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Unraveling The Organic Geochemical Signature and Hydrocarbon Potential of Deltaic Source Rocks in The Kutai Kartanegara Area, East Kalimantan

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ABSTRACT

The Kutai Kartanegara area, East Kalimantan, is part of the Mahakam deltaic system, which is recognized as one of Indonesia's major hydrocarbon-producing regions. This study aims to characterize deltaic source rocks and evaluate their hydrocarbon potential using an integrated organic geochemical approach. Geochemical analyses of twelve Miocene shale samples reveal Total Organic Carbon (TOC) values ranging from 1.3 to 5.32 wt.%, with an average of 2.37 wt.%, indicating good to very good organic matter richness. Hydrogen Index (HI) and Tmax data indicate that the organic matter is predominantly Type III kerogen, with minor contributions from Type II/III kerogen, mainly derived from higher terrestrial plants. T_{max} values ranging from 425 to 447°C and vitrinite reflectance values of 0.64–0.77% suggest thermal maturity levels from immature to early mature stages. Pr/n-C_{17} and Ph/n-C_{18} ratios indicate deposition under fluctuating oxic to anoxic conditions within deltaic to shallow-marine environments under a humid equatorial climate. Statistical and cluster analyses reveal source rock heterogeneity controlled by facies variations and thermal maturity. These results indicate that Miocene shales in the Kutai Kartanegara Area have high potential as gas-prone and mixed hydrocarbon source rocks and play a significant role in the petroleum system of the Mahakam Delta region.

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INTRODUCTION

The Mahakam Delta, located in eastern Kalimantan, Indonesia, is one of the most prolific deltaic systems in Southeast Asia and has long been recognized as a major hydrocarbon-producing province (Permana et al., 2018; Jamaluddin et al., 2023; Sutadiwiria et al., 2024). The delta's sedimentary successions record complex interactions among fluvial, deltaic, and shallow marine processes, which strongly influence the accumulation, preservation, and transformation of organic matter. These dynamic depositional environments have played a crucial role in the formation and evolution of potential hydrocarbon source rocks within the basin (Widodo et al., 2009; Liu et al., 2018; Husein & Lambiase, 2013; Jamaluddin et al., 2023).

Organic geochemistry provides a powerful framework for assessing the characteristics of source rocks, including their quality, maturity, and depositional environment (Praptisih 2022). Geochemical parameters such as total organic carbon (TOC), hydrogen index (HI), oxygen index (OI), and T_{max}, combined with molecular biomarker data, enable detailed evaluation of the type and origin of organic matter, its level of thermal alteration, and its hydrocarbon generation potential (Praptisih 2022). Integrating these datasets allows for a more comprehensive understanding of organic facies development and their relationship to sedimentary processes (Sutadiwiria et al., 2024; Jamaluddin et al., 2024a).

Despite extensive hydrocarbon exploration and production in the Mahakam Delta, detailed and integrated organic geochemical studies focusing on deltaic source rocks, particularly within stratigraphic intervals beneath the modern delta, remain limited. Previous studies have largely emphasized reservoir characterization, structural controls, or regional basin evolution, while systematic evaluations that combine bulk geochemical parameters and biomarker signatures to constrain organic facies variability and depositional redox conditions in deltaic settings are still scarce. This gap hampers a refined understanding of source rock heterogeneity and its implications for hydrocarbon generation and expulsion timing within the Mahakam Delta petroleum system.

This study focuses on the characterization of deltaic source rocks in the Mahakam Delta through an integrated organic geochemistry approach. The main objectives are to (1) determine the type and quality of organic matter, (2) assess the thermal maturity and hydrocarbon generation potential, and (3) interpret the depositional environment based on biomarker and bulk geochemical signatures. Based on these objectives, this study tests the hypothesis that Miocene deltaic shales in the Mahakam Delta contain predominantly terrestrial-derived organic matter (Type III to II/III kerogen) preserved under fluctuating oxic to suboxic–anoxic conditions, resulting in gas-prone to mixed hydrocarbon generation potential at early to moderate thermal maturity levels.

The unique contribution of this research lies in its integrated evaluation of bulk geochemical and biomarker data to systematically link organic matter characteristics with deltaic depositional processes in a tropical setting. By addressing previously underexplored stratigraphic intervals beneath the modern Mahakam Delta, this study provides new constraints on source rock quality, maturity, and depositional environments, thereby refining petroleum system models and offering practical guidance for future hydrocarbon exploration in complex deltaic basins.

Geological setting

The study area lies within the tectonically active region of Southeast Asia, where the interactions between the Eurasian Plate, the Philippine Sea Plate, and the Indo-Australian Plate have played a major role in shaping the geological framework of Borneo (Figure 1a) (Husein and Lambiase, 2013; Jamaluddin et al., 2023; Jamaluddin et al., 2024b,c). The Kutai Basin (~60,000 km², up to 15 km of Cenozoic sediments) consists of Upper and Lower sub-basins. The Upper Kutai contains Paleogene deposits with NW–SE structural trends, while the Lower Kutai, dominated by Miocene sediments, hosts the NNE-trending Samarinda Anticlinorium with folded anticlines and synclines filled by siliciclastic deltaic sediments (Chambers and Daley, 1997; Permana et al., 2018; Hall and

Nichols 2002). Kutai Basin is positioned on the Sunda Shelf and influenced by regional subduction systems such as the Java Trench and the Philippine Trench, which have governed long-term basin development and sediment dispersal across the region. The Kutai Basin occupies the eastern flank of the island, bordered by the Central Kalimantan Ranges to the west and the Mangkalihat Peninsula to the northeast (Satyana et al., 1999).

This basin is one of the largest Tertiary depocenters in Southeast Asia and hosts thick successions of Neogene deltaic and marine sediments derived primarily from uplifted hinterlands in central Borneo (Figure 1b). The basin developed as a result of complex tectonic interactions between the Eurasian, Indo-Australian, and Pacific plates, which led to extensive subsidence and sediment accumulation from the Late Cretaceous to the present.

The Mahakam Delta itself represents the youngest and most dynamic depositional system within the Kutai Basin, characterized by thick Neogene to Quaternary siliciclastic successions (Hall, 2002; 2012). Sedimentation in the Mahakam Delta is primarily controlled by a balance between high sediment supply from the Mahakam River and active subsidence in the basin depocenter (Hall & Nichols 2002). The delta exhibits a typical mixed tide–wave influence, producing a complex mosaic of distributary channels, tidal flats, and shallow-marine environments. These environments have given rise to alternating sequences of sandstone, siltstone, shale, and coal, reflecting frequent changes in depositional energy and organic input (Marshall et al., 2015).

The southeastern margin of the Eurasian Plate, or Sundaland, is influenced by interactions among the Indian-Australian, Pacific, and Eurasian plates. Sundaland consists of continental blocks, volcanic arcs, and suture zones, shaped by subduction, continental collision, rifting, and strike-slip faulting (Metcalfe, 2011; Hall 2012).

