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RESEARCH ARTICLE

Paleoenvironmental Influences Evaluation on Sedimentary Organic Matter of the Kampungbaru Formation, Lower Kutai Basin: Organic and Inorganic Geochemical Approaches

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Abstract

The study of paleoenvironmental influences on sedimentary organic matter has become a critical field of research, particularly in understanding the depositional conditions that control the accumulation and preservation of organic matter. In present study, Upper Miocene-Pliocene Kampungbaru Formation of the Lower Kutai Basin, Indonesia was evaluated by utilizing geochemical proxies to interpret the role of paleoclimate, paleosalinity, and paleoredox conditions on the enrichment of sedimentary organic matter. The rock unit is mostly comprised of shale, coaly shale and coal. The sediments of the Kampungbaru Formation were mostly deposited in a freshwater to brackish depositional environment, likely representing swampy or deltaic settings with transitions between weakly anoxic to oxic environments. A fluctuation between humid and arid climates with higher total organic carbon (TOC) values associated with humid conditions that enhanced the organic matter preservation. The geochemical results indicate that the analyzed samples have a TOC content between 1.50 wt.% to 43.68 wt.%, indicating a good to excellent organic matter content. Organic matter in the Kampungbaru Formation is composed of type III (gas-prone) and type II-III (mixed oil and gas prone) kerogen, with HI values ranging from 91 to 269 mg HC/g TOC. The pyrolysis T_{max} of the Kampungbaru Formation range from 301 to 427 °C which indicate that sediments are thermally immature, bordering on the limit of 435ºC. The closure of the Indonesian Seaway during the Miocene-Pliocene restricted marine water exchange between the Indian and Pacific Oceans. This tectonic event likely reduced marine influence in the Lower Kutai Basin promoting freshwater-dominated depositional settings such as swamps and deltas.

Keywords: Kampungbaru Formation-Lower Kutai Basin-Paleoenvironmental-Sedimentary Organic Matter-Upper Miocene – Pliocene.

1. Introduction

The investigation of sedimentary organic matter (OM) and its paleoenvironmental controls are fundamental for reconstructing depositional environments and evaluating source rock potential in sedimentary basins (Li et al., 2018). These factors are essential for evaluating the hydrocarbon generation potential of the formation as a source rock (Permana et al., 2018; Jamaluddin et al., 2023). Redox sensitive trace elements provide valuable insight into ancient depositional environments, particularly in reconstructing the oxygen levels and conditions favorable for organic matter preservation. By studying the concentrations and behavior of elements e.g. Mo, U, V, etc., scientists can infer whether ancient environments were oxygenated, anoxic, or euxinic, thus evaluate how these conditions influenced the accumulation and preservation of organic matter (Dypvik and Harris, 2001; Rakocinski et al., 2018; Algeo and Liu, 2020).

The Lower Kutai Basin in Indonesia is a prolific hydrocarbon province that has garnered significant attention due to its extensive organic-rich sedimentary deposits, particularly those from the Miocene epoch (Satyana et al., 1999; Jamaluddin et al., 2024a-b). In the Upper Miocene–Pliocene Kampungbaru Formation, located in the Lower Kutai Basin, Indonesia geochemical approaches have increasingly been used to assess paleoenvironmental factors such as paleosalinity, paleoredox and paleoclimate conditions which play critical roles in organic matter accumulation and preservation of the formation (Hu et al., 2018; Permana et al., 2022). These factors determine the primary productivity, preservation potential and depositional environments of organic material. This study employs an integrated organic and inorganic geochemical approaches to examine the paleosalinity, paleoredox, and paleoclimate conditions of the Kampungbaru Formation. Paleosalinity indicators provide insights into marine or freshwater influence, while paleoredox proxies reveal the oxygenation state of bottom waters, and paleoclimatic data can help to reconstruct past temperature and precipitation patterns (Demaison et al., 1980; Emerson et al., 1988; Arthur et al., 1994; Sageman et al., 2014).

Geochemical analyses play a crucial role in unraveling the dynamic paleoenvironmental processes that influenced sedimentary organic matter (OM) deposition in the Lower Kutai Basin during the Upper Miocene–Pliocene. These studies focus on key paleoenvironmental factors, including paleosalinity, paleoredox, and paleoclimate conditions, which are critical for understanding how the depositional environment shaped OM accumulation and preservation.

2. Geological Setting

The research area in Samboja, East Kalimantan is situated within the Lower Kutai Basin, one of Southeast Asia's most prolific sedimentary basins. The basin is a back- arc basin that formed due to extensional processes during the Eocene, followed by thermal subsidence and later compression during the Miocene. The research area in Samboja lies in the eastern part of the basin, where subsidence and sedimentation were prominent. Structural elements such as growth faults and roll-over anticlines, which developed due to sediment loading and tectonic activity, are prevalent in the area (Fig 1A).

The Lower Kutai Basin is a prolific hydrocarbon province due to its favourable geological history, extensive sedimentary sequences, organic-rich source rocks, and well-developed reservoir and trapping systems (Paterson et al., 1997; Jamaluddin et al., 2024a-b). The basin formed due to a combination of tectonic processes, including rifting, subsidence, and sedimentation during the Tertiary period. The tectonic evolution of the basin was influenced by the interaction between the Australian and the Eurasian Plates, leading to significant subsidence and sediment accumulation. Its structural evolution was influenced by regional tectonics that created an ideal environment for the accumulation of thick sedimentary sequences and organic-rich deposits (Allen, 1970; Cloke et al., 1997). The extensional tectonics resulted in the creation of accommodation space for thick sedimentary sequences, including the Kampungbaru Formation, while the subsequent compressional tectonics led to the development of structural traps, such as anticlines and fault-bounded structures, which are crucial for hydrocarbon accumulation (Allen, 1970; Paterson et al., 1997; Cloke et al., 1997; Moss et al., 1997).

The stratigraphic sequence of the Lower Kutai Basin reflects the sedimentation patterns driven by tectonic and sea-level changes. It contains thick accumulations of Tertiary sediments, primarily from the Paleogene and Neogene periods with later Quaternary deposits (Moss and Chamber, 1997; McClay et al., 2000). The Kampungbaru Formation is part of the Tertiary stratigraphic sequence of the Lower Kutai Basin. This formation belongs to the Miocene epoch, which is a key period of sedimentation in the basin (Fig 1B). The Kampung baru Formation is characterized by its clastic sedimentary rocks deposited primarily in a deltaic and shallow marine environment (Marks et al., 1982). The lithology of the Kampungbaru Formation includes sandstones, siltstones, shales, and coal. The Kampungbaru Formation reflects the influence of both fluvial and tidal processes, indicating a tide dominated deltaic system. This is consistent with the general depositional style of the Mahakam Delta, which has a strong tidal influence, resulting in well sorted sandstones and laminated shales (Satyana et al., 1999; Jamaluddin et al., 2024a).

