

Article

Process-Based Geochemical Constraints on Organic Matter Enrichment and Shale Oil Potential in the Upper Jiufotang Formation, Ludong Sag, NE China

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Abstract

Accurately identifying organic-rich shale intervals remains a major challenge in lacustrine shale oil exploration, particularly in continental rift basins characterized by rapid environmental change and pronounced vertical heterogeneity. This study investigates the upper Jiufotang Formation in the Ludong Sag, Kailu Basin, NE China, using total organic carbon (TOC), vitrinite reflectance, multi-stage programmed rock pyrolysis, and major and trace element geochemistry to constrain the processes governing organic matter enrichment and hydrocarbon occurrence. The studied shales contain abundant organic matter, with TOC values ranging from 1.91% to 7.55% and averaging 4.22%. Type II₂ kerogen and vitrinite reflectance values of 0.60–0.94% indicate oil-prone organic matter at low-mature to mature stages within the oil generation window. Multi-stage pyrolysis shows that the hydrocarbon assemblage is dominated by bound oil and residual kerogen-derived fractions, whereas the low-temperature movable oil fraction is limited. TOC is more strongly associated with the high-temperature pyrolysis fractions than with the light free-oil fraction, indicating that organic matter abundance primarily controls residual hydrocarbon generation potential but does not directly determine present-day movable oil content. Multiple elemental proxies are collectively consistent with deposition in a hydrologically restricted, variably brackish–saline lacustrine system with water-mass differentiation. Redox-sensitive indicators, including V/(V + Ni) and Mo, suggest persistent weakly reducing to reducing bottom-water conditions. After correction for carbonate- and phosphate-associated Ca, CIA values fall within a narrow range of approximately 67–70, indicating moderate and relatively stable source area chemical weathering. Organic matter enrichment was governed by the coupled effects of organic matter supply, preservation under stratified oxygen-deficient waters, and sedimentary dilution. We therefore propose a two-stage process framework in which depositional productivity–preservation coupling first promoted organic matter accumulation, whereas subsequent thermal maturation, hydrocarbon expulsion, retention, and adsorption reshaped the present hydrocarbon occurrence state. The results demonstrate that high organic matter abundance and residual generation potential do not necessarily translate into high movable oil content and provide a well-scale geochemical basis for source rock evaluation and future multi-well assessment in continental rift lake systems.



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Keywords: lacustrine shale oil; organic matter enrichment; restricted rift lake; brackish-saline lake; elemental geochemistry

1. Introduction

The global energy landscape has undergone a profound paradigm shift over the past two decades, characterized by the transition from conventional to unconventional hydrocarbon resources [1–4]. Shale oil, as a crucial component of unconventional resources, has become a major driver of global reserve and production growth [5–7]. While the commercial success of marine shale oil in North America (e.g., the Bakken and Eagle Ford shales) has revolutionized the industry, the exploration focus in China has been strategically directed toward continental lacustrine shale oil, given the nation's unique geological framework [8,9]. Extensive exploration breakthroughs in major Chinese basins, such as the Songliao, Ordos, Junggar, and Bohai Bay basins, have confirmed the massive resource potential of continental shale oil [10–12]. However, compared to relatively stable marine environments, continental lacustrine basins are intrinsically characterized by rapid facies variations, multiple sediment provenances, and strong sensitivity to paleoclimatic and tectonic perturbations [13,14]. Consequently, continental shale oil systems exhibit extreme vertical and lateral heterogeneity, making the prediction of organic-rich sweet spots a primary scientific challenge. The enrichment of organic matter (OM) in lacustrine source rocks is a complex process controlled by the dynamic coupling of primary productivity, preservation conditions, and clastic dilution. Reconstructing the depositional paleoenvironment, including paleoclimate, paleosalinity, and bottom-water redox conditions, is essential for decoding the mechanisms of OM accumulation [15–19]. Previous studies have proposed various accumulation models, debating whether OM enrichment in specific basins is predominantly productivity-driven or preservation-driven. Furthermore, active continental rift basins are frequently accompanied by episodic geological events, such as volcanic ash falls and hydrothermal activities [20–22]. These abrupt events can drastically alter the water chemistry, input terrestrial nutrients, and induce water column stratification, thereby exerting a profound impact on the organic carbon cycle. In addition, volcanic and hydrothermal inputs not only alter the composition of lake water but also introduce a significant amount of heat. When hydrothermal fluids or volcanic material enter the relatively cool lake water, they can create a localized thermal shock effect on the surrounding rocks or sediments. This rapid temperature change generates thermal stress, which in turn alters their physical and mechanical properties and pore structure [23]. Deciphering the geochemical fingerprints of these events and their exact role in shale oil formation remains a frontier in unconventional petroleum geology.

The Kailu Basin, an important Mesozoic fault-depressed rift basin in Northeast China, has shown promising exploration prospects [24,25]. Within the Ludong Sag of the Kailu Basin, the Lower Cretaceous Jiufotang Formation is widely recognized as a regional prolific source rock. Deposited during the peak period of the Jehol Biota, the Jiufotang Formation records significant paleoclimatic fluctuations. Despite its well-confirmed hydrocarbon potential, the high-frequency paleoenvironmental evolution of the upper Jiufotang Formation and its internal control over OM enrichment remain enigmatic. Specifically, the relationship between extreme geological events and the development of exceptional quality source rocks is poorly constrained. This knowledge gap severely hinders the accurate evaluation of shale oil potential and the optimization of future drilling targets in the sag. To fill this knowledge gap, this study systematically investigates the upper Jiufotang Formation in the Ludong Sag using high-resolution geochemical data derived from a newly drilled

well. By integrating TOC contents, thermal maturity (R_o), and a comprehensive suite of major and trace element ratios, this study aims to quantitatively reconstruct the temporal evolution of the depositional paleoenvironment and identify geochemical anomalies linked to episodic geological events, thereby establishing a comprehensive organic enrichment model governed by the interplay of paleoproductivity, preservation conditions, and clastic dilution. Ultimately, these integrated approaches are utilized to evaluate the shale oil potential of the studied interval, providing crucial insights into the formation mechanisms of continental shale oil in rift basins and offering practical guidance for unconventional exploration in Northeast China.

2. Geological Setting

The Kailu Basin is a typical Mesozoic continental rift basin located in the eastern part of Inner Mongolia, NE China, structurally situated at the southwestern margin of the Songliao Basin [26–29]. Its formation and evolution were profoundly controlled by the regional extensional tectonic regime triggered by the subduction of the Paleo-Pacific Plate beneath the Eurasian Plate during the Late Jurassic to Early Cretaceous [30–32]. Consequently, the basin is composed of a series of NE- and NNE-trending grabens and half-grabens developed on a pre-Mesozoic metamorphic basement. Driven by intense regional faulting and crustal thinning, the Kailu Basin experienced episodic rifting and subsidence, providing a favorable paleogeomorphological framework and substantial accommodation space for continuous lacustrine deposition. The study area is situated within this dynamic extensional background, making it an ideal natural laboratory for investigating the coupling mechanisms between tectonic-environmental evolution and organic matter accumulation.

The Ludong Sag, located in the easternmost part of the Kailu Basin [24,25,33], is one of the most hydrocarbon-prolific secondary structural units within the region (Figure 1a). Tectonically, it exhibits a characteristic half-graben structural style—typically “faulted on one side and overlapping on the other” (faulted in the east and overlapping in the west)—constrained by regional major boundary faults. Based on its internal structural differentiation, the Ludong Sag can be further subdivided into several distinct micro-structural belts, including the steep slope zone, the central depression zone, and the gentle slope zone. The sedimentary fill of the sag is dominated by a thick sequence of Lower Cretaceous terrestrial clastic rocks, representing a complete syn-rift to post-rift depositional cycle. The central depression zone, where subsidence was most rapid, served as the primary depocenter, accumulating massive amounts of fine-grained sediments and serving as the focal area for hydrocarbon generation. The Lower Cretaceous strata in the Ludong Sag mainly comprise the Yixian, Jiufotang, and Fuxin formations from bottom to top. The Jiufotang Formation was deposited during the peak rifting and maximum lake expansion phase of the basin. It is stratigraphically subdivided into the lower and upper members. The upper Jiufotang Formation was predominantly developed under a deep to semi-deep lake depositional environment, characterized by an exceptionally thick sequence of dark-gray to black shales and massive mudstones (Figure 1b). This fine-grained sequence is frequently intercalated with thin siltstones, fine sandstones, and localized tuffaceous layers, which are direct sedimentary responses to Milankovitch climate cycles. These organic-rich dark shales of the upper Jiufotang Formation represent the most critical regional source rocks and serve as the primary specific object of this study. Their continuous deposition provides a high-resolution geological archive for deciphering paleoenvironmental fluctuations and evaluating shale oil potential.

