figure 1**). These are wells TMH-1X and TMH-2X.

## 3. Materials and Methods

### 3.1. Materials

A total of 154 cuttings samples from two oil wells (TMH-1X and TMH-2X) were used in this study. These samples were collected from the offshore sedimentary



**Figure 1.** Geographical location of the studied drillings in the offshore basin of Côte d'Ivoire.

basin of the Abidjan margin (Côte d'Ivoire). It is important to note that the stratigraphic stages were delineated through biostratigraphic studies. The samples were analyzed using Rock-Eval 6 at the laboratory of the Center for Analysis and Research of the National Oil Operations Company of Côte d'Ivoire.

## 3.2. Methods

### 3.2.1. Sample Processing

The method builds upon the work of [16], which determined the organic matter accumulation rate and kerogen type in the rock using parameters such as TOC, HI, S<sub>2</sub>, and T<sub>max</sub>.

Samples consist of 20g of already ground rock cuttings placed in a beaker. Liquid soap and water are added, and the mixture is allowed to settle for half an hour. The samples are then processed with water through a column composed of two sieves (800 and 100 μm), followed by drying in an oven at a temperature between 30°C and 50°C. The dried samples are crushed and homogenized in an agate mortar. Subsequently, 65 to 100 mg of each sample is weighed using a precision balance. These samples are then placed in crucibles and loaded into the carousel of the Rock-Eval apparatus for analysis.

### 3.2.2. Analysis Principle of Sample or Programmed Pyrolysis Method

Rock-Eval pyrolysis is a physico-chemical method that involves heating a quantity of 65 to 100 mg of ground rock at a progressive temperature increase of 25°C/min up to 650°C under an inert atmosphere (helium). This process determines the quantity and quality of hydrocarbon and oxygenated compounds (CO<sub>2</sub>) released during pyrolysis (Figure 2).

The essential data is acquired through a single analysis lasting one hour per sample. The effluents emitted during the temperature ramp-up are collected and quantified. The parameters measured or calculated in this study are:

- **S<sub>2</sub>**: This represents the oil potential or hydrocarbons derived from pyrolysis. It corresponds to the quantity of hydrocarbon compounds generated by the



**Figure 2.** Photo of the rock-eval apparatus.

**Table 1.** Petroleum potential of source rocks [18].

Organic Matter (OM)		Petroleum potential
Rock-Eval parameters		
COT (% poids)	S2 (mg HC/g roche)	
0 < COT < 0.5	0 < S2 < 2.5	Poor
0.5 < COT < 1	2.5 < S2 < 5	Fair
1 < COT < 2	5 < S2 < 10	Good
2 < COT < 4	10 < S2 < 20	Very good
COT > 4	S2 > 20	Excellent

cracking of kerogen when the rock is heated up to 600°C. It is expressed in mg HC/g of rock (Table 1).

- **TOC (Total Organic Carbon):** This gives the weight proportion of total organic matter in one gram of sample (% weight). It helps determine the petroleum potential of source rocks. While essential for classifying source rocks, TOC is less relevant than S2 in estimating oil potential because it includes inert carbons incapable of generating hydrocarbons (Table 1).
- **T<sub>max</sub> (°C):** This is the pyrolysis temperature and a key parameter of Rock-Eval. It quantifies the thermal maturity of a rock and represents the temperature of maximum hydrocarbon generation. T<sub>max</sub> values are less reliable when S2 < 0.2 mg HC/g rock [17]. T<sub>max</sub> allows a coarse evaluation of the degree of organic matter maturation (Table 2). This maturity level depends on other factors, including the type of organic matter.
- **HI (Hydrogen Index):** This is the proportion of hydrocarbon effluents emit-

ted during pyrolysis relative to TOC. Its formula is:  $HI = (100 \times [S2/TOC])$ , expressed in mg HC/g TOC. It is important to note that the hydrogen content of organic matter is one of the most significant factors controlling the generation of oil and gas. [20] demonstrated that the hydrogen in kerogen is proportional to the hydrocarbons S2 released during pyrolysis, and that the hydrogen index correlates with the H/C ratio of kerogen. Therefore, marine organisms and algae have higher HI values compared to terrestrial organisms. HI is used to assess the type and origin of organic matter in sedimentary rocks (Table 3).

**Table 2.** Thermal maturity [19].

Rock-Eval parameters $T_{max}$ (°C)	Thermal maturity
$T_{max} < 435$	Immature
$435 < T_{max} < 445$	Early maturity
$445 < T_{max} < 450$	Peak maturity
$450 < T_{max} < 470$	Advanced maturity
$T_{max} > 470$	Overmature

**Table 3.** Type of kerogen and expelled products.

IH (mg HC/g TOC)	Type of kerogen	Hydrocarbons formed
<50	IV	-
50 - 200	III	Gas
200 - 300	III/II	Oil and Gas
300 - 600	II	Oil
>600	I	Oil

## 4. Results et Interpretation

### 4.1. Well TMH-1X

With the tops of the stratigraphic units identified through biostratigraphic data, geochemical divisions were conducted based on these different units.

#### 4.1.1. Albian (2230 - 3560 m)

Forty-four (44) samples were analyzed within this interval. The quantity of organic matter (OM) is determined by the Total Organic Carbon (TOC) content. TOC varies between 0.06% and 1.93% by weight, with an exception at 3510 m (2.15% by weight), averaging 0.55% by weight (Figure 3), indicating relatively good TOC content. However, the petroleum potential (S2) shows low values, averaging 0.50 mg HC/g rock (Figure 4), indicating a low S2 within this interval. The values of the  $T_{max}$  (maximum pyrolysis temperature) range from 422 to 451°C, averaging 436.59°C. The organic matter (OM) in the Albian is thus at an

early maturity stage. The Hydrogen Index (HI) generally ranges from 53 to 192 mg HC/g TOC, and locally from 6 to 41 mg HC/g TOC, indicating a Type III organic matter, sometimes with Type IV (Figure 5).

