

Article

Paleo-Sedimentary Environment and Formation Mechanism of the Organic-Rich Shale of the Permian Lucaogou Formation, Jimsar Sag, Junggar Basin, China

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Abstract: The Jimsar Sag is an important shale oil exploration target area in the Junggar Basin, northwestern China. The Permian Lucaogou Formation, with a thickness of 200–300 m, is the primary exploration target. High-frequency variation in lithology is a typical feature of the Lucaogou Formation, reflecting the fluctuation of the depositional environment and organic matter enrichment. The evolution of the depositional environment and accumulation mechanism of organic matter still need to be elucidated for the Lucaogou Formation. High-resolution sampling of the entire Lucaogou Formation was applied to a 248 m long core from Well JX in the Jimsar Sag to examine the depositional environment and organic matter enrichment. The findings unveiled that the Lucaogou Formation was deposited under a hot and arid climate, within the confines of a closed saline paleo-lake, where sediments endured an extended period of anoxic conditions, displayed periodic oscillations in paleo-temperature and paleo-salinity values over time, alongside a continuous rise in paleo-water depth. The predominant source lithology of the Lucaogou Formation is felsic igneous rock. Small-scale transgression and hydrothermal sedimentation occurred during the deposition of the Lucaogou Formation. The prevailing hot climate and enduring reducing environment fostered ideal circumstances for the enrichment of organic matter in the Lucaogou Formation. Due to different sedimentary environments and enrichment mechanisms, organic matter is enriched in two modes in the Lucaogou Formation.

Keywords: sedimentary environment; organic-rich shale; formation mechanism; Lucaogou formation; Jimsar Sag; Junggar Basin



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1. Introduction

The Jimsar Sag, located in the southeastern part of the Xinjiang Junggar Basin, is an important oil exploration area in China (Figure 1) [1–4]. The Permian Lucaogou Formation in the Jimsar Sag, one of the important shale oil targets in China, had produced a total of 1.51 million tons of shale oil by the end of 2021, with an annual oil production of 42.6×10^4 t (2.98 million barrels) [5]. Therefore, the Lucaogou Formation is a hot spot for shale oil research, characterized by a set of organic-rich lacustrine fine-grained sediments.

Although a large amount of research has been conducted on the geochemical characteristics of the hydrocarbon source rocks, reservoir properties, and accumulation laws of the Lucaogou Formation [6–10], studies on the paleo-sedimentary environment and the depositional mechanism of the organic-rich Lucaogou Formation are still not well developed [11–14]. The heterogeneous lithology of the Lucaogou Formation has sparked a debate regarding the paleoclimate conditions. This climate controversy is primarily divided into two camps: one asserts that the finely laminated mudstones at a millimeter scale indicate profundal features formed under humid conditions [15,16], while the opposing viewpoint suggests that the presence of dolomitic rocks (including sandy dolomite, dolarenite, dolomicrite, and dolomitic siltstones), gypsum pseudomorphs, and drying

fragments points towards arid evaporative conditions [10,17]. In addition, multiple models for organic matter enrichment in the Lucaogou Formation have been proposed, mainly concentrating on the roles of primary productivity, preservation condition, and mineral dilution. The substantial presence of primary producers in the water column is likely to have consumed dissolved oxygen, leading to an anoxic environment that facilitated the preservation of organic matter in the Lucaogou Formation [10,14]. Additionally, various studies have documented hydrothermal activity during the deposition of the Lucaogou Formation [18–20]. Despite the notion of high productivity, some research indicates that the Lucaogou Formation was actually deposited under dry climatic conditions, resulting in limited chemical weathering, insufficient nutrient availability, and low primary productivity [21–23].

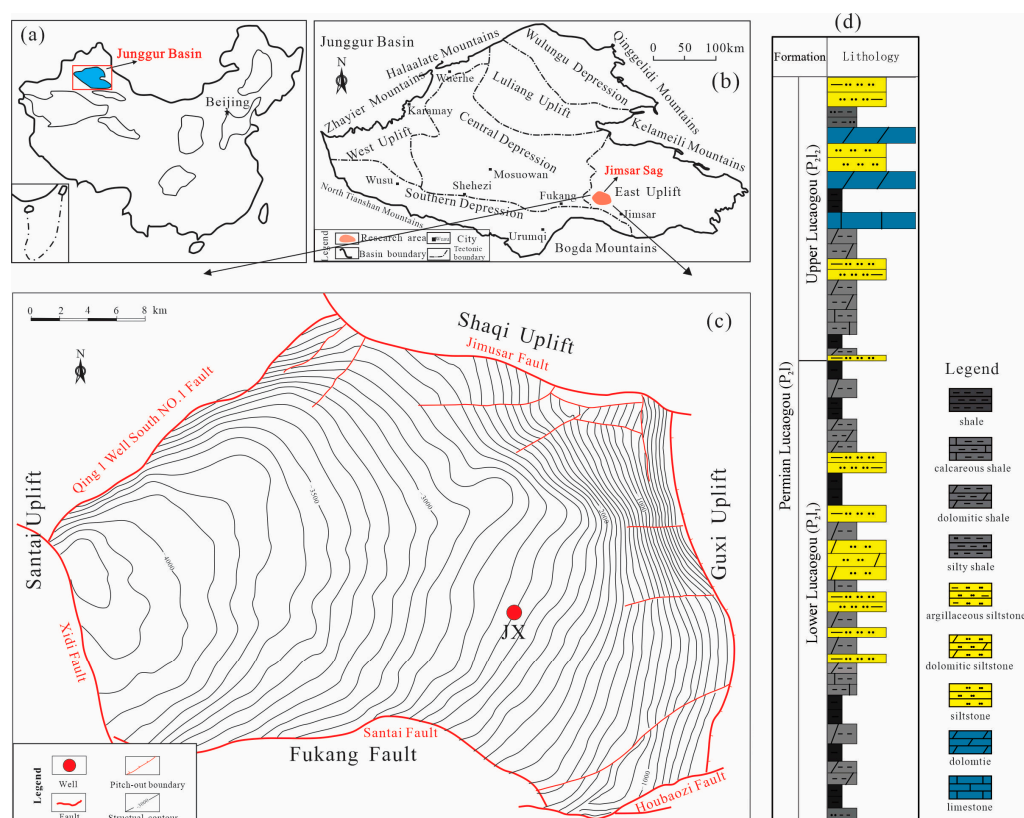


Figure 1. Location maps of the study area and stratigraphic column of Permian Lucaogou Formation (P_{2l}) in the Jimsar Sag (modified after [23]). (a) The location of the Junggar Basin; (b) the location of the Jimsar Sag; (c) the location of wells and structure contour map of P_{2l} ; (d) stratigraphic column of P_{2l} .

In this study, we aim to conduct an in-depth study on the paleo-sedimentary environment characteristics of the Lucaogou Formation in the Jimsar Sag and explore the mechanism of organic-rich shale formation, providing a scientific basis for the exploration and development of shale oil resources in this area. Based on core observations, petrographic and maceral analyses, elemental and isotopic analyses, scanning electron microscopy, and mineral energy spectrum scanning analysis, a systematic investigation of the paleo-sedimentary environment and formation mechanism of organic-rich shale from the Permian Lucaogou Formation was carried out. The primary objectives of this study are as follows: (1) clarify the evolution of the sedimentary environment, and (2) elucidate the formation mechanism of the organic-rich shale. The results of this study are of great significance for understanding the genesis and spatial distribution characteristics of the source rocks, as well as for exploring the shale oil in the Lucaogou Formation in the Junggar Basin.

2. Geological Background

The Junggar Basin, located in the northwestern part of China, is a prolific petroleum basin with an area of $130 \times 10^3 \text{ km}^2$ (Figure 1a) [23]. The Jimsar Sag, part of the southeastern margin of the Junggar Basin, has a tectonic unit area of 1278 km^2 and is a dustpan-shaped sag with deep faulting in the west and shallow overlap in the east (Figure 1b). The tectonic evolution of the Jimsar Sag unfolded through four distinct stages [24]. In the initial stage, which transpired during the Permian period, the Jimsar Sag was linked with the Bogeda Piedmont Sag in the east and the Fukang Sag. By the middle Permian, the Jimsar Sag underwent independent tectonic subsidence, leading to the deposition of the Lucaogou Formation (P_2l). The second stage occurred in the late Triassic, marked by significant uplift in the eastern part of the Jimsar Sag, resulting in erosion of the Permian and Triassic formations in that region. The third stage, spanning from the Cretaceous to the Cenozoic, saw pronounced uplift in the southeastern sector of the Jimsar Sag, leading to the erosion of Cretaceous strata. The final stage, which occurred during the Cenozoic era, involved the tilting of the entire sag from east to west due to the forward thrusting of the Bogeda Mountains.