The stratigraphic framework of the Kutai Basin records a long and complex depositional history

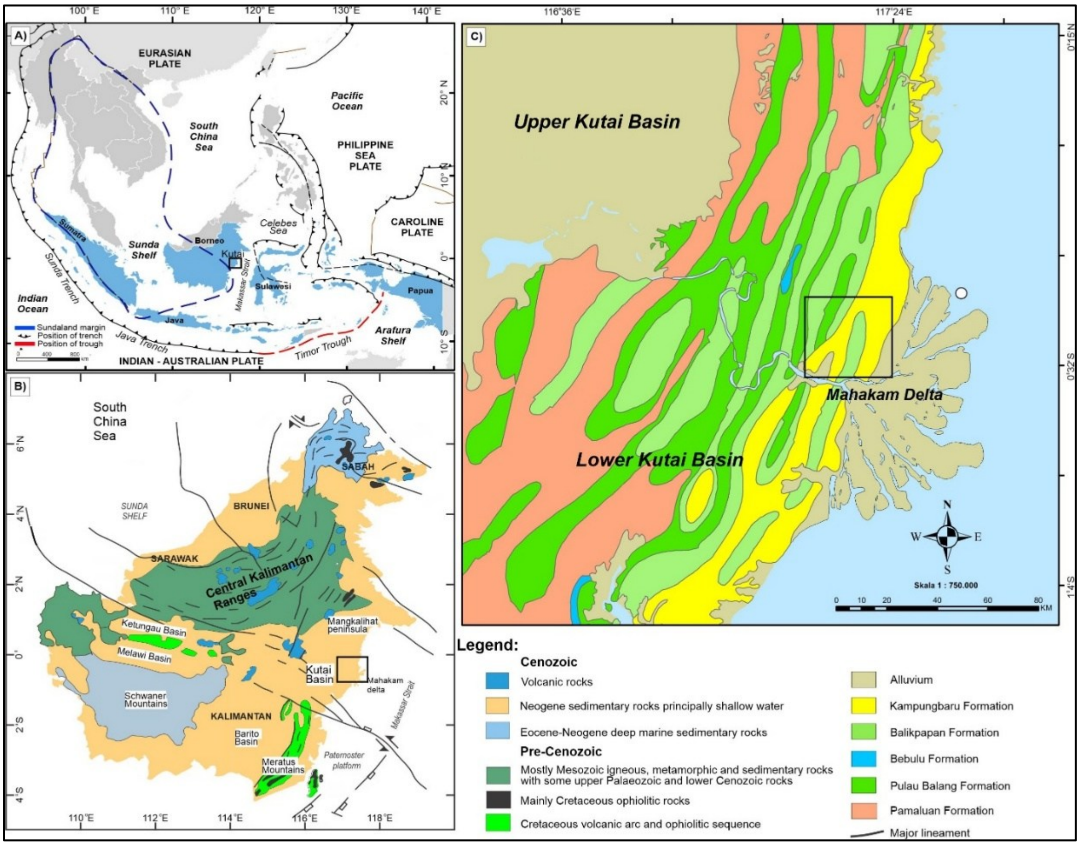

Figure 1. (a) Principal tectonic plates of South-east Asia (modified from Fikri et al., 2022). (b) simplified geological and tectonic map of Borneo. Indicated are the major lineaments that may have been active during the cenozoic (modified from Hall & Nichols, 2002). (c) simplified geological map of the Kutai Kartanegara Area.

from the Late Cretaceous to the Quaternary. The sedimentary succession exceeds 10 km in thickness and is dominated by clastic sequences derived from the uplifted hinterland of Borneo. The stratigraphy reflects a transition from early syn-rift to post-rift sedimentation, strongly influenced by regional tectonics, eustatic sea-level changes, and deltaic progradation of the Mahakam River system (Permana et al., 2022; Jamaluddin et al., 2023) (Figure 1c).

During the Early to Middle Miocene, rapid sedimentation occurred with the development of the Kampung baru and Pulau balang formations, characterized by alternating sandstone, shale, and coal layers deposited in delta-plain to shallow-marine environments (Cibaj et al., 2007). These formations contain significant source rock intervals with high total organic carbon (TOC) content, representing the main hydrocarbon-generating sequences of the basin.

The Late Miocene to Pliocene is dominated by the Balikpapan and Kampung baru formations, consisting of thick deltaic to prodeltaic deposits related to the progradation of the Mahakam Delta. These sediments reflect strong fluvial influence and active deltaic lobes that built outward into the Makassar Strait (Chambers and Daley, 1997; Allen and Chambers, 1998).

In the Quaternary, deposition continued under the modern Mahakam Delta system, which remains active today. The stratigraphic succession shows clear evidence of repeated transgressive–regressive cycles influenced by sea-level fluctuations, sediment supply, and tectonic subsidence (Permana et al., 2022; Jamaluddin et al., 2024a,b). Collectively, these stratigraphic sequences record the evolution of one of the most dynamic deltaic basins in Southeast Asia and provide the foundation for its prolific petroleum system.

METHODOLOGY

This study is based on the analysis of twelve sidewall core samples and ten crude oil samples collected from the Kutai Kartanegara Area, Lower Kutai Basin, Indonesia. The sidewall core samples represent sedimentary rock material, while the crude oil samples were obtained from producing intervals within the same structural domain, allowing integrated organic geochemical characterization and oil–source rock correlation.

These samples were utilized to establish a geochemical correlation between the extracted hydrocarbons and the potential source rocks in the Mahakam Delta. The integrated organic geochemical workflow applied for the characterization of deltaic source rocks. The workflow includes geological fieldwork and sampling, followed by laboratory analyses comprising TOC, Rock-Eval pyrolysis, vitrinite reflectance (Ro%), biomarker analysis of crude oil using GC–MS, and stable isotope analysis (Figure 2).

All samples were cleaned to remove drilling mud contamination, air-dried, and then crushed to <63 µm using an agate mortar to avoid metal contamination. Prior to organic geochemical analyses, the powdered samples were Soxhlet-extracted for 72 hours using a dichloromethane–methanol (93:7, v/v) solvent mixture. The resulting total extractable organic matter (EOM) was concentrated under a gentle stream of nitrogen.

Total organic carbon (TOC) content was determined to quantify the amount of organic matter present in the rock samples, providing a measure of potential hydrocarbon generation capacity. Although TOC does not reflect organic matter quality, it remains a key indicator of source rock richness. TOC measurements were performed using a LECO™ carbon analyzer with an experimental error of ±0.2%.

Rock-Eval pyrolysis was conducted using a Rock-Eval II™ pyroanalyzer, with each sample analyzed in duplicate to ensure data reliability. The S_1 and S_2 peaks were recorded to determine the quantities of free and generated hydrocarbons (expressed in mg HC/g rock). The maximum temperature of hydrocarbon generation (T_{max}, °C) was used as an indicator of thermal maturity. Derived parameters such as the Hydrogen Index ($HI = S_2 \times 100 / TOC$, mg HC/g TOC) and Generation Potential ($PY = S_1 + S_2$, mg HC/g rock) were calculated to evaluate the kerogen type and hydrocarbon potential (Espitalie et al., 1977). Vitrinite reflectance (Ro%) measurements were