Although the organic matter is at an early maturity stage in the Albian interval, it shows average TOC content and low petroleum potential. These sediments, which produce gas in very low proportion, originate from continental sources (Type III) and lack the qualities of a source rock.

#### 4.1.2. Cenomanian (1830 - 2210 m)

The evolution of geochemical parameters allowed the subdivision of the Cenomanian interval into three parts:

- **Interval from (1830 - 1970 m)**

In this interval, five (5) samples were analyzed. The Total Organic Carbon (TOC) values measured are high, ranging from 1.22% to 3.96% by weight, with an average of 2.38% by weight, characteristic of a very good quantity of organic matter (OM) (Figure 3). This OM has been well preserved. Additionally, the petroleum potential indicates values ranging from 1.44 to 8.23 mg HC/g rock, averaging 4.68 mg HC/g rock (Figure 4). These S2 values indicate that this zone is conducive to hydrocarbon generation. Furthermore, this organic matter is immature, with an average  $T_{max}$  of 421 °C (<435 °C). The Hydrogen Index (HI) values range from 77 to 502 mg HC/g TOC, averaging 219 mg HC/g TOC, indicating Type III/II organic matter, meaning mixed origin (continental and marine) (Figure 5). At maturity, this organic matter will generate oil and gas.

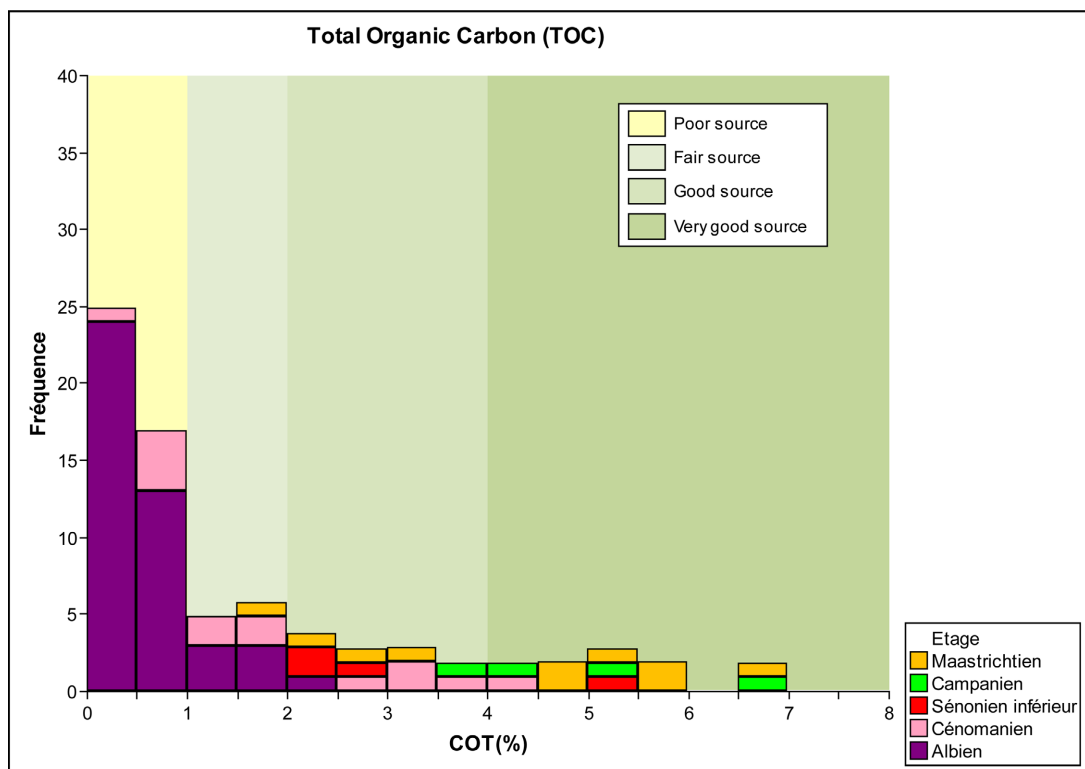
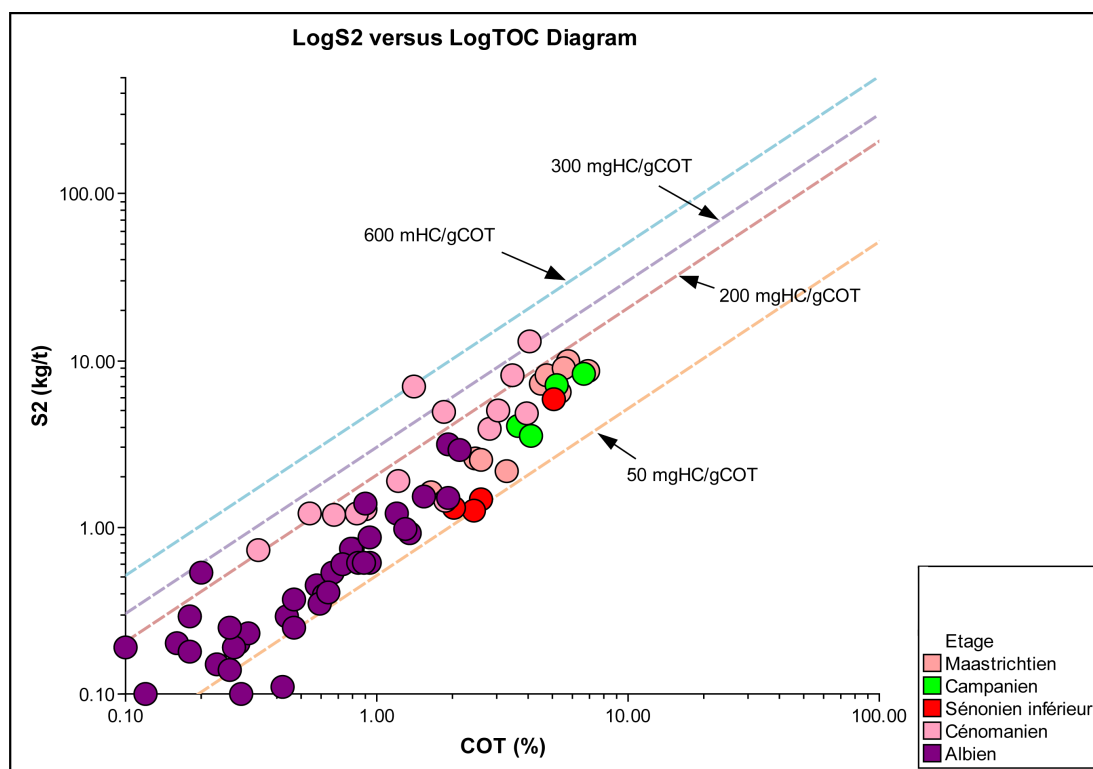