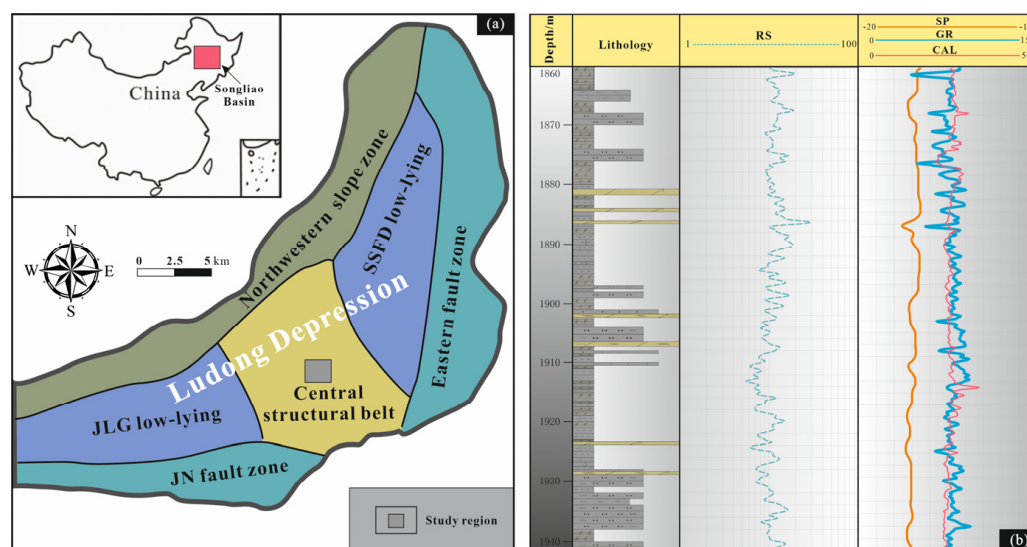


Figure 1. Geological map of Kailu Basin. (a) Star indicates location of study area; (b) the upper Jiufotang Formation lithological columnar section.

3. Materials and Methods

3.1. Sample Collection

A total of 36 fresh core samples of dark-gray to black shales were systematically collected from the upper Jiufotang Formation in the studied well within the Ludong Sag. The sampling depths ranged from 1880.4 m to 1932.0 m, covering the major organic-rich intervals. To prevent any influence from drilling fluid contamination or surface weathering, the outer rinds of the core samples were carefully removed. The fresh inner portions were then washed with distilled water, dried at low temperatures, and divided into several aliquots. Subsequently, the aliquots were crushed and pulverized to different particle sizes to meet the specific requirements of the following geochemical and petrological analyses.

3.2. TOC, Ro and Multi-Stage Programmed Rock Pyrolysis Analyses

The Total Organic Carbon (TOC) content and Rock-Eval pyrolysis analyses were conducted to evaluate the organic matter abundance and kerogen type [34,35]. For TOC determination, approximately 100 mg of powdered samples (200 mesh) were repeatedly treated with dilute hydrochloric acid (10% HCl) at 60 °C to completely remove inorganic carbonates. After washing with distilled water to a neutral pH and drying, the residues were analyzed using a LECO CS-230 carbon-sulfur analyzer (LECO Corporation, St. Joseph, MI, USA). The vitrinite reflectance (Ro) measurements were carried out to determine the thermal maturity of the source rocks. The rock blocks were crushed to 1–2 mm, embedded in epoxy resin, and ground to produce highly polished sections. The measurements were performed using a Zeiss Axio Imager Z1 polarizing microscope (Carl Zeiss MicroImaging GmbH, Jena, Germany) equipped with a microphotometer under oil immersion objectives, following the standard procedure. For each sample, at least 20 to 30 valid measuring points on the vitrinite macerals were recorded to calculate the average Ro value. Representative shale sections from depths of 1880.4, 1887.9, and 1913.5 m were examined under transmitted-light and fluorescence illumination using a 10× objective. Paired photomicrographs were used to characterize the microscopic textures of the shale and the spatial distribution of fluorescent hydrocarbon-bearing components. Multi-stage programmed rock pyrolysis was performed using a MOSCIS-II closed-system field rock pyrolysis analyzer (Guande, China). Approximately 100 mg of powdered sample was progressively heated to separate four temperature-defined hydrocarbon fractions: S_{f-1} (<200 °C), repre-

senting light free hydrocarbons; S_{f-2} (200–350 °C), representing light- to medium-weight free hydrocarbons; S_{p-1} (350–450 °C), representing relatively heavy and bound hydrocarbons; and S_{p-2} (450–600 °C), representing hydrocarbons generated from residual kerogen pyrolysis. The pyrolysis yields were reported in mg/g rock. All images contain a scale bar of 100 μ m. The relevant element index data are provided in full in Table 1.

3.3. Major and Trace Element Analyses

The major and trace element concentrations of the bulk rock samples were determined to reconstruct the paleo-depositional environment [36,37]. Prior to the tests, the samples were ground to less than 200 mesh and heated in a muffle furnace at 1000 °C to determine the loss on ignition (LOI). The major element oxides (such as Al, Ti, Ca, K, etc.) were measured using a PAN alytical Axios PW4400/40 fully automatic wavelength-dispersive X-ray fluorescence spectrometer on fused glass beads prepared with a lithium tetraborate flux. The analytical precision for major elements was generally better than 2%. For trace element analyses (including V, Ni, Mo, Sr, Ba, U, Th, etc.), approximately 50 mg of the powdered sample was completely dissolved in a mixture of concentrated HNO_3 and HF in sealed Teflon bombs at 190 °C for 48 h. After complete digestion and subsequent dilution, the trace element concentrations were analyzed using a Thermo Fisher X-Series-2 Inductively Coupled Plasma Mass Spectrometer (ICP-MS). The analytical precision and accuracy, monitored by certified international reference materials, were better than 5% for most trace elements. The relevant element index data are provided in full in Table 2. Based on Nesbitt and Young (1982) [38], the most widely used chemical weathering proxy is Chemical Index of Alteration (CIA), calculated as $CIA = [Al_2O_3 / (Al_2O_3 + CaO^* + Na_2O + K_2O)] \times 100$ (molar proportions), to express the transformation degree of feldspars to clays during chemical weathering processes. According to McLennan (1993) [39], the CaO^* refers to the CaO molar proportions in the silicate fractions of the rock other than in the apatite and/or carbonate fractions, which is calculated as $CaO^* = \min(CaO - 10/3 \times P_2O_5, Na_2O)$.

Table 1. Organic petrological and thermal maturity parameters of shales from the upper Jiufotang Formation in the Ludong Sag.

Samples	Depth (m)	Exinite Group (%)			Vitrinite Group (%)	Inertinite Group	Total	Type Index (TI)	Kerogen Type	Vitrinite Reflectance (Ro%)		
		Cutinite	Sporinite	Humic Amorphinite	Normal Vitrinite					Minimum Value	Maximum Value	Average Value
1	1880.4	/	/	86	13	1	100	32.3	II ₂	0.48	0.73	0.6
2	1884.3	/	/	71	27	2	100	13.3	II ₂	0.5	0.74	0.62
3	1887.9	/	/	80	18	2	100	24.5	II ₂	0.52	0.76	0.64
4	1892.1	/	/	75	23	2	100	18.3	II ₂	0.56	0.85	0.7
5	1895.7	3	/	75	20	2	100	22.0	II ₂	0.52	0.9	0.72
6	1900.5	2	/	76	21	1	100	22.3	II ₂	0.58	0.92	0.75
7	1904.2	3	/	80	16	1	100	28.5	II ₂	0.53	0.9	0.72
8	1906.9	/	/	73	24	3	100	15.5	II ₂	0.58	0.94	0.76
9	1907.7	/	/	69	29	2	100	10.8	II ₂	0.56	0.93	0.75
10	1910.7	5	1	65	27	2	100	13.3	II ₂	0.52	0.89	0.71
11	1911.9	3	1	74	20	2	100	22.0	II ₂	0.64	0.94	0.8
12	1912.5	2	1	70	24	3	100	15.5	II ₂	0.66	0.96	0.81
13	1913.5	2	/	68	28	2	100	12.0	II ₂	0.69	0.99	0.84
14	1915.0	2	/	72	23	3	100	16.8	II ₂	0.68	1.04	0.86
15	1915.6	1	1	76	21	1	100	22.3	II ₂	0.7	1.04	0.87
16	1918.7	2	/	65	29	4	100	7.8	II ₂	0.79	1.03	0.92
17	1920.5	4	1	65	27	3	100	11.8	II ₂	0.72	1.05	0.88
18	1921.2	3	/	64	31	2	100	8.3	II ₂	0.76	1.03	0.9
19	1922.2	/	/	67	29	4	100	7.8	II ₂	0.75	1.06	0.91
20	1925.8	1	/	74	23	2	100	18.3	II ₂	0.77	1.1	0.94

Table 2. Elemental geochemical ratios and paleoenvironmental proxies of shales from the upper Jiufotang Formation in the Ludong Sag.

