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RESEARCH ARTICLE

Reconstruction of sedimentary paleoenvironment of Permian Lucaogou Formation and its implications for the organic matter enrichment in south-eastern Junggar Basin, China

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Abstract The Permian Lucaogou Formation represents one of the most important hydrocarbon source rock intervals in the Junggar Basin, although the sedimentary paleoenvironment and organic matter enrichment mechanism of the Lucaogou Formation remain controversial. We studied the temporal evolution of the sedimentary paleoenvironment in the Lucaogou Formation by analyzing the elemental composition and total organic carbon content of 27 hydrocarbon source rock samples from the J305 well in the Jimsar Sag. Using these data, we found that the Lucaogou Formation overall was deposited in a semisaline to saline, reducing lake basin under an arid climate. We identified five organic matter-enriched intervals, which can be correlated with the parameters that indicate a wetter climate and a more anoxic lake environment. To compare sedimentary environments spatially, we compiled environmental indicators from 10 cores and outcrops in three sags around the Bogda Mountains. The compilation shows that the organic matter-enriched Jimsar Sag experienced a more arid climate and a more saline and anoxic lake environment during the deposition of the Lucaogou Formation, which was possibly controlled by the paleogeographic position. We conclude that the spatially arid climate and anoxic environment induced organic matter burial in the Jimsar Sag, while temporal events of a more humid climate and more anoxic environment triggered the enrichment of organic matter in some intervals of the Lucaogou Formation.

Keywords paleoenvironment, organic matter enrichment, Lucaogou Formation, Jimsar Sag, Junggar Basin

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1 Introduction

The Junggar Basin, located in northern Xinjiang Uygur Autonomous Region, is the second-largest inland basin with rich hydrocarbon resources in China (Carroll et al., 2010; Zou et al., 2019). Two sets of main source rocks developed in the Permian in the Junggar Basin: Fengcheng Formation source rocks in the north-western area and Lucaogou Formation source rocks in the eastern area (Cao et al., 2016; Fang et al., 2019). The Lucaogou Formation is considered to be one of the most important hydrocarbon source rock intervals in the Junggar Basin (Zhi et al., 2019). In recent years, many studies have been conducted on the hydrocarbon source rocks of the Permian Lucaogou Formation, mainly in the Jimsar Sag, the perimeter of the Bogda Mountains, and the Fukang Sag in the Junggar Basin (Liu et al., 2022a). The shale oil resources of the Permian Lucaogou Formation in the Jimsar Sag are especially abundant, and several sets of favorable layers for exploitation are developed vertically (Hu et al., 2018). The analysis of the sedimentary paleoenvironment and organic matter enrichment mechanism of the Lucaogou Formation in the Jimsar and adjacent sags would be beneficial to the detailed characterization of sedimentary evolution and shale oil exploitation.

Previous studies have focused on the sedimentary paleoenvironment and organic matter enrichment of the Lucaogou Formation. There are two different views on the evolution of the sedimentary environment of the Lucaogou Formation: one view argues that this formation was deposited in an arid, highly saline, anoxic environment, whereas the strata from the bottom to the top represent a gradual transition toward a more humid climate state, with a lower degree of salinization and more oxic conditions (Jiang et al., 2020; Liu et al., 2022b; Luo et al., 2022; Wang et al., 2022). On the other hand, it is thought that the lower part of the Lucaogou Formation was formed under a warm and humid climate, while the upper part was formed under an arid climate with increased salinization and a more reduced lake environment (Zhao, 2016; Chen et al., 2017; Lin et al., 2019; Zhang et al., 2021a). The Lucaogou Formation was deposited in semideep to deep lake facies, although estimates of relative lake-level change are not consistent (Luo et al., 2022; Wang et al., 2022). To clarify the organic matter enrichment, there are various explanations, including productivity and preservation models (Demaison and Moore, 1980; Arthur and Sageman, 1994). Some researchers suggest that the main factor controlling organic matter enrichment in the Lucaogou Formation is paleoproductivity, while others consider that a reduced lake environment dominated (Zhang et al., 2018; Lin et al., 2019). In addition, proposals state that an enriched organic content is the result of the combined effect of terrestrial debris input, redox conditions, paleoproductivity, and paleoclimate (Luo et al., 2022). Furthermore, researchers have proposed that volcanic hydrothermal activity may be the cause of the formation of dolomitic rocks in the Lucaogou Formation, which likely promoted the production and enrichment of organic matter (Tao et al., 2022).