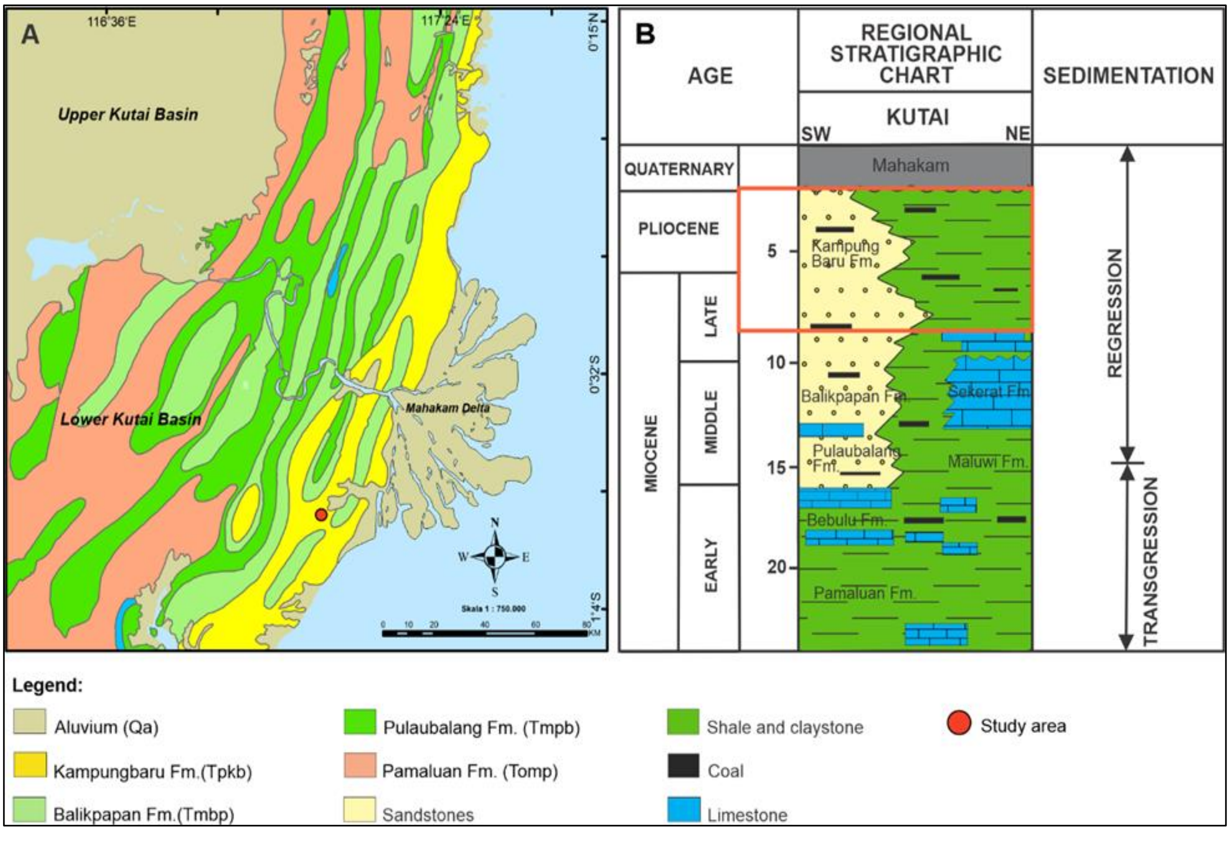

Fig 1. (A) The study area is located in the Samboja area; (B) Stratigraphy and lithology of the Kutai Basin (Satyana et al., 1999; Jamaluddin et al., 2024a). This study focused on the Kampungbaru Formation, as indicated by the orange box.

3. Materials and Methods

3.1 Samples

A total of 40 cutting samples, comprising of shale, coaly shale, and coal were collected from the Samboja area within the depth interval of 57 to 505 meters (Tabel 1). The samples are representative of the Upper Miocene–Pliocene Kampungbaru Formation in the Lower Kutai Basin, Indonesia. X-ray fluorescence (XRF) analysis was conducted to determine major and trace element compositions for interpreting depositional conditions. Total organic carbon (TOC) and Rock-Eval pyrolysis analyses were performed to evaluate the quantity, type, and maturity of organic matter. Five representative samples were further examined using scanning electron microscopy (SEM) to observe the morphology, distribution, and preservation of organic matter and its association with mineral matrices. These combined methods provide integrated geochemical and microtextural insights into the depositional and diagenetic conditions of the Kampungbaru Formation.

3.2 X-Ray Fluorescence (XRF)

40 cutting samples for the bulk rock geochemical analysis, a 10 g aliquot of each sample was milled into a fine powder using an agate mortar and pestle to avoid contamination. The powdered samples were then carefully transferred into plastic cups, ensuring that the base of each cup was lined with a 25 mm diameter thin plastic wrap to hold the powdered material securely and prevent spillage or contamination. Quantitative analysis of the major and trace elements was performed using the TRACER IV-SD energy dispersive X-ray fluorescence (ED-XRF) device from Bruker AXS. This analysis was conducted at the Department of Geology, Faculty of Earth Sciences, Geography, and Astronomy, University of Vienna, Austria.

3.3 Organic Geochemistry

TOC was determined on ~100 mg of powdered samples using a LECO RC-612 Carbon Analyzer (LECO Corporation, USA) with an analytical precision better than ±1%. Prior to analysis, samples were acidified to remove inorganic carbon, rinsed, and dried. Analyses were conducted at the Department of Geology, University of Vienna, Austria, employing high-temperature combustion to oxidize carbon to CO_2 for quantification.

Rock- Eval pyrolysis (Tissot and Welte, 1984; Espitalie et al., 1985; Setyawan et al., 2020) was performed using a Vinci Technologies Rock-Eval 6 analyzer on 60–80 mg of powdered material. Parameters measured included S_1, S_2, and the temperature of maximum pyrolysis yield (Tmax), from which the hydrogen index (HI) and petroleum potential yield (PY) were calculated. Samples were initially heated to 300 °C, with the S_1 peak representing free hydrocarbons released at constant temperature for three minutes. The temperature was then increased to 550 °C at 25 °C/min to generate the S_2 peak, representing hydrocarbons released from kerogen through thermal cracking.

The S_2 peak was characterized by these hydrocarbons. CO_2 was emitted throughout the heating process and detected as the S_3-peak by an infrared detector, however this value was not recorded in this investigation. The temperature of maximal hydrocarbon production (T_{max}) was determined using the maximum S_2-peak value. The addition of S_1 and S_2 identifies the hydrocarbon generating potential of a sample. The hydrogen index (HI) was calculated by the following equation: $HI=S_2/TOC \times 100$ [mg HC/g TOC].

3.4 Scanning Electron Microscope (SEM).

Five cutting samples were prepared for scanning electron microscopy (SEM) analysis and coated with a thin carbon film to enhance surface conductivity. The selection was based on lithofacies type, total organic carbon (TOC) content, hydrogen index (HI), and pyrolysis T_{max} values to ensure coverage of the full range of organic richness, kerogen type, and thermal maturity within the Kampungbaru Formation. The selected samples include high TOC shale facies representing both organic-rich and organic-lean intervals. SEM and electron backscatter diffraction (EBSD) analyses were performed using an Inspect S-50 instrument at the University of Vienna, Austria, operating at an accelerating voltage of 12.50 kV.

4. Results

4.1. Oxide and element ratio

To evaluate the influence of detrital sediment flux, paleosalinity, paleoredox, and paleoclimate, variations in major oxides and elemental ratios were examined. Diagnostic oxides include Fe_2O_3, Al_2O_3, CaO, and MgO, while key geochemical ratios such as Sr/Cu, Rb/Sr, Rb/K, Sr/Ba, Cu/Zn, and V/(V+Ni) provide additional environmental insights. The Kampungbaru Formation exhibits moderate to high SiO_2 and Al_2O_3 contents. SiO_2 ranges from 14.1% to 39.2% (avg. 30.1%), reflecting variable siliceous input from sandstone, siltstone, and shale lithologies. Al_2O_3 varies from 0% to 13.5% (avg. 10%), indicating the presence of alumina-bearing phases such as clay minerals and feldspars. MgO content (0.43–6.93%, avg. 4.3%) suggests contributions from magnesium-bearing minerals, e.g., olivine, whereas CaO content is low (0.15–1.44%, avg. 0.5%), implying limited carbonate input. Fe_2O_3 ranges from 2.52% to 7.85% (avg. 4.6%), reflecting the presence of iron oxides such as hematite and goethite (Table 1).

The Sr/Cu ratio ranges from 2.5 to 11.4 with an average of 3.9 indicating a moderate influence of felsic minerals, possibly suggesting a mixed source area with contributions from both felsic and mafic rocks. The Rb/Sr ratio, which varies from 0.1 to 1.1 and average at 0.7 suggests moderate weathering or sedimentary maturity indicating that the sediments have undergone some degree of alteration and reworking. The Rb/K ratio ranging from 0.001 to 0.005 with an average of 0.003 indicates a relatively low degree of rubidium enrichment. The Sr/Ba ratio ranges from 0.02 to 0.11, with an average of 0.06. The Cu/Zn ratio (0.28 - 0.89; average 0.43) suggests that the formation was deposited under relatively oxidizing conditions, which is further supported by the presence of ferric oxides. The V/(V+Ni) ratio ranging from 0.54 to 0.95 with an average of 0.80 points to highly oxidizing conditions during deposition indicating that oxygen was abundant in the environment at the time (Table 1).