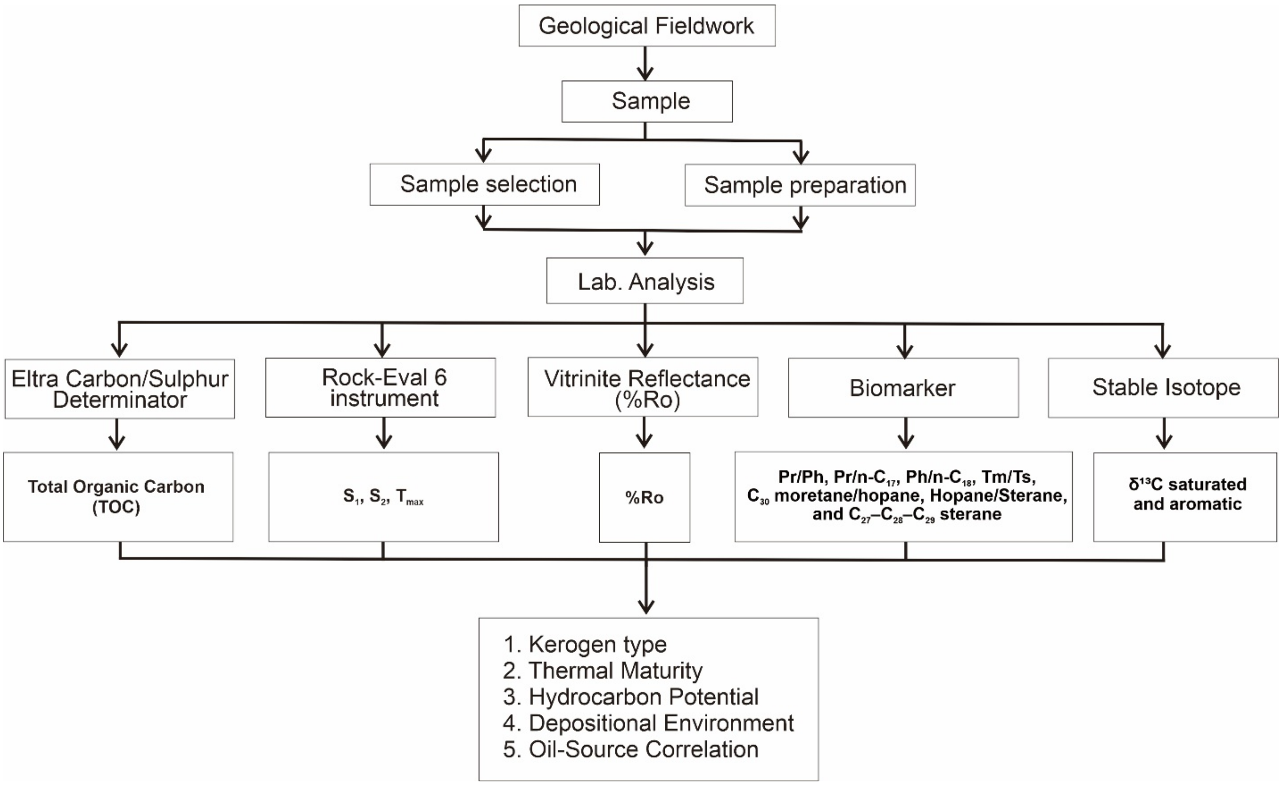

Figure 2. Flowchart illustrating the integrated organic geochemical workflow applied for the characterization of deltaic source rocks.

performed in accordance with AS 2486 standards using a Leitz MPV 1.1 photometer mounted on a Leitz Orthoplan microscope equipped with a 50× NPL oil-immersion objective lens.

Furthermore, the saturate and aromatic fractions of Kutai 1-Kutai 10 were separated and analyzed by gas chromatography–mass spectrometry (GC–MS). Biomarker distributions obtained from these analyses were used to interpret the organic facies, depositional environment, and potential source–oil correlation within the Mahakam Delta system. Gas chromatography analyses of the saturated hydrocarbon fractions were conducted using a GC system equipped with a flame ionization detector (FID) and a non-polar capillary column (e.g., HP-5 or equivalent). The oven temperature was programmed from 50 °C (held for 1 min) to 300 °C at a rate of 3 °C/min, with a final hold of 20 min.

Biomarker characterization was performed using gas chromatography–mass spectrometry (GC–MS) operated in selected ion monitoring (SIM) mode, targeting m/z 191 for hopanes and m/z 217 for steranes. Biomarker ratios, including Pr/Ph, Pr/n-C_{17}, Ph/n-C_{18}, Tm/Ts, C_{30} moretane/hopane, and C_{27}–C_{28}–C_{29} sterane distributions, were calculated following standard procedures.

Stable carbon isotope compositions ($\delta^{13}C$) of the saturated and aromatic hydrocarbon fractions were determined using gas chromatography–combustion–isotope ratio mass spectrometry (GC–C–IRMS). Isotope ratios are reported in per mil (‰) relative to the Vienna Pee Dee Belemnite (VPDB) standard. Analytical precision was better than ±0.2‰ based on repeated measurements of laboratory reference standards.

RESULT AND DISCUSSION

The results of the organic geochemical analyses are summarized based on the vertical distribution of Total Organic Carbon (TOC), Potential Yield (PY), Hydrogen Index (HI), thermal maturity indicators (Tmax), and vitrinite reflectance (%Ro) (Table 1). These parameters provide quantitative constraints on organic matter richness, kerogen quality, hydrocarbon generative potential, and thermal maturity of the studied interval. Systematic variations in geochemical properties with depth reflect changes in depositional conditions, organic matter input, and burial-related thermal evolution. Collectively, this integrated dataset forms the basis for evaluating source rock characteristics and hydrocarbon generation potential within the study area.

Organic matter richness and petroleum generative potential

The organic matter richness within the Middle to Early Miocene succession displays considerable variability, with TOC values spanning from 1.16 to 5.32 wt.%. This range reflects a depositional system influenced by changes in sediment supply, productivity, and redox conditions. TOC values above 3 wt.% observed at several depths indicate intervals where either organic productivity was elevated or preservation conditions were favorable. Conversely, lower TOC values (<1.5 wt.%) may reflect periods of intense clastic influx or more oxic bottom-water conditions that promoted organic matter degradation. The occurrence of highly enriched intervals at 1201 m and 1241 m suggests episodic establishment of conditions conducive to the accumulation of organic-rich facies. These intervals likely correspond to phases of reduced terrigenous dilution or enhanced preservation, possibly linked to fluctuations in relative sea level, basin restriction, or changes in sedimentation rate. The presence of a rich organic section at 1939 m within the Early Miocene strata implies that such favorable conditions were not limited to a single depositional phase but recurred at discrete stratigraphic intervals.

The TOC depth distribution for the Early and Middle Miocene intervals demonstrates clear variations in organic richness that align with the known depositional architecture of the Mahakam Delta within the Kutai Basin (Table 1; Figure 3). Middle Miocene samples predominantly fall within the good to excellent TOC categories, reflecting the period of intensified delta progradation and high sediment supply characteristic of the growing Mahakam Delta system.

During this phase, alternating delta-front to prodelta environments favored the accumulation and preservation of organic matter, especially terrestrial plant debris derived from extensive coastal plain vegetation. This is consistent with the elevated TOC values observed in the dataset.

Early Miocene samples show TOC values ranging from good to very good, indicating significant but slightly less variable organic

Table 1. Geochemical results of miocene shale samples, Kutai Kartanegara Area, Indonesia including total organic carbon analyses, rock-eval pyrolysis, and vitrinite reflectance (%Ro).

Age	Depth (mD)	TOC (wt.%)	Rock - eval pyrolysis					%Ro
			S_1 (mg HC/g)	S_2 (mg HC/g)	T_{max} (°C)	Potential yield (mg HC/g)	HI (mgHC/g TOC)	
middle Miocene	1201	5.32	1.07	7.3	425	8.37	137	0.64
	1214	1.59	0.61	1.57	424	2.18	99	0.64
	1241	4.24	0.93	3.5	434	4.43	83	0.66
	1270	1.16	0.16	0.63	433	0.79	54	0.65
	1277	1.72	0.36	1.63	440	1.99	95	0.7
	1282	1.46	0.34	1.29	433	1.63	88	0.7
	1579	1.16	0.48	1.14	438	1.62	98	0.66
early Miocene	1879	1.3	0.24	1.03	438	1.27	79	0.7
	1939	3.65	1.37	3.61	438	4.98	99	0.72
	2003	2.8	0.27	2.86	447	3.13	102	0.73
	2060	1.48	0.15	1.55	443	1.7	5	0.77
	2213	1.4	0.16	1.38	447	1.54	99	0.76
Mean		2.37	0.51	2.42	436.8	2.80	86.83	0.69
Standard Deviation (SD)		1.39	1.39	1.88	7.42	2.16	32.22	0.05
Error		±0.1	±0.05	±0.11	±2	-	-	±0.02

enrichment. This pattern aligns with the earlier developmental stage of the Mahakam Delta, when accommodation space was greater, sedimentation rates were lower, and depositional settings were dominated by more distal marine to prodelta environments.