Samples	Depth/m	Element Ratio										TOC (%)
		Sr/Ba	Th/U	(Zn + Ni)/(Ga*5)	Y/HO	REE + Y	Sr/Cu	Rb/Sr	V/(V + Ni)	Mo	CIA	
1	1880.4	0.43	2.87	1.23	28.10	222.72	8.12	0.47	0.74	8.34	68.89	4.73
2	1883.3	0.50	3.60	1.13	29.21	184.24	6.83	0.44	0.73	8.45	72.88	3.57
3	1884.3	3.46	0.85	1.16	33.92	59.24	137.22	0.01	0.92	8.22	63.12	5.77
4	1885.9	0.85	1.55	1.42	31.48	161.51	14.34	0.19	0.77	13.77	69.64	2.29
5	1887.9	1.19	1.92	1.37	34.38	174.77	16.10	0.15	0.75	20.40	69.34	5.23

Table 2. Cont.

Samples	Depth/m	Element Ratio										TOC (%)
		Sr/Ba	Th/U	(Zn + Ni)/(Ga*5)	Y/HO	REE + Y	Sr/Cu	Rb/Sr	V/(V + Ni)	Mo	CIA	
6	1892.1	1.27	2.01	1.24	36.09	179.56	23.45	0.13	0.78	17.19	69.98	6.15
7	1895.7	0.90	2.31	1.06	35.53	192.90	12.52	0.24	0.80	5.56	69.67	5.72
8	1897.5	0.90	0.89	1.39	31.26	98.87	6.21	0.08	0.75	42.02	70.32	4.90
9	1900.5	0.85	2.19	1.26	37.24	167.81	9.39	0.28	0.79	15.68	70.30	4.71
10	1901.3	2.29	1.63	1.24	43.75	124.61	33.41	0.09	0.82	15.86	70.41	5.53
11	1903.8	1.14	1.47	1.16	37.91	164.68	16.81	0.17	0.80	6.63	68.63	4.88
12	1904.2	0.99	1.63	1.73	41.57	153.71	9.18	0.24	0.71	34.59	68.43	7.16
13	1906	0.75	2.07	1.27	40.34	153.85	8.94	0.30	0.77	23.00	67.90	4.26
14	1906.9	1.48	1.56	1.55	41.65	132.13	17.52	0.14	0.75	29.58	67.78	4.45
15	1907.7	0.73	2.27	1.20	39.82	155.02	9.60	0.31	0.75	14.38	67.84	4.38
16	1910.43	0.96	2.16	1.20	40.82	157.48	12.53	0.25	0.78	16.53	68.93	3.46
17	1910.73	0.95	2.01	1.34	40.08	154.33	12.89	0.24	0.78	12.93	67.77	3.27
18	1911.33	1.48	1.86	1.23	40.19	151.95	18.11	0.14	0.78	14.05	67.10	4.82
19	1911.9	0.86	2.16	1.39	39.31	150.92	11.48	0.26	0.75	25.26	67.97	2.80
20	1912.2	0.78	2.24	1.20	39.73	155.45	14.01	0.25	0.80	13.77	68.47	3.24
21	1912.5	0.85	2.28	1.22	40.14	161.54	12.76	0.27	0.79	15.51	68.88	2.80
22	1913.3	0.96	2.27	1.04	40.42	202.31	18.82	0.24	0.81	7.58	68.58	2.96
23	1913.5	0.81	2.08	1.13	38.63	184.34	13.22	0.29	0.78	14.01	67.56	5.01
24	1914.4	0.85	2.33	1.06	38.85	158.20	16.59	0.26	0.83	5.06	68.44	3.13
25	1915	0.99	2.68	0.99	36.72	159.12	24.07	0.21	0.85	4.41	68.88	2.73
26	1915.3	1.05	2.47	0.95	38.44	166.96	23.88	0.19	0.84	4.87	68.38	3.13
27	1915.63	0.90	2.34	1.07	37.30	163.72	13.16	0.25	0.81	6.30	67.46	6.31
28	1916.1	3.32	1.43	2.33	42.91	84.13	91.57	0.03	0.68	9.35	67.53	1.91
29	1918.7	0.70	2.81	0.98	37.15	181.07	14.87	0.27	0.76	11.32	69.41	4.90
30	1920.5	1.09	1.64	1.06	37.43	171.62	23.51	0.17	0.80	8.30	68.79	4.31
31	1920.7	0.89	2.39	1.06	38.05	158.80	15.88	0.27	0.82	6.44	68.53	2.91
32	1921.2	1.13	2.49	1.03	38.70	165.04	24.64	0.21	0.83	3.43	67.71	2.77
33	1921.6	0.63	2.45	1.09	39.17	128.88	8.94	0.41	0.79	4.04	66.98	7.55
34	1922.2	0.96	1.32	1.13	34.59	121.57	12.21	0.12	0.83	6.82	69.42	3.09
35	1925.8	0.97	2.21	1.15	37.64	161.59	16.31	0.24	0.79	5.44	67.93	4.70
36	1932	0.76	2.80	1.01	37.74	149.51	15.35	0.31	0.84	1.95	66.95	2.57

4. Results

4.1. Organic Matter Abundance and Thermal Maturity

The TOC contents of the 36 shale samples from the upper Jiufotang Formation vary from 1.9% to 7.5%, with an average value of 4.2% (Figure 2). The lowest TOC value occurs at 1916.1 m, whereas the highest value is recorded at 1921.6 m. Among the analyzed samples, 35 samples have TOC contents greater than 2.0%, 20 samples have TOC contents greater than 4.0%, and 9 samples have TOC contents greater than 5.0%. Relatively high TOC values above 6.0% are observed at 1892.1 m, 1904.2 m, 1915.6 m, and 1921.6 m, with values of 6.1%, 7.1%, 6.3%, and 7.5%, respectively. The lower part of the studied interval, particularly between approximately 1920 and 1932 m, is represented by fewer samples than the shallower section. It should also be noted that TOC does not show a persistent downward decrease in this interval; instead, it varies substantially and reaches the highest value of the entire profile at 1921.6 m. Therefore, the deeper interval is interpreted as vertically heterogeneous rather than uniformly organic-lean. The vitrinite reflectance data were obtained from 20 shale samples within the depth interval of 1880.4–1925.8 m (Table 1). The measured minimum R_o values range from 0.48% to 0.79%, whereas the maximum R_o values range from 0.73% to 1.10%. The average R_o values range from 0.60% to 0.94%, with a mean value of 0.79%. The lowest average R_o value is recorded at 1880.40 m, and the highest average R_o value is recorded at 1925.8 m. All analyzed samples are characterized by type II2 kerogen. The soluble hydrocarbon fractions S_{f-1} and S_{f-2} are relatively low and vertically variable, with values of 0.02–0.08 and 0.17–0.54 mg/g, respectively (Figure 2). The S_{p-1} and S_{p-2} fractions are considerably higher, ranging from 3.01 to 17.39 mg/g and from 6.04 to 39.89 mg/g, respectively. Several intervals with high TOC, particularly those around 1904.2, 1915.6, and 1921.6 m, also contain relatively high S_{p-1} and S_{p-2} values. This correspondence indicates that organic-rich intervals generally retain greater bound and residual hydrocarbon generation fractions. However, the vertical distributions remain heterogeneous, and the S_{f-1} and S_{f-2} fractions do not show a consistent relationship with depth or TOC.