Table 1. The concentrations of various oxides and element ratios in sediment samples taken at different depths.

Depth (m)	Lithology	MgO (%)	Al_2O_3 (%)	SiO_2 (%)	CaO (%)	Fe_2O_3 (%)	Sr/Cu	Rb/Sr	Rb/K	Sr/Ba	Cu/Zn	V/(V+Ni)
57	Shale	5.81	8.03	23.6	0.88	3.9	2.5	0.8	0.002	0.080	0.55	0.95
70	Shale	4.12	9.15	26.8	1.07	4.56	2.9	0.8	0.002	0.073	0.42	0.94
91	Coal	5.53	0.00	20.9	1.42	3.49	3.2	0.7	0.001	0.100	0.47	0.95
100	Shale	4.73	10.50	26.6	0.23	4.4	2.9	1.1	0.003	0.052	0.36	0.93
110	Shale	4.73	9.16	26.2	0.25	4.8	3.4	0.7	0.002	0.064	0.36	0.95
120	Shale	4.85	10.00	24.4	0.06	5.16	4.4	0.7	0.002	0.068	0.35	0.92
130	Shale	5.02	10.10	26	0.12	4.88	3.3	0.9	0.002	0.053	0.32	0.79
140	Shale	6.93	8.45	28.8	0.87	3.02	2.8	0.8	0.002	0.089	0.39	0.87
143	Shale	4.08	9.27	33.3	0.00	5.36	4.3	0.4	0.004	0.027	0.47	0.80
145	Coal	5.36	7.93	22.6	1.44	2.67	2.9	0.5	0.001	0.080	0.60	0.91

155	Shale	6.15	10.00	23.8	0.74	5.26	3.0	0.9	0.003	0.072	0.31	0.73
165	Coaly Shale	2.41	10.50	33.6	0.00	2.71	6.8	0.3	0.005	0.020	0.68	0.83
175	Shale	3.38	10.70	32.9	0.00	4.86	4.7	0.4	0.004	0.041	0.50	0.85
185	Shale	4.62	10.80	28.3	0.00	5.28	2.8	0.8	0.004	0.044	0.50	0.75
195	Coal	0.43	3.15	14.1	0.00	3.63	6.8	0.1	0.003	0.041	0.89	0.86
205	Shale	4.25	10.20	33.7	0.60	4.28	2.6	0.7	0.004	0.050	0.45	0.77
225	Shale	4.66	7.92	28.4	0.00	4.6	4.3	0.4	0.003	0.043	0.48	0.77
235	Coal	2.46	6.85	20.7	0.15	3.95	11.4	0.1	0.004	0.097	0.69	0.78
245	Shale	3.80	10.80	32	0.28	6.2	4.4	0.5	0.004	0.055	0.36	0.68
255	Shale	4.89	13.50	34.2	0.00	2.85	4.4	0.7	0.004	0.052	0.39	0.73
265	Shale	4.09	11.90	36	0.22	4.58	3.5	1.1	0.004	0.047	0.30	0.80
275	Shale	3.87	10.60	34.3	0.43	6.01	4.6	0.5	0.004	0.061	0.35	0.81
285	Shale	3.44	11.50	31	0.96	7.15	3.9	0.7	0.004	0.066	0.35	0.79
295	Shale	4.28	12.60	37.6	0.21	3.43	3.8	0.8	0.004	0.056	0.34	0.75
305	Coaly Shale	5.89	11.50	30.7	0.88	3.29	3.0	1.0	0.004	0.070	0.35	0.78
320	Shale	3.23	12.40	33.1	0.96	6.7	3.2	0.9	0.005	0.069	0.28	0.85
330	Coal	4.82	12.90	27.1	1.34	3.58	4.0	0.6	0.004	0.092	0.58	0.90
340	Shale	3.92	12.40	33.7	1.30	7.85	3.6	0.7	0.005	0.087	0.31	0.80
350	Shale	6.20	9.49	30.6	0.00	4.51	5.2	0.4	0.003	0.054	0.36	0.80
365	Shale	4.52	9.57	35.2	0.00	3.57	2.9	0.6	0.003	0.027	0.45	0.81
375	Shale	4.09	10.30	34.4	0.62	5.34	4.1	0.4	0.003	0.078	0.47	0.79
385	Shale	4.16	11.90	33	1.35	4.79	3.0	0.9	0.004	0.107	0.38	0.55
395	Shale	3.61	11.80	32.8	0.70	6.16	2.9	0.9	0.004	0.056	0.34	0.54
405	Coaly Shale	5.48	10.40	30.2	0.82	3.8	3.5	0.8	0.004	0.081	0.40	0.77
415	Shale	2.89	12.00	33.6	0.68	6.28	3.9	0.6	0.004	0.080	0.37	0.75
440	Shale	3.38	10.20	34.7	0.29	4.99	2.7	0.7	0.003	0.068	0.45	0.79
457	Shale	4.29	11.10	31.8	0.76	5.5	3.4	0.8	0.004	0.042	0.38	0.78
485	Coaly Shale	4.04	10.90	34.7	0.36	3.65	3.2	0.6	0.003	0.065	0.37	0.76
505	Shale	3.61	11.40	39.2	0.00	2.52	4.6	0.5	0.004	0.063	0.38	0.75

4.2 Total Organic Carbon (TOC) and Rock Eval Pyrolysis

Bulk geochemical parameters derived from total organic carbon (TOC) measurements and Rock-Eval pyrolysis data are summarized in Table 2. The investigated interval consists predominantly of organic-rich shales, coaly shales, and coal. Coal samples exhibit TOC values ranging from 23.58 to 43.86 wt.% (average 35.6 wt.%), whereas non-coal lithologies show TOC contents between 1.50 and 17.61 wt.% (average 5.4 wt.%). TOC values vary significantly across different lithologies and depths. Coal samples (e.g., at depths 91 m, 145 m, 195 m, 235 m, and 330 m) generally exhibit very high TOC values, often exceeding 30%. The sulfur content of the shale (0.09 – 4.13 wt.%; average 1.02 wt.%), coaly shale (1.73 – 2.74 wt.%; average 2.28 wt.%), and coal (0.29 – 3.25 wt.%; average 1.64 wt.%). The results of S1 yields (free hydrocarbon) of shale (0.18 – 37.68 mg HC/g rock), coaly shale (31.19 – 44.4 mg HC/g rock), and coal (4.5 – 53.46 mg HC/g rock). The Rock-Eval pyrolysis parameter S2 values for the shale (2.72 – 17.74 mg HC/g rock), coaly shale (17.59 – 34.85 mg HC/g rock), and coal (48.02 – 82.29 mg HC/g rock). The Tmax values show the maturity level of organic matter with relatively low T_{max} values, ranging from 301 – 427 °C with an average of 415 °C. HI values of the samples from Kampungbaru Formation (coals: 133 – 232 mg/g TOC; coaly shales: 169 – 198 mg/g TOC; shales: 91– 269 mg/g TOC). The TOC/S ratios range from approximately 1.31 to 63.5 (average 12.53) across the depths provided. The generation potential (GP) values for shale (2.9 – 49.4 mg HC/g rock), coaly shale (58.3 – 66 mg HC/g rock), and coal (32.9 – 134.7 mg HC/g rock). Coal and coaly shale have the highest GP values compared to shale. Most shale layers have moderate potential with a few layers standing out with higher GP values (Table 2).

4.3 Scanning Electron Microscope (SEM)

The SEM images of samples from the Kampungbaru Formation reveal a complex interplay between organic matter, pyrite, and mineral components such as clay, quartz, and feldspar. Organic matter is observed in close association with framboidal pyrite, indicating that sulfur reduction and pyritization were significant diagenetic processes in this formation. The presence of pyrite framboids which are typically formed in low oxygen, organic-rich environments, suggests a depositional setting where organic matter was preserved, and sulfurization occurred during early diagenesis stage (Fig 2A-B). The presence of vitrinite and sporinite, two key macerals indicative of organic matter maturity, suggesting that the Kampungbaru Formation has experienced some thermal maturation, with potential for hydrocarbon generation. Vitrinite reflects a coal like organic component, while sporinite points to plant derived material, hinting at terrestrial influences in the depositional environment (Fig 2C,F). A mixed detrital input with clay, quartz, and feldspar grains distributed throughout the matrix. This combination of organic matter and mineral grains implies that the formation experi-enced varied depositional conditions, possibly alternating between marine and terrestrial influences. The matrix's heterogeneity, especially the interplay between silicate minerals and pyrite is indicative of complex sedimentary processes (Fig 2D-E).