The Lucaogou Formation is extensively distributed across the entire sag, with a thickness ranging from 200 to 350 m (Figure 1c). It sits above the Lower Permian Jingjingzigou Formation and below the Upper Permian Wutonggou Formation. Typically, the formation exhibits a thinning trend from east to west. Based on a regional maximum flooding surface, the Lucaogou Formation can be subdivided into a lower member (P_{2l1}) and an upper member (P_{2l2}) (Figure 1d) [1–3].

The Permian Lucaogou Formation is the main source rock in the Jimsar Sag and the main stratum for shale oil exploration. The Lucaogou Formation has a complex lithology and strong heterogeneity [1]. The multiple sets of interbedded high-quality source rocks are mainly composed of siliceous and carbonate shales, while the tight reservoirs are mainly composed of siliceous and carbonate siltstones (Figure 1d).

3. Samples and Methods

This study conducted high-resolution sampling of the Lucaogou Formation in Well JX, located in the eastern part of the Jimsar Sag (Figure 1), with a core length of 248 m. Thus, 294 samples were collected from the top to the bottom of the Lucaogou Formation in Well JX, with sample spacing as uniform as possible.

Full-core observation and description were conducted for the entire 248 m well section. The 294 samples were subjected to total organic carbon (TOC) content measurements and petrographic analysis. The 32 samples were subjected to scanning electron microscopy (SEM) analysis, mineral energy spectrum scanning analysis, and maceral analysis. Further, 70 samples were analyzed for major, trace, and rare earth elements (REEs), respectively, and 38 samples were subjected to carbon and oxygen isotopic analyses.

The TOC measurement was performed on a Rock-Eval 6 machine (Vinci Technologies, Nanterre, France), following standard procedures described by Peters [25]. Petrographic observation was conducted on thin sections, using an Axio Imager 2 Pol-polarized light microscope (ZEISS, Oberkochen, Germany). Maceral observation was made under plane-polarized reflected white light and incident blue light. SEM analysis was performed using an FEI Helios Nanolab 600i high-resolution field-emission SEM instrument (Thermo Fisher Scientific, Waltham, MA, USA). All SEM samples were carbon-coated and conducted using the secondary electron beam, backscatter electron and energy-dispersive spectroscopy for mineral identification. The major and trace elements were analyzed using inductively coupled plasma mass spectrometry (ICP-MS), and the REEs were analyzed using atomic absorption spectrometry. Both of these analyses have an analytical error of $<5\%$. Carbon and oxygen isotopic analyses were performed using the MAT-252 isotope ratio mass spectrometer method. The $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ errors are both $\pm 1 \times 10^{-4}$, and all results are reported relative to the Vienna Pee Dee belemnite (VPDB) standard. The above analyses

were conducted at the Key Laboratory of Petroleum Geochemistry and Reservoirs of China National Petroleum Corporation (CNPC).

4. Results and Discussion

4.1. Paleo-Environment Analysis

4.1.1. Stratigraphic Division

Based on the comprehensive analysis of the sequence, lithology, logging response characteristics, physical properties, geochemical properties, and sedimentary structures, we established a new scheme for the stratigraphic division of the Lucaogou Formation. In this study, the Lucaogou Formation is divided into six layers (L6 to L1), from bottom to top (Figure 2).

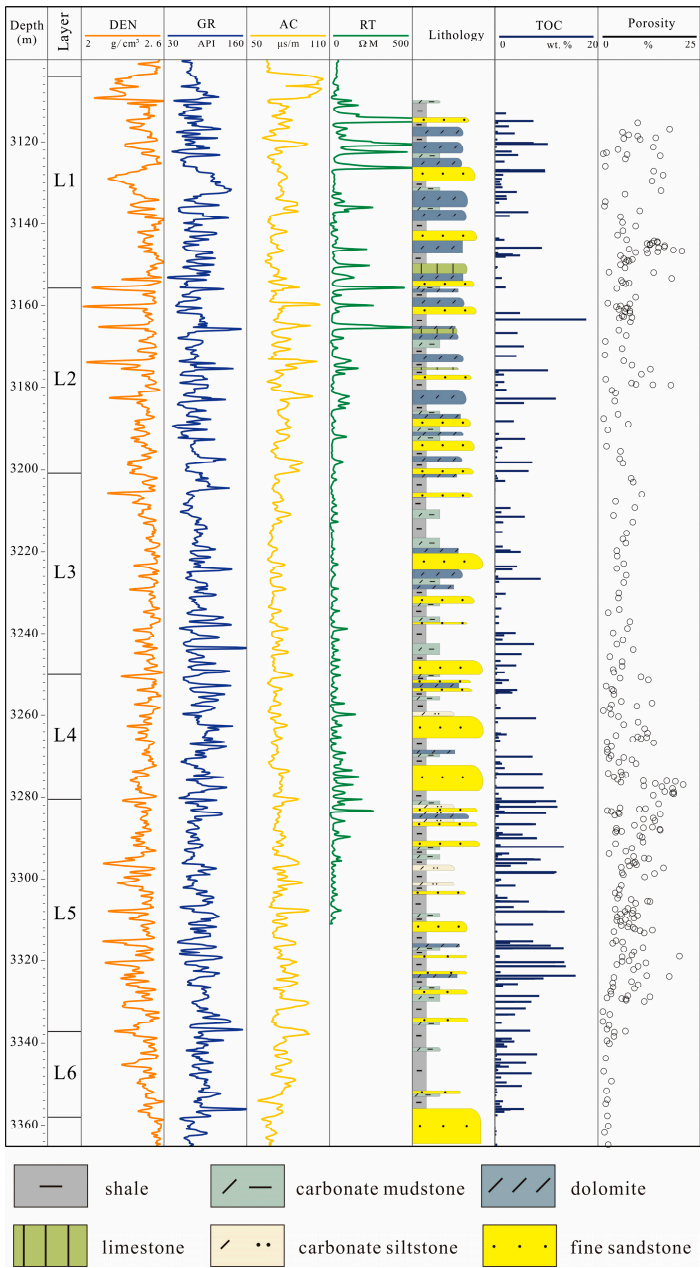


Figure 2. Division of the Lucaogou Formation in Well JX.

The overall sedimentary structure of the Lucaogou Formation is dominated by horizontal laminations, which gradually decrease upwards (Table 1). The secondary sedimentary

structures in each layer exhibit some differences (Figure 3). Among them, L6 contains a high number of 0.5 to 1.0 m thick deformation structures, while L5 and L3 exhibit abundant bioturbation structures. L4 displays small localized cross laminations, L3 features turbidity sedimentary structures, and L1 shows scour and detachment structures. The logging responses of the six layers vary in terms of electrical properties, acoustic wave characteristics, and density (Table 1).

Table 1. Sedimentary structural characteristics, log response characteristics and geochemical properties of the six layers of the Lucaogou Formation in Well JX.