These conditions supported moderate preservation of organic matter, with deeper samples exhibiting higher TOC that may reflect more anoxic bottom-water conditions or increased delivery of terrestrial organic input from early delta initiation The clustering of most samples above the 1 wt.% boundary highlights the consistent presence of productive source-rock intervals within the Kutai Kartanegara Area stratigraphy. The dominance of good to excellent TOC categories in both Miocene intervals underscores the well-documented efficiency of the Mahakam Delta as a major petroleum source system, where abundant terrigenous organic matter derived from tropical lowland forests was repeatedly trapped within deltaic to marginal-marine mudstones.

The S_1 versus TOC cross-plot (Figure 4a) provides insight into the presence of indigenous versus migrated hydrocarbons. All samples plot well below the migrated-hydrocarbon threshold line, indicating that the S_1 values (0.15–1.37 mg HC/g rock) are consistent with indigenous hydrocarbons. No samples display anomalously high S_1 relative to TOC, suggesting minimal contamination, no significant bitumen staining, and no evidence for hydrocarbon charging from external sources. This is supported by S_1/TOC ratios, which remain low across the dataset, reflecting in situ generation rather than migration effects.

The S_2 yields range widely from 0.63–7.30 mg HC/g rock in the middle Miocene interval and 1.38 –3.61 mg HC/g rock in the early Miocene samples. Rock–Eval S_2 results, which quantify the remaining hydrocarbon-generating potential within the sediment, similarly exhibit broad variability.

S_2 values as high as 7.3 mg HC/g rock at 1201 m classify the interval as having excellent generative potential, indicating that the organic matter has not been completely depleted by thermal cracking. This horizon likely contains a higher proportion of hydrogen-rich components, which correspond to enhanced hydrocarbon yields upon pyrolysis. In contrast, S_2 values below 1 mg HC/g reflect poor generative potential and may indicate extensive thermal degradation, low initial organic richness, or the presence of inert organic matter.

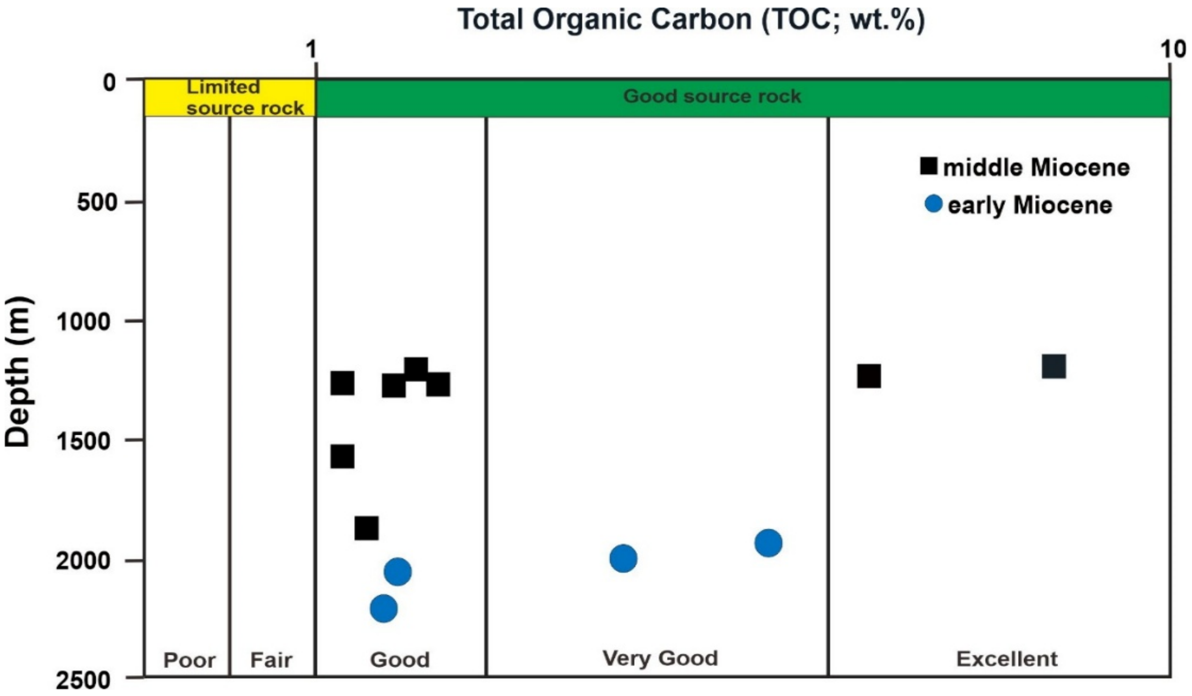

Figure 3. Depth distribution of Total Organic Carbon (TOC) values for Early and Middle Miocene samples.

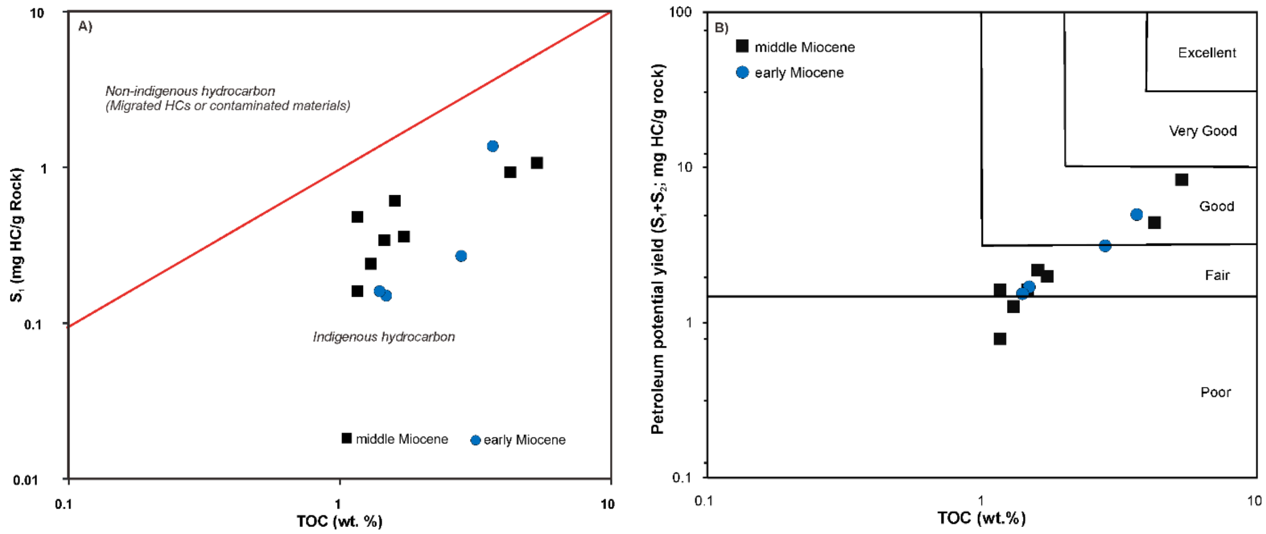

Figure 4. (a) S1 versus TOC (wt. %) crossplot shows all the miocene shales samples Kutai Kartanegara Area are in the zone of indigenous hydrocarbon; (b) TOC content versus petroleum yields, showing poor to good generation potential.

Moderate S_2 values (2 – 4 mg HC/g rock) detected in several samples indicate that these intervals still maintain a reasonable capacity for hydrocarbon generation. Although they do not match the richness of the most prolific horizons, their cumulative contribution to basin-scale hydrocarbon accumulation should not be underestimated. Such moderate intervals may collectively supply substantial amounts of gas, especially in mature systems dominated by Type III kerogen. Moreover, the distribution of these intervals across the stratigraphy may support multi-phase generation over time as the basin matures.When combined with TOC, these values result in petroleum potential yields (S_1+S_2) between 0.79 and 8.37 mg HC/g rock. According to the classification diagram (Figure 4b), the majority of the samples fall within the fair to good generative potential fields. Only one sample at 1201 m (middle Miocene) reaches the lower boundary of the very good zone due to its particularly high TOC and S_2 combination (TOC 5.32%; S_2 7.3 mg HC/g). This makes the 1201 m interval the most promising source rock horizon in the dataset.