Table 2. Bulk Geochemical Results of Rock-Eval and Total Organic Carbon (TOC) Analyses with Calculated Parameters of the Kampungbaru Formation. S, sulfur (wt.%); TOC, total organic carbon (wt.%); S_1, volatile hydrocarbon (HC) content (mg HC/g rock); S_2, remaining HC generative potential (mg HC/g rock); T_{max}, temperature at maximum of S_2 peak; HI, hydrogen index = $S_2 \times 100$/TOC, mg HC/g TOC. GP, genetic potential (S_1+S_2).

Depth (m)	**Lithology**	**TOC**	**S**	**S_1**	**S_2**	**$T_{max.}$**	**HI**	**TOC/S**	**GP**
57	Shale	1.62	0.10	0.18	2.72	425	167	17.08	2.9
70	Shale	1.75	0.09	0.31	3.31	421	189	20.27	3.6
91	Coal	36.14	0.76	4.5	48.04	412	133	46.42	52.5
100	Shale	4.37	2.36	0.41	3.96	404	91	1.85	4.4
110	Shale	2.66	0.50	0.27	3.77	416	142	5.27	4.0
120	Shale	3.59	2.04	0.59	3.37	407	94	1.76	4.0
130	Shale	5.53	2.11	0.73	5.02	409	91	2.63	5.8
140	Shale	1.50	0.11	0.39	3.48	427	233	13.98	3.9
143	Shale	4.89	0.62	20.49	11.28	421	231	7.88	31.8
145	Coal	37.37	0.29	5.82	59.66	414	160	127.67	65.5
155	Shale	2.63	1.17	1.74	3.01	414	114	2.25	4.8
165	Coaly Shale	17.61	2.01	31.19	34.85	417	198	8.78	66.0
175	Shale	8.97	1.52	24.86	17.74	417	205	5.69	42.6
185	Shale	7.02	4.13	24.5	7.92	389	113	1.70	32.4
195	Coal	43.68	3.25	53.46	81.21	413	186	13.44	134.7
205	Shale	3.97	0.33	25.46	10.06	420	253	12.12	35.5
225	Shale	5.85	0.73	24.46	13.87	424	237	8.00	38.3
235	Coal	37.22	3.06	52.02	82.29	416	221	12.16	134.3
245	Shale	4.04	0.61	22.54	10.07	426	249	6.60	32.6
255	Shale	6.47	0.58	23.88	15.36	423	245	10.81	39.2
265	Shale	3.04	2.32	19.78	7.08	301	233	1.31	26.9
275	Shale	3.79	0.92	26.1	9.67	426	255	4.13	35.8
285	Shale	3.63	0.89	23.16	9.75	426	269	4.06	32.9
295	Shale	4.30	0.19	22.43	9.98	424	244	21.37	32.4
305	Coaly Shale	12.27	1.73	39.25	22.57	417	184	7.08	61.8
320	Shale	3.89	0.52	26.61	9.72	422	250	7.55	36.3
330	Coal	23.58	0.82	47.17	54.62	425	232	28.83	101.8
340	Shale	3.48	0.46	18.66	8.53	422	245	7.61	27.2
350	Shale	3.72	0.84	20.76	9.58	423	257	4.46	30.3
365	Shale	4.21	1.11	27.97	9.37	425	212	4.00	37.3
375	Shale	3.80	0.61	29.64	8.54	424	225	6.20	38.2
385	Shale	5.04	0.80	36.39	11.21	421	240	5.87	47.6
395	Shale	4.90	0.57	34.09	10.98	419	224	8.67	45.1
405	Coaly Shale	10.05	2.65	40.7	17.59	409	175	3.79	58.3
415	Shale	5.85	1.36	35.1	11.81	421	202	4.30	46.9
417	Shale	4.92	0.22	32.14	11.61	426	236	22.57	43.8
440	Shale	5.91	0.27	37.68	11.67	422	197	21.62	49.4
457	Coaly Shale	11.49	2.74	44.4	19.09	407	169	4.12	63.5
485	Shale	5.59	2.76	30.08	12.5	420	224	2.02	42.6
505	Shale	4.39	0.82	22.99	11.56	424	263	5.32	34.6

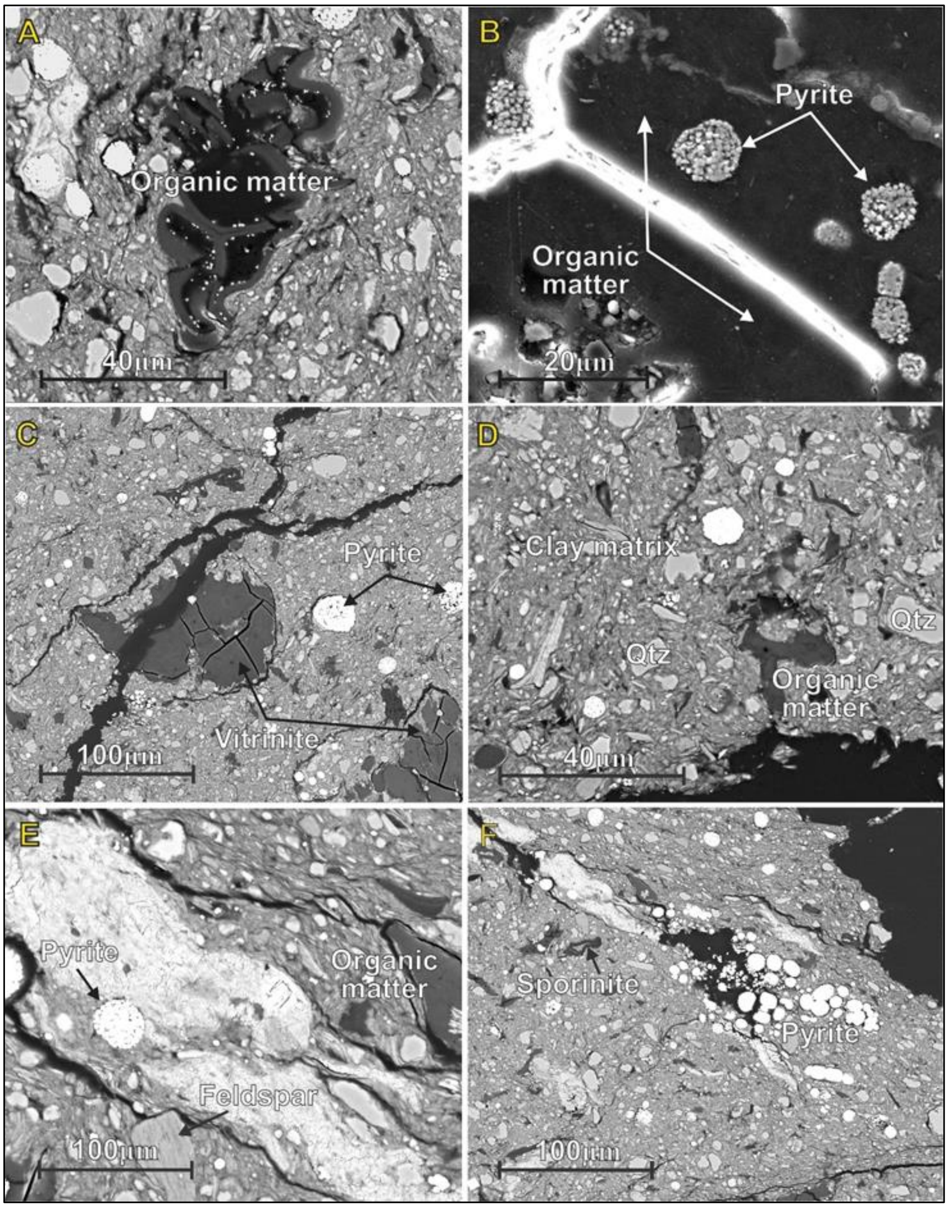

Fig 2. SEM images illustrating the microstructural and mineralogical characteristics of samples taken from 155 m; (A) Organic matter showing irregular shapes embedded within the sediment matrix; (B) Organic matter associated with framboidal pyrite indicative of sulfur reduction during diagenesis; (C) Vitrinite along with pyrite in a fractured matrix, indicating thermal maturation of organic material; (D) Organic matter dispersed within a clay matrix with quartz (Qtz) grains present; (E) Pyrite and feldspar co-occurring with organic matter, highlighting the heterogeneous composition of the formation; (F) Sporinite associated with pyrite suggesting terrestrial plant origins.