Layer	Sedimentary Structures	Logging Response Characteristics	TOC (%)	Lithology
L1	Numerous scour structures, fewer horizontal and cross laminations, with a certain amount of bioturbation	Low (<20 ohm) to high (>1000 ohm) electrical resistivity; very low (<2.5 g/cc) density, with slower change than that of other layers; large interval transit time (>80 us/ft)	2.7/0–10	Shale and dolomite interbedding, amount of shale increases upward, locally sandwiched dolomitic sandstone
L2	Fewer horizontal laminations, abundant biological disturbance, and numerous scour structures	Large fluctuations in electrical resistivity, saw-toothed curve with spikes and large average value (~1000 ohm); extremely low density of local thin laminae (<2.3 g/cc), with saw-toothed spikes; general interval transit time of >70 us/ft, with local magnification (>90 us/ft) and saw-toothed spikes.	4.3/0–18	Dolomitic shale, with locally sandwiched dolomitic sandstone
L3	Several horizontal laminations and bioturbation, with some turbidity structures	Low electrical resistivity (<100 ohm)	1.9/0–9	mudstone
L4	More horizontal laminations and cross laminations, with occurrence of thick turbidites	Electrical resistivity increases (high value > 100 ohm), with a dense saw-tooth profile; average density < 2.5 g/cc; large interval transit time (average > 70 us/ft)	2.0/0–9.5	Dolomitic silty sandstone
L5	Numerous horizontal laminations, and frequent bioturbation	Electrical resistivity < 40 ohm; density < 2.45 g/cc, saw-toothed curve; saw-toothed interval transit time with an average of >75 us/ft	4.5/0–16	Dolomitic mudstone and dolomitic shale, with sandwiched silty sandstone
L6	Numerous thick horizontal laminations with obvious deformation structures	Low (<2.5 g/cc) to high (>2.6 g/cc) density; large (>80 us/ft) to small (<60 us/ft) interval transit times	1.9/0–8	Calcareous clay

Additionally, there are significant variations in TOC content and porosity among the different layers. L5 and L2 have higher TOC values compared to the other layers, while L4 and L1 exhibit higher porosities relative to the other layers (Figure 2).

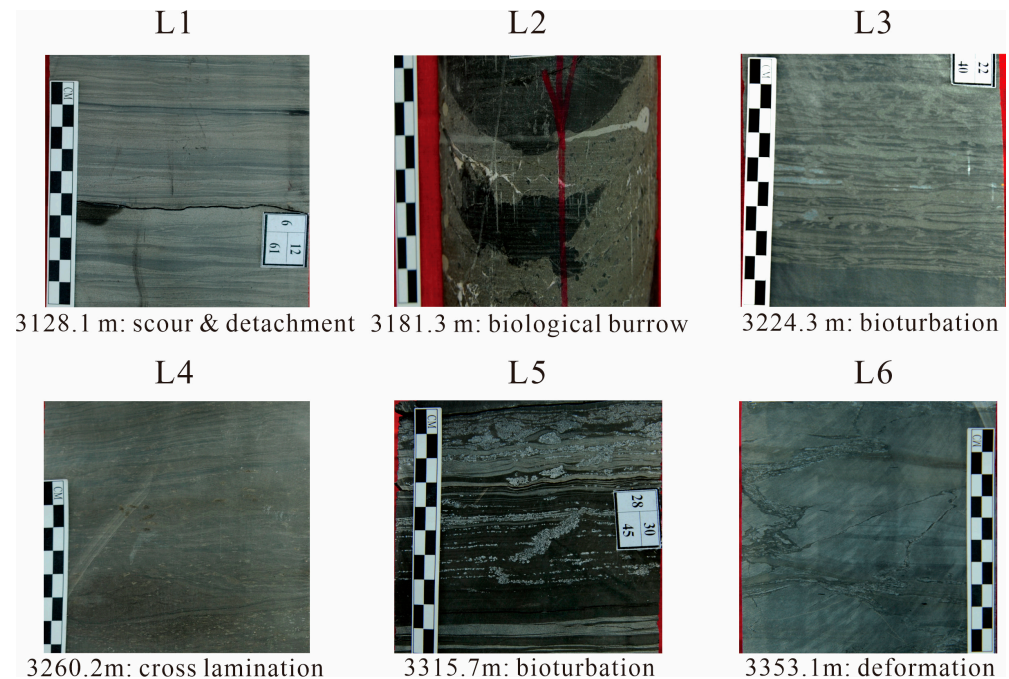


Figure 3. Typical sedimentary structures from six layers of the Lucaogou Formation in Well JX.

4.1.2. Paleo-Climate Analysis

A previous study showed that the Sr/Cu ratio of lake sediments is very sensitive to climatic changes [26]. In general, $1.3 < \text{Sr/Cu} < 5$ indicates a warm humid climate, and $\text{Sr/Cu} > 5$ indicates a hot arid climate [26]. In the study area, the majority of Sr/Cu ratios surpass 5, with a median Sr/Cu ratio of 17.69, suggesting a prevailing hot and arid climate throughout the deposition of the Lucaogou Formation (Table 2, Figure 4). The carbon isotopes of authigenic lacustrine carbonate also serve as a sensitive indicator of a lake's paleo-climate [26–28]. When the climate becomes hot and arid, carbonates tend to exhibit a higher $\delta^{13}\text{C}$ value. Conversely, in warm and humid climates, carbonates typically show a lower $\delta^{13}\text{C}$ value [27,28]. The $\delta^{13}\text{C}$ value of the study area is between 4.4‰ and 10.4‰, with a median of 8.4‰ (Table 2), which indicates a hot and arid climate. The $\delta^{13}\text{C}$ values demonstrate a clear periodic pattern, with temperatures increasing during the deposition of L6, exhibiting frequent oscillations throughout the deposition of L5, reaching a peak in the middle and late stages of L5 deposition. Subsequently, temperatures progressively declined after L5 deposition, only to rise once more during the deposition of L1 (Figure 4).

Table 2. Summary of paleo-environmental parameters of the Lucaogou Formation in Well JX.