Debates on the sedimentary environment and organic matter burial mechanism are due to a lack of temporally continuous and spatially correlated data. In this work, we collected continuous shale samples from the J305 well in the Jimsar Sag, studied the elemental geochemical characteristics and organic matter content, and reconstructed the sedimentary paleoenvironment of the hydrocarbon source rocks. Furthermore, we compiled data from 10 wells and outcrop sections in three sags around the Bogda Mountains and compared the spatial differences in the sedimentary environment. Through an analysis of the temporal and spatial evolution of the sedimentary environment in the Lucaogou Formation, we infer that the enrichment of organic matter was tightly linked to the paleoclimate and lake environment.

2 Geological setting

The Junggar Basin, located in north-western China, covers an area of approximately 130×10^3 km^2 (Bian et al., 2010). Tectonically, it is a superimposed basin located at the intersection of the Kazakhstan, Siberian, and Tarim plates (He et al., 2018). The maximum thickness of sediments in the Junggar Basin can reach 15 km, with an age span from Carboniferous to Quaternary (Chen et al., 2016; Gao et al., 2020). Since the late Paleozoic, the basin has experienced several tectonic movements, such as the opening and closure of the paleo-Asian Ocean, the closure of the Tethyan Ocean and the uplift of the Tibetan Plateau (Zhao et al., 2014; Xu et al., 2015).

The Jimsar Sag is located in the eastern part of the basin. It is a west-to-east transcontinental skip-shaped sag that developed on the upper Carboniferous folded basement (Luo et al., 2007; Kuang et al., 2015). Its peripheral boundaries are three faults to the north, south and west and a gradual uplifted slope to the east (Zhang et al., 2021b; Liu et al., 2022a). The Jimsar Sag has been connected with the sags in front of the Bogda Mountains and the water body in the western Fukang Sag since the end of the Carboniferous (Zhi et al., 2022). In the Permian, strong tectonic subsidence occurred in the Jimsar Sag; therefore, the sag, as a relatively independent sedimentary unit, received a set of lacustrine deposits, including the Jingjingzigou Formation and the Lucaogou Formation, forming the most important hydrocarbon source rocks in the region (Qiu et al., 2016; Tian, 2021). In the late Permian to early Triassic, the deposition of the Wutonggou Formation and the Jiucaiyuanzi Formation indicates the secession of the deep lacustrine environment (Tian, 2021).

The Fukang Sag is located in the south-eastern margin of the Junggar Basin and at the northern foot of the Bogda Mountains. It is part of the secondary sag in the eastern Junggar Basin. It is the sag with the most complete stratigraphic development, the thickest source rocks, and the mildest tectonic change in the eastern Junggar Basin (Shi et al., 2018). The Chaiwopu sag is located on the southern margin of the Junggar Basin, between Yilinhebiergen Mountain and Bogda Mountain (Zheng et al., 2022). Although the thickness and grain size of the Lucaogou Formation in the three sags are different, similar lithologic trends are present from the lower member to the upper member of the Lucaogou Formation (Liu et al., 2022a).

The lithology of the Lucaogou Formation in the study area is mainly mudstone, siltstone, and dolomitic rock in lacustrine facies, with the occurrence of fish fossils. According to the lithology and logging curve characteristics, the Lucaogou Formation can be divided into a lower section and an upper section from bottom to top (Luo et al., 2022). Well J305 produced a continuous core of the Lucaogou Formation and contains almost the entire sedimentary section of the hydrocarbon source rock interval (Liu et al., 2019a). Previous studies suggest that the depositional environment of the Lucaogou Formation may have changed frequently during the deposition process, whereas the sweet spot intervals were mainly deposited in the shallow lake to shoreface saline lake environment under an overall dry climate (Liu et al., 2019a, 2019b). In addition, there are multiple core and outcrop data sets in adjacent sags, e.g., the Fukang Sag and the Chaiwopu Sag around the Bogda Mountains-(Fig. 1). Few studies have focused on a synthesis of the paleoenvironmental evolution in different sags.