Figure 3. Total Organic Carbon (TOC) distribution by stage of TMH-1X well.



**Figure 4.** Variation of Rock-Eval S2 versus Total Organic Carbon (TOC) by stage of TMH-1X well.

- **Interval from (1970 - 2090 m)**

Measurements of TOC conducted on the five (5) samples collected in this interval show values ranging from 0.34% to 2.84% by weight (**Figure 3**). The values have an average of 1.02% by weight, characteristic of a good quantity of organic matter (OM). However, the petroleum potential (S2) is low, averaging 1.58 mg HC/g rock (**Figure 4**). The average  $T_{max}$  is 430°C, indicating the thermal immaturity of this OM from a petroleum perspective. The Hydrogen Index (HI) values in this part of the Cenomanian indicate that the OM is Type IV (since  $IH < 50$  mg HC/g TOC) (**Figure 5**). In terms of origin, this is oxidized organic matter that cannot be attributed to any specific original biomass. Unlike Types I, II, and III, Type IV often represents a remobilization of organic matter through erosion of pre-existing sedimentary rocks or highly altered residues of various biomasses. No source rock has been identified in this interval.

- **Interval from (2090 - 2230 m)**

Four (4) samples were studied in this interval. The evolution of TOC values indicates very good quantity of organic matter (OM), with an average of 2.73% by weight (2% < TOC < 4% by weight) (**Figure 3**). The S2 values range from 3.16 to 13.14 mg HC/g rock, averaging 6.57 mg HC/g rock, indicating a good petroleum potential (**Figure 4**). The combination of TOC and S2 parameters leads us to conclude that this interval possesses a source rock with good petroleum potential.  $T_{max}$  values range from 425°C to 431°C, averaging 428°C, indicating that the organic matter is immature for hydrocarbon generation. The Hydrogen In-

dex (HI) values obtained range from 164 to 322 mg HC/g TOC, averaging 230 mg HC/g TOC, characterizing a Type III/II organic matter of mixed origin (Figure 5).

#### 4.1.3. Turonian (1810 - 1830 m)

Only one sample was analyzed in this thin interval of the Turonian. Measurements show a very good Total Organic Carbon (TOC) content (3.96% by weight) and a fairly good petroleum potential ( $S_2 = 4.81$  mg HC/g rock). This organic matter is immature ( $T_{max} = 425^\circ\text{C}$ ) and of Type III, as indicated by the Hydrogen Index (HI) estimated at 121 mg HC/g TOC.

#### 4.1.4. Lower Senonian (1700 - 1810 m)

Three (3) samples were analyzed in the Lower Senonian. The quantity of organic matter (OM) is very good with an average of 3.04% by weight (Figure 3), but the petroleum potential of this interval is low, with an average  $S_2$  of 2.48 mg HC/g rock (Figure 4).  $T_{max}$  ranges from  $425^\circ\text{C}$  to  $437^\circ\text{C}$ , with an average of  $432^\circ\text{C}$ , and the Hydrogen Index (HI) ranges from 51 to 116 mg HC/g TOC. This OM is Type III, indicating continental origin, and can potentially produce gas upon maturation (Figure 5).

Due to  $S_2$  values below 2.5 mg HC/g rock, these sediments are not considered source rocks.

#### 4.1.5. Campanian (1580 - 1700 m)

The average Total Organic Carbon (TOC) content measured in the four (4)