No.	Depth (m)	Sr/Cu	Sr/Ba	V/(V + Ni)	Mn/Fe	Zr (ppm)	HREE (ppm)	LREE (ppm)	Ga (ppm)	V (ppm)	Th/Cr	Th/Sc	La/Sc	La/Co	Al/(Al + Fe + Mn)	Fe/Ti	$\delta^{13}\text{C}$ (VPDB, ‰)	$\delta^{18}\text{O}$ (VPDB, ‰)
1	3111.04	1.57	0.23	0.53	0.00	405.00	8.59	57.53	12.00	59.30	0.05	0.63	2.94	0.91	0.73	7.69	5.90	−9.20
2	3113.34	93.14	4.39	0.76	0.13	109.00	14.29	69.34	6.53	17.20	0.41	0.81	3.40	2.35	0.91	10.03		
3	3114.27	3.40	0.31	0.75	0.03	362.00	18.67	117.39	17.50	118.00	0.09	0.53	2.62	1.58	0.77	6.23		
4	3121.20	1.64	0.25	0.81	0.01	471.00	24.19	148.07	18.50	87.30	0.13	1.68	6.82	1.89	0.87	3.09		
5	3124.84	3.19	0.41	0.66	0.04	397.00	33.46	181.92	13.30	61.00	0.47	1.08	2.54	4.36	0.87	2.92	10.40	−10.30
6	3124.80	252.98	4.50	0.95	0.09	73.80	22.25	84.91	2.26	94.60	0.30	0.33	0.86	3.24	0.43	27.25	8.30	−9.20
7	3118.18	11.10	2.34	0.76	0.08	242.00	17.81	112.26	12.40	110.00	0.12	0.52	2.39	1.67	0.75	6.20		
8	3135.11	3.90	1.15	0.88	0.03	338.00	17.37	118.45	12.80	95.80	0.13	0.63	2.89	1.88	0.75	6.75		
9	3127.02	6.30	0.30	0.86	0.02	301.00	24.67	141.87	21.80	83.20	0.17	0.74	3.62	4.12	0.75	9.82	4.70	−14.50
10	3127.00	4.27	0.27	0.73	0.01	351.00	27.55	152.74	24.70	94.50	0.16	0.76	3.63	5.20	0.74	9.24	4.40	−14.30
11	3141.55	3.90	0.40	0.78	0.00	356.00	16.57	133.05	21.70	154.00	0.12	0.90	4.20	2.10	0.72	7.86		
12	3143.82	35.02	3.27	0.78	0.03	187.00	15.76	86.11	6.67	60.30	0.12	0.27	0.96	1.07	0.74	6.07		
13	3145.19	83.24	4.81	0.87	0.03	191.00	12.79	76.44	5.61	63.20	0.13	0.32	1.32	2.37	0.64	11.33		
14	3145.29	72.37	2.35	0.89	0.02	181.00	19.51	134.52	7.82	64.10	0.11	0.23	1.83	5.70	0.58	16.50		
15	3146.10	3.33	0.34	0.81	0.02	296.00	12.68	95.34	14.40	131.00	0.09	0.53	2.91	1.38	0.80	5.48	5.40	−5.60
16	3162.81	12.78	1.03	0.72	0.01	303.00	15.21	102.85	15.60	72.80	0.09	0.89	4.64	1.87	0.78	5.77		
17	3181.77	6.44	0.97	0.73	0.02	260.00	11.54	83.27	13.10	92.80	0.04	0.30	2.17	1.35	0.75	6.95	8.30	−9.60
18	3190.64	485.53	5.61	0.96	0.04	61.70	12.16	55.50	1.33	75.50	0.11	0.04	0.40	3.48	0.32	55.59		
19	3192.50	8.59	0.71	0.78	0.01	230.00	9.77	74.20	12.30	66.40	0.06	0.45	2.72	1.65	0.73	8.13		
20	3199.99	32.97	1.44	0.81	0.03	288.00	22.27	127.66	15.40	103.00	0.10	0.76	3.41	3.02	0.81	5.45	6.90	−7.70
21	3200.04	21.56	1.30	0.77	0.03	286.00	22.98	141.78	13.40	85.70	0.12	0.82	4.21	2.94	0.80	5.48	7.30	−6.10
22	3217.63	60.52	5.34	0.75	0.05	134.00	30.52	133.79	5.52	53.10	0.36	0.33	1.31	2.61	0.76	5.48	7.00	−5.30
23	3228.90	16.91	1.09	0.81	0.01	234.00	20.87	117.89	14.20	74.70	0.22	1.48	3.91	3.17	0.75	7.61		
24	3235.38	31.70	1.91	0.75	0.04	250.00	19.03	102.88	11.20	65.00	0.14	0.47	1.85	1.99	0.71	8.12		
25	3237.77	9.57	2.49	0.73	0.03	221.00	18.48	101.66	9.49	83.20	0.23	0.85	2.05	1.47	0.72	6.67		
26	3242.98	20.36	4.21	0.87	0.04	56.40	14.72	77.46	2.55	90.00	0.16	0.11	0.64	2.04	0.40	21.56	9.60	−1.50
27	3244.62	125.23	4.55	0.86	0.05	139.00	15.39	97.35	5.08	63.20	0.16	0.18	0.71	2.92	0.55	16.37		
28	3246.26	12.74	0.94	0.83	0.00	254.00	13.67	86.61	14.60	79.50	0.08	0.70	2.65	1.18	0.47	30.87	6.70	−8.30
29	3246.21	16.21	1.09	0.61	0.00	366.00	23.54	135.95	19.50	113.00	0.14	0.91	3.69	3.16	0.78	6.37	6.00	−9.30
30	3250.08	43.28	2.64	0.77	0.03	179.00	16.34	99.58	7.59	49.30	0.12	0.37	2.19	2.59	0.70	8.37		
31	3258.69	13.10	2.11	0.73	0.03	194.00	20.44	121.82	9.38	99.40	0.46	1.84	2.49	2.27	0.68	8.05		
32	3263.36	57.84	2.51	0.76	0.03	218.00	20.73	105.84	10.80	70.50	0.17	0.61	1.95	3.18	0.73	7.79		
33	3264.16	4.58	1.27	0.72	0.02	289.00	17.91	91.74	12.60	76.10	0.16	1.29	3.06	1.51	0.80	4.81	9.10	−4.40

Table 2. Cont.

No.	Depth (m)	Sr/Cu	Sr/Ba	V/(V + Ni)	Mn/Fe	Zr (ppm)	HREE (ppm)	LREE (ppm)	Ga (ppm)	V (ppm)	Th/Cr	Th/Sc	La/Sc	La/Co	Al/(Al + Fe + Mn)	Fe/Ti	$\delta^{13}\text{C}$ (VPDB, ‰)	$\delta^{18}\text{O}$ (VPDB, ‰)
34	3269.74	46.07	2.88	0.86	0.03	269.00	16.77	100.06	11.70	115.00	0.05	0.23	1.61	1.87	0.70	9.21		
35	3275.25	11.76	0.99	0.66	0.03	296.00	20.39	95.23	14.40	76.70	0.10	0.79	2.51	1.34	0.79	6.38	8.60	−5.40
36	3278.33	42.46	2.11	0.79	0.04	266.00	20.77	98.62	10.40	93.80	0.07	0.23	2.20	2.58	0.73	7.12	10.00	−2.80
37	3279.11	12.95	2.57	0.80	0.04	265.00	13.09	91.94	6.85	103.00	0.22	0.66	1.95	1.86	0.71	6.96	9.70	−5.80
38	3279.01	6.60	1.78	0.85	0.03	272.00	18.03	124.86	10.10	116.00	0.59	2.99	3.02	1.57	0.72	7.03	8.90	−7.60
39	3280.07	83.43	2.82	0.83	0.04	241.00	14.44	101.93	6.63	87.20	0.09	0.24	1.91	3.05	0.66	10.93		
40	3280.53	30.96	1.75	0.82	0.04	272.00	20.29	122.51	9.75	92.40	0.10	0.38	2.65	2.93	0.79	5.27		
41	3285.45	47.59	2.24	0.79	0.03	266.00	17.95	110.91	11.80	79.00	0.05	0.27	2.00	2.46	0.78	5.86		
42	3286.00	38.03	2.02	0.86	0.02	332.00	20.99	125.64	12.20	42.70	0.08	0.70	5.26	3.44	0.87	3.18		
43	3286.14	24.20	1.25	0.84	0.03	304.00	20.33	160.04	12.00	80.20	0.08	0.56	5.88	4.14	0.84	4.38		
44	3286.06	21.01	1.07	0.70	0.01	320.00	21.72	161.76	16.30	97.60	0.07	0.69	7.35	3.53	0.78	6.20		
45	3287.39	27.34	1.86	0.81	0.02	251.00	12.04	70.85	7.21	54.30	0.22	0.88	2.56	1.95	0.76	6.90	10.10	−7.10
46	3287.98	15.75	2.58	0.82	0.03	248.00	17.17	122.11	6.76	84.20	0.27	0.93	3.38	2.27	0.65	8.96		
47	3284.63	19.31	2.89	0.72	0.03	168.00	12.42	80.94	5.98	89.90	0.20	0.44	1.11	2.21	0.65	9.93	10.40	−9.00
48	3284.61	22.02	3.11	0.75	0.03	193.00	17.67	115.95	6.26	73.90	0.37	0.99	1.78	2.17	0.70	7.64	9.10	−12.40
49	3292.01	11.39	1.70	0.74	0.02	217.00	23.65	115.93	7.31	63.80	0.17	0.65	2.83	2.68	0.61	11.51	10.20	−3.30
50	3299.63	12.14	2.93	0.80	0.04	222.00	18.86	110.82	8.31	95.20	0.17	0.58	2.46	2.05	0.72	6.94		
51	3303.39	32.84	1.89	0.82	0.01	209.00	15.19	99.17	8.98	69.10	0.10	0.48	2.44	2.04	0.62	17.56	7.20	−3.90
52	3303.42	21.57	1.47	0.68	0.03	244.00	19.70	119.46	11.60	112.00	0.11	0.55	2.31	2.31	0.76	6.55	8.50	−1.50
53	3303.47	17.12	1.14	0.85	0.01	283.00	15.96	100.90	15.50	117.00	0.07	0.49	2.19	1.43	0.75	7.64	6.00	−6.10
54	3303.48	69.57	6.67	0.83	0.13	86.20	8.55	46.66	2.84	40.10	0.26	0.63	1.57	1.06	0.64	7.03	9.90	−11.00
55	3303.45	16.42	3.80	0.76	0.02	186.00	24.41	98.78	5.85	81.00	0.26	0.70	1.59	0.97	0.71	6.27	7.40	−2.00
56	3303.43	22.82	4.76	0.84	0.03	154.00	18.80	118.75	5.67	72.10	0.31	0.71	2.33	1.61	0.67	7.85	7.00	−3.40
57	3304.91	14.51	0.86	0.80	0.01	351.00	24.44	109.26	14.00	83.50	0.14	0.67	2.36	2.12	0.74	6.03	8.70	0.20
58	3304.86	78.91	3.00	0.88	0.05	236.00	15.98	88.59	8.56	64.70	0.12	0.29	1.28	1.96	0.67	11.70	9.50	−2.20
59	3304.80	62.38	5.37	0.87	0.05	243.00	15.51	92.29	7.62	80.80	0.11	0.18	0.96	2.59	0.61	12.00	9.20	−2.40
60	3305.88	11.32	4.33	0.83	0.03	145.00	23.67	107.43	5.52	92.70	0.29	0.87	2.24	1.93	0.63	8.98		
61	3306.69	27.16	1.97	0.82	0.00	264.00	18.77	102.42	11.30	51.60	0.12	0.74	2.85	1.49	0.24	58.52		
62	3302.13	18.25	1.10	0.60	0.03	291.00	14.93	100.99	13.00	96.70	0.07	0.42	1.92	1.61	0.79	6.12	8.10	−4.60
63	3313.18	9.63	3.02	0.83	0.03	254.00	21.89	122.94	8.52	125.00	0.12	0.50	3.46	2.29	0.62	9.90	9.50	−6.90
64	3314.20	9.19	3.52	0.74	0.02	247.00	21.34	111.90	9.26	124.00	0.19	0.74	2.08	1.60	0.63	9.64	7.30	−11.70
65	3314.18	94.72	3.52	0.76	0.07	165.00	12.79	73.27	5.06	56.00	0.19	0.79	2.68	1.95	0.70	6.69	7.90	−13.60