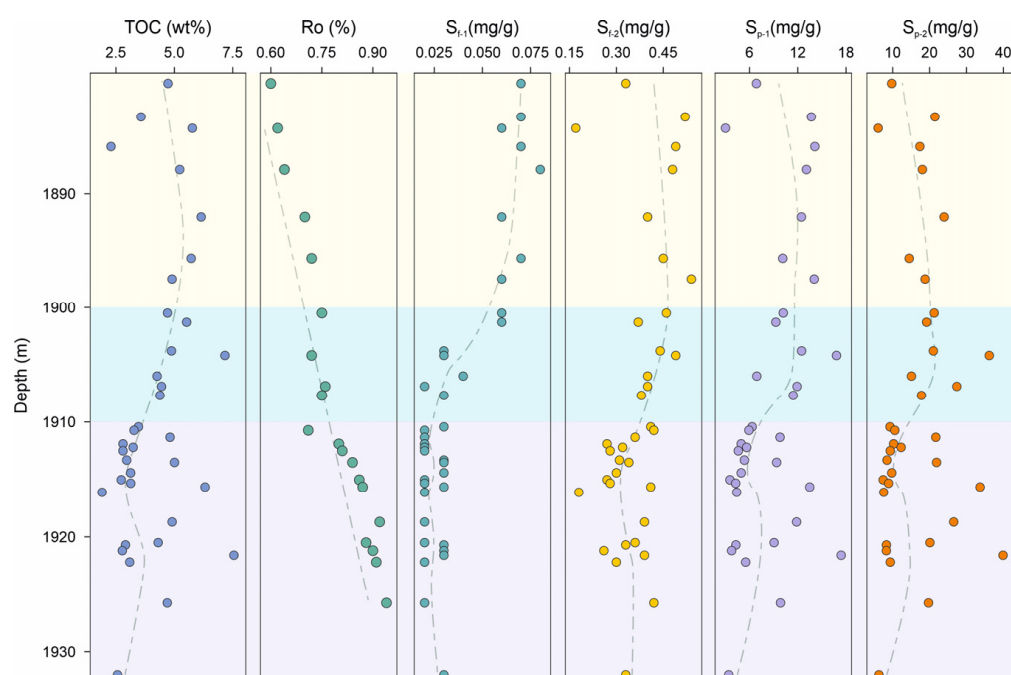


Figure 2. Vertical profiles of TOC, vitrinite reflectance (R_o), and staged-pyrolysis fractions in the upper Jiufotang Formation of the studied well.

Representative transmitted-light and fluorescence photomicrographs of shale samples from depths of 1880.4, 1887.9, and 1913.5 m are shown in Figure 3. Under transmitted light, the samples are dominated by a dark, fine-grained matrix with visible lamination and heterogeneous distributions of mineral and organic components. Under fluorescence illumination, all three samples exhibit distinct yellow to yellow-green fluorescence. The fluorescent components occur as disseminated spots, irregular patches, and locally lamina-associated accumulations. The samples from 1880.4 and 1887.9 m show relatively widespread and locally intense fluorescence, indicating heterogeneous but abundant fluorescent hydrocarbon-bearing components within the shale matrix. The sample from 1913.5 m also exhibits clear fluorescence, although the fluorescent material is more localized and unevenly distributed. These observations demonstrate that oil-bearing components occur in all three samples.

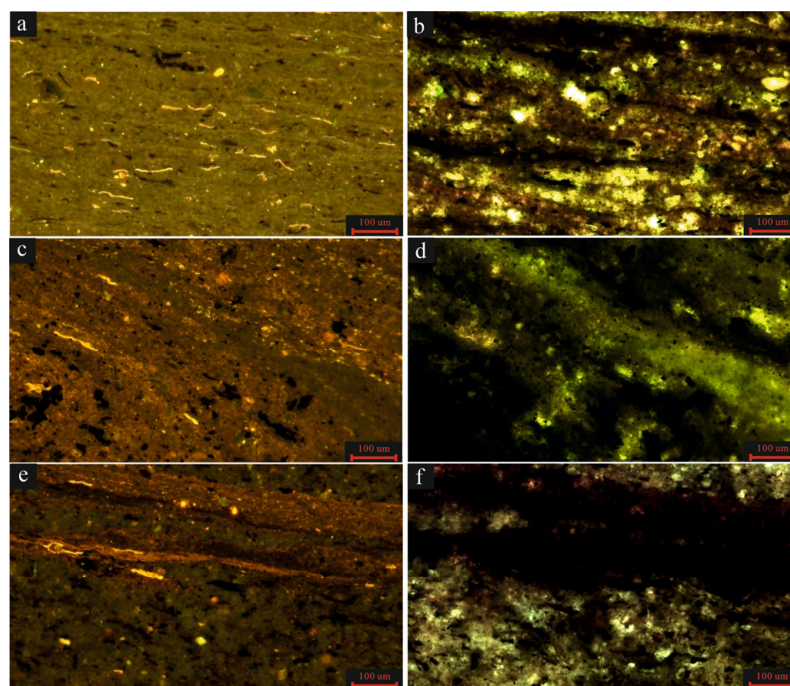


Figure 3. Paired transmitted-light and fluorescence photomicrographs showing the microscopic occurrence of hydrocarbon-bearing components in shales from the upper Jiufotang Formation. (a) Transmitted-light image of the sample from 1880.4 m; (b) fluorescence image of the sample from 1880.4 m; (c) transmitted-light image of the sample from 1887.9 m; (d) fluorescence image of the sample from 1887.9 m; (e) transmitted-light image of the sample from 1913.5 m; and (f) fluorescence image of the sample from 1913.5 m. Yellow to yellow-green fluorescence indicates the presence of fluorescent hydrocarbon-bearing components, which occur as disseminated spots, irregular patches, and locally lamina-associated accumulations. Images were acquired using a 10× objective.

4.2. Elemental Geochemistry

The elemental geochemical parameters of the 36 shale samples from the upper Jiufotang Formation show variable vertical distributions within the depth interval of 1880.4–1932.0 m (Table 2). The Sr/Ba ratios range from 0.43 to 3.46, with an average value of 1.10. Most samples have Sr/Ba values lower than 1.50, whereas relatively high values are recorded at 1884.3 m, 1901.3 m, and 1916.1 m, with values of 3.46, 2.29, and 3.32, respectively. The lowest Sr/Ba value occurs at 1880.4 m. The Sr/Cu ratios show a relatively wide range from 6.21 to 137.22, with an average value of 20.68. The highest Sr/Cu value occurs at 1884.3 m, followed by high values at 1916.1 m and 1901.3 m, with values of 91.57 and 33.41, respectively. The lowest Sr/Cu value is recorded at 1897.5 m. The Rb/Sr ratios range

from 0.01 to 0.47, with an average value of 0.23. The maximum Rb/Sr value appears at 1880.4 m, whereas the minimum value is recorded at 1884.3 m.

The Th/U ratios vary from 0.85 to 3.6, with an average value of 2.09. The highest Th/U value is observed at 1883.3 m, while the lowest value occurs at 1884.3 m. Most samples display Th/U values between 1.50 and 2.8. The V/(V + Ni) ratios range from 0.68 to 0.92, with an average value of 0.79. The highest V/(V + Ni) value occurs at 1884.3 m, whereas the lowest value is recorded at 1916.1 m. Most samples have V/(V + Ni) values between 0.75 and 0.83. The Mo values range from 1.95 to 42.02, with an average value of 12.81. The maximum Mo value occurs at 1897.50 m, and the minimum value occurs at 1932.0 m. Relatively high Mo values greater than 20 are recorded at 1887.9 m, 1897.5 m, 1904.2 m, 1906.0 m, 1906.9 m, and 1911.9 m. The (Zn + Ni)/(Ga + 5) ratios range from 0.95 to 2.33, with an average value of 1.22. The highest value occurs at 1916.1 m, whereas the lowest value occurs at 1915.3 m. Most samples have (Zn + Ni)/(Ga + 5) ratios between 1.0 and 1.4, while relatively high values are recorded at 1904.2 m, 1906.9 m, and 1916.1 m, with values of 1.73, 1.55, and 2.33, respectively. The Y/Ho ratios range from 28.1 to 43.75, with an average value of 37.67. The minimum value occurs at 1880.4 m, and the maximum value is recorded at 1901.3 m. Samples with Y/Ho values greater than 40.0 mainly occur between 1901.3 m and 1916.1 m. REE + Y ranges from 59.24 to 222.72 (mean 155.95).