Kerogen type and thermal maturity

The Hydrogen Index (HI) values, ranging from 54 to 137 mg HC/g TOC, reveal a clear dominance of Type III kerogen, which is typically associated with terrestrial higher-plant material such as cellulose, lignin, and woody debris (Durand & Oudin 1979; Afifah & Setiawan 2019). This organic matter is characterized by low hydrogen content and a predisposition to generate gas rather than liquid hydrocarbons. The low to moderate HI values suggest that the depositional environment was strongly influenced by fluvial or deltaic systems that supplied large quantities of plant-derived organic debris into the basin (Friederich et al., 2016; Fikri et al., 2022).

Despite the overall dominance of Type III kerogen, the HI value at 1201 m (137 mg HC/g TOC) indicates a slight shift toward a more hydrogen-rich composition. Although still within the upper range of Type III, this interval likely contains a minor contribution from Type II kerogen commonly derived from algal or planktonic organic matter which would enhance its oil-generative potential (Bachtiar et al., 2013). This mixed kerogen assemblage strengthens the interpretation that the 1201 m sample represents the most prolific source-rock horizon within the dataset. The kerogen composition of the Miocene shales in the Kutai Kartanegara Area is strongly constrained by Rock–Eval parameters, particularly Hydrogen Index (HI) and T_{max} (Figure 5a). The analyzed samples exhibit HI values ranging from 54 to 137 mg HC/g TOC, which is characteristic of Type III kerogen. This kerogen type is typically derived from terrestrial higher plants, dominated by cellulose and lignin-rich materials that inherently yield lower hydrogen contents and are therefore more gas-prone. The limited occurrence of higher HI values (>120 mg HC/g TOC), such as the interval at 1201 m (HI = 137 mg HC/g TOC), suggests the presence of minor mixed Type II/III kerogen, likely reflecting localized inputs of algal or lipid-rich organic matter into an otherwise dominantly terrestrial system.

Geologically, Type III kerogen is consistent with the paleoenvironmental context of the Kutai Kartanegara Area during the Miocene. The basin was characterized by extensive fluvial - deltaic systems supplying abundant terrestrial organic material into coastal and prodelta settings. The dominance of vitrinite-rich macerals, which form through the degradation and transformation of woody tissues, further reinforces the interpretation of terrestrial provenance (Jamaluddin et al., 2023; Jamaluddin et al., 2025).

Thermal maturity in the studied succession is evaluated using a combination of Rock–Eval T_{max} and vitrinite reflectance (% Ro) (Figure 5b), both of which provide internally consistent results. T_{max} values range from 424 to 447°C, while vitrinite reflectance spans 0.64 - 0.77% Ro, placing the samples within the early mature stage of hydrocarbon generation. These maturity indicators suggest that the Miocene shales have entered the onset of the oil window but have not yet reached the primary zone of peak oil generation (~0.85 - 1.0% Ro). The shallowest samples (e.g., 1201 - 1282 m) display lower Tmax values (424 - 434°C), consistent with the earliest phase of thermal cracking of kerogen. Meanwhile, deeper intervals at 2003 m and 2213 m, with Tmax values of 447°C, indicate more advanced early maturity, approaching the transition toward the main oil window.

The maturity profile with depth is not uniform, however. The observed irregularities in the maturity depth trend particularly the lack of a smooth increase in T_{max} and % Ro with burial point to complex tectono-thermal evolution. The Kutai Kartanegara Area is structurally influenced by contractional tectonics, including thrust faulting and uplift. These deformation processes have likely altered burial histories, producing zones of elevated or suppressed maturity independent of present-day

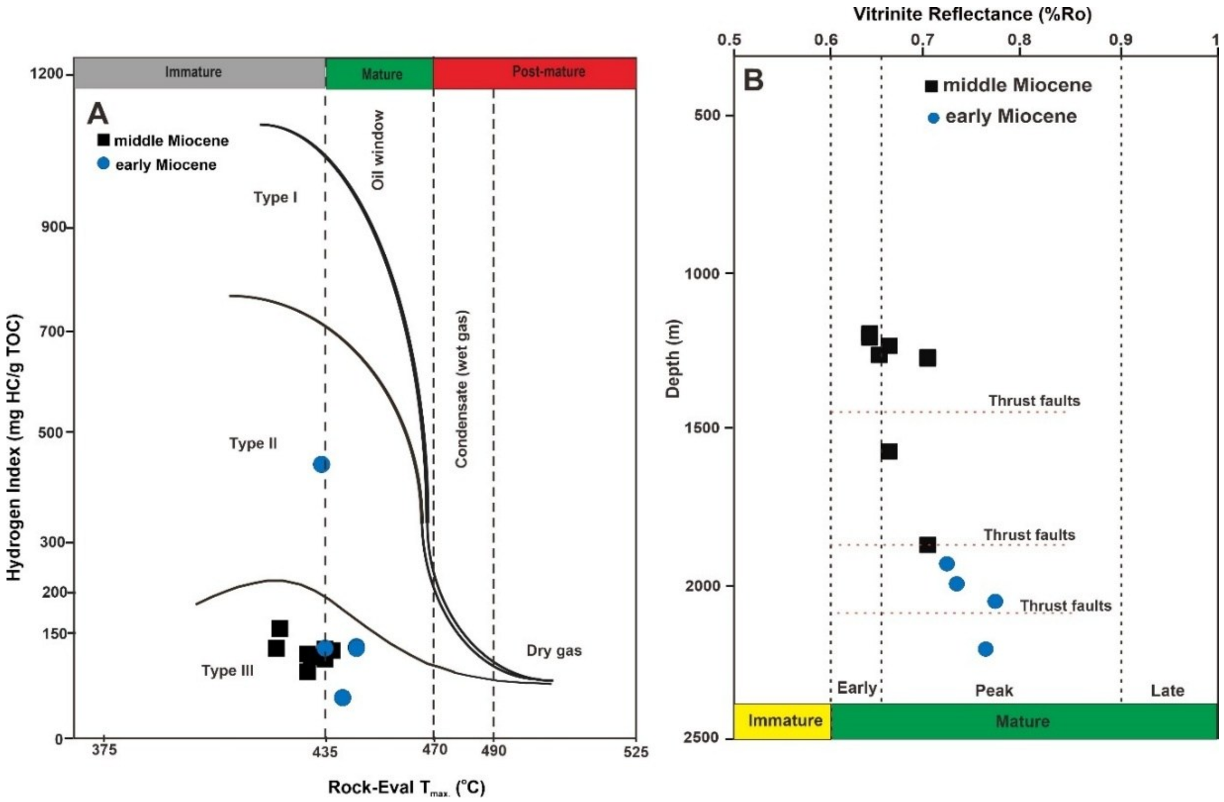

Figure 5. (a) Cross-plot of HI versus T_{max}; (b) distribution of measured %Ro versus depths of the analyzed miocene samples showing that the shale samples are currently still mature source rocks.