Table 2. Cont.

No.	Depth (m)	Sr/Cu	Sr/Ba	V/(V + Ni)	Mn/Fe	Zr (ppm)	HREE (ppm)	LREE (ppm)	Ga (ppm)	V (ppm)	Th/Cr	Th/Sc	La/Sc	La/Co	Al/(Al + Fe + Mn)	Fe/Ti	$\delta^{13}\text{C}$ (VPDB, ‰)	$\delta^{18}\text{O}$ (VPDB, ‰)
66	3318.35	10.91	5.34	0.81	0.03	244.00	15.81	114.26	6.95	118.00	0.20	0.61	2.51	1.58	0.63	8.56		
67	3318.36	13.14	4.61	0.82	0.04	235.00	14.82	116.33	5.70	98.40	0.26	0.59	2.27	1.57	0.64	8.56		
68	3322.25	19.05	5.86	0.83	0.04	125.00	19.92	123.21	5.00	90.90	0.30	0.59	2.55	2.05	0.63	8.65	8.90	−4.30
69	3322.29	10.35	3.90	0.84	0.04	219.00	17.24	108.73	8.98	122.00	0.33	1.00	3.56	2.25	0.72	7.46	8.70	−9.40
70	3338.05	14.27	4.26	0.86	0.03	232.00	19.39	87.07	7.91	114.00	0.17	0.52	2.86	2.41	0.73	6.28	5.60	−9.10

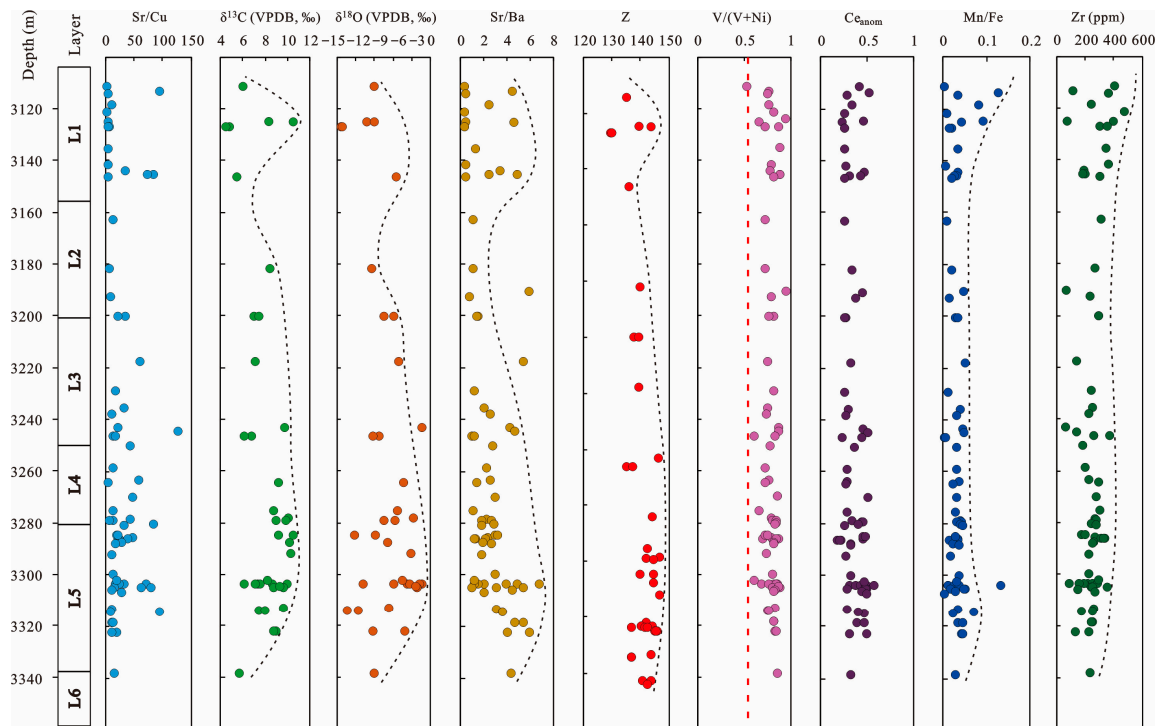


Figure 4. Profile of indicators for paleo-climate (Sr/Cu and $\delta^{13}\text{C}$), paleo-salinity (Sr/Ba and Z), paleo-limnology ($\delta^{18}\text{O}$ and $\delta^{13}\text{C}$), redox condition (V/(V + Ni) and Ce_{anom}), and paleo-water depth (Mn/Fe and Zr). Black dashed line represents the outer envelope of data points. Red dashed line is the threshold of anoxic reducing condition (V/(V + Ni) = 0.54).

4.1.3. Paleo-Salinity Analysis

The Sr concentration or the Sr/Ba ratio can be used as a sensitive indicator of paleo-salinity [29]. In general, Sr and Ba concentrations are low in freshwater. As salinity increases, Sr exhibits a higher concentration, while the Ba content shows no increase, resulting in much higher Sr/Ba values [29]. The thresholds of Sr/Ba for siliciclastic sediments were proposed based on a large database of geochemical data, with <0.2, 0.2–0.5, and >0.5 indicative of freshwater, brackish, and marine facies, respectively [29,30]. In the study area, the Sr/Ba ratio ranges from 0.23 to 6.67, with a median of 2.18, indicating a saline sedimentary environment (Figures 4 and 5).

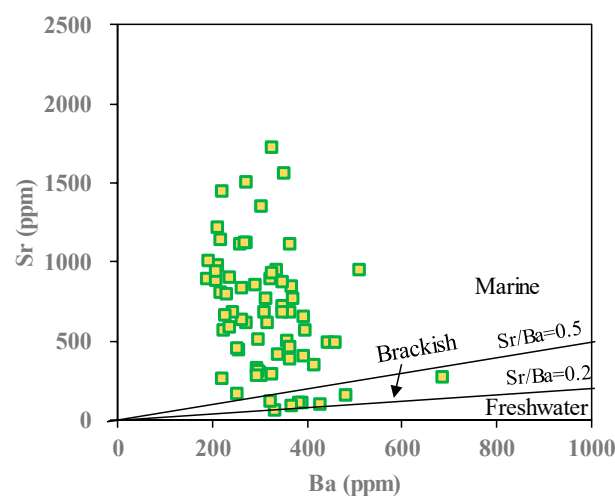


Figure 5. Plot of Sr versus Ba concentrations. Thresholds for Sr/Ba were suggested by Wei and Algeo (2020) [29].

Carbon and oxygen isotopes can also aid in deciphering the paleo-salinity levels of lakes. Assuming minimal impact from burial diagenesis and the absence of metamorphism in the carbonate sediments, the aquatic conditions prevailing during the formation of sedimentary rocks can be determined using the formula below [31]:

$$Z = a(\delta^{13}\text{C} + 50) + b(\delta^{18}\text{O} + 50)$$

where the values of $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ are relative to the PDB standard, $a = 2.048$, and $b = 0.498$. The Z value represents the level of paleo-salinity in the lake water, where higher Z values correspond to greater paleo-salinity in the lake. A value of $Z \geq 120$ indicates salt water-brackish water, while a value of $Z < 120$ indicates freshwater [31]. The Z values of the studied samples were calculated using the above formula.