To evaluate the potential influence of diagenetic K metasomatism on the weathering indices, an A–CN–K ternary diagram was constructed using the molar proportions of Al_2O_3 , $\text{CaO}^* + \text{Na}_2\text{O}$, and K_2O , where A, CN, and K represent Al_2O_3 , $\text{CaO}^* + \text{Na}_2\text{O}$, and K_2O , respectively. CaO^* represents only silicate-bound Ca. The sample distribution was compared with the average upper continental crust composition (UCC) and the ideal weathering trend to assess whether the samples experienced systematic displacement toward the K apex. In the A–CN–K diagram, the samples cluster mainly along the ideal weathering trend extending from the average upper continental crust composition toward the Al apex. No systematic displacement toward the K apex is observed. This distribution suggests that diagenetic K metasomatism exerted only a limited influence on the overall weathering trend and that the corrected CIA values reasonably reflect chemical alteration of the silicate fraction (Figure 4). After recalculation from molar oxide proportions and correction for non-silicate Ca, CIA ranges from 63.12 to 72.88, with a mean of 68.52 and median of 68.50 (Table 2). The A–CN–K data are similarly clustered; 31 of 36 samples lie slightly on the K side of the reference weathering direction. Two carbonate-rich samples at 1884.3 and 1916.1 m display a distinctive geochemical association. Their CaO contents reach approximately 26 wt.%, whereas their REE + Y concentrations are relatively low, at 59.24 and 84.13, respectively. These samples also have low Rb/Sr ratios of 0.01 and 0.03 but anomalously high Sr/Cu ratios of 137.22 and 91.57. After correction for non-silicate Ca and recalculation using oxide molar proportions, their CIA values were consistent with the overall sample population.

The 36 systematically collected core samples provide sufficient stratigraphic resolution to characterize organic matter abundance, thermal maturity, and vertical paleoenvironmental variations within the studied upper Jiufotang interval. The dataset is therefore suitable for evaluating process relationships at the well and stratigraphic-interval scales. Nevertheless, all samples were obtained from a single well. The present dataset cannot fully resolve lateral facies variation, spatial changes in sediment supply, or basin-scale heterogeneity across the Ludong Sag. Accordingly, the proposed organic matter enrichment framework should be regarded as a well-scale process interpretation. Its regional applicability and use in shale oil sweet-spot prediction require validation using additional wells, logging data, seismic-stratigraphic constraints, and mineralogical observations.

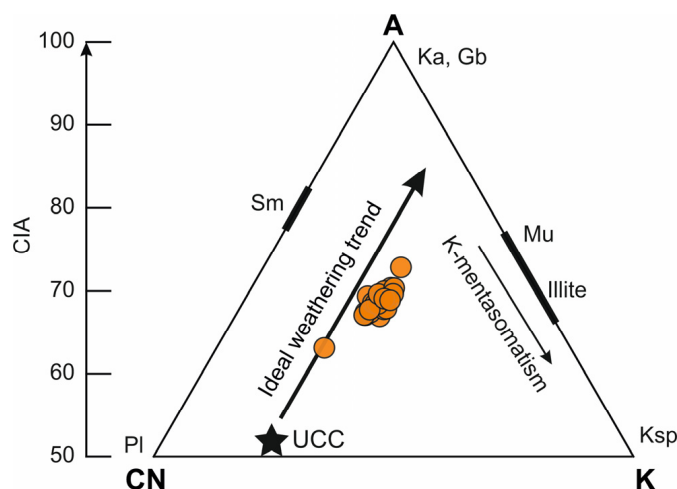


Figure 4. A–CN–K ternary diagram showing the sample distribution relative to the average upper continental crust composition, the ideal weathering trend, and the direction of K metasomatism of the upper Jiufotang Formation shales in the Ludong Sag. A, CN, and K represent Al_2O_3 , $\text{CaO}^* + \text{Na}_2\text{O}$, and K_2O , respectively.

5. Discussion

5.1. Source Rock Quality and Shale Oil Potential

Evaluating the abundance, type, and thermal maturity of organic matter is the fundamental precursor for assessing the quality of lacustrine shales and predicting their shale oil resource potential [40–43]. Standard screening plots categorized by TOC thresholds indicate that the upper Jiufotang Formation shales in the Ludong Sag represent a suite of highly prolific, top-tier source rocks. With a mean TOC content of 4.22% and peak values reaching up to 7.55%, over 95% of the analyzed samples fall squarely within the “excellent” to “exceptional” source rock categories (Figure 5a). This consistently high organic matter abundance satisfies the rigorous geochemical prerequisites required for extensive oil generation and accumulation within fine-grained continental reservoirs. The uniform identification of Type II₂ kerogen across the studied section further underscores a substantial oil-generating proclivity, as this mixed sapropelic–humic maceral assemblage typically exhibits high transformation ratios to liquid hydrocarbons under appropriate thermal regimes.

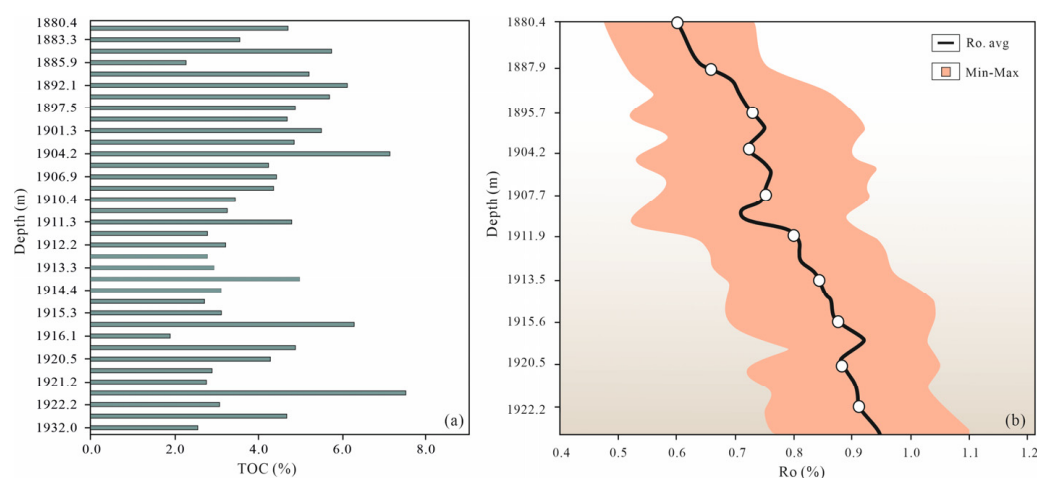


Figure 5. Vertical variation characteristics of TOC and vitrinite reflectance (Ro) of shales from the upper Jiufotang Formation in the Ludong Sag. (a) Vertical distribution of total organic carbon (TOC) content; (b) Depth profile of vitrinite reflectance (Ro).

The thermal maturity framework, mapped via vitrinite reflectance (R_o), provides critical insights into the dynamic hydrocarbon generation phase of these organic-rich shales. The mean R_o values, spanning from 0.60% to 0.94%, demonstrate that the entire upper Jiufotang Formation has successfully entered the mature stage, precisely operating within the early to peak oil generation window (Figure 5b). Vertically, the progressive increase in R_o with depth tracks the baseline geothermal cooking of the basin, passing the critical threshold for oil expulsion. Crucially, within the petroleum geology paradigm, when a source rock reaches the peak oil window, it undergoes massive kerogen degradation and subsequent hydrocarbon expulsion.

The staged pyrolysis and solvent-related hydrocarbon data further support the hydrocarbon generation potential of these shales. The soluble oil fractions, including S_{f-1} and S_{f-2} , are relatively low in absolute abundance, with S_{f-1} values ranging from 0.02 to 0.08 mg/g and S_{f-2} values ranging from 0.17 to 0.54 mg/g. In comparison, the bound oil and residual kerogen-related hydrocarbon generation components are much higher. The S_{p-1} values range from 3.01 to 17.39 mg/g, with an average of 8.73 mg/g, whereas the S_{p-2} values range from 6.04 to 39.89 mg/g, with an average of 16.58 mg/g. The combined hydrocarbon generation-related components, including S_{p-1} and S_{p-2} , range from 9.05 to 57.28 mg/g, with an average of 25.30 mg/g (Figure 6b,d). These values indicate that the studied shales retain considerable hydrocarbon-generating and hydrocarbon-bearing capacity.