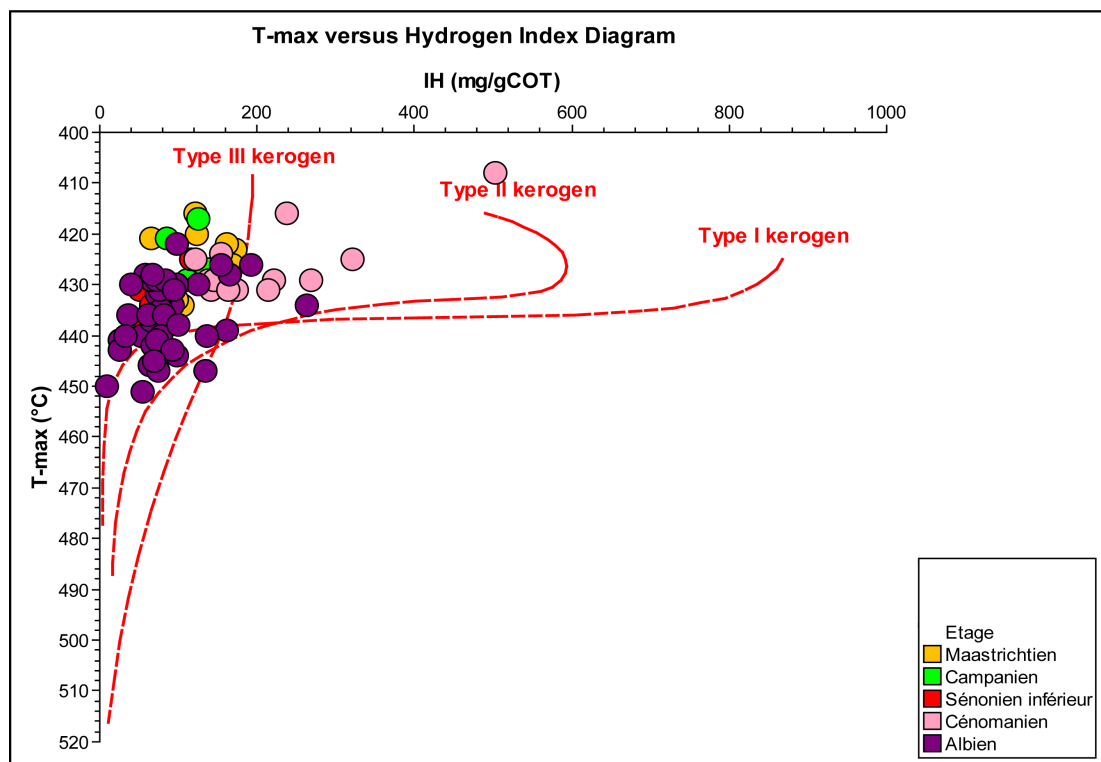


Figure 5. Variation of hydrogen index versus Rock-Eval  $T_{max}$  by stage of TMH-1X well.

samples analyzed is estimated at 4.51% by weight (**Figure 3**). This interval therefore contains an excellent quantity of organic matter (OM). The Campanian interval in well TMH-1X exhibits the characteristics of a good source rock. Indeed, these sediments have a good petroleum potential with an average S<sub>2</sub> of 5.14 mg HC/g rock, ranging between 3.51 and 7.1 mg HC/g rock (**Figure 4**).

However, the average T<sub>max</sub> values are below 435°C, indicating immature organic matter (OM). Hydrogen Index (HI) measurements ranging from 125 to 137 mg HC/g TOC (**Figure 5**) suggest Type III continental origin organic matter that generates gas hydrocarbons upon maturation. The Campanian of the TMH-1X well is therefore a favorable zone for hydrocarbon generation, although this organic matter is immature.

#### 4.1.6. Maastrichtian (1240 - 1580 m)

- **Interval from (1240 - 1300 m)**

Measurements on the three (3) samples processed in this interval show a Total Organic Carbon (TOC) content of very good quantity, averaging 2.24% by weight (**Figure 3**). However, this organic matter does not have the capacity to generate hydrocarbons, as the average S<sub>2</sub> is 2.25 mg HC/g rock (**Figure 4**). Additionally, this OM is immature, with T<sub>max</sub> values below 435°C. The average Hydrogen Index (HI), ranging between 97 and 106 mg HC/g TOC (HI = 100.33 mg HC/g TOC), indicates Type III kerogen, characteristic of continental origin organic matter (**Figure 5**).

- **Interval from (1300 - 1580 m)**

Among the eight (8) samples analyzed, the average TOC value is 5.35% by weight (**Figure 3**). These high TOC values observed at the base of the Maastrichtian indicate an excellent quantity of organic matter (OM) in this part. This interval also shows a good petroleum potential, with an average S<sub>2</sub> of 7.47 mg HC/g rock (**Figure 4**). However, this source rock does not have the capacity to generate oil and gas as it is immature, with an average T<sub>max</sub> of 421°C (<435°C). Hydrogen Index (HI) measurements, ranging from 65 to 172 mg HC/g TOC, indicate continental origin organic matter (**Figure 5**).

## 4.2. Well TMH-2X

### 4.2.1. Albian (4500 - 4570 m)

Eight (8) samples were processed in this interval. Measurements show generally good organic matter contents, with an average Total Organic Carbon (TOC) of 1.15% by weight (**Figure 6**). The petroleum potential varies between 0.51 and 4.33 mg HC/g rock in the analyzed cuttings, with an average of 2.11 mg HC/g rock (<2.5 mg HC/g rock) (**Figure 7**). Thus, although the organic matter (OM) shows a good quantity of TOC, it is not capable of producing hydrocarbons. The combination of these two parameters clearly indicates the absence of a source rock in this interval. Moreover, the T<sub>max</sub> value (438°C > 435°C) indicates that this OM is in the early stage of maturity. Hydrogen Index (HI) measurements on the samples indicate an average content of 183.63 mg HC/g TOC, characteristic

of continental origin organic matter (Figure 8).

#### 4.2.2. Reworked Zone (Turonian-Cenomanian-Albian): 4070 - 4500 m

A reworked zone includes characteristic microfossils from different stages. The Total Organic Carbon (TOC) contents calculated in this interval, composed of forty (40) samples, range between 0.41% and 1.4% by weight, with an average of 0.87% by weight (Figure 6). This content is indicative of organic matter of fairly good quantity. The average Hydrogen Index (HI) of 179 mg HC/g TOC indicates that the organic matter is Type III (Figure 8). With an average  $T_{max}$  of 137°C, this organic matter is in the early stage of maturity. Unfortunately, its petroleum potential (S2) is low, with an average of 1.52 mg HC/g rock (Figure 7). Therefore, there is no source rock in this reworked zone.