In the study area, the fluctuations in Z value, $\delta^{18}\text{O}$ value, Sr concentration, and Sr/Ba ratio exhibit consistency, indicating periodic variations in lake water salinity during the deposition of the Lucaogou Formation (Figure 4). Specifically, the salinity started to rise during the deposition of L6, peaked in the middle of L5 deposition, gradually decreased, and then rose again during L1 deposition. These fluctuations in paleo-salinity closely correlated with past climatic changes. During hot and arid climates (L5), salinity experienced a notable increase. Conversely, in relatively warm and humid climates (L2), salinity decreased, potentially as a result of increased precipitation or reduced evaporation. Consequently, the water depth during the deposition of the Lucaogou Formation progressively increased over time.

4.1.4. Paleo-Limnological Analysis

Talbot and Kelts analyzed the carbon and oxygen isotopic data of lacustrine carbonates to study the paleolimnological signatures from organic carbon-rich lacustrine sediments [32]. They found that in open lake basins, there is no significant correlation between the carbon and oxygen isotopes. In a coordinate system with $\delta^{18}\text{O}$ as the horizontal axis and $\delta^{13}\text{C}$ as the vertical axis, the data of lacustrine carbonates from open lakes, such as Greifensee Lake in Switzerland, Henderson Lake in the United States, and Huleh Lake in Israel, fall in the third quadrant, and there is no significant correlation between $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ (Figure 6). In closed lake basins, on the other hand, carbonates show a strong covarying relationship between oxygen and carbon isotopes. Most of the data from closed lakes, such as the Great Salt Lake, Turkala Lake, and Natron-Magadi Lake in the United States, fall in the first and fourth quadrants (Figure 6). In these cases, there is a clear linear correlation between $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$. In general, lakes that exhibit greater proximity to a closed system tend to display a higher correlation coefficient (R^2). Lakes meeting the criterion of $R^2 > 0.5$ are categorized as closed systems [32–34].

The $\delta^{18}\text{O}$ of the Lucaogou Formation in the study area ranges from -14.5‰ to 0.2‰ with a median of -6.5‰ . The $\delta^{13}\text{C}$ value ranges from 4.4‰ to 10.4‰ with a median of 8.4‰ (Table 2). The data almost fall in the fourth quadrant, implying that the lake basin was closed during the deposition of the Lucaogou Formation. However, with an R^2 value of 0.12 for the relationship between $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$, it is evident that the lake is not a completely closed system (Figure 5).

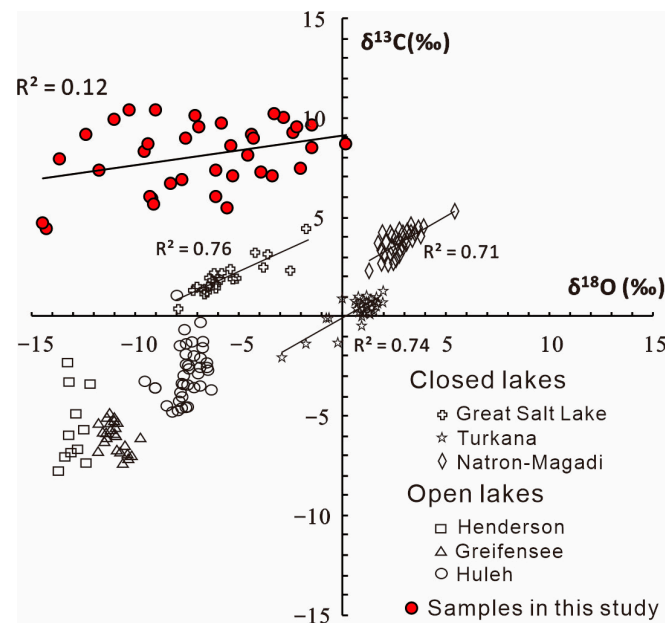


Figure 6. Relationship between $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ for the Lucaogou Formation and lacustrine carbonates from different modern lakes (modified from [32]).

4.1.5. Redox Condition

The $\text{V}/(\text{V} + \text{Ni})$ ratio is a reliable indicator of sedimentary environments [35,36]. A $\text{V}/(\text{V} + \text{Ni})$ ratio > 0.54 reflects an anoxic-reducing condition, a $\text{V}/(\text{V} + \text{Ni})$ ratio between 0.46 and 0.60 indicates a dysoxic condition, and a $\text{V}/(\text{V} + \text{Ni})$ ratio < 0.46 indicates an oxic condition [35]. The $\text{V}/(\text{V} + \text{Ni})$ ratio of the studied samples ranges from 0.53 to 0.95, with a median of 0.81, indicating an anoxic-reducing condition during the deposition of the Lucaogou Formation (Figure 7).

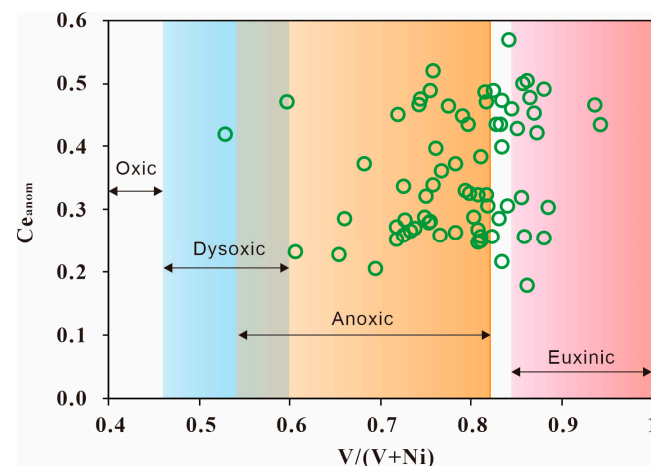


Figure 7. Plot of Ce_{anom} versus $\text{V}/(\text{V} + \text{Ni})$ for the studied samples. Thresholds for $\text{V}/(\text{V} + \text{Ni})$ were suggested by Hatch and Leventhal (1992) [35].

The REE characteristics, such as Ce and Eu anomalies, are also indicative of the redox condition of the sedimentary environment [37]. Ce anomalies (Ce_{anom}) are caused by a change in Ce relative to the adjacent La and Nd. Ce anomalies are calculated using the following formula [37]:

$$\text{Ce}_{\text{anom}} = \log [3\text{Ce}/(2\text{La} + \text{Nd})]$$

Using the North American shale standard, it is determined that $\text{Ce}_{\text{anom}} > -0.1$ reflects the enrichment of Ce and indicates an anoxic-reducing paleo-aquatic environment, while

$Ce_{anom} < -0.1$ reflects the depletion of Ce and indicates an oxidative paleo-aquatic environment. The Ce_{anom} values of the studied samples range from 0.18 to 0.57, with a median of 0.33, reflecting the significant enrichment of Ce and indicating a reducing paleo-aquatic environment (Figures 4 and 7).

4.1.6. Paleo-Water Depth Analysis

The distribution and dispersion of elements are linked to variations in water depth (offshore distance). Major elements, trace elements, and REEs are valuable markers for determining the paleo-water depth [38–41]. Fe is prone to oxidation and tends to accumulate in shallow water or nearshore regions. In contrast, Mn is more stable than Fe and can accumulate in areas further offshore. Therefore, a higher Mn/Fe ratio indicates greater relative water depth [38,39]. Zr is a continental element, primarily transported by mechanical processes, and is typically deposited in nearshore regions [39,41]. Hence, it is commonly utilized as an indicator of distance from the source area. A diminishing Zr content in rocks signifies greater distance from the source area. The Mn/Fe and Zr ratios of the studied samples suggest that the paleo-water depth of the Lucaogou Formation generally increased from L6 to L1 (Figure 4).