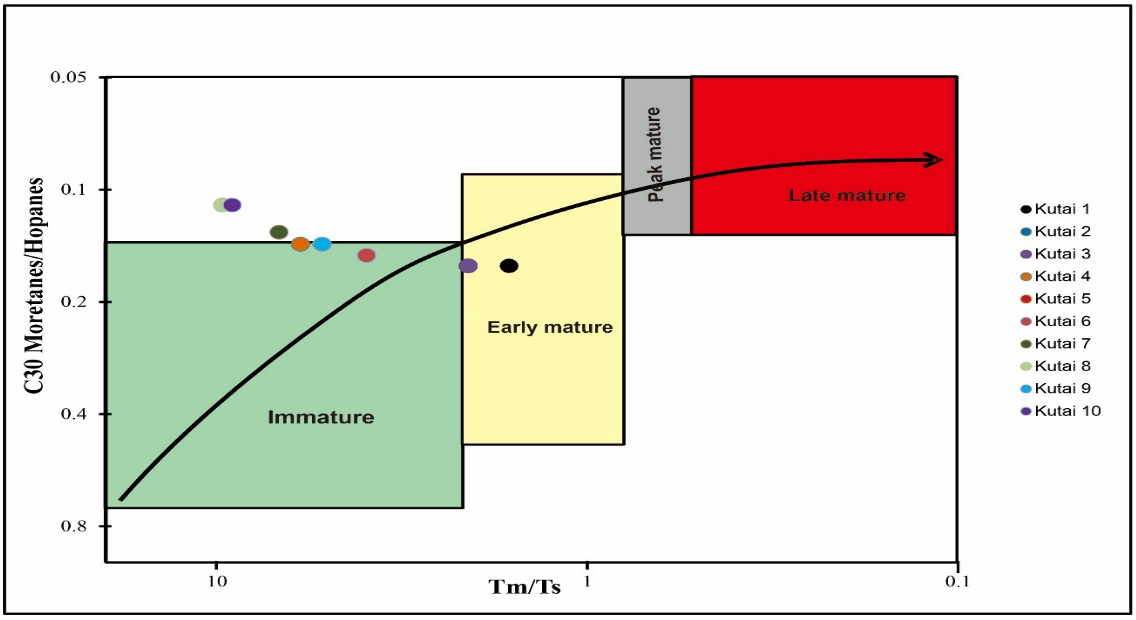

Figure 6. Cross-plot of C_{30} moretanes/hopanes versus Tm/Ts ratios illustrating the thermal maturity evolution of the analyzed samples.

depth. Such structural features may have acted as thermal discontinuities, locally elevating temperatures or reducing burial rates, and significantly impacting the maturation trajectory of the Miocene shales.

Importantly, the early maturity levels suggest that the analyzed samples themselves have generated limited quantities of hydrocarbons, consistent with their kerogen type and hydrogen indices. However, structural analysis and thermal modeling imply that deeper, more mature source rocks within the basin have expelled hydrocarbons that migrated vertically into shallower traps. This interpretation is supported by calculated vertical migration distances of ~945 m for oil and ~1920 m for gas and condensate, as well as the lack of geochemical evidence for mixing with immature gases. These observations point to rapid, fault-assisted migration within a structurally complex deltaic setting, underscoring the importance of tectonics in shaping the petroleum system of the Kutai Kartanegara Area.

The cross-plot of C_{30} Moretane/Hopane versus Tm/Ts provides insight into the thermal maturity of the Kutai Basin samples (Figure 6). The cross-plot of C_{30} moretanes/hopanes versus Tm/Ts provides a robust biomarker-based assessment of the thermal maturity and diagenetic evolution of the studied samples. In this diagram, Tm/Ts ratios decrease with increasing maturity due to preferential degradation of Ts relative to Tm during thermal evolution, while C_{30} moretane/hopane ratios decline as the thermodynamically less stable moretanes are progressively converted to hopanes. Most samples cluster within the immature to early mature fields, characterized by relatively high Tm/Ts ratios (>1) and moderate to elevated C_{30} moretane/hopane values (~0.12 - 0.20). This distribution indicates that the organic matter has experienced limited thermal stress and remains largely within the early stages of catagenesis. Such biomarker signatures are typical of sediments that have not yet undergone extensive hydrocarbon generation, consistent with low to moderate burial temperatures. A few samples plot closer to the early mature domain, showing slightly reduced Tm/Ts ratios (~1.0–1.3) and lower C_{30} moretane/hopane values, suggesting the onset of sterane and hopane isomerization processes. None of the samples fall within the peak mature or late mature fields, indicating that the succession has not reached optimal oil-window conditions. The overall biomarker trend, highlighted by the maturity evolution curve, demonstrates a systematic decrease in both ratios with increasing maturity, supporting a coherent thermal evolution pathway rather than mixed or reworked organic matter inputs. This implies that the studied interval represents a marginally mature to early oil-prone source rock, where hydrocarbon generation potential is present but not fully realized.

The vertical variation in source-rock quality, organic matter type, and thermal maturity across the Miocene interval. Overall, TOC and S_1+S_2 values indicate poor to fair organic richness, suggesting limited to moderate hydrocarbon potential. Low S_1 concentrations further imply minimal free hydrocarbons present in the rock. The $S_1/(S_1+S_2)$ ratios show that the organic matter is largely indigenous, with no evidence of migrated hydrocarbons. Hydrogen Index values fall within the Type III to mixed kerogen range, indicating predominantly terrestrial, gas-prone organic matter rather than oil-prone inputs. Collectively, the data suggest that the Miocene sequence is dominated by humic organic matter with low to moderate generation potential and has not yet reached optimal maturity for substantial hydrocarbon expulsion (Figure 7).

The Miocene shale interval in the Kutai Kartanegara area, underlying the modern Mahakam Delta, shares several characteristics with other major deltaic and passive margin basins, such as the Niger Delta and the Gulf of Mexico. Like the Niger Delta, these shales are enriched in terrestrial organic matter and dominated by Type III kerogen with minor Type II/III input, reflecting a deltaic to shallow-marine depositional environment. Both basins exhibit fluctuating redox conditions influenced by rapid sedimentation and high fluvial input, although the Kutai shales are currently at an immature to early mature stage, favoring gas-prone hydrocarbon generation, whereas the deeper Niger Delta shales have reached a broader maturity range capable of generating both oil and gas.

In contrast, source rocks in the Gulf of Mexico are typically older, marine in origin, and dominated by Type II kerogen, with higher hydrogen content, widespread distribution, and greater burial, making them more oil-prone. Overall, the Kutai shales resemble the Niger Delta in kerogen type and depositional setting but differ from the Gulf of Mexico, which is characterized by marine, algal-rich source rocks with extensive oil-generating potential.

Oil - source rock correlation and depositional environment

The Pr/Ph ratio serves as an indicator of redox conditions in the depositional environment. Values of Pr/Ph < 1 suggest anoxic environments, commonly associated with high porphyrin and sulfur contents, whereas Pr/Ph > 1 indicates oxic conditions typical of terrestrial or deltaic settings (Didyk et al., 1978; Peters et al., 2005; Sabra & Saleh 2025).

The Pr/n-C_{17} versus Ph/n - C_{18} diagram (Figure 8a) is widely applied to evaluate organic matter source input, redox conditions, biodegradation, and maturity effects. The analyzed samples cluster at low Ph/n - C_{18} (<0.5) and moderate Pr/n - C_{17} (~1.2 - 1.6) values, placing them dominantly within the terrigenous organic matter field. This distribution indicates a strong contribution from higher-plant–derived organic matter deposited under sub-oxic to mildly oxic conditions. The lack of samples trending toward elevated Pr/n - C_{17} and Ph/n - C_{18} values suggests minimal biodegradation, while their limited dispersion along the maturation vector indicates low to early thermal maturity.

Furthermore, the absence of data points in the algal marine - reducing field implies only a minor marine algal contribution. Overall, the biomarker signatures reflect deltaic to fluvio-deltaic depositional settings, where terrestrial organic matter dominates and early diagenetic oxidation is relatively common.

The stable carbon isotope cross-plot of saturate and aromatic fractions (Figure 8b) provides complementary evidence for organic matter provenance. The isotopic signatures also plot near or slightly above the waxy–non-waxy oil dividing line, indicating that if hydrocarbons were generated from these shales, they would likely fall into the non-waxy to moderately waxy oil family (Sofer, 1984).

Most samples plot within the terrigenous organic matter domain, with relatively depleted $\delta^{13}C$ values (approximately −29.8 to −27.0‰ for saturates and −29.5 to −26.8‰ for aromatics).

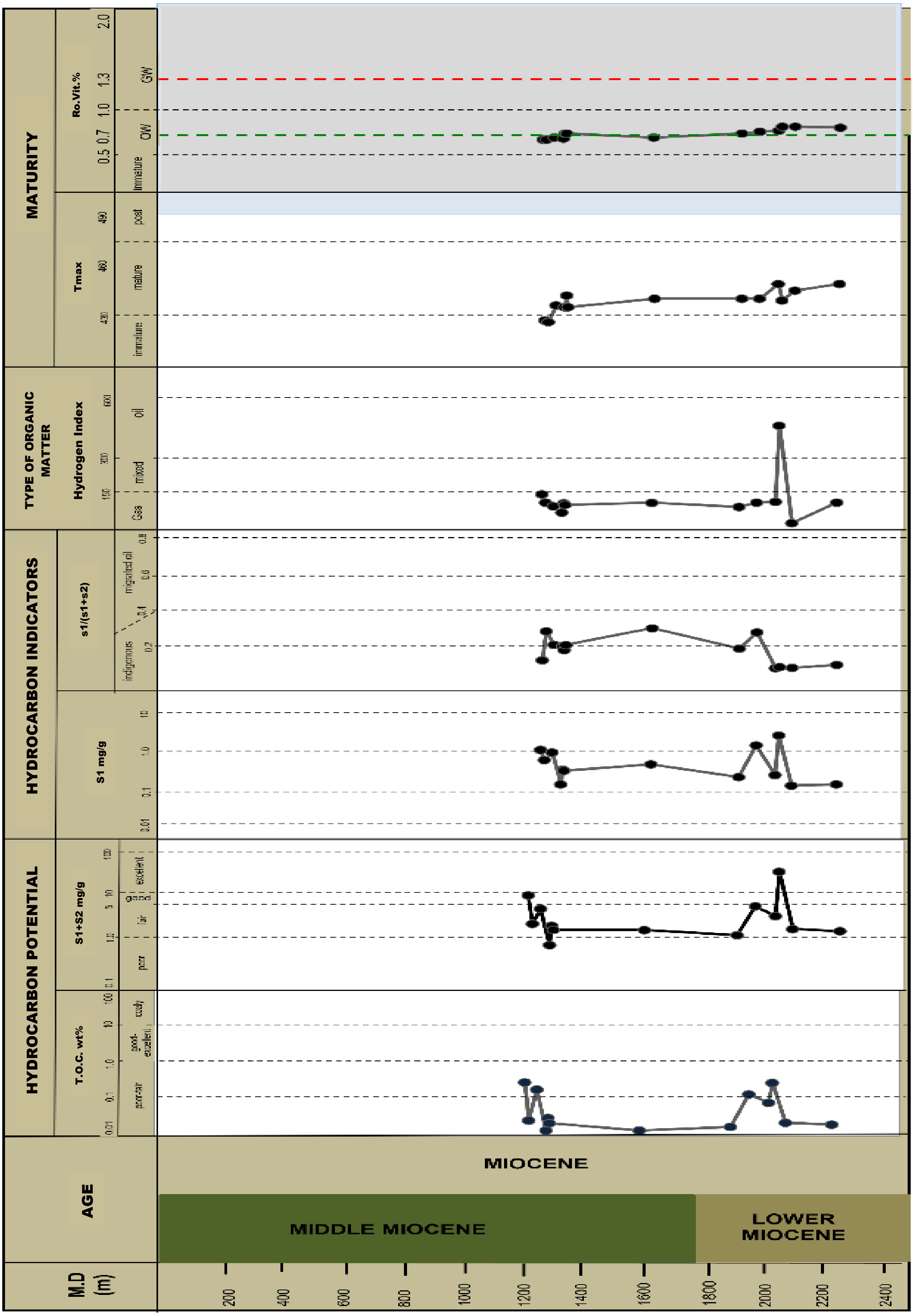

Figure 7. (a) Composite geochemical profile of the Miocene interval in the Mahakam Delta, Kutai Basin, showing depth-based variations in hydrocarbon potential, organic matter type, and maturity parameters.

These isotopic signatures are characteristic of C_3 higher-plant–derived organic matter, consistent with continental input. Several samples fall close to the waxy–non-waxy oil discrimination line, further supporting the dominance of waxy, land-plant–derived hydrocarbons.

No samples plot within the marine organic matter field, confirming that marine algal contributions are subordinate. The isotopic coherence between saturate and aromatic fractions also suggests limited secondary alteration and a relatively uniform source facies.

Taken together, the biomarker ratios and compound-specific carbon isotope data consistently indicate that the studied hydrocarbons were generated predominantly from terrigenous organic matter deposited in a deltaic to marginal-marine environment, under predominantly oxic to sub-oxic conditions and at immature to early mature thermal stages.

The ternary diagram of C_{27}–C_{28}–C_{29} regular steranes (Figure 9) is a well-established proxy for reconstructing organic matter sources and depositional environments. In this study, the

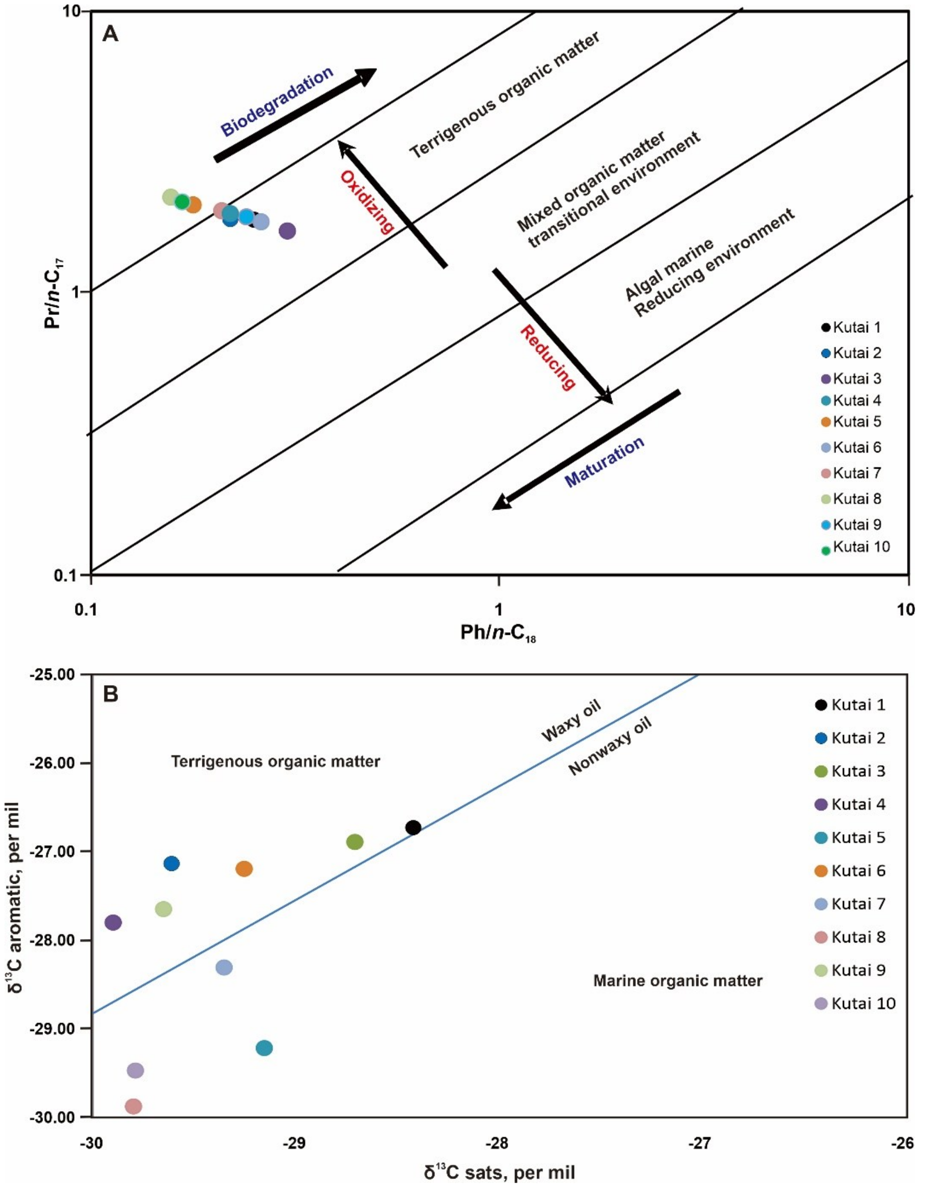

Figure 8. (A) Cross-plot of Pr/n-C_{17} versus Ph/n-C_{18} illustrating organic matter source input, redox conditions, biodegradation, and maturity trends. (B) Cross-plot of $\delta^{13}C$ saturates versus $\delta^{13}C$ aromatics (‰ VPDB) showing that the analyzed samples cluster within the terrigenous organic matter domain, consistent with C_3 land-plant sources and waxy hydrocarbon characteristics.

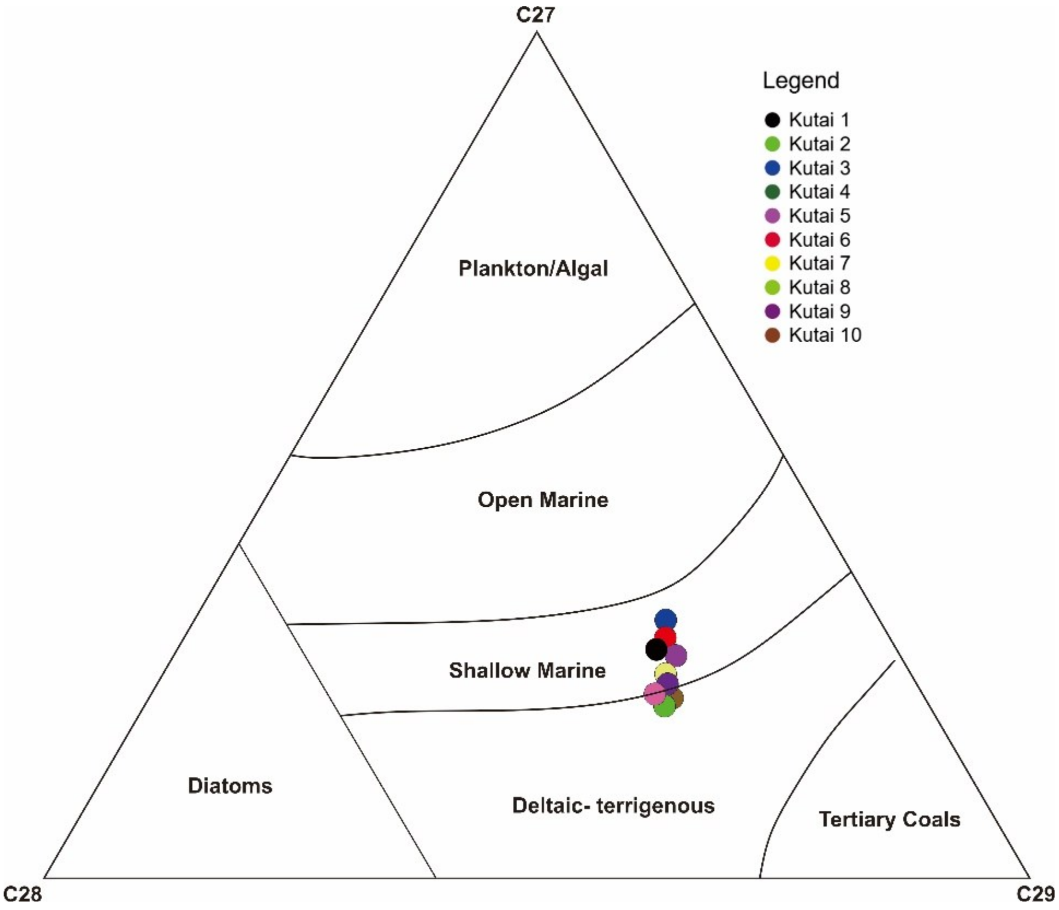

Figure 9. Ternary diagram of C_{27}–C_{28}–C_{29} regular sterane distributions illustrating organic matter source and depositional environment.

analyzed samples cluster tightly toward the C_{29} sterane apex with subordinate contributions from C_{27} and C_{28} steranes. This compositional pattern indicates a dominant higher-plant–derived organic matter input, reflecting significant terrigenous influence.

Most data points plot within the deltaic–terrigenous to shallow-marine fields, suggesting deposition in a marginal-marine to deltaic environment where terrestrial organic matter was mixed with minor marine algal input. The relatively low proportions of C_{27} steranes imply a limited contribution from planktonic/algal organic matter typically associated with open-marine settings, while the moderate C_{28} contents may reflect minor contributions from diatoms or mixed algal sources.

The narrow dispersion of the data cluster suggests consistent source facies and depositional conditions across the sampled interval, with no evidence for significant mixing from multiple, distinct organic matter sources. This sterane distribution is characteristic of delta -front to prodelta environments influenced by fluvial discharge, consistent with sedimentation under variable energy conditions and fluctuating salinity regimes.

CONCLUSION

Geochemical parameters collectively indicate that the sediments are enriched in terrestrial organic matter, dominated by Type III kerogen with subordinate Type II/III input. TOC values between 1.3 and 5.32 wt.% (average 2.5 wt.%) demonstrate good to excellent organic richness, confirming that these shales contain sufficient quantities of preserved organic matter to serve as effective source rocks within the basin. Thermal maturity assessments based on T_{max} (425–447°C) and vitrinite reflectance (0.64–0.77%) place the interval within the immature to early mature stage of hydrocarbon generation. Coupled with moderate

Hydrogen Index values characteristic of gas-prone kerogen, these results highlight the strong potential for dominantly gaseous hydrocarbons and mixed products upon further burial and maturation.

Integrated biomarker and stable carbon isotope analyses consistently indicate that the studied samples are dominated by terrigenous, higher-plant–derived organic matter deposited in a deltaic to shallow-marine setting. Sterane ternary distributions (C_{27}–C_{28}–C_{29}) show a strong C_{29} predominance, confirming substantial land-plant input with only minor marine algal contributions. Pr/n-C_{17}–Ph/n-C_{18} ratios and related redox indicators suggest sub-oxic to mildly oxic depositional conditions with negligible biodegradation. Thermal maturity proxies, including Tm/Ts and C_{30} moretane/ hopane ratios, place the organic matter at immature to early mature stages, prior to peak oil generation. Consistent $\delta^{13}C$ signatures of saturate and aromatic fractions further support a waxy, terrestrial source facies with limited secondary alteration. Collectively, these results define a terrigenous-dominated, marginal-marine source rock system with early-stage hydrocarbon potential, characteristic of deltaic successions in the Kutai Basin.

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GLOSSARY OF TERMS AND SYMBOLS

Terms & Symbols	Definition	Unit
Total Organic Carbon (TOC)	Amount of organic carbon in source rock	wt.%
S_1	Volatile hydrocarbons present in rock	mg HC/g rock
S_2	Hydrocarbons generated from kerogen cracking	mg HC/g rock
Hydrogen Index (HI)	Hydrogen richness of kerogen indicating oil potential	mg HC/g TOC
Temperature Maximum (T_{max})	Temperature at maximum hydrocarbon generation during pyrolysis	°C

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