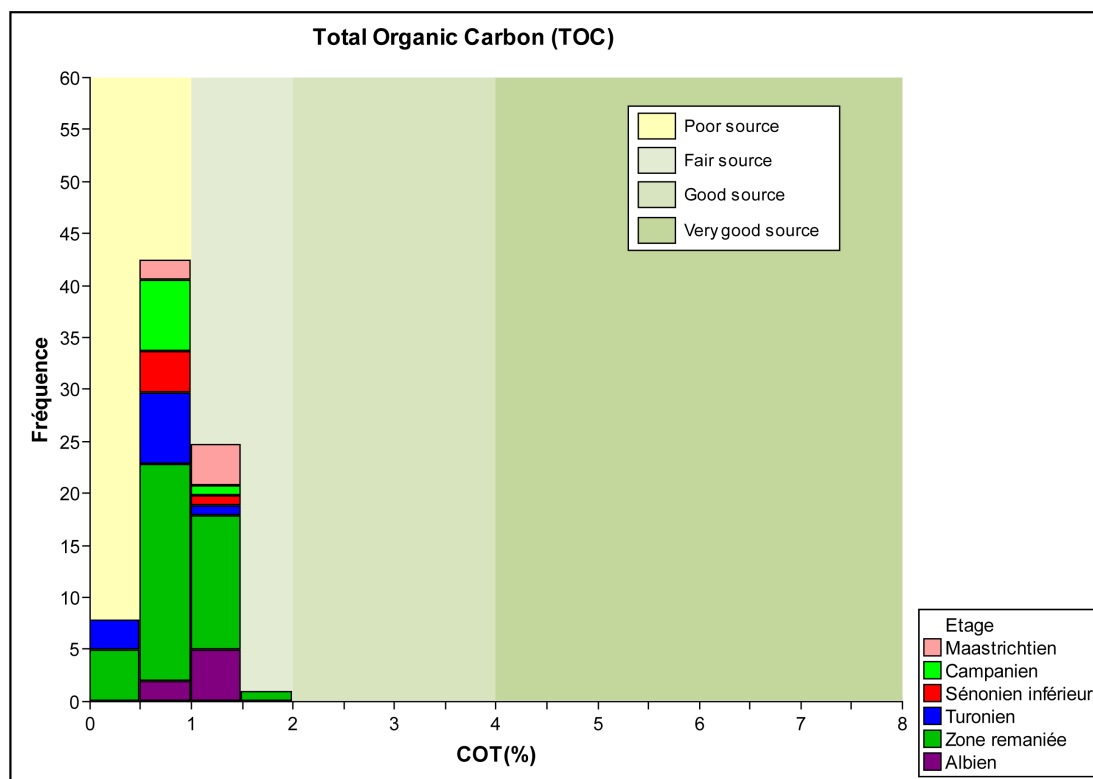
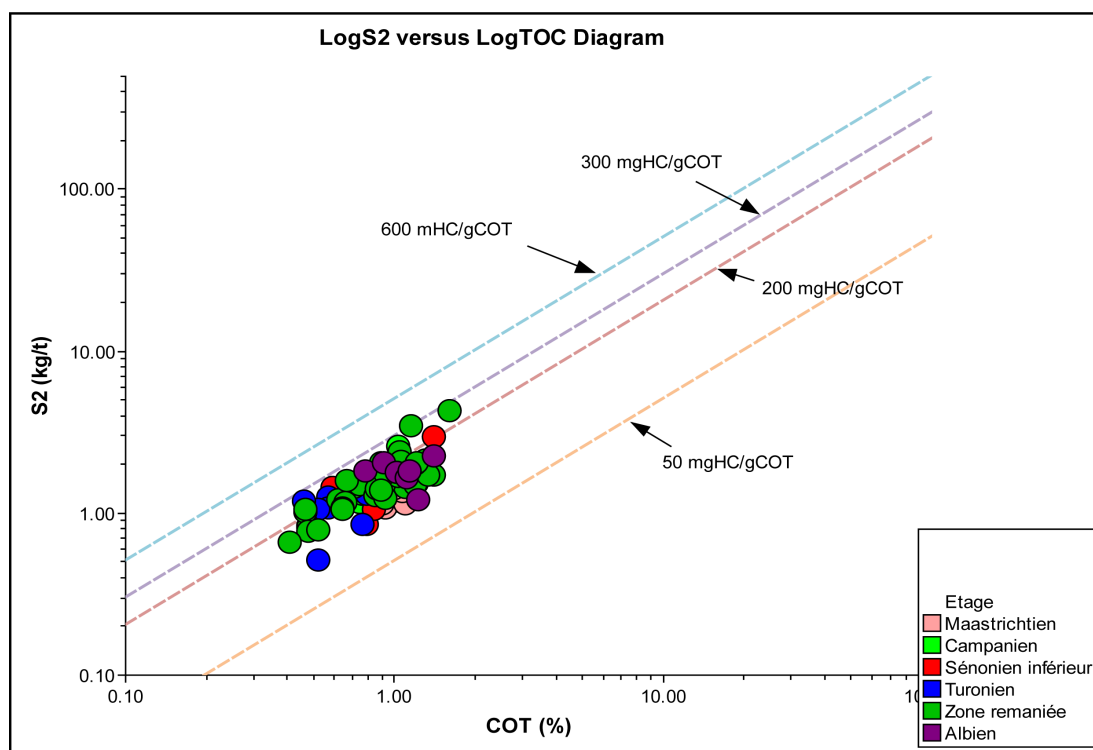


Figure 6. Total Organic Carbon (TOC) distribution by stage of TMH-2X well.

#### 4.2.3. Turonian (3870 - 4070 m)

Ten (10) samples were analyzed from the Turonian level. Measurements on these samples indicate that the Total Organic Carbon (TOC) values range between 0.48% and 1.2% by weight, with an average of 0.69% by weight (Figure 6). This content suggests organic matter of fairly good quantity. However, the petroleum potential (S2) is low, with an average of 1.13 mg HC/g rock (Figure 7). Therefore, there is no source rock in the Turonian of well TMH-2X. Moreover, the average  $T_{max}$  is below 435°C, indicating the immaturity of this organic matter. However, the average Hydrogen Index (HI) of 170 mg HC/g TOC is characteristic of continental origin organic matter (Type III) (Figure 8).