5. Discussion

5.1. Clastic Influx Proxies

The The crossplot ($Fe_2O_3 + Al_2O_3$)/(CaO + MgO) ratios and TOC can be directly connected to clastic influx proxies, which are indicators used to assess the input of terrigenous (land-derived) sediments into a depositional environment (Ding et al., 2015). Clastic influx proxies often include elements such as aluminum (Al), silicon (Si), titanium (Ti), and the ratio of iron oxides to calcium and magnesium oxides, as these elements are primarily associated with detrital minerals like clays, quartz, and heavy minerals commonly derived from the weathering of continental rocks (Canfield, 1994; Ding et al., 2015; Winantris et al., 2017). The crossplot ($Fe_2O_3 + Al_2O_3$)/(CaO + MgO) ratios and TOC (Fig 3A) suggest that organic matter in the Kampungbaru Formation derived from a terrestrial source and this is confirmed by vitrinites dominated (Fig 2). The organic matter of Kampungbaru Formation transported in suspension by tropical rivers are mostly highly degraded. Shale samples exhibit low TOC values (< 10 wt.%), indicating a predominantly terrigenous origin with little organic matter. In contrast, coal samples show significantly higher TOC values (up to 50 wt.%), reflecting environments conducive to high organic accumulation, such as swamps or peat forming settings. The high TOC values in coal samples in the Kampungbaru Formation reflect environments where biochemical processes and organic matter accumulation dominate. Coaly shale occupies an intermediate position representing mixed depositional conditions. The observed trend, where shale samples cluster at lower TOC values with higher ratios, supports the interpretation of clastic-dominated sediment input in these samples. Durand and Oudin’s (Durand and Oudin, 1979) study concluded that terrestrial organic matter primarily derived from land plants and transported into the Mahakam Delta by rivers, served as the primary source rock material responsible for hydrocarbon formation in the region. The terrestrially derived organic matter deposited in a tropical fluvio-tidally influenced delta primarily originates from materials like bark, wood, and leaves. Analysis of fine-grained noncoal and coal samples from the study area suggests that the organic matter has a terrestrial source (Permana et al., 2018; Afifah and Setiawan, 2019; Jamaluddin et al., 2023). The accumulation of this organic material in the Kampungbaru Formation is interpreted to be mainly linked to a lower delta plain environment, which would have been covered by Nypa palms and mangrove swamps (Winantris et al., 2017; Jamaluddin et al., 2024a-b).

In sedimentary geochemistry, titanium (Ti), silicon (Si), and aluminum (Al) are widely recognized as proxies for terrigenous clastic input (Murphy et al., 2000). Ti is typically associated with clay and heavy minerals, Si occurs mainly in quartz, feldspar, and biogenic silica, while Al commonly bound in aluminosilicate minerals such as clays and feldspars serves as a stable reference for aluminosilicate content during transport and deposition (Kidder et al., 2001; Winantris et al., 2017). Geochemical analysis of Kampungbaru Formation samples shows a moderate positive correlation between Ti and Al ($R^2 = 0.28$) and a stronger correlation between Si and Al ($R^2 = 0.55$), suggesting a relatively uniform and consistent detrital supply from stable source areas (Fig 3B–C).

Organic matter within the Kampungbaru Formation is predominantly derived from higher plants, including angiosperms and immature coals. Delta plain environments facilitated the preservation and accumulation of this organic material, with vegetal debris such as wood and leaves deposited in situ and buried rapidly, forming thick coaly shale layers and coal beds.

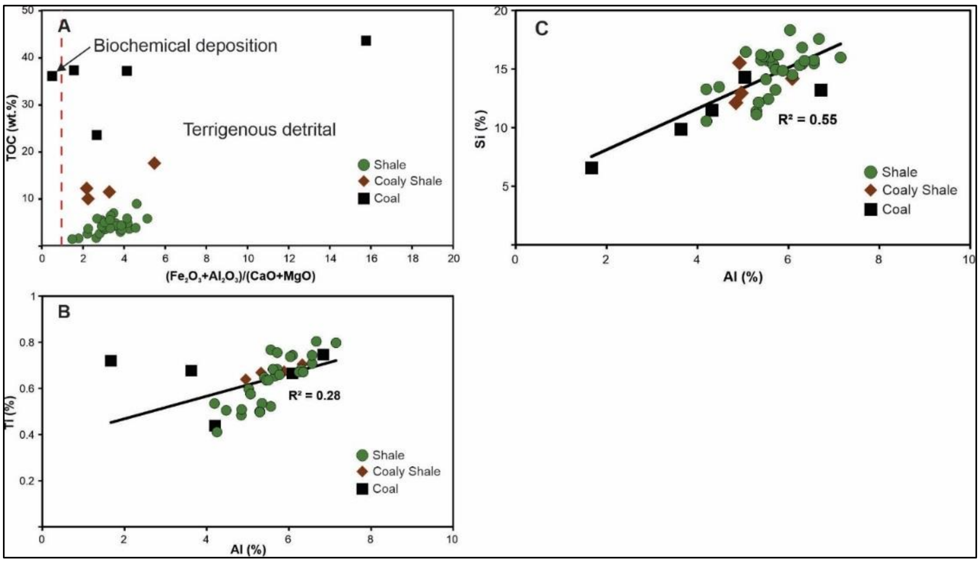

Fig 3. Geochemical relationships reflecting clastic influx and depositional environments in shale, coaly shale, and coal samples. (A) Total Organic Carbon (TOC, wt.%) vs. $(Fe_2O_3 + Al_2O_3)/(CaO + MgO)$ ratio; (B) Correlation between titanium (Ti) and aluminum (Al) concentrations in samples from the Kampungbaru Formation, showing a moderate positive correlation ($R^2 = 0.28$); (C) Stronger correlation between silicon (Si) and aluminum (Al) concentrations in samples from the Kampungbaru Formation ($R^2 = 0.55$), suggesting a more consistent detrital supply.

5.2. Paleoclimate Proxies

The Köppen-Geiger climate classification system identifies the dominant climate type in Kalimantan as the tropical rainforest climate (Af). This climate type is characterized by high temperatures throughout the year and abundant rainfall, with no distinct dry season (Peel et al., 2007). The Sr/Cu and Rb/Sr ratios provide insights into the paleoclimate, with fluctuations between values indicating alternating arid and humid conditions, reflecting cyclic climatic variations during deposition (Roy et al., 2013; Sarki Yandoka et al., 2015). The Sr/Cu ratio in sedimentary records can be used as an indicator for paleoclimate conditions (Lerman, 1978; Yin et al., 2017). Sr/Cu ratio between 1.3 and 5.0 suggests a humid climate, while Sr/Cu ratio higher than 5.0 suggests an arid climate (Sarki Yandoka et al., 2015: Yin et al., 2017; Xu et al., 2017). The Sr/Cu ratio in the Kampungbaru Formation ranges from 2.52 to 11.44 with an average value of 4.14 suggests alternating arid and humid conditions, which may reflect cyclic climatic variations during the formation's deposition.

The Rb/Sr ratio serves as a reliable paleoclimate indicator owing to its sensitivity to chemical weathering intensity. Values below 0.5 generally reflect arid climatic conditions, whereas ratios exceeding 0.5 are characteristic of more humid environments (Afifah and Setiawan, 2019; Zou et al., 2021). The sample of the Kampungbaru Formation have Rb/Sr ratios that range from 0.12 to 1.09 (avg. 0.65) are associated with more intense chemical weathering and thus more humid conditions (Fig 4).