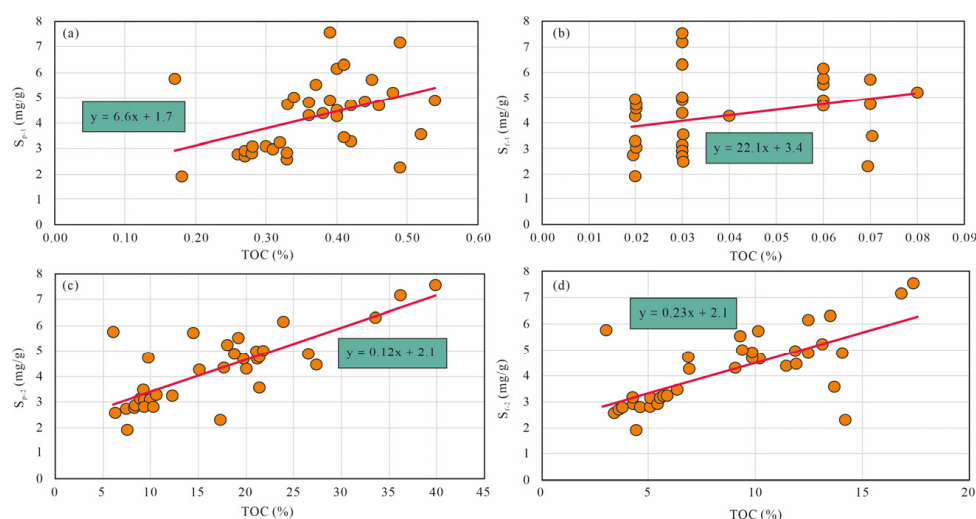


Figure 6. Correlation diagram of TOC and hydrocarbon generation potential parameters of shales from the upper Jiufotang Formation in the Ludong Sag.

The relationships between TOC and different hydrocarbon fractions reveal that organic matter abundance exerts an important control on hydrocarbon generation potential. The cross-plots show positive relationships between TOC and the hydrocarbon fractions, especially for S_{p-1} and S_{p-2} . Samples with higher TOC values generally show higher bound oil and residual kerogen-related hydrocarbon contents. For example, the samples at 1904.2 m, 1915.6 m, and 1921.6 m have TOC values of 7.16%, 6.31%, and 7.55%, respectively, and correspondingly high S_{p-1} and S_{p-2} values. The sample at 1921.6 m records the highest TOC value and also has the highest S_{p-1} and S_{p-2} values, reaching 17.39 mg/g and 39.89 mg/g, respectively (Figure 6a,c). This consistency indicates that the organic-rich intervals have stronger hydrocarbon generation potential than the relatively organic-lean intervals. Overall, the upper Jiufotang Formation in the Ludong Sag contains organic-rich shales with good to excellent source rock quality, suitable maturity, and considerable hydrocarbon generation potential. The most favorable shale oil intervals are mainly associated with

layers showing high TOC values, type II₂ kerogen, mature Ro values, and high S_{p-1} and S_{p-2} contents.

5.2. Depositional Paleoenvironment of the Upper Jiufotang Formation

5.2.1. Paleoclimate

Elemental geochemical proxies provide important constraints on the depositional paleoenvironment of the upper Jiufotang Formation in the Ludong Sag [44,45]. In this study, Sr/Ba, Th/U, (Zn + Ni)/(Ga*5), and Y/Ho ratios were used to evaluate paleosalinity and water-mass restriction; CIA and Sr/Cu were applied to assess paleoclimate and chemical weathering intensity; and V/(V + Ni) and Mo contents were used to reconstruct bottom-water redox conditions [46–50]. The coupled occurrence of high CaO, low REE + Y and Rb/Sr, and high Sr/Cu at 1884.3 and 1916.1 m suggests that these horizons are compositionally distinct and affected by carbonate enrichment. Carbonate accumulation dilutes aluminosilicate-associated elements, including Rb and most REE + Y, whereas Sr may be preferentially incorporated into carbonate minerals. Consequently, the high Sr/Cu ratios and low bulk REE + Y concentrations at these depths should not be interpreted solely as evidence of abrupt paleoclimatic or hydrological change. The corrected CIA values of these samples are comparable to those of the remaining succession, indicating that their silicate components experienced a similar moderate degree of chemical weathering (Figure 7a).

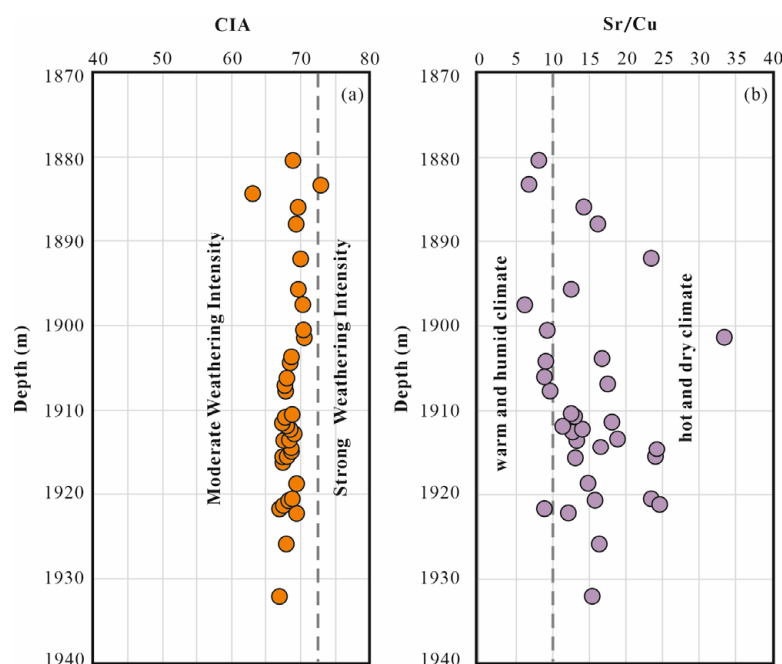


Figure 7. Vertical variations in CIA and Sr/Cu proxies of shales from the upper Jiufotang Formation in the Ludong Sag. (a) CIA vs. depth; (b) Sr/Cu vs. depth. Note: Two extreme outlier data points, (1884.3, 137.22) and (1916.1, 91.57), are omitted from the plots to optimize the visual presentation of the main data clusters in (b).

The Sr/Cu ratios also display strong vertical variability. The values range from 6.21 to 137.22, with an average value of 20.68 (Figure 7b). In general, low Sr/Cu values are more commonly associated with relatively humid conditions, whereas high Sr/Cu values may indicate relatively dry and hot climatic conditions or enhanced evaporation. Several samples have Sr/Cu values lower than 10, including those at 1880.4 m, 1883.3 m, 1897.5 m, 1900.5 m, 1904.2 m, 1906.0 m, 1907.7 m, 1921.6 m, and 1932.0 m, indicating relatively humid episodes. In contrast, most samples have Sr/Cu values greater than 10, and exceptionally

high values occur at 1884.3 m and 1916.1 m, with values of 137.22 and 91.57, respectively. Sr/Cu is retained only as a qualitative supporting proxy because it is also sensitive to carbonate mineralogy, Sr partitioning, and detrital composition. In particular, the 1884.3 and 1916.1 m peaks are not interpreted as stand-alone dry-hot climatic events.

5.2.2. Paleosalinity

Geochemical Under a predominantly semiarid climate with high evaporation rates, lacustrine water bodies are highly susceptible to salinization [51,52]. The salinity-related proxies show that the upper Jiufotang Formation was deposited under a lacustrine water body with relatively elevated salinity and variable hydrological restriction (Figure 8). The Sr/Ba ratios of the studied samples range from 0.43 to 3.46, with an average value of 1.1. Sr/Ba ratios higher than 0.2 generally suggest deposition under water bodies with increased salinity relative to freshwater conditions, whereas values higher than 0.5 commonly indicate brackish to saline conditions. In the studied interval, nearly all samples have Sr/Ba values equal to or higher than 0.5, except for the sample at 1880.4 m, which has a Sr/Ba value of 0.43. Several samples show distinctly high Sr/Ba values, especially those at 1884.3 m, 1901.3 m, and 1916.1 m, with values of 3.46, 2.29, and 3.32, respectively. These high values indicate short-term episodes of enhanced salinity or stronger hydrological restriction within the lacustrine system. The Th/U ratios provide additional evidence for a non-freshwater depositional setting. The Th/U values range from 0.85 to 3.6, with an average value of 2.09, and all samples are lower than 6.0 (Figure 8b). In fine-grained sediments, low Th/U values are commonly associated with deposition under relatively restricted, reducing, or saline-influenced water conditions (Figure 8a). The consistently low Th/U values in the studied shales suggest that the upper Jiufotang Formation was not deposited in a well-oxygenated freshwater lake, but rather in a more restricted lacustrine environment with enhanced salinity and reduced bottom-water exchange.