4.1.7. Extreme Environmental Response Analysis

The distribution of light REEs (LREE) signifies a terrigenous input, while heavy REEs (HREEs) tend to be enriched in marine settings, reflecting marine sedimentation. When LREE predominates over HREE, the sedimentary environment is characterized by continental facies, typically associated with lacustrine deposition. Conversely, if HREE surpasses LREE in a localized area or region, a transgressive event is likely. Elemental concentrations of Sr, Ga, V, and B along with their ratios can provide insights into neritic and continental sedimentation [30]. In the study area, all samples exhibited LREE dominance over HREE, indicating a continental sedimentary setting during the deposition of the Lucaogou Formation (Figure 8). Nevertheless, notable reductions in the discrepancy between LREE and HREE suggest the incursion of seawater during the deposition of L5, L3, L2, and L1 (Figure 8). This interpretation finds support in the fluctuation of Ga and V concentrations (Figure 9).

Source rocks give rise to sedimentary rocks as a result of external processes, like weathering, erosion, transportation, and sediment deposition. During these processes, not all elements undergo fractionation [42–44]. Previous studies have demonstrated that many elements exhibit minimal to no fractionation during external processes, making them useful indicators for determining the source rock of sedimentary formations [43–45]. Cullers (2000) proposed the thresholds for Th/Sc, Th/Cr, La/Sc, and La/Co ratios to identify felsic and mafic source rocks [45]. By analyzing the Th/Sc, Th/Cr, La/Sc, and La/Co ratios of the studied samples, it is suggested that the predominant source lithology for the Lucaogou Formation is primarily felsic igneous rock (Figure 10). Some samples fall within the mafic and intermediate ranges, indicating several transient changes in source rocks during the deposition of the Lucaogou Formation (Figure 10).

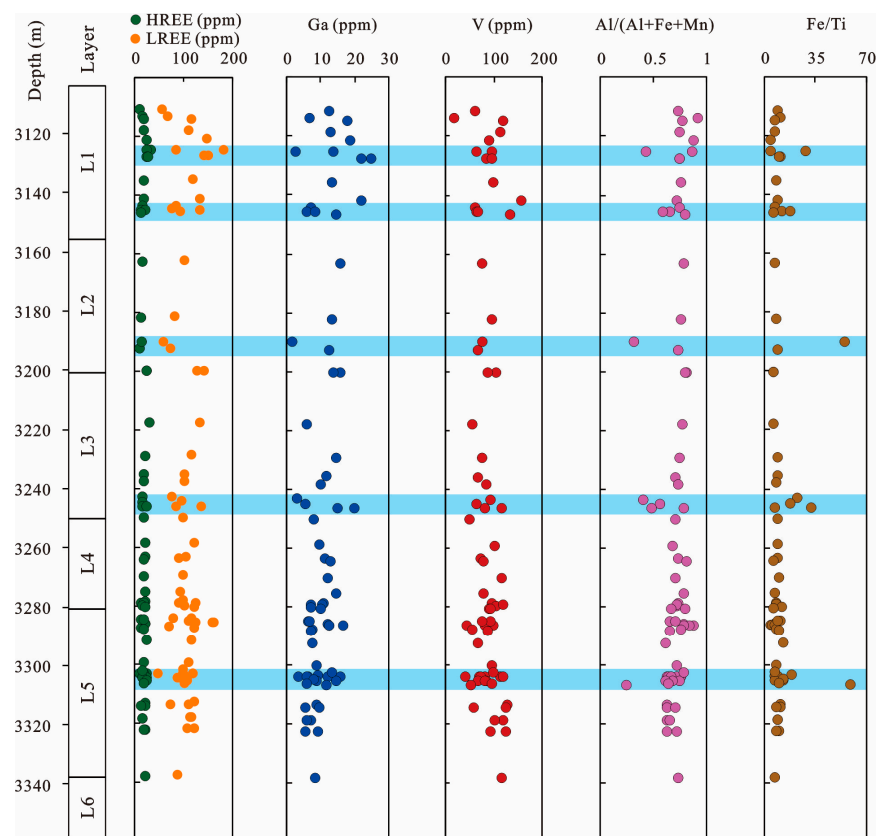


Figure 8. Profile of extreme environmental parameters including transgression parameters (HREE, LREE, Ga, and V), and hydrothermal sedimentation parameters ($Al/(Al + Fe + Mn)$ and Fe/Ti). Colored areas represent the occurrence of transgression and hydrothermal sedimentation, identified by low values of the difference between LREE and HREE, high Ga and V values, low $Al/(Al + Fe + Mn)$ ratio, and high Fe/Ti ratio.

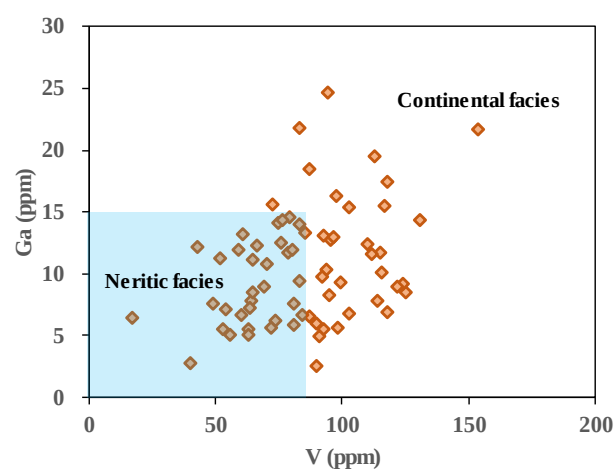


Figure 9. Cross plots of V and Ga. Thresholds were suggested by Chen et al. (1997) [30].

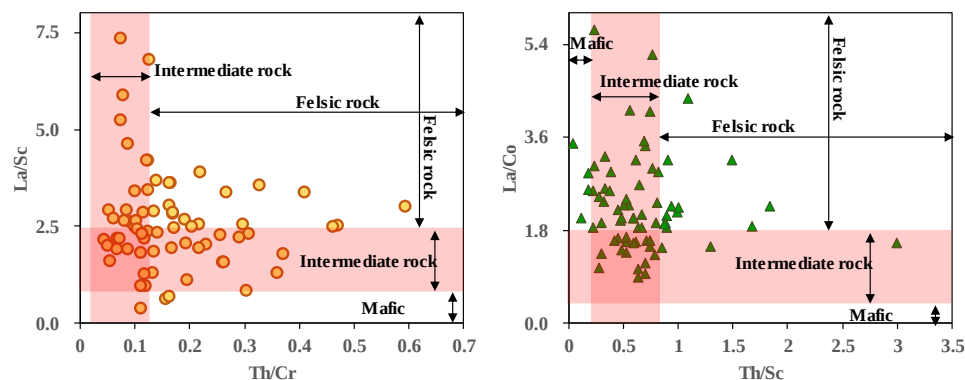


Figure 10. Discriminant diagrams for sedimentary provenance for the studied samples. Thresholds were suggested by Cullers (2000) [45]. Th/Cr: Felsic (0.13–2.7), intermediate (0.016–0.13), mafic (0.018–0.016); La/Sc: felsic (2.5–16.3), intermediate (0.86–16.3), mafic (0.43–0.86); Th/Sc: felsic (0.84–20.5), intermediate (0.22–0.84), mafic (0.05–0.22); La/Co: felsic (1.8–13.8), intermediate (0.38–1.8), mafic (0.14–0.38).

In hydrothermal sedimentary regions, high contents of Fe and Mn are commonly found and are closely linked to each other [46]. In contrast, in normal sedimentary rocks, Fe and Mn are not correlated. Bostrom (1973) highlighted that the Fe/Ti and Al/(Al + Fe + Mn) ratios in marine sediments serve as indicators of the hydrothermal influence on the sediments [47]. Values exceeding 20 and below 0.4 for the aforementioned ratios are generally considered indicative of sediments sourced from hydrothermal origins. In the Lucaogou Formation of the Jimsar Sag, normal lacustrine sedimentation prevails. However, hydrothermal sedimentation occurred during the deposition of L5, L3, L2, and L1, as evidenced by alterations in Al/(Al + Fe + Mn) and Fe/Ti ratios (Figure 8). Moreover, all phases of hydrothermal sedimentation coincided with transgressive events (Figure 8).

4.2. Formation Mechanism of Organic-Rich Shale

4.2.1. Organic Matter Enrichment Mode

In the Lucaogou Formation, organic matter primarily has two enrichment modes, one in which organic matter is enriched in a matrix form, and the other in which organic matter is enriched in a laminar form.