Combining the insights from both Sr/Cu and Rb/Sr ratios it can be concluded that the Kampungbaru Formation experienced a dynamic climate during the Upper Miocene. This climate was characterized by an overall moderate humidity with notable fluctuations that included both arid and humid phases. Such climatic variability would have influenced sedimentation patterns and the preservation of organic matter within the formation, reflecting a complex interplay of regional and possibly global climatic forces. The paleoclimate during the deposition of the Kampungbaru Formation can also be further inferred from the types of sediments and preserved organic matter. Samples from the Kampungbaru Formation are characterized by a dominant vitrinite maceral group. These findings suggest that the region was covered by abundant vegetation during the Upper Miocene–Pliocene period. Vitrinite is derived from the degradation of woody plant material, while sporinite originates from the remains of spores and cuticles of plants. These macerals are often associated with terrestrial plants that grew in humid climates. The association of these macerals suggests that the Kampungbaru Formation likely received significant terrestrial input, pointing to a climate that was humid and supported vegetation during deposition. This humid climate would favor the growth of vegetation, which was subsequently transported to the depositional basin. Additionally, the association of organic matter with clay minerals indicates a likely fluvial input, suggesting that the climate was humid enough to sustain rivers that transported sedi-ment and organic matter to the basin (Fig 2A-C).

The TOC decreases as the Rb/Sr ratio increases (Fig 5A), suggesting that organic-rich sediments were more prevalent during periods of increased chemical weathering, which is consistent with a more humid climate. Conversely, higher Rb/Sr ratios (indicating less weathering) are associated with arid climates, which correspond to lower TOC values. The trend suggests that organic matter accumulation was favored under more humid conditions, while arid conditions reduced organic carbon preservation. Sr/Cu ratio is a proxy for distinguishing between humid and arid climates, with lower Sr/Cu values indicative of humid conditions and higher values of arid climates. Copper is typically concentrated in organic-rich soils and marine environments, whereas strontium is more abundant in evaporitic settings or during periods of reduced rainfall.

5.3. Paleosalinity Proxies

The mineral assemblage and the association of organic matter with pyrite and clays hint at fluctuating salinity conditions. The presence of quartz and feldspar (Fig 2D-E) are common in terrestrial environments, combined with the marine indicators (pyrite and organic matter), suggesting that the Kampungbaru Formation likely experienced shifts between more saline (marine) and less saline (fluvial or brackish) conditions. The paleosalinity conditions of the Kampungbaru Formation during the Upper Miocene can be inferred from the analysis of the Rb/K and Sr/Ba ratios . Low Sr/Ba Ratios (<1) indicate terrestrial or freshwater environments. Intermediate Sr/Ba Ratios (0.5-1.0) suggest a transitional or brackish environment. High Sr/Ba ratios (>1) are common in open ocean or marine-influenced settings, indicating high salinity and a strong marine influence (Wei and Algeo, 2020). The moderate Sr/Ba ratio (0.02 - 0.11; average 0.06) and low Rb/K ratio (0.001 - 0.005; average 0.004) of the Kampungbaru Formation suggests that the formation was primarily deposited in a freshwater environment. The low ratio indicates that the water in which the sediments were deposited had low salinity, typical of freshwater conditions (Fig 4).

The low Sr/Ba ratios observed in most samples from the Kampungbaru Formation suggest a depositional environment predominantly influenced by freshwater conditions. The higher Total Organic Carbon (TOC) values observed in the coal samples indicate significant organic matter accumulation in these sediments. Higher TOC values often reflect conditions conducive to the preservation and accumulation of plant material, such as in swampy, anoxic environments where decay rates are reduced. These high TOC values in the coal layers suggest that organic matter accumulation was enhanced in these freshwater conditions, where low salinity and stagnant water would have sup-ported dense vegetation and the formation of peat. Over time, this peat could transform into coal, as seen in the Kampungbaru Formation (Fig 5).

5.4. Paleoredox Proxies

Paleoredox conditions in the Kampungbaru Formation during the Upper Miocene were assessed using Cu/Zn and V/(V+Ni) ratios, which are established geochemical proxies for depositional redox state and its impact on organic matter preservation (Jones and Manning, 1994; Rimmer, 2004). Elevated Cu/Zn ratios indicate reducing conditions, whereas lower values reflect more oxic environments. Similarly, higher V/(V+Ni) ratios (> 0.5) are indicative of anoxic to suboxic settings, while lower ratios (V/(V + Ni) < 0.5) suggest oxic conditions (Zuo et al., 2020).

The Cu/Zn ratios (0.28 - 0.89; average 0.43) and V/(V+Ni) ratio (0.54 - 0.95; average of 0.79) of the Kampungbaru Formation indicate a depositional environment characterized by predominantly reducing conditions with significant periods of anoxia. These conditions were highly favorable for the preservation of organic matter, contributing to its enrichment in the formation (Fig 4). The presence of pyrite is a strong indicator of anoxic to suboxic conditions during diagenesis. Pyrite typically forms in environments where sulfate-reducing bacteria thrive, reducing sulfate to sulfide, which then reacts with iron to form pyrite. The framboidal pyrite observed in particularly diagnostic of anoxic bottom water conditions, as it forms in reducing environments with limited oxygen availability. The association of pyrite with organic matter suggests that sulfu-rization occurred as organic matter was decomposed, indicating reducing conditions persisted long enough for diagenetic processes to affect both organic and inorganic materials. Therefore, the depositional environment likely fluctuated between oxic and anoxic states, supporting the notion of a reducing environment conducive to pyrite formation (Fig 2B). The majority of samples with high TOC are from anoxic environments, where or-ganic matter is better preserved due to the lack of oxygen and slower rates of decom-position. In contrast, the samples from oxic conditions have much lower TOC, as organic matter is more likely to degrade in oxygenated environments (Fig 5).

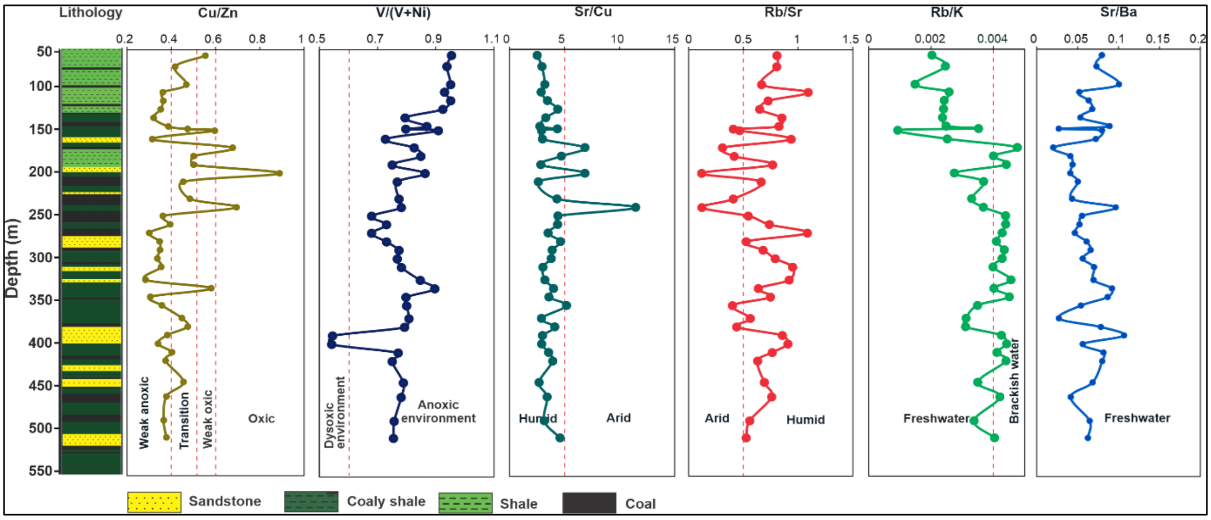

Fig 4. Lithological and geochemical profile of the Kampungbaru Formation, illustrating variations in lithology, redox conditions, paleoclimate, and salinity with depth from the samples analysed through this study