**Figure 7.** Variation of Rock-Eval S2 versus Total Organic Carbon (TOC) by stage of TMH-1X well.

#### 4.2.4. Lower Senonian (3760 - 3870 m)

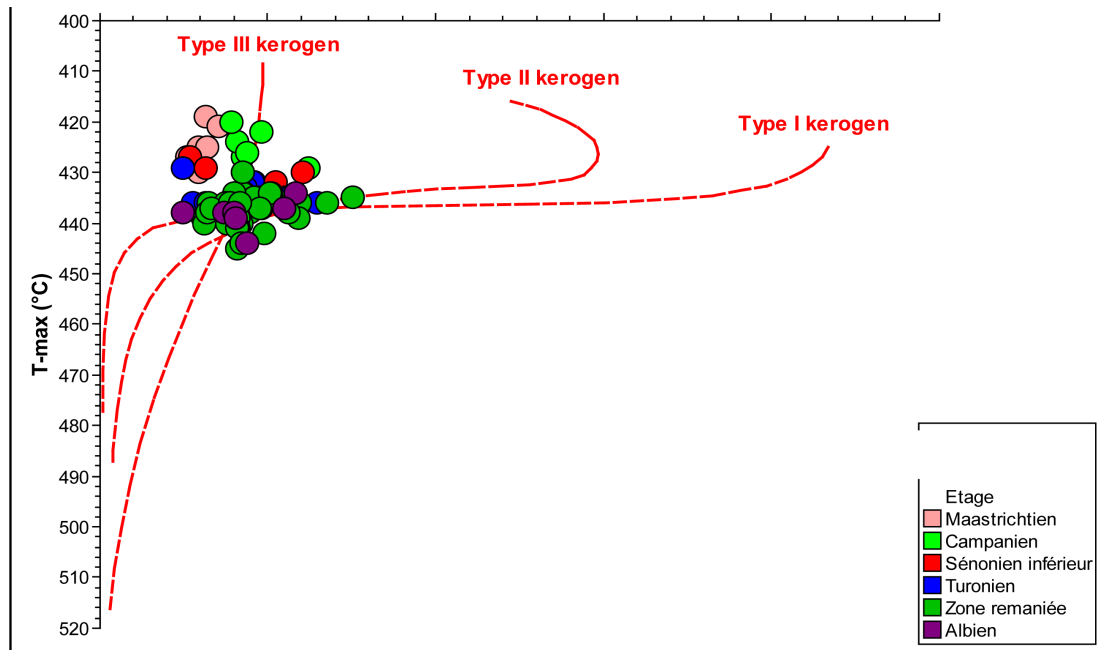
In this interval, measurements were conducted on five (5) drill cuttings. The analyses show that the Total Organic Carbon (TOC) values range from 0.59% to 1.4% by weight, with an average of 0.91% by weight (Figure 6). The petroleum potential is low, with an average below 2.5 mg HC/g rock (Figure 7). The Hydrogen Index (HI) values range from 108 to 248 mg HC/g TOC, indicating predominantly Type III organic matter with some Type II in places (Figure 8). However, this organic matter is immature, as the average  $T_{max}$  is below 435°C. Given that the petroleum potential is low, this interval is therefore not conducive to hydrocarbon generation.

#### 4.2.5. Campanian (3610 - 3760 m)

In the Campanian interval, eight (8) samples were analyzed using Rock-Eval pyrolysis. The evolution of Total Organic Carbon (TOC) values indicates organic matter of reasonably good quantity, with an average of 0.81% by weight (Figure 6). The average S2 values are 1.39 mg HC/g rock, potentially indicating low petroleum potential (Figure 7). There is no source rock in this interval, reflecting poor preservation of organic matter in this environment. The Hydrogen Index (HI) generally ranges between 157 and 193 mg HC/g TOC (Figure 8), indicating the presence of Type III kerogen (of continental origin). However,  $T_{max}$  values ranging from 420 to 432°C indicate the thermal immaturity of this kerogen.

#### 4.2.6. Maastrichtian (3500 - 3760 m)

Six (6) samples were analyzed by Rock-Eval in the Maastrichtian interval. The



**Figure 8.** Variation of Hydrogen Index versus Rock-Eval  $T_{max}$  by stage of TMH-2X well.

measurements of Total Organic Carbon (TOC) indicate that the sediments contain a good quantity of organic matter (Figure 6). However, these sediments do not constitute good source rocks, as the petroleum potential is low ( $1.08 \text{ mg HC/g rock} < S_2 < 1.14 \text{ mg HC/g rock}$ ) (Figure 7). Thus, while high TOC values are present, they are not sufficient criteria for high-quality source rocks. The type of organic matter and the potential for hydrocarbon generation must be considered for better characterization of source rocks. Similar to the Campanian, the kerogen encountered in the Maastrichtian is Type III (with an average HI =  $122 \text{ mg HC/g TOC}$ ) (Figure 8), and it is immature, with an average  $T_{max} < 435^\circ\text{C}$ .