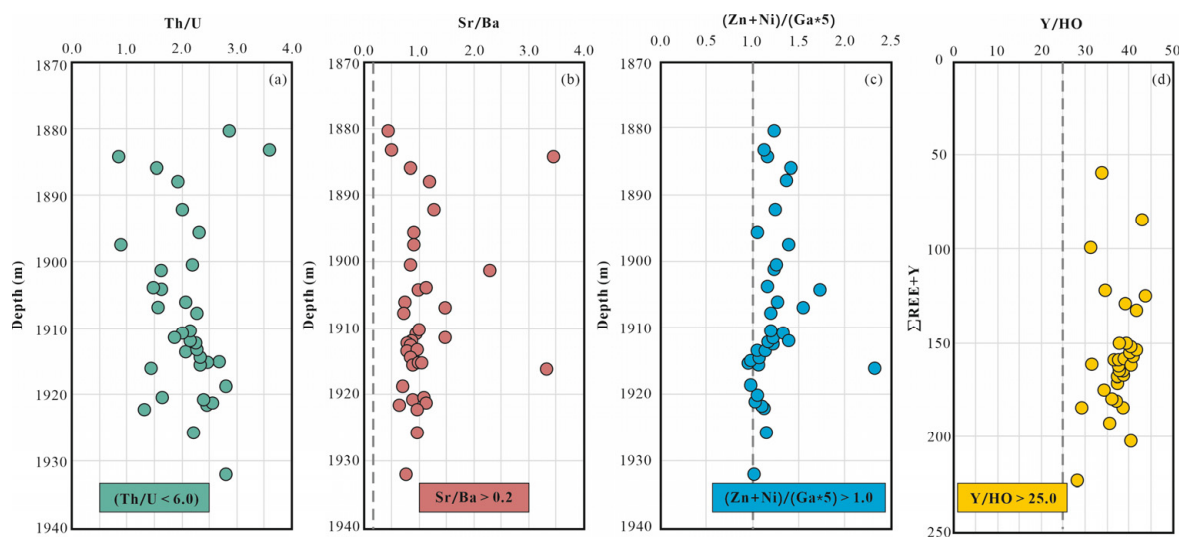


Figure 8. Vertical variations in Th/U, Sr/Ba, (Zn + Ni)/(Ga* 5), and Y/Ho proxies of shales from the upper Jiufotang Formation in the Ludong Sag. (a) Th/U vs. depth; (b) Sr/Ba vs. depth; (c) (Zn + Ni)/(Ga* 5) vs. depth; (d) Y/Ho vs. REE + Y.

The (Zn + Ni)/(Ga*5) ratios further support this interpretation. The values range from 0.95 to 2.33, with an average value of 1.22. Most samples have values higher than 1.0, and several samples show relatively high values, particularly at 1904.2 m, 1906.9 m, and 1916.1 m (Figure 8c). These elevated values are consistent with a saline or brackish lacustrine depositional setting. The sample at 1916.1 m records the highest (Zn + Ni)/(Ga*5)

value of 2.33, coinciding with a high Sr/Ba value of 3.32. The Y/Ho ratios range from 28.10 to 43.75, with an average value of 37.67. All samples have Y/Ho values higher than 25.0, and most values fall between 35 and 42 (Figure 8d). Compared with typical freshwater systems, elevated Y/Ho ratios generally indicate stronger water-mass differentiation and more pronounced salinity effects. The consistently high Y/Ho values in the upper Jiufotang Formation therefore provide further support for deposition in a brackish to saline lake (Table 2). In combination, the Sr/Ba, Th/U, (Zn + Ni)/(Ga*5), and Y/Ho proxies indicate that the studied interval was deposited in a restricted lacustrine basin characterized by brackish to saline water conditions, with episodic increases in salinity at specific depths.

These proxies are potentially affected by provenance, grain size, detrital input, authigenic mineral formation, organic matter abundance, and diagenesis. Therefore, their absolute values were interpreted cautiously, and emphasis was placed on the convergence of multiple indicators rather than on fixed threshold values. Taken together, the available evidence is consistent with deposition in a hydrologically restricted lacustrine system that experienced variable brackish to saline conditions.

5.2.3. Bottom-Water Redox Conditions

The redox-sensitive proxies indicate that the upper Jiufotang Formation was mainly deposited under weakly reducing to reducing bottom-water conditions. The $V/(V + Ni)$ ratios range from 0.68 to 0.92, with an average value of 0.79 (Figure 9a). In general, $V/(V + Ni)$ values lower than 0.60 indicate oxic conditions, values between 0.60 and 0.84 indicate dysoxic to weakly reducing conditions, and values higher than 0.84 indicate more strongly reducing or anoxic conditions. All samples from the upper Jiufotang Formation have $V/(V + Ni)$ values higher than 0.60, indicating that oxic bottom-water conditions were generally absent during deposition of the studied interval. Most samples have $V/(V + Ni)$ values between 0.75 and 0.83, suggesting that weakly reducing conditions dominated the depositional environment. Several samples have values close to or higher than 0.84, such as those at 1884.3 m, 1915.0 m, and 1915.3 m, indicating more reducing bottom-water conditions during these intervals. The lowest $V/(V + Ni)$ value occurs at 1916.1 m, but even this value is 0.68, still within the dysoxic to weakly reducing range. Therefore, the $V/(V + Ni)$ data suggest that the upper Jiufotang Formation was deposited in a persistently oxygen-deficient lacustrine water body.

Mo contents provide additional evidence for redox variation [53,54]. The Mo values range from 1.95 to 42.02, with an average value of 12.81 (Figure 9b). Mo enrichment commonly occurs under reducing conditions, particularly when bottom-waters are oxygen-deficient and organic matter preservation is enhanced. In the studied interval, relatively high Mo values greater than 20 are recorded at 1887.9 m, 1897.5 m, 1904.2 m, 1906.0 m, 1906.9 m, and 1911.9 m. These Mo-enriched horizons indicate episodic strengthening of reducing conditions. The highest Mo value occurs at 1897.5 m, reaching 42.02, suggesting that this depth interval may represent one of the most reducing depositional episodes in the studied section. The combined $V/(V + Ni)$ and Mo data suggest that the upper Jiufotang Formation was deposited under a generally reducing lacustrine setting, with several intervals showing stronger oxygen depletion. Such redox conditions were likely related to water column stratification in a restricted saline lake. Increased salinity would have promoted density stratification, reduced vertical mixing, and limited oxygen renewal in bottom-waters. This process could have favored the preservation of organic matter in fine-grained sediments.

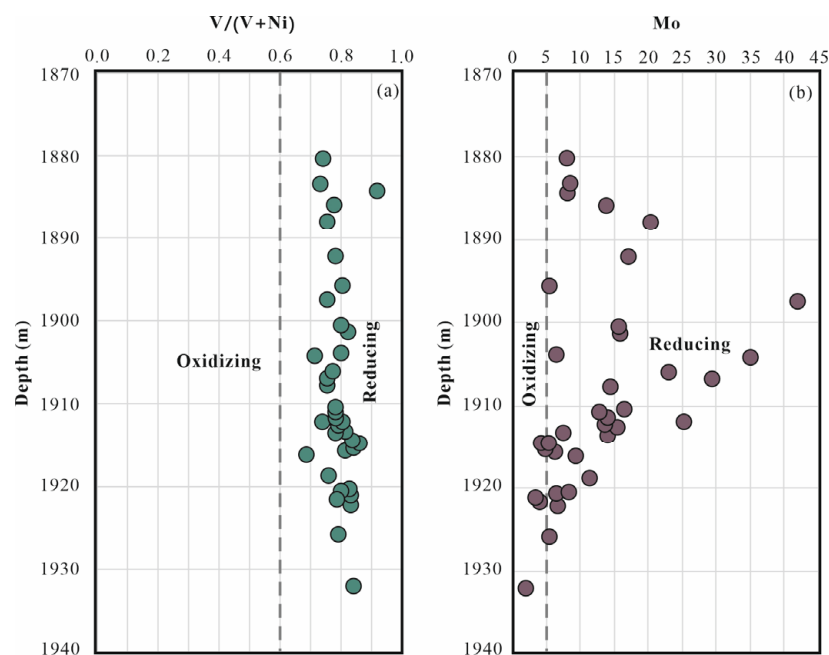


Figure 9. Vertical variations in $V/(V + Ni)$, Mo proxies of shales from the upper Jiufotang Formation in the Ludong Sag. (a) $V/(V + Ni)$ vs. depth; (b) Mo vs. depth.