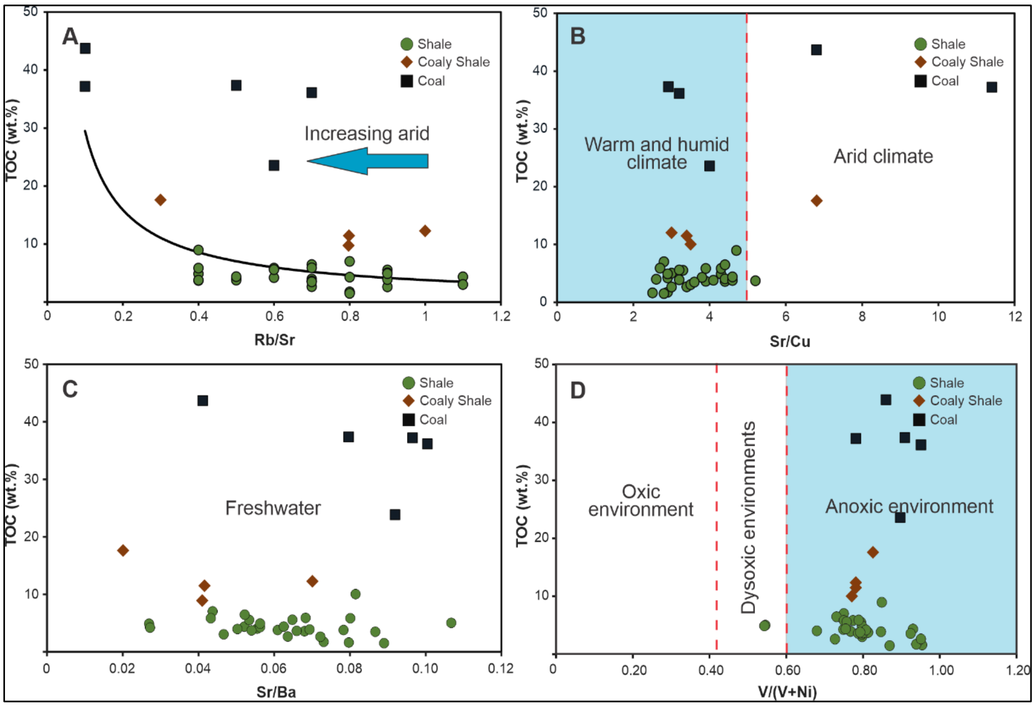

Fig 5. Geochemical proxies used to interpret the paleoclimate, paleosalinity, and paleoredox conditions of shale, coaly shale, and coal samples from the Kampungbaru Formation in relation to Total Organic Carbon (TOC, wt.%). (A) Rb/Sr vs. TOC; (B) Sr/Cu vs. TOC; (C) Sr/Ba vs. TOC; (D) V/(V+Ni) vs. TOC.

5.5. Source rock characteristics

The total organic carbon (TOC) content of the source rocks is used as a measure for the amount of organic matter that is readily available. Peters and Cassa (Peters, 1986), who rated TOC contents of 0 – 0.5 wt.% as poor, 0.5 – 1 wt.% as fair, 1 – 2 wt.% as good, 2 – 4 wt.% as very good, and more than 4 wt.% as excellent for immature rocks, are often cited. Based on the classification proposed by Peters and Cassa (1994), the total organic carbon (TOC) content of the Kampungbaru Formation sediments can be categorized into three classes: (1) good source rock potential, with TOC values ranging from 1.50 to 1.75 wt.%; (2) very good source rock potential, with TOC values between 2.63 and 3.97 wt.%; and (3) excellent source rock potential, with TOC values from 4.04 to 43.68 wt.%. Overall, TOC data indicate that the Kampungbaru Formation possesses organic richness ranging from good to excellent (1.50 – 43.68 wt.% TOC). These elevated TOC values reflect favorable depositional and preservation conditions for organic matter accumulation.

Following the recommendations of Peters (1986), Espitalié et al. (1985) and Setyawan et al., (2020), rocks with S_2 values exceeding 5 mg HC/g rock are considered to have good hydrocarbon generation potential, while values greater than 10 mg HC/g rock indicate very good potential. In the Kampungbaru Formation, S_2 values range from 2.72 to 82.29 mg HC/g rock, with an average of 15.54 mg HC/g rock, signifying fair to excellent source rock potential. Coal samples display the highest hydrocarbon generation capacity, attributable to their elevated TOC and S_2 values, placing them predominantly in oil-prone (Type I) and mixed oil-and-gas-prone (Type II) kerogen categories. Coaly shale samples also show significant petroleum potential, mainly within the oil-and-gas-prone (Type II) range. Shale samples, in contrast, are largely gas-prone (Type III), with comparatively lower TOC and S_2 values (Fig 6 and Fig 7).

Hydrogen Index (HI) versus T_{max} plots (Fig 7A) reveal that the organic matter in the Kampungbaru Formation consists mainly of mixed Type II/III kerogen, with Tmax values ranging from 301°C to 427°C. This indicates that most shale samples are thermally immature to marginally mature, and primarily gas-prone in their hydrocarbon potential, as supported by HI values of 91–269 mg HC/g TOC. In contrast, coal and coaly shale samples generally fall within the oil and gas generation window (T_{max}: 420–440°C), suggesting a mature thermal stage with the capacity to produce both oil and gas. Notably, several coal and coaly shale samples plot near the effective HI line, implying a high hydrocarbon generation potential relative to their current maturity level (Fig 7B).

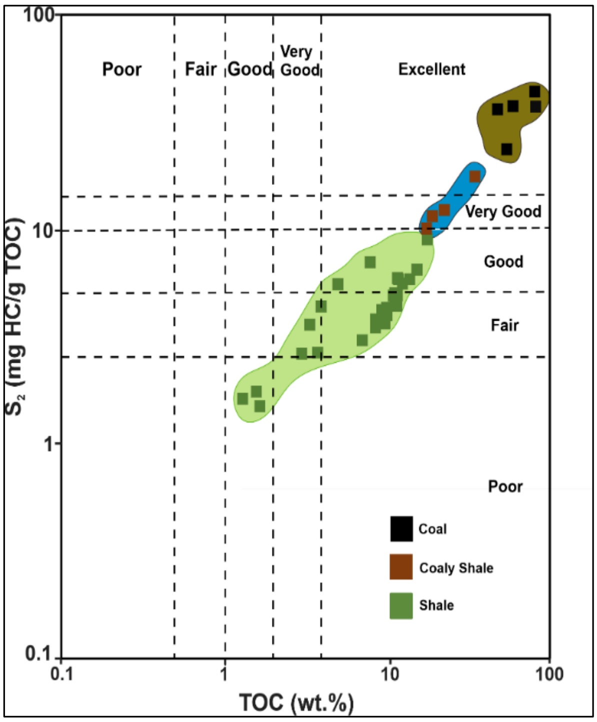

Fig 6. Pyrolysis S_2 and total organic carbon (TOC) cross plot of the Kampungbaru Formation indicates their hydrocarbon.