## 5. Synthesis of Drilling TMH-1X and TMH-2X

### 5.1. Drilling TMH-1X

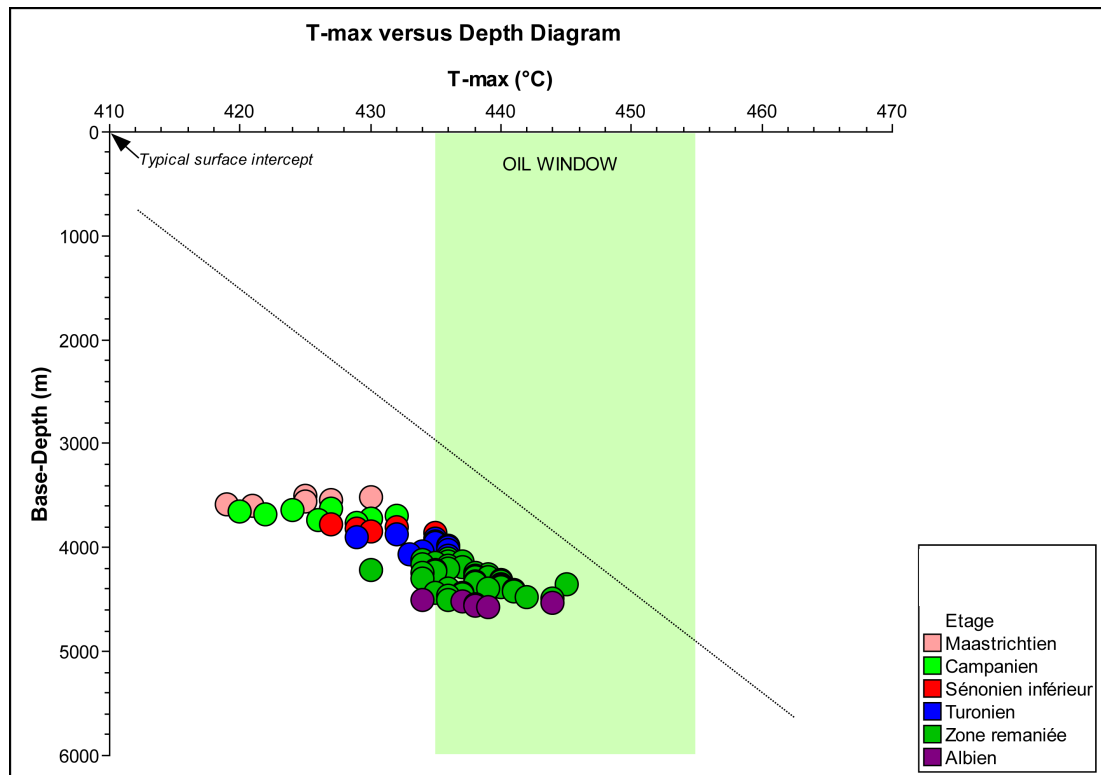
Geochemical analysis (Rock-Eval pyrolysis) conducted on drilling TMH-1X reveals a variety of characteristics in terms of petroleum potential, organic matter, and identification of zones favorable for hydrocarbon generation (Figure 9).

In the Albien, although the organic matter quantity is moderate, the petroleum potential is low, limiting its ability to generate hydrocarbons.

The Cenomanian shows variations, with intervals (1830 m - 1970 m) and (2090 m - 2230 m) displaying organic matter of very good quality and a petroleum potential conducive to hydrocarbon generation. However, these intervals indicate immature organic matter.

In the Turonian, although the quantity of organic matter is good, its petroleum potential is quite promising but it remains immature.

The lower Senonian presents organic matter suitable for gas production at



**Figure 9.** Variation of  $T_{max}$  versus Depth diagram by stage of TMH-1X well.

maturity, but does not constitute source rocks.

The Campanian contains an abundant quantity of organic matter with a good petroleum potential, generating gaseous hydrocarbons at maturity.

The Maastrichtian contains organic matter of continental origin, with a good quantity but immature for hydrocarbon generation.

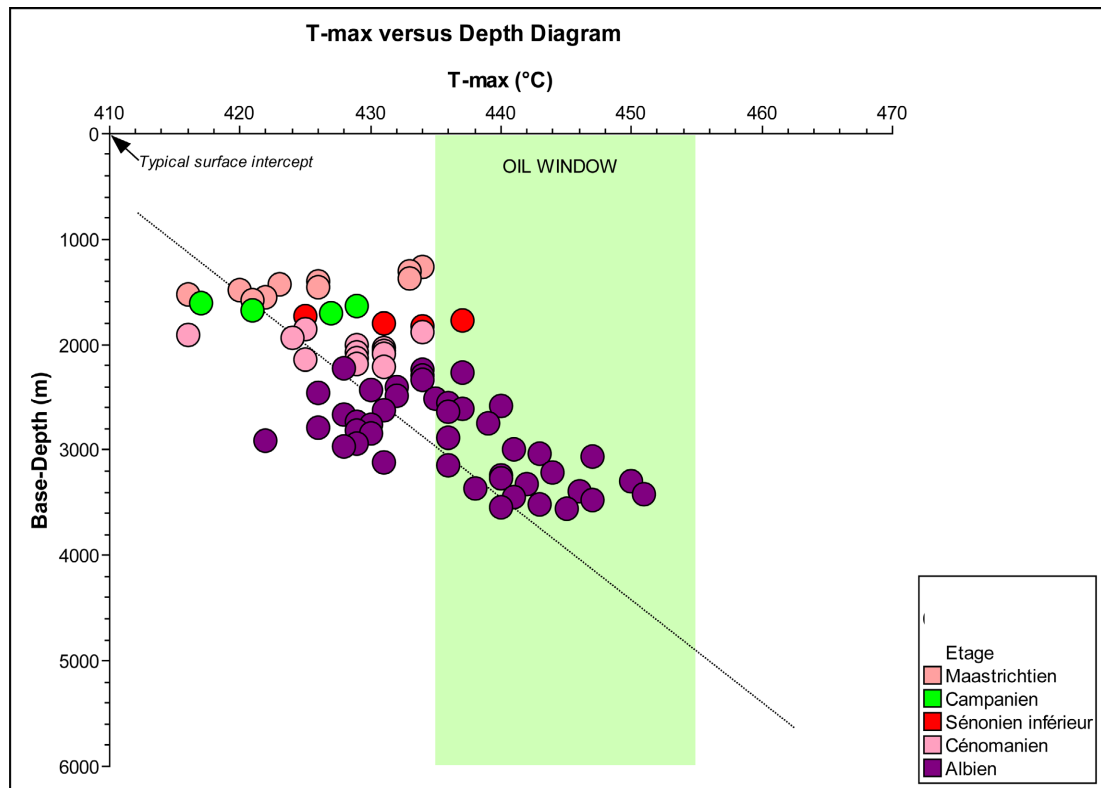
The intervals favorable for hydrocarbon generation in well TMH-1X are the Cenomanian and Campanian, distinguished by their more favorable petroleum potential, while the other intervals exhibit varied characteristics, reflecting the diversity of organic matter and its maturity in these geological formations.