5.3. Coupling Between Depositional Paleoenvironment and Organic Matter Enrichment

Organic matter enrichment in the upper Jiufotang Formation was jointly controlled by lake-water chemistry, bottom-water redox conditions, and organic matter supply. As discussed above, the elemental geochemical proxies indicate that the studied interval was mainly deposited in a restricted brackish to saline lacustrine environment, with weakly reducing to reducing bottom-water conditions. Such a depositional setting was favorable for water column stratification, which could have weakened vertical mixing between surface and bottom-waters and maintained long-term oxygen-deficient conditions in the lower water column. This process would have reduced organic matter oxidation and degradation, thereby improving organic matter preservation efficiency.

At the same time, the semi-deep to deep lake setting provided a relatively stable accommodation space for fine-grained sedimentation and continuous organic matter input. Nutrients supplied by terrigenous runoff, together with lake-water salinity fluctuations, may have promoted aquatic productivity and increased organic matter flux from the surface water to the lake floor. Terrestrial plant debris could also have been transported into the lake by runoff and mixed with aquatic organic matter. The occurrence of type II₂ kerogen, together with relatively high TOC contents and hydrocarbon generation potential, suggests that both organic matter supply and preservation conditions were favorable in several intervals of the studied succession.

However, TOC values do not show a strict one-to-one relationship with any single paleoenvironmental proxy, indicating that organic matter enrichment was not controlled by one factor alone. Instead, it resulted from the combined effects of productivity, preservation conditions, and sedimentary dilution. Organic-rich shale was most likely to develop when enhanced organic matter input coincided with reducing bottom-water conditions and relatively weak clastic dilution. Therefore, organic matter enrichment in the upper Jiufotang Formation reflects a multi-factor coupling mechanism, providing the basis for the productivity–preservation dual-control model discussed below.

5.4. Implications for Shale Oil Enrichment: A Dual-Control Model

Based on the integrated evidence from TOC contents, kerogen type, thermal maturity, hydrocarbon generation parameters, and elemental geochemical proxies, a dual-control model is proposed for shale oil enrichment in the upper Jiufotang Formation of the Ludong Sag (Figure 10). This model emphasizes the combined control of organic matter productivity and preservation conditions on the formation of organic-rich shale.

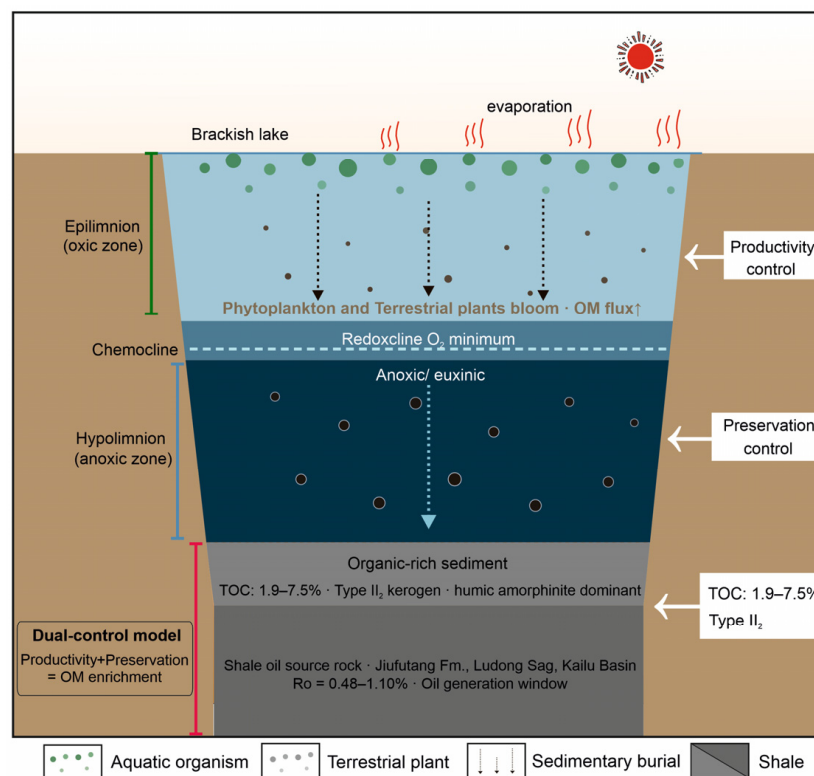


Figure 10. Dual control mode of organic matter enrichment in the upper Jiufotang Formation in the Ludong Sag.

The first control is organic matter supply. During deposition of the upper Jiufotang Formation, the Ludong Sag developed a semi-deep to deep lacustrine environment with brackish lake-water conditions. Aquatic organisms in the surface water, together with terrestrial plant-derived organic matter transported by runoff, provided the main organic matter sources. Periodic increases in nutrient supply may have promoted phytoplankton productivity, resulting in enhanced organic matter flux from the surface water to the lake floor. The occurrence of type II₂ kerogen indicates a mixed organic matter source with oil-prone to oil-gas-prone characteristics, which provided a favorable material basis for shale oil generation.

The second control is organic matter preservation. The restricted brackish to saline lake promoted water column stratification, which separated the oxic epilimnion from the oxygen-deficient hypolimnion. Under such conditions, the redoxcline shifted upward, and the bottom-water remained weakly reducing to reducing for prolonged periods. The V/(V + Ni) and Mo data indicate persistent oxygen-deficient bottom-water conditions during deposition. These reducing conditions limited microbial degradation and oxidation of organic matter, thereby improving organic matter preservation efficiency in the fine-grained sediments.

The dual-control model suggests that the enrichment of organic matter in the upper Jiufotang Formation was most effective when high organic matter input coincided with strong preservation conditions. In the upper water column, aquatic productivity and

terrestrial organic input increased the organic matter flux. In the lower water column and sediment–water interface, stratified and reducing conditions enhanced organic matter preservation. The combined effect of these two processes led to the formation of organic-rich shale with TOC values of 1.91–7.55%, type II₂ kerogen, and Ro values within the oil generation window.

This model also explains the vertical heterogeneity of shale oil potential in the studied interval. Layers with relatively high TOC values and high hydrocarbon generation parameters, such as those around 1904.2 m, 1915.6 m, and 1921.6 m, likely represent intervals where productivity and preservation conditions were both favorable. In contrast, intervals with lower TOC values may reflect weaker organic matter supply, less efficient preservation, or stronger dilution by clastic or mineral components. Therefore, the most favorable shale oil intervals in the upper Jiufotang Formation are expected to occur in layers where organic matter supply, reducing bottom-water conditions, and limited dilution were optimally coupled.

The proposed dual-control model has important implications for shale oil exploration in continental rift basins. For the upper Jiufotang Formation in the Ludong Sag, high-quality shale oil source rocks are not simply controlled by organic matter abundance or maturity alone. Instead, favorable shale oil intervals should be identified through the integrated evaluation of organic matter abundance, hydrocarbon generation potential, paleosalinity, redox conditions, and sedimentary dilution. Restricted brackish to saline lake systems with persistent reducing bottom-waters are particularly favorable for the development of organic-rich shale and may represent key targets for future shale oil exploration in the Kailu Basin.

6. Conclusions

- (1) The shales of the upper Jiufotang Formation in the Ludong Sag are characterized by high organic matter abundance and moderate thermal maturity, indicating favorable shale oil potential. The TOC contents range from 1.91% to 7.55%, with an average value of 4.22%. The organic matter is dominated by type II₂ kerogen, and the average Ro values range from 0.60% to 0.94%, suggesting that the studied shales are generally within the low-mature to mature stage and have entered the oil generation window.
- (2) Major and trace element geochemical proxies indicate that the upper Jiufotang Formation was deposited in a brackish to saline lacustrine environment with a certain degree of hydrological restriction and water column stratification. The Sr/Ba, Th/U, (Zn + Ni)/(Ga*5), and Y/Ho ratios collectively suggest that the studied interval was not deposited in a typical freshwater lake, but rather in a restricted saline lacustrine system.
- (3) Redox-sensitive indicators, including V/(V + Ni) and Mo, indicate that the bottom-water was mainly in a weakly reducing to reducing state during the deposition period, but there were also several periods showing enhanced reducing conditions. CIA and Sr/Cu values reflect hot and dry paleoclimate conditions and overall moderate chemical weathering. The alternation of relatively humid and dry evaporation periods regulated the input of terrigenous material, nutrient supply, and sediment dilution.
- (4) Organic matter enrichment and shale oil development in the upper Jiufotang Formation were controlled by a productivity–preservation dual mechanism. Brackish to saline lake-water conditions promoted water column stratification and bottom-water oxygen deficiency, improving organic matter preservation. Meanwhile, aquatic productivity and terrestrial organic input jointly increased organic matter supply. The coupling of these two processes controlled the development of organic-rich shale and the distribution of favorable shale oil intervals.

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