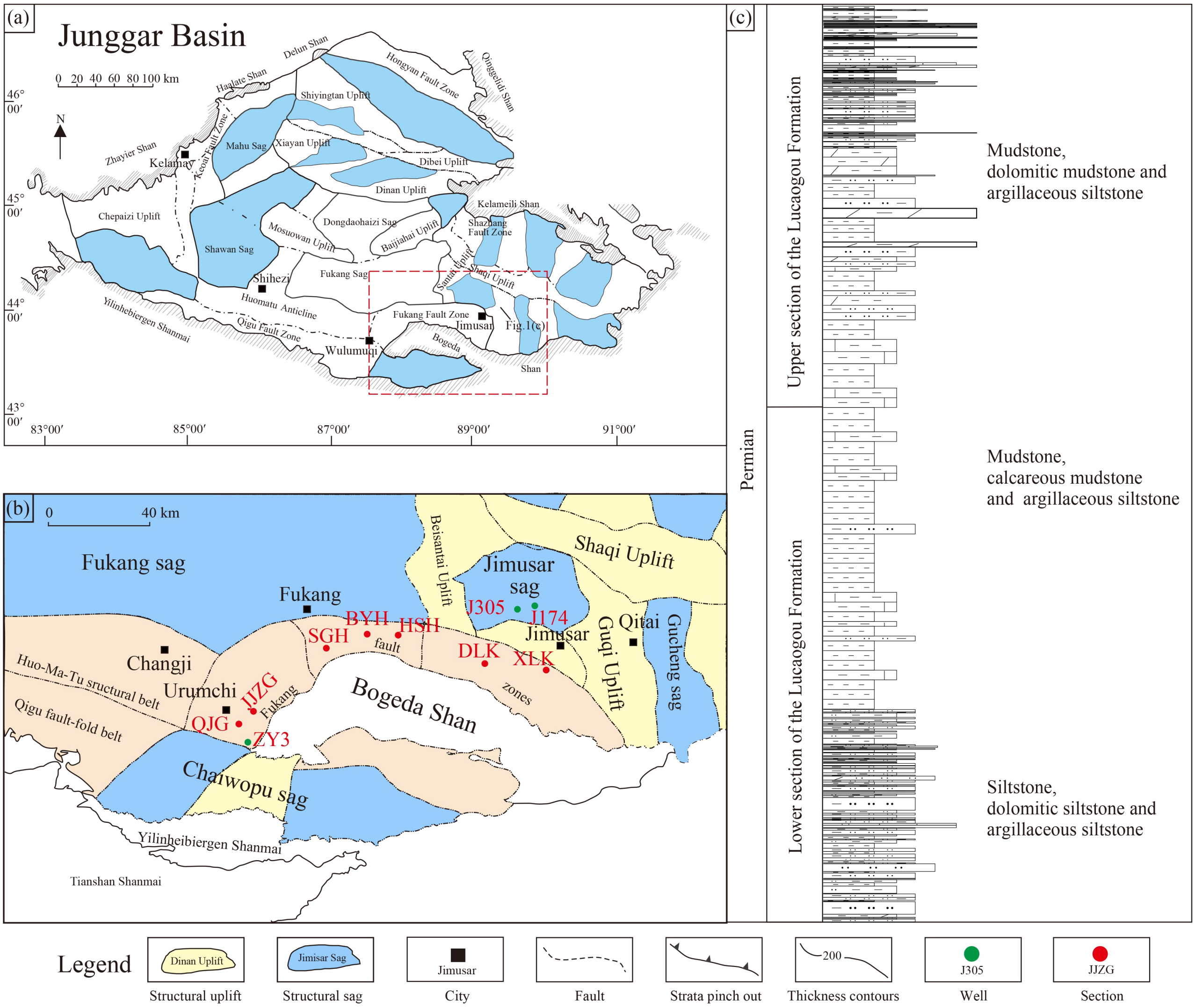

Fig. 1 Geological setting of the south-eastern Junggar Basin and the lithological profile of well J305. (a) Schematic diagram of secondary uplifts in the Junggar Basin; (b) location of well J305 in the Jimsar Sag and other wells/outcrops in adjacent sags compiled in this study; (c) lithological profile of well J305 (modified from Tao et al., 2022).

3 Samples and methods

3.1 Samples

The samples studied in this paