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Influence of Depositional Environment on Source Rock Potential: A Case Study of Fluvio-Estuarine Sediments in the Lower Tanjung Formation, Martapura Area, Barito Basin, South Kalimantan

Sugeng Widada[1], Mochammad Prahastomi[1], Muchammad O.B. Nugroho[1] , Aga Rizky[1], Yody Rizkianto[1], Istiana[1], Desi K. Isnani[1] , Wahyuni A. Humairoh[1]

[1]Geological Engineering Department, Faculty of Mineral Technology and Energy, Universitas Pembangunan Nasional "Veteran" Yogyakarta, Indonesia.
**Corresponding Author: moch.prahastomi@upnyk.ac.id*

ABSTRACT

The Tanjung Formation in the Barito Basin, South Kalimantan, is a proven hydrocarbon-bearing interval; however, its source rock potential and controlling factors remain uncertain in the Martapura area. This study evaluates the influence of depositional environment on source rock quality, hydrocarbon generation potential, and thermal maturity within fluvio-estuarine sediments of the Lower Tanjung Formation. An integrated approach combining field observations, facies analysis, palynology, and geochemical data (TOC, Rock-Eval pyrolysis, and vitrinite reflectance) was applied to 49 samples from 11 locations. The formation is characterized by a transgressive, upward-fining succession of shale, mudstone, coal, and minor sandstone, deposited in fluvio-estuarine settings including floodplains, swamps, interdistributary bays, and oxbow lakes during the Late Eocene. Geochemical results show highly variable organic richness (TOC <0.5% to >70%) and hydrogen index (HI <100 to >500 mg HC/g TOC), indicating heterogeneous source rock quality in the Lower Tanjung Formation. Coal and coaly shale facies exhibit excellent oil-prone potential, whereas most mudstone and claystone facies are poor to moderate source rocks. Vitrinite reflectance values (Ro 0.38–0.46%) indicate immature thermal conditions. Our findings suggest that the coals in the study area constitute oil-prone source rocks characterized by very high TOC and HI values, and are interpreted to have been deposited in freshwater lacustrine to reducing floodplain environments associated with meandering river systems and oxbow lake development. Despite the presence of high-quality source facies, their limited thickness and lateral extent significantly restrict overall hydrocarbon generation potential.

Keywords: Barito Basin, Fluvio-estuarine environment, Source rock potential, Hydrocarbon generation, Lower Tanjung Formation.

ABSTRAK

Formasi Tanjung di Cekungan Barito, Kalimantan Selatan, merupakan interval pembawa hidrokarbon yang telah terbukti. Namun, potensi batuan induk dan faktor-faktor yang mengontrolnya masih belum banyak diteliti di daerah Martapura. Penelitian ini bertujuan untuk mengevaluasi pengaruh lingkungan pengendapan terhadap kualitas batuan induk, potensi pembentukan hidrokarbon, dan kematangan termal pada sedimen fluvio-estuari Formasi *Lower Tanjung*. Pendekatan yang digunakan adalah mengkombinasikan observasi lapangan, analisis fasies, palinologi, dan data geokimia (TOC, pirolisis Rock-Eval, serta reflektansi vitrinit) pada 49 sampel dari 11 lokasi. Formasi ini dicirikan oleh suksesi transgresif yang semakin menghalus ke arah atas, terdiri atas serpih, batulempung, batubara, dan batupasir, yang diendapkan pada lingkungan fluvio-estuari seperti dataran banjir, rawa, *interdistributary bays*, dan *oxbow lake* selama Eosen Akhir. Hasil geokimia menunjukkan variasi kekayaan organik yang sangat tinggi (TOC <0,5% hingga >70%) dan indeks hidrogen (HI <100 hingga >500 mg HC/g TOC), yang mengindikasikan kualitas batuan induk yang heterogen pada Formasi Tanjung Bawah. Fasies batubara dan serpih karbonan menunjukkan potensi sangat baik sebagai batuan induk pembentuk minyak, sedangkan sebagian besar fasies batulempung dan batulanau memiliki kualitas buruk hingga sedang sebagai batuan induk. Nilai reflektansi vitrinit (Ro 0,38–0,46%) menunjukkan kondisi termal belum matang. Batubara dengan karakteristik HI dan TOC sangat tinggi diinterpretasikan terendapkan pada lingkungan lakustrin air tawar hingga *floodplain* reduktif yang berkembang pada sistem sungai meandering dan pembentukan *oxbow lake*. Meskipun terdapat fasies batuan induk berkualitas tinggi, ketebalan dan persebaran lateralnya yang terbatas secara signifikan membatasi potensi pembentukan hidrokarbon secara keseluruhan.

Kata kunci: Barito Basin, Fluvio-estuarine environment, Source rock potential, Hydrocarbon generation, Lower Tanjung Formation.

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I. INTRODUCTION

Situated in southeastern Kalimantan, Indonesia, the Barito Basin has long been recognized as one of the country's productive hydrocarbon provinces. Petroleum exploration activities since the early twentieth century led to the discovery of several oil-producing areas, including the Tanjung and Kabitin fields during the late 1930s, followed later by the Warukin and Tapian Timur fields in the 1960s. These discoveries, grouped within the Tanjung Raya producing area (Satyana, 1995), demonstrate the existence of effective petroleum systems supported by mature organic-rich source rocks capable of generating and expelling hydrocarbons into available reservoir units.

The tectonic evolution of the Barito Basin involved multiple episodes of extension, subsidence, uplift, and inversion that controlled basin architecture and petroleum accumulation (van de Weerd & Armin, 1992; Satyana et al., 1999). Later tectonic inversion and uplift events also contributed significantly to hydrocarbon migration pathways and trap development (Satyana & Idris, 2006). Among the Paleogene stratigraphic units, the Eocene Tanjung Formation is regarded as one of the most important intervals because it functions both as a major source rock and as a prospective reservoir target. The formation consists predominantly of shale, claystone, mudstone, coal-bearing intervals, and subordinate sandstone beds. Stratigraphically, it rests unconformably on pre-Tertiary metamorphic basement and is overlain conformably by the Berai Formation. Previous studies interpreted the depositional system of the Tanjung Formation as ranging from fluvial-deltaic to estuarine environments (Witts et al., 2011; Witts et al., 2012). Although exploration drilling continued after the discovery of the Tapian Timur Field, additional commercial hydrocarbon discoveries within the area remain limited. This condition highlights ongoing challenges related to understanding the spatial distribution, richness, maturity, and hydrocarbon-generating capability of the basin's source rocks.

Source rock performance is closely linked to depositional processes and sedimentary environment because these factors govern organic matter input, preservation conditions, and the geometry of organic-rich intervals. Variations in depositional facies may therefore strongly influence source rock quality and hydrocarbon generation potential. Comparable controls between depositional setting and petroleum system elements have also been documented in fluvio-estuarine successions by previous authors, including Widada et al. (2024). Accordingly, this study focuses on reconstructing depositional facies of the Tanjung Formation and integrating geochemical parameters such as total organic carbon (TOC), hydrogen index (HI), and vitrinite reflectance (Ro) to assess the relationship between facies distribution, source rock quality, thermal maturity, and hydrocarbon generation potential in the Martapura area and adjacent parts of the Barito Basin, South Kalimantan (Figure 1).

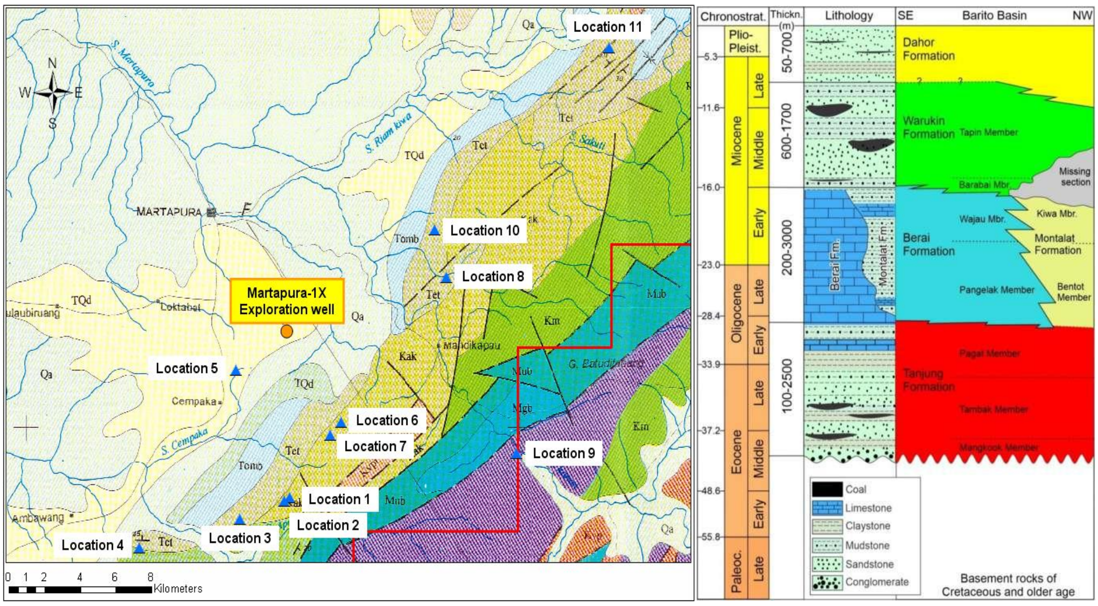

Figure 1. Regional geology and stratigraphic column of Barito Basin (Supriatna et al., 1994; Witts et al., 2014)

II. METHODOLOGY

This study employs an integrated approach combining field observations and laboratory analyses. Fieldwork was conducted to examine stratigraphic profiles from outcrops in order to interpret depositional facies, followed by systematic sampling for laboratory analysis. The analytical framework includes both paleontological and geochemical investigations.

Paleontological analysis was carried out to determine the age and paleobathymetry based on microfossil assemblages, including foraminifera (micropaleontology) and pollen/spores (palynology). Geochemical analysis includes the determination of total organic carbon (TOC), Rock-Eval pyrolysis, and thermal maturity assessment of the source rocks. Rock-Eval pyrolysis and TOC analysis were conducted following standard procedures (Peters, 1986; Waples, 1985). The analytical procedures are described as follows:

Sample Preparation

Samples were first cleaned using cold water and then crushed into pea-sized fragments. These fragments were subsequently used for kerogen preparation or further geochemical analysis.

Total Organic Carbon (TOC)

TOC content was determined by pulverizing the samples, followed by careful treatment with warm hydrochloric acid (HCl) to remove carbonate minerals. The remaining carbon content was then analyzed using a LECO Carbon-Sulfur Determinator. TOC values were interpreted based on standard source rock evaluation criteria: values below 0.5 wt% are considered non-source, 0.5–1.0 wt% as fair, 1.0–2.0 wt% as good, 2.0–4.0 wt% as very good, and values greater than 4.0 wt% as excellent source rocks.

Hydrogen Index (HI)

The Hydrogen Index (HI) is a key parameter derived from Rock-Eval pyrolysis that reflects the relative hydrogen richness of organic matter. It is used to assess kerogen type, hydrocarbon generation potential, and source rock quality. HI is calculated using the equation 1 (Tissot and Welte, 1984).

$$HI = (S2 / TOC) \times 100 \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(Eq. 1)}$$

where S2 represents the amounts of hydrocarbons generated from kerogen during pyrolysis between 300°C and 600°C (mg HC/g rock), and TOC is the total organic carbon content (wt%). HI expresses the mass of hydrocarbons (mg) available per gram of organic carbon.

High HI values indicate hydrogen-rich kerogen with strong oil-generating potential, whereas low HI values reflect oxygen-rich terrestrial organic matter with a tendency to generate gas. Source rock quality based on HI is classified as follows:

Table 1. The relationship between HI value and Source Rock Quality (Tissot and Welte, 1984)

Source Rock Quality	HI (mgHC/g TOC)
Oil-prone	>300
Gas-oil prone	200 – 300
Gas prone	110 – 200
Non –source	<100

Vitrinite Reflectance (Ro)

Thermal maturity of the source rocks was determined using vitrinite reflectance (Ro) analysis. This method is based on the optical reflectance properties of vitrinite particles, which increase with thermal maturation. Changes in reflectance are controlled by temperature and duration of heating, resulting in progressive changes in vitrinite optical properties.

Polished rock samples were prepared by mounting on glass slides using epoxy resin, followed by grinding with progressively finer abrasives and final polishing with alumina. Measurements were conducted under oil immersion (refractive index = 1.516) using a reflected light microscope equipped with a photomultiplier and digital voltmeter. Calibration was performed using standard glass reflectance materials.

III. RESULTS AND DISCUSSIONS

Environment of Deposition

The Tanjung Formation in the investigated area crops out extensively along the NW of the Meratus High. Geological observations and sample collection were completed at eleven measured outcrop stations (Figure 1). Field investigations indicate that the formation is mainly composed of thick mudstone and shale successions interlayered with thin coal beds, accompanied by subordinate sandstone intervals that are more abundant in the lower stratigraphic section. Upward in the succession, shale becomes increasingly dominant, reflecting a general fining-upward trend. The shale commonly displays dark gray to brown colors, soft consistency, fissile character, and silty to sandy textures. Most intervals are non-calcareous to weakly calcareous and locally contain carbonaceous material. Minor pyrite occurrences, thin limestone intercalations, and coal seams are also present. Coal layers vary from black to brownish black, are moderately hard to hard, brittle, lightweight, and commonly show vitreous luster with conchoidal fracture surfaces. Individual seam thickness ranges from less than 0.5 m to approximately 2 m. The vertical facies arrangement suggests a transgressive succession with an overall upward-fining character.

The sandstone intervals are generally yellowish to pinkish in color and range from very fine- to coarse-grained. Petrographic analysis shows that the sandstones are quartz-dominated, with minor feldspar and lithic fragments, and are mainly classified as sublitharenite to quartzarenite. Carbonaceous material and authigenic kaolinite are locally present. Sedimentary structures observed in the field include parallel lamination, cross-bedding, bioturbation, wavy lamination, and massive bedding (Figure 2). Earlier studies by Satyana et al. (2001), Heryanto (2009), and Winantris et al. (2017) interpreted the Tanjung Formation as having formed within a fluvio-deltaic depositional system. In the present study, lithological characteristics and vertical facies development suggest deposition within a terrestrial to marginal marine setting, most likely a coastal plain influenced by estuarine channels within a fluvio-estuarine system. This interpretation is supported by palynological data from shale samples showing abundant mangrove-derived pollen together with the absence of foraminiferal assemblages, indicating deposition in coastal swamp environments.

TOC and Hydrogen Index Analysis

A total of 49 rock samples from 11 observation locations were collected to evaluate the organic content (TOC) of Lower Tanjung Formation rocks with potential as source rocks. Laboratory analysis shows that coal and thin coaly shale samples from Location 1 (Figure 3a) represent good source rocks, with TOC values of 59% and 47%, and Hydrogen Index (HI) values of 431 and 205 mg HC/g TOC, respectively. In contrast, two medium-gray claystone samples—one underlying a coal seam and the other beneath a massive sandstone layer—are classified as non-source rocks, with TOC values of 0.35% and 1.07%, and HI values of 20 and 69 mg HC/g TOC, respectively.

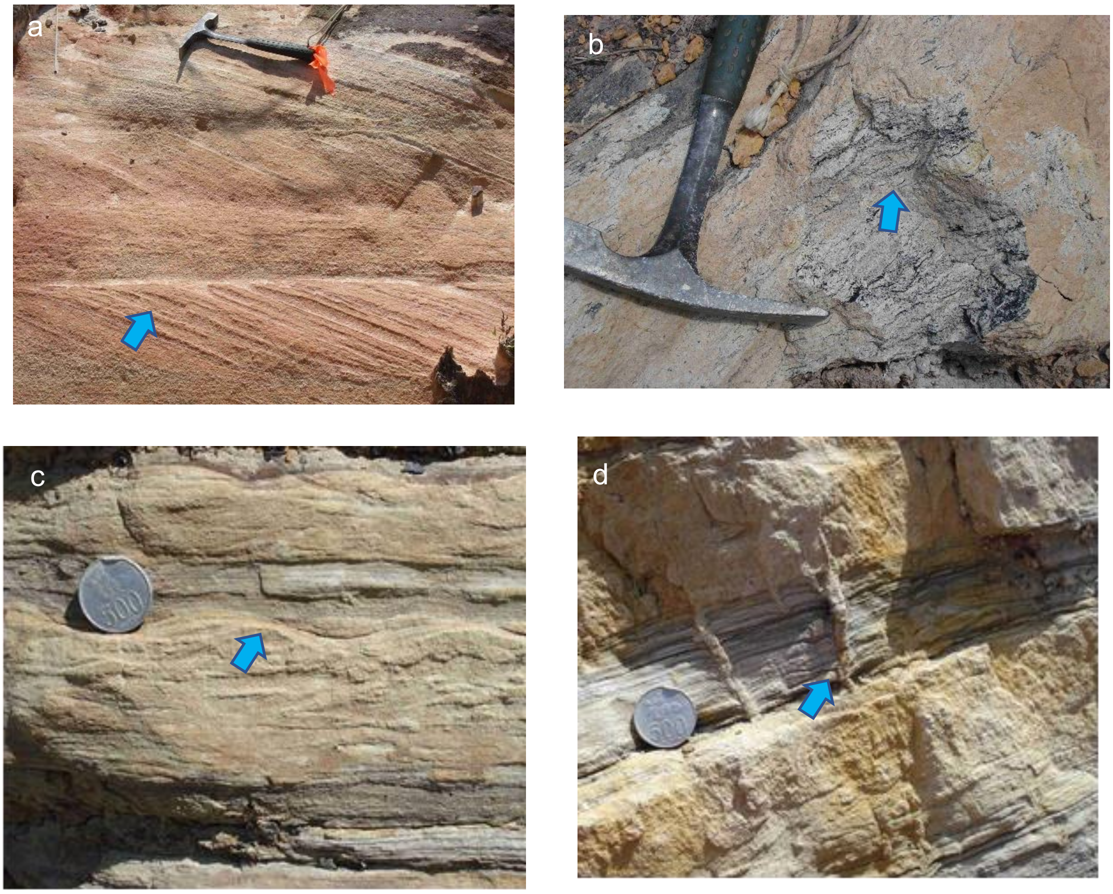

Figure 2. Sedimentary structures observed in the studied area: (a) cross-bedding at Location 4, (b) wavy lamination at Location 3, (c) ripple lamination at Location 10, and (d) bioturbation at Location 10. These structures may indicate variable energy conditions and alternating current regimes, which are characteristic of transitional environments influenced by both fluvial and tidal processes.

A pinkish brown shale sample with mica and carbonaceous laminations interbedded with very fine-grained sandstone exhibiting wavy lamination, collected from Location 2 (Figure 3b), is classified as a non-source rock, with a TOC value of only 0.67% and an HI of 54 mg HC/g TOC. In contrast, coal and coaly shale samples obtained from mining remnants at the same location show significantly higher organic richness, with TOC values of 71.4% and 42.9%, and HI values of 456 and 257 mg HC/g TOC, respectively.

Sub-fissile mudstone samples from LP 3, ranging in color from brownish-gray to dark gray, yield a TOC value of 3.43% and an HI of 264 mg HC/g TOC. These samples contain a considerable amount of calcareous material. In contrast, an overlying claystone unit characterized by pale white to light gray colour and very low organic content, shows a TOC value of 0.11%, with S2 values too low to allow reliable HI calculation.

A black coaly shale layer sampled at LP 4 (Figure 3c) exhibits a TOC value of 40.6% and an HI of 168 mg HC/g TOC, indicating excellent source rock potential with a strong tendency for gas generation. A light- to medium-gray claystone sample underlying a sandstone layer at the same location, containing plant fragments, shows a TOC value of 25% and an HI of 203 mg HC/g TOC, suggesting potential as a mixed oil- and gas-prone source rock.

Coal samples collected from mine tailings at LP 6 show very high organic content, with a TOC value of 76% and an HI of 421 mg HC/g TOC. Additionally, carbonaceous claystone samples from the same tailings, light to medium gray in color, exhibit a TOC value of 1.45% and an HI of 522 mg HC/g TOC. These samples represent good to excellent quality source rocks with strong oil-generating potential.

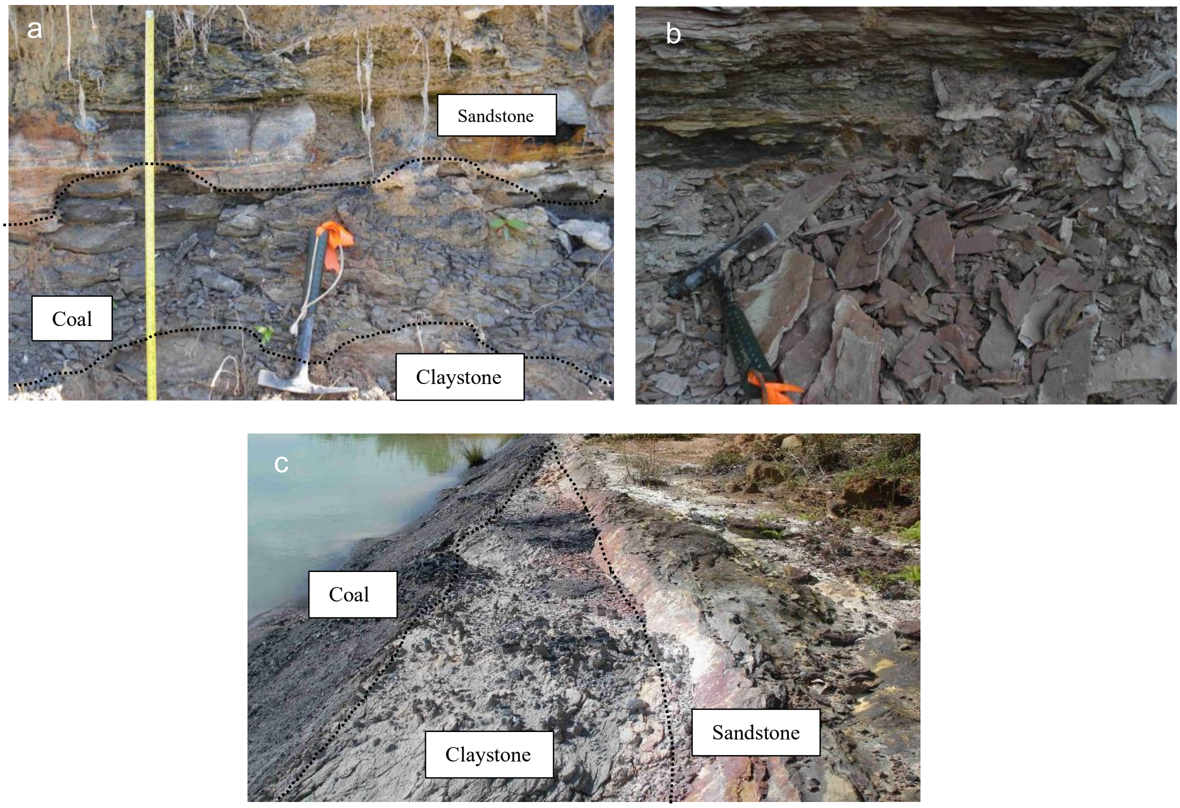

Figure 3. Photographs of outcrops at Locations 1, 2, and 4. (a) Thin coal seam overlying gray claystone at Location 1. Rock-Eval pyrolysis indicates that the coal exhibits significantly higher source rock quality compared to the underlying claystone. (b) Pinkish-brown shale interbedded with very fine-grained sandstone at Location 2, indicating poor source rock quality. (c) Interbedded sandstones, claystones, and coal at Location 4, showing a claystone-filled channel characterized by claystone bed pinch-out geometry. Coal samples from this outcrop exhibit excellent TOC values with strong gas-generation potential, whereas light- to medium-gray claystone shows moderate TOC values and potential as an oil–gas prone source rock.

Eight samples, including in-situ coal, coaly shale, and carbonaceous mudstone, were collected from LP 10, an abandoned mining area. A representative section of the layer was examined in detail and systematically sampled (Figure 4). The analytical results from LP 10 reveal significant variability in source rock potential within the fine-grained lithological units of the Lower Tanjung Formation. A white claystone sample (Sample 1002), which lacks organic material, and a gray shale sample (Sample 1003) both indicate non-source rock characteristics. The white claystone yields a TOC value of 0.5% and an HI of 48 mg HC/g TOC, while the gray claystone shows a TOC of 1% and an HI of 152 mg HC/g TOC. In contrast, the coaly shale sample (Sample 1004) exhibits a TOC value of 3.6% and an HI of 199 mg HC/g TOC, indicating good source rock quality with the potential to generate both oil and gas. A sample taken from a thin coal seam (Sample 1006) shows a TOC value of 66% and an HI of 335 mg HC/g TOC, suggesting excellent source rock quality with strong oil-generating potential.

Seven samples, including two in-situ coal samples, were collected from LP 11 (Figure 5), an active mining site. At this location, four coal seams were identified, consisting of three major seams and one minor seam with a thickness of approximately 200 cm, resulting in a total cumulative thickness of 3.7 meters. Each of the major coal seams has an approximate thickness of 2 meters.

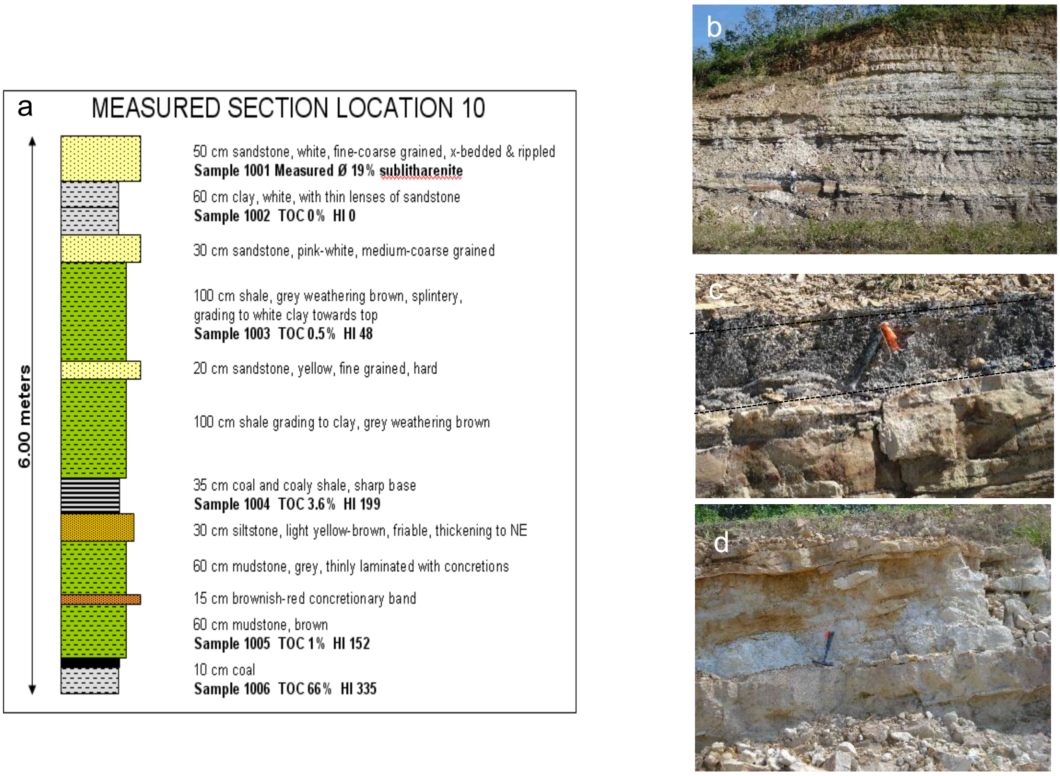

Figure 4. Measured section and representative outcrop photographs at Location 10. (a) and (b) The measured section shows interbedded sandstone, shale, mudstone, and coal units with a total thickness of approximately 6 m. Coal and coaly shale intervals are associated with higher TOC and HI values, indicating good to excellent source rock potential, whereas light-gray claystone and gray shale exhibit poor source rock potential (c) Close-up of a 30 cm thick coaly shale bed sampled at Location 10 (Sample 1004). (d) Upper part of the measured section showing white claystone with sandstone lenses; this unit was sampled and is barren of organic matter (Sample 1002).

Two coal samples from LP 11 were analyzed and exhibit very high organic richness, with TOC values of 66% and 78%, and Hydrogen Index (HI) values of 397 and 345 mg HC/g TOC, respectively.

These results indicate that the coals at this location represent excellent source rocks with strong oil-generating potential. Coaly shale underlying the first coal seam also demonstrates excellent source rock potential for oil generation, with a TOC value of 6.5% and an HI of 323 mg HC/g TOC. A mudstone sample shows moderate to good source rock potential for both oil and gas, with a TOC value of 2.4% and an HI of 214 mg HC/g TOC. In contrast, other mudstone and claystone samples from this location are classified as non-source rocks due to their low organic content and poor geochemical characteristics.

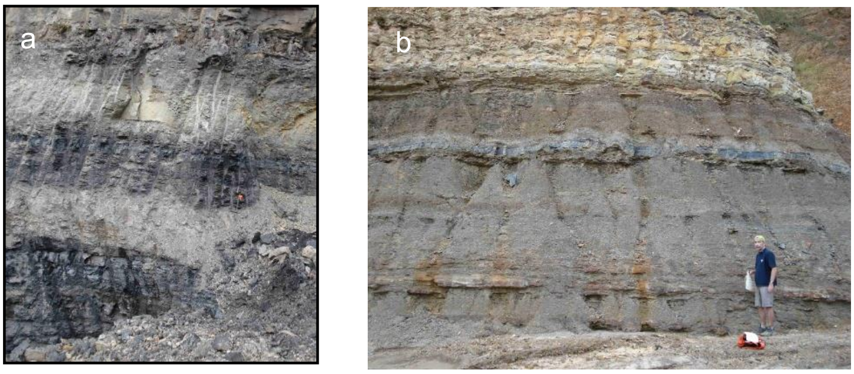

Figure 5. Outcrop at Location 11. (a) Three coal seams exhibiting excellent source rock potential, characterized by high TOC values and oil-prone hydrogen index. (b) Mudstone unit exhibiting low TOC values (<1%) and low HI values (<100 mg HC/g TOC), indicating poor source rock potential.

Thermal Maturity Analysis

The thermal maturity of the source rocks in the study area was determined based on vitrinite reflectance analysis. A total of nine samples were analyzed for vitrinite reflectance, consisting of seven coal samples, one carbonaceous mudstone sample, and one coaly shale sample from the Lower Tanjung Formation. The mean V_{ro} values for the Lower Tanjung samples range from 0.38% to 0.46%, with an average of 0.42%. A vitrinite reflectance value of approximately 0.5% is generally considered the threshold for the onset of oil generation.

The vitrinite reflectance (V_{ro}) data indicate that Lower Tanjung Formation sedimentary rocks exposed at the surface along the flank of the Meratus High in the study area are thermally immature. These results are summarized in Table 2 and representative histograms are shown in Figure 6.

Table 2. Vitrinite reflectance (VRo) data of the Lower Tanjung Formation. All samples fall within the immature thermal maturity range.

Sample	Lithology	Mean V_{ro}	Standard Deviation	Number of Measurements	Range
101	Coal	0.42%	0.041	54	0.33%-0.50%
205	Coal	0.40%	0.045	53	0.33%-0.49%
302	Mudstone	0.38%	0.055	29	0.28%-0.49%
401	Shale	0.43%	0.055	57	0.33%-0.52%
602	Coal	0.42%	0.044	50	0.34%-0.52%
804	Coal	0.46%	0.053	50	0.35%-0.53%
1006	Coal	0.42%	0.051	50	0.34%-0.52%
1102	Coal	0.43%	0.046	53	0.35%-0.53%
1111	Coal	0.45%	0.041	50	0.36%-0.50%

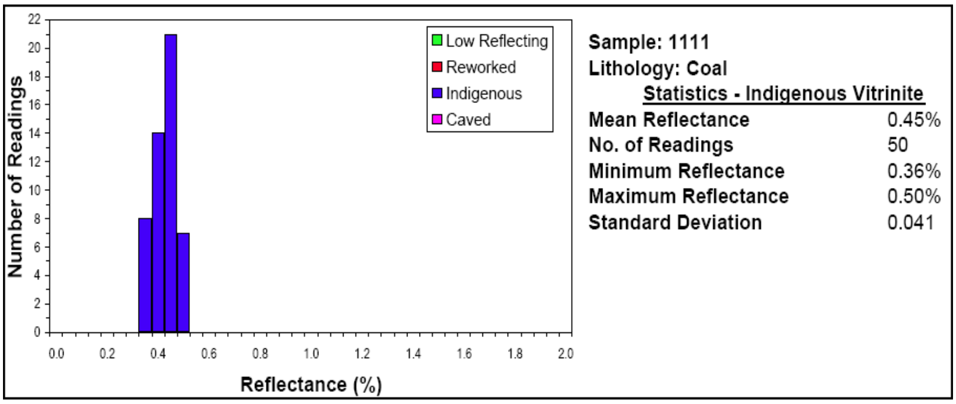

Figure 6. Vitrinite reflectance (VRo) histogram for Sample 1111 (coal) from Location 11, showing a tight distribution with a mean value of 0.45%.

A favorable temporal relationship is inferred between hydrocarbon generation–expulsion and trap formation within the petroleum system of the study area. Hydrocarbon maturation and expulsion from the Tanjung Formation are interpreted to have resulted from increased burial loading during the Late Miocene to Pliocene. This process likely postdates the inversion of the Meratus High and the development of structural traps, indicating effective charge timing relative to trap formation.

Relationship between Depositional Environment and Source Rock Potential

The quality and hydrocarbon-generating potential of source rocks are primarily controlled by organic richness, kerogen type, and thermal maturity (Tissot & Welte, 1984; Selley, 1985). These parameters are strongly influenced by depositional environmental conditions, which control organic productivity, preservation processes, and the geometry of source rocks, ultimately determining the volume of hydrocarbons generated.

Several fine-grained sedimentary facies within the Lower Tanjung Formation exhibit source rock potential, including coal, coaly shale, carbonaceous mudstone, mudstone, and claystone. Laboratory analyses indicate that these lithologies display a wide range of organic richness, with TOC values varying from less than 0.5% (poor) to up to 80% (very rich), and HI values ranging from less than 100 mg HC/g TOC (non-generative) to as high as 550 mg HC/g TOC (oil-prone).

Geochemical analysis of seven coal samples collected from various locations shows that coal facies represent excellent oil-prone source rocks, with TOC values exceeding 55% and HI values ranging from 330 to 460 mg HC/g TOC. These coals are interpreted to have been deposited in freshwater lacustrine or floodplain pond environments under reducing conditions, likely associated with meandering river systems forming oxbow lakes. The organic matter is dominated by liptinite-rich macerals (e.g., sporinite, cutinite, resinite), derived from a mixture of algal material and wax- or resin-rich higher plants. This composition suggests the predominance of Type I kerogen, which is highly oil-prone upon maturation.

Geochemical data from seven coaly shale and carbonaceous mudstone samples indicate variable source rock quality. TOC values range from 2.5% (rich) to 50% (very rich), with HI values between 160 mg HC/g TOC (gas-prone) and 522 mg HC/g TOC (oil-prone). These facies represent source rocks capable of generating gas, mixed oil and gas, and oil, with good to excellent quality. Gas-prone coaly shale and carbonaceous mudstone are interpreted to have formed in plant-rich swamp environments, while mixed oil–gas facies were deposited in floodplain or swamp settings with mixed detrital and terrestrial organic input. Oil-prone facies are interpreted to have formed in oxbow lake (abandoned channel) environments, where detrital material is mixed with algal and lipid-rich organic matter.

Geochemical analysis of nine mudstone samples also shows variable source rock potential. TOC values range from less than 1% (poor) to 7% (rich), with HI values from less than 100 mg HC/g TOC (non-source) to 520 mg HC/g TOC (oil-prone). TOC versus HI plots (Figure 7) indicate that most samples (six) are non-source rocks, one sample represents a moderate-quality oil–gas source rock, and two samples are classified as good oil-prone source rocks. Oil-prone mudstones are interpreted to have been deposited in oxbow lake environments, while non-source mudstones formed in swamp, interdistributary bay, or mudflat environments under non-reducing conditions, which limited organic matter preservation.

Similarly, geochemical analysis of nine claystone samples indicates variable source rock characteristics. TOC values range from less than 1% (poor) to 3.4% (rich), with HI values from less than 100 mg HC/g TOC (non-source rock) to 280 mg HC/g TOC (oil–gas prone). TOC versus HI plots (Figure 7) show that most samples (six) are non-source rocks, one sample represents a moderate gas-prone source rock, one indicates moderate oil–gas potential, and one is classified as a good oil–gas source rock. Gas-prone claystones are interpreted to have formed in plant-rich swamp or mudflat environments, while oil–gas prone claystones reflect mixed organic input in swamp settings. Non-source claystones were deposited in interdistributary bay or mudflat environments under non-reducing conditions, resulting in poor preservation of organic matter.

Overall, these variations indicate that organic matter enrichment is strongly controlled by depositional setting (Table 3), particularly the development of low-energy, reducing environments within abandoned channel and floodplain systems, where conditions favor both high organic productivity and effective preservation.

Table 3. Relationship Between Facies, Organic Richness, Hydrogen Index, Hydrocarbon Potential, And Possible Facies Distribution Occurrence of The Lower Tanjung Formation.

No	TOC (%)	HI (mg/g)	Hydrocarbon Potential	Possible Occurrence
1.	>55	330 - 460	Oil prone	Oxbow lake
2.	2.5 -50	160 - 522	Gas prone, Oil-gas prone, Oil prone	Swamp, Flood Plain, Oxbow lake
3.	<1 - 7	<100-520	Non source, Oil-gas prone, Oil prone	Interdistributary bay, Mud flat, Swamp, Oxbow lake
4.	<1 - 3.4	<100-280	Non source, Gas prone, Oil-gas prone,	Interdistributary bay, Mud flat, Swamp

Based on source rock potential analysis indicates that oil-generating facies within the Lower Tanjung Formation are mainly restricted to coal, coaly shale, and carbonaceous mudstone in the lower part of the formation. In contrast, most claystone and mudstone intervals are classified as non-source rocks or exhibit limited gas-generating potential. The Upper Tanjung Formation is not exposed in the study area; therefore, its source rock potential cannot be evaluated.

Despite locally excellent source rock quality, the overall hydrocarbon generation potential is limited due to the thin and laterally discontinuous nature of the organic-rich facies. The net thickness of coal, coaly shale, and carbonaceous mudstone is relatively thin compared to the total thickness of the Tanjung Formation in the study area. The cumulative thickness of these source rock intervals in the Lower Tanjung Formation is estimated to be less than 5 meters. In contrast, the gross thickness of claystone and mudstone exceeds 500 meters, although most of these intervals do not qualify as effective source rocks. This condition can be explained as follows.

Coal-bearing facies formed within oxbow lake systems are inherently limited in lateral extent due to their origin as small, localized geomorphological features within floodplain environments. These systems develop from abandoned meander bends and persist only for relatively short periods, typically tens to hundreds of years, before being progressively infilled by fine-grained floodplain sediments (Hidayat et al., 2011; Constantine et al., 2010). Although stagnant and reducing conditions favor the preservation of organic matter, the restricted spatial extent and short duration of deposition result in thin, laterally discontinuous accumulations. Consequently, coal and associated carbonaceous facies occur as isolated lenses with limited thickness and continuity.

Geochemical data further indicate that seven coal samples and five additional samples plot within the oil-prone field of the TOC versus HI diagram (Figure 7), while nine other samples fall within the oil–gas prone to gas-prone fields. This distribution reflects the coexistence of multiple source rock types with varying generative characteristics. The overall pattern suggests the operation of a dual-phase hydrocarbon system, involving both oil- and gas-prone source rocks. Hydrocarbons generated in deeper, thermally mature zones were subsequently expelled and migrated into available reservoirs, consistent with a petroleum system in which the timing of generation, expulsion, and trap formation is favourably aligned.

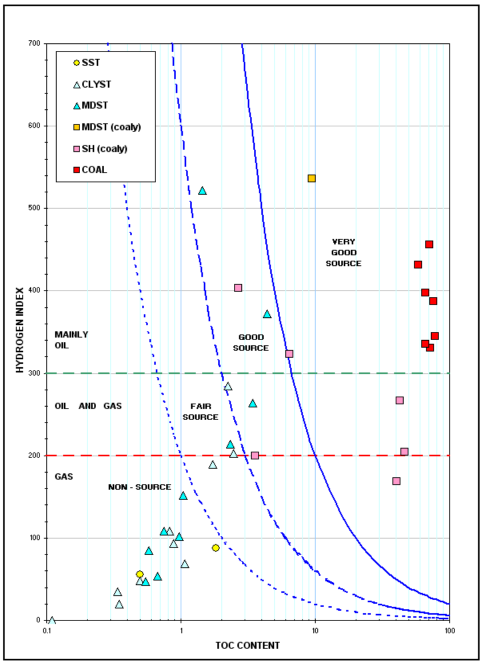

Figure 7. Cross-plot of TOC and Hydrogen Index (HI) for fine-grained sediments of the Lower Tanjung Formation.

The high Hydrogen Index (HI) values obtained in this study are consistent with previously reported data from the Tanjung Formation. For instance, Fikri et al., (2022) reported consistently high HI values in coal seams, ranging from approximately 352 to 413 mg HC/g TOC, with a maximum of

470 mg HC/g TOC observed in coaly shale intervals. In contrast, associated floor and roof rocks display significantly lower HI values, typically ranging from 81 to 231 mg HC/g TOC. This vertical variability reflects a strong facies control on organic matter quality, where coal and coaly intervals are enriched in hydrogen-rich organic matter, while adjacent fine-grained siliciclastic units contain more terrestrially derived and oxygen-rich organic material. A similar pattern is observed in the present study, where coal and coaly shale facies consistently exhibit higher HI values compared to mudstone and claystone units. This correspondence suggests that the distribution of oil-prone kerogen in the Tanjung Formation is primarily controlled by localized depositional environments, particularly reducing settings such as oxbow lakes and floodplain ponds, where preservation of labile organic matter is enhanced. Furthermore, the lack of a clear vertical trend in HI and Tmax values reported by Fikri et al., (2022) supports the interpretation that source rock quality is more strongly influenced by facies heterogeneity than by systematic stratigraphic variation.

Overall, the distribution of source rock quality in the Lower Tanjung Formation is highly heterogeneous and facies-dependent, with the highest potential restricted to coal and coaly intervals formed in localized, reducing environments, while most claystone and mudstone units deposited under more oxidizing conditions exhibit poor source rock characteristics.

IV. CONCLUSIONS

The Tanjung Formation in the Martapura area was deposited in a Late Eocene fluvio-estuarine system characterized by a transgressive, upward-fining succession of shale, mudstone, coal, and minor sandstone. The study demonstrates that depositional environment plays a fundamental role in controlling source rock potential through its influence on organic matter accumulation, preservation, and facies distribution.

Coal and coaly shale facies represent the most effective source rocks, exhibiting very high TOC values (>55%) and high hydrogen index (330–460 mg HC/g TOC), indicating excellent oil-prone characteristics associated with reducing environments such as oxbow lakes and swamp settings. In contrast, mudstone and claystone facies are generally poor to moderate source rocks due to lower organic content and less favorable preservation conditions in more oxidizing environments such as interdistributary bays and mudflats. Despite the presence of high-quality source facies, vitrinite reflectance data (Ro 0.38–0.46%) indicate that the studied interval remains thermally immature at outcrop level. Furthermore, the limited thickness and lateral discontinuity of organic-rich facies, particularly those formed in oxbow lake settings, significantly constrain the overall hydrocarbon generation potential. These findings highlight that while fluvio-estuarine systems may host high-quality source rocks, their spatial restriction represents a key limitation for effective hydrocarbon accumulation.

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