The matrix organic-rich shales primarily consist of flat-lens-like structures resulting from the compaction of a mixture of 0.5 mm particles of organic matter and clay. The entire thin section exhibits high fluorescence, with the saprolite matrix displaying a short band and an amorphous shape, while dolomite, quartz, and liptodetrinite are substrate-cemented (Figure 11). Organic matter is densely distributed in shale, with algae and saprolite being particularly abundant, constituting over 65% of the maceral composition. In contrast, other organic macerals are less developed, with an exinite content of less than 10% and the sum of vitrinite and inertinite being less than 20% of the maceral composition. These findings imply that algal blooming is the main formation mechanism, which often leads to the formation of biogenetic quartz (Figure 11) and enrichment of pyrite.

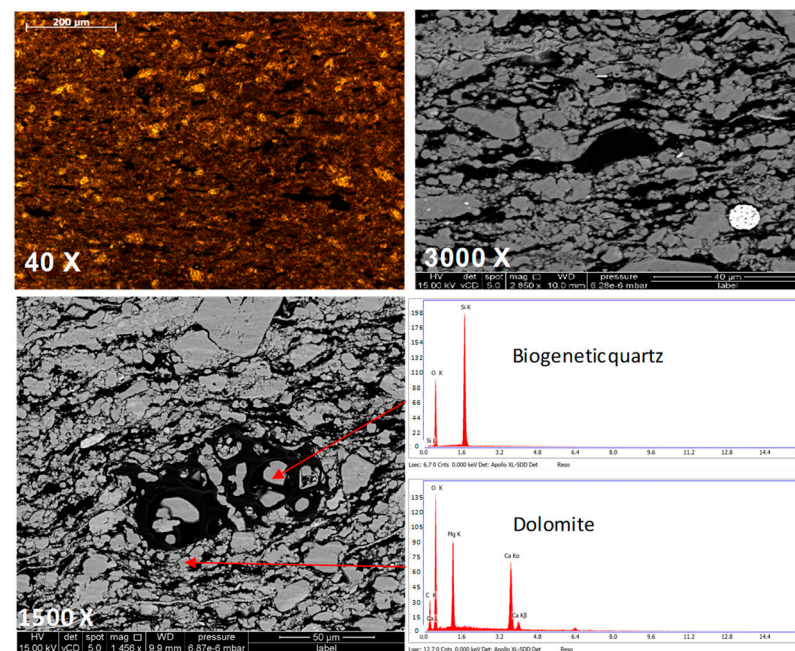


Figure 11. Enrichment mode of matrix organic matter.

The laminar organic-rich shales consist of clear alternating layers of organic-poor calcite and organic-rich silicate mineral layers (Figure 12). Organic matter is primarily concentrated in the dark lamina of the dolomite and feldspar. Sapropelinite appeared as irregular bands interspersed with mineral matrix bitumen, while small vitrodetrinite forms were sandwiched in between, and pyrite particles were widely dispersed. Algae and saprolite are abundant, constituting over 45% of the maceral composition. The vitrinite and inertinite content significantly increased, accounting for 35% to 40% of the maceral composition, while exinite is poorly developed, making up less than 10% of the maceral composition. Their main formation mechanisms involve resuspension and bottom load transport, and these shales typically form in shallow lake slopes with an abundant supply of calcite.

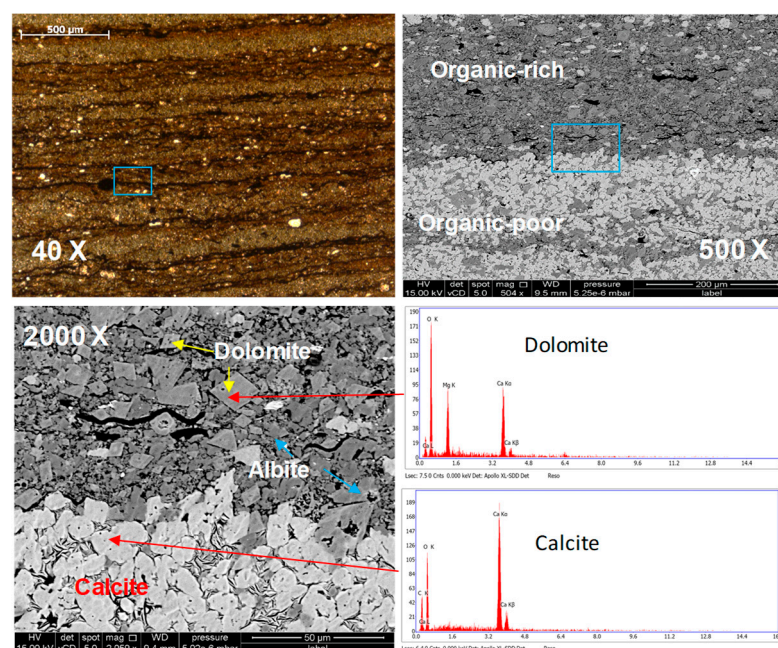


Figure 12. Enrichment mode of laminar organic matter.

4.2.2. Organic-Rich Shale Sedimentation Model

During the deposition of the Lucaogou Formation, the prevailing climate was hot, and the lake water exhibited high salinity and productivity levels. In the initial stages of L6 deposition, the lake was situated in a low-level zone within a brackish water environment, with restricted circulation and low productivity. This condition led to the development of calcite-rich mixed rocks. During L5 deposition, as the lake expanded and deepened due to water influx, occasional connections to the adjacent sea resulted in a significant increase in salinity. The combination of high salinity and hot climate created a stratified water body, with varying temperature and salinity levels, fostering an anoxic lake bottom environment conducive to organic matter preservation. During this period, the lake water was turbid, and calcite was not prominently formed. Instead, deep-water micro-biogenic dolomite predominantly developed, with euhedral dolomite particles forming within the organic-rich lamina. This suggests that the presence of organic matter may play a role in promoting or expediting the formation of dolomite. Subsequently, as seawater retreated from the Junggar Basin, the lake became less affected by marine influences. Increased precipitation events led to a decrease in the lake's salinity, coinciding with a shift in climate from hot and arid to warm and humid. During L2 deposition, with increasing water depth, the input of terrigenous material diminished, and the mixing dynamics weakened, resulting in the formation of a vast, brackish, and restricted lake basin.

The two distinct types of organic-rich shale found in the Lucaogou Formation are indicative of different sedimentary environments. The formation of matrix organic-rich shale is associated with a deep-water continental lake environment, characterized by a hot climate, while the formation of laminar organic-rich shale occurred in a low-salinity shallow water environment with limited circulation and a warm climate.

The presence of organic matter promotes the formation of biogenic microcrystalline dolomite, characterized by euhedral development solely in the organic-rich lamina. Therefore, water stratification and periodic resuspension are proposed as the main mechanisms responsible for the preservation of organic matter in the Lucaogou Formation. The hot, highly saline environment, along with a stable, warm, and brackish water environment, has contributed to the enrichment and preservation of organic matter in the Lucaogou Formation.

5. Conclusions

1. The Lucaogou Formation, divided into six layers (L6 to L1) from bottom to top, showcases varying lithology, logging response, geochemical attributes, and sedimentary structures. The deposition of this formation primarily occurred within a hot and arid climate, in a saltwater depositional environment marked by salinity fluctuations that corresponded with changes in climate conditions.
2. The Lucaogou Formation formed through semi-closed lake sedimentation, characterized by the lake not being completely closed, and exhibited an anoxic-reducing environment. The paleo-water depth increased gradually from L6 to L1, reflecting concurrent changes in climate and salinity. The predominant source lithology is felsic igneous rock. Small-scale transgression and hydrothermal sedimentation occurred during the deposition.
3. The Lucaogou Formation is organically rich due to the stable reducing environment and hot climate. Organic matter is enriched in matrix and laminar modes, formed, respectively, by algal blooming and resuspension transport mechanisms. The matrix organic-rich shale developed in a hot deep-water environment, while the laminar organic-rich shale formed in a shallow water setting, characterized by a warm climate, low salinity, and restricted circulation. The enrichment of organic matter likely contributed to the formation of primary biogenetic dolomite.

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