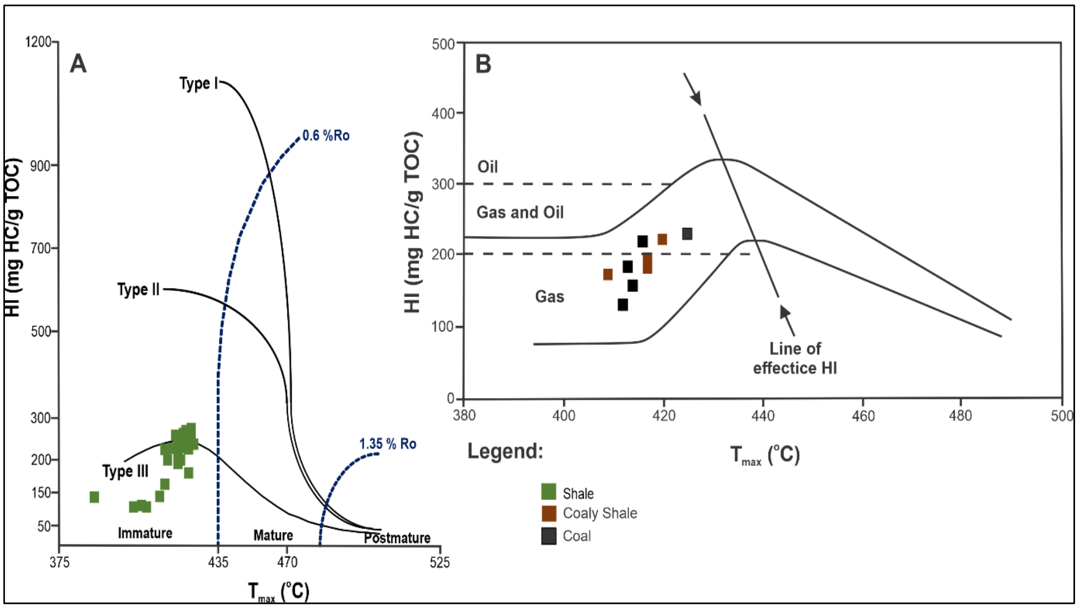

Fig 7. (A) Plots Hydrogen Index (HI) vs. T_{max} classifies organic matter into kerogen types and maturity stages. Shale samples classifiesd into type III kerogen with low HI values and T_{max} around 435°C, indicating that they are primarily gas-prone and range from immature to early mature; (B) Plot HI vs. T_{max} (Sykes and Snowdon, 2002) for coal and coaly shale showing the the samples primarily fall within the gas and oil generation window (T_{max} between 420°C and 440°C) suggesting they are mature with substantial potential to produce both oil and gas.

Sedimentary organic matter is transformed to hydrocarbons as a result of heat flow within the basin, and here time and temperature play a major factor in the generation of hydrocarbons. Geochemical analyses of organic-rich sediments from the Kampungbaru Formation indicate that the possible source rocks are delta plain-delta front coals and shales containing predominately type III kerogen organic matter, with early peak maturation, and are regarded as having good to excellent potential as gas source rocks.

5.6. The influences of sedimentary environments on organic matter enrichment

The sedimentary environments of the Upper Miocene–Pliocene Kampungbaru Formation significantly influenced organic matter enrichment. Kampungbaru Formation consisting of shale, coaly shale, and coal, was deposited in freshwater to brackish settings typical of swampy and deltaic systems. These depositional environments, characterized by transitions between weakly anoxic to oxic conditions, were conducive to organic matter accumulation and preservation, as oxygen limited environments reduced microbial decay. Climate fluctuations between humid and arid periods further affected organic matter preservation, with humid conditions enhancing vegetation productivity and reducing oxidation, leading to higher Total Organic Carbon (TOC) values. The organic matter in the Kampungbaru Formation primarily consists of gas-prone Type III kerogen and mixed oil and gas-prone Type II-III kerogen, reflecting a dominance of terrestrial inputs, such as vegetation from swamps and delta plains, with minor aquatic contributions (Fig 8).

Deltaic depositional environments play a pivotal role in the enrichment and preservation of organic matter, particularly under warm and humid paleoclimatic conditions conducive to high biological productivity. This study delineates a characteristic deltaic system comprising several well-defined subenvironments: upper delta plain, lower delta plain, distributary channels, mouth bars, delta front, and prodelta. Each zone exhibits distinct sedimentological, hydrodynamic, and redox-related traits that strongly influence organic matter accumulation. In the upper delta plain, abundant terrestrial plant detritus fosters the formation of organic-rich peat and swamp deposits, particularly under persistently reducing (suboxic to anoxic) conditions. Conversely, distributary channels and lower delta plains act as conduits for both clastic sediments and organic debris, facilitating their redistribution within the deltaic network. Transition zones such as mouth bars and delta-front settings mark dynamic interactions between fluvial and marine processes, leading to a complex interplay of sediment grain sizes, nutrient availability, and oxygen levels. Prodelta regions, by contrast, are characterized by low-energy depositional conditions where fine-grained sediments accumulate; in such environments, reduced bottom-water oxygen saturation frequently supports enhanced organic preservation. Collectively, factors such as terrestrial organic influx, marine productivity, sediment accumulation rates, and redox dynamics underpin the stratigraphic distribution of organic enrichment, with low-oxygen or high-productivity subenvironments emerging as critical loci for enhanced preservation. Specifically, the upper delta plain, rich in terrestrial vegetation like Nypa Palms, is a key area where organic matter, such as plant debris, accumulates, often leading to coal formation under anoxic conditions that limit microbial decay. Moving further toward the lower delta plain, where mangrove swamps thrive, the depositional environment becomes even more favorable for organic matter preservation, as these mangrove ecosystems trap fine sediments and produce large amounts of organic material in anoxic, waterlogged conditions. In contrast, environments like the distributary channels and mouth bars, which are more exposed to high energy and mixing with marine waters, experience greater reworking of sediments and are less effective in preserving the organic matter due to higher oxygenation and less favorable conditions for preservation.

The delta front and prodelta regions, located closer to the marine influence, provide environments where fine sediments and organic material can settle in low-energy settings, such as deeper water zones, allowing for better preservation due to anoxic conditions that prevent the decomposition of organic matter. These different sedi-mentary environments, influenced by the dynamic interplay between climate, vegetation productivity, and water chemistry, lead to varying degrees of organic matter enrichment across the deltaic system. Ultimately, it affects the types of kerogen found in the sediments, such as gas prone type III and mixed oil and gas-prone type II-III kerogen.

The depositional setting of the Kampungbaru Formation appears to have been influenced by broader regional tectonic and paleoceanographic changes during the Late Miocene–Pliocene. During this period, the progressive closure of the Indonesian Seaway significantly restricted the marine water exchange between the Indian and Pacific Oceans. This tectonic event altered oceanic circulation patterns and reduced the extent of marine transgressions into the eastern Sundaland margin, including the Lower Kutai Basin. As a result, depositional environments in this region evolved toward more continental and marginal-marine settings dominated by freshwater input. The geochemical characteristics of the Kampungbaru Formation, including low S/TOC ratios, predominance of type III and mixed type II–III kerogen, and the presence of coaly shale and coal facies, collectively indicate limited marine influence and enhanced terrestrial organic matter contribution. These observations are consistent with a depositional system governed by deltaic to swampy environments, where fluctuating water salinity and redox conditions facilitated both the accumulation and partial preservation of organic matter. Thus, the reduced marine connectivity following the seaway restriction likely played an indirect but significant role in promoting freshwater-dominated sedimentation and organic matter enrichment within the Kampungbaru Formation.

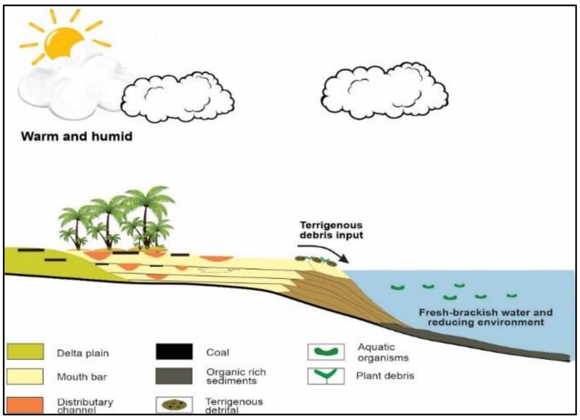

Fig 8. Depositional model illustrating sedimentary organic matter enrichment in the Kampungbaru Formation.

6. Conclusions

The combined interpretation of paleoclimate, paleosalinity, and paleoredox conditions indicates that the Kampungbaru Formation experienced a dynamic climate with fluctuating arid and humid periods. The geochemical proxies from the Kampungbaru Formation suggest a depositional environment that fluctuated between humid and arid climates, with organic-rich layers forming during humid periods. The depositional setting was primarily influenced by freshwater conditions, likely within swamp or coastal plain environments, where anoxic conditions in organic-rich intervals promoted exceptional preservation of organic matter. These conditions account for the elevated total organic carbon (TOC) values (1.50–43.68 wt.%), indicating good to excellent organic matter enrichment. Organic geochemical data show the presence of type III (gas-prone) and type II–III (mixed oil- and gas-prone) kerogen with hydrogen index values of 91–269 mg HC/g TOC. These depositional and geochemical characteristics the Kampungbaru Formation's significance as an excellent petroleum source rock in the Lower Kutai Basin, Indonesia.

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