## 5.2. Drilling TMH-2X

In well TMH-2X, the analysis of various geological stages reveals a consistent presence of organic matter, but with significant variations in terms of petroleum potential and thermal maturity (Figure 10).

In the Albian, despite an abundance of organic matter, the petroleum potential is low, excluding the presence of source rock. This trend continues in the reworked zone and the Turonian, where type III organic matter is only at the beginning of its maturity, offering limited petroleum potential. The lower Senonian shows similar organic matter, but it is thermally immature.

Finally, in the Campanian and Maastrichtian, although organic matter is sufficient in quantity, it remains type III and thermally immature, resulting in low petroleum potential. These observations indicate that, despite the presence of



**Figure 10.** Variation of  $T_{\max}$  versus Depth diagram by stage of TMH-1X well.

organic matter across these different stages, the conditions necessary for a good petroleum potential are not met.

## 6. Discussion

The quantity of organic matter (OM) in geological formations varies depending on various factors, including depositional conditions, preservation of organic matter, and post-depositional processes (diagenesis). Based on the results from both boreholes TMH-1X and TMH-2X, it is important to discuss why certain intervals show poor quantities of OM and why there are no hydrocarbon generation-prone zones in these intervals.

- **Quantity of organic matter**

The amount of OM, expressed as total organic carbon (TOC), is a crucial indicator for assessing the petroleum potential of a geological formation. However, several factors influence this quantity:

**Depositional conditions:**

Depositional environments play a crucial role in the accumulation and preservation of organic matter. According to [21], marine anoxic environments favor OM preservation by limiting decomposition from microorganisms, unlike continental or oxic environments where organic matter degrades more rapidly. Based on [22] deep marine environments and vegetation-rich deltas often provide an abundance of OM. Conversely, continental environments or high-energy zones like beaches and sand bars are often poor in organic matter.

**Preservation of organic matter:**

Anoxic conditions (absence of oxygen) and rapid sedimentation rates favor the preservation of organic matter. Formations such as the Albian in TMH-1X show poor OM preservation likely due to predominantly oxic or semi-oxic conditions [23].

**Thermal maturity:**

Thermal maturity, measured by the maximum pyrolysis temperature ( $T_{\max}$ ), affects the quality of OM for hydrocarbon generation. In the studied boreholes, except for the Albian stage in both TMH-1X and TMH-2X, and the reworked zone in TMH-2X which show thermal maturity, other stages exhibit immature OM ( $T_{\max} < 435^{\circ}\text{C}$ ), limiting their petroleum potential despite high TOC levels as shown by [24].

- **Type of organic matter**

The type of OM, determined by the hydrogen index (HI), indicates the origin and hydrocarbon generation potential:

**Type III and IV kerogen:** Type III kerogens are of terrestrial origin and primarily generate gas. They are often associated with continental environments rich in vascular plants [25] [26]. This is the case for the Albian, Lower Senonian, and Maastrichtian stages in both boreholes, which show Type III OM with low to moderate HI values, indicating a continental origin and limited hydrocarbon generation potential.

Type IV kerogen is highly oxidized and altered OM, often derived from the remobilization of pre-existing organic matter. It has little potential for hydrocarbon generation [27] [28]. For instance, the Cenomanian interval (1970 -2090 m) in TMH-1X shows HI values indicating Type IV OM, reflecting oxidized organic matter.

- **Absence of zones conducive to hydrocarbon generation**

Several reasons explain why certain zones are not conducive to hydrocarbon generation:

**Low petroleum potential (S<sub>2</sub>):**

The S<sub>2</sub> values, indicating petroleum potential, are low in several intervals of the studied boreholes. For example, the Albian interval in borehole TMH-1X shows an average S<sub>2</sub> of 0.50 mg HC/g rock, which is insufficient to consider this zone as a source rock, as demonstrated by [17].

**Thermal immaturity:**

Immature OM, observed in several intervals with  $T_{\max}$  values below  $435^{\circ}\text{C}$ , cannot generate hydrocarbons despite a good amount of TOC. This is the case for the Campanian in TMH-1X and the Maastrichtian (TMH-1X and TMH-2X), which show  $T_{\max}$  values below  $435^{\circ}\text{C}$ , indicating immature OM, as indicated by [29].

**Poor preservation of OM:**

According to [30], oxic conditions favor OM degradation. In the studied boreholes, some zones show poor OM preservation, thus limiting their petroleum potential. This is the case for the Campanian interval in TMH-2X, which

shows poor OM preservation, as indicated by low S2 values (1.39 mg HC/g rock).

The variability in the quantity and type of organic matter in the different stages of boreholes TMH-1X and TMH-2X is mainly due to depositional conditions, OM preservation, and thermal maturation. The absence of zones conducive to hydrocarbon generation is often linked to low petroleum potential, immature OM, and poor OM preservation. Environmental and geochemical factors play a crucial role in these processes, directly influencing the petroleum potential of the studied geological formations.

## 7. Conclusions

This geochemical study reveals that the TMH-1X and TMH-2X boreholes exhibit varied characteristics of organic matter and petroleum potential. However, only certain intervals of borehole TMH-1X, particularly in the Cenomanian and Campanian stages, show significant potential for hydrocarbon generation. In contrast, borehole TMH-2X does not present favorable zones for significant hydrocarbon generation due to thermal immaturity, low petroleum potential, and the type of kerogen present.

These results highlight the importance of thermal maturity, as well as the quantity and type of organic matter, in evaluating the petroleum potential of sedimentary basins.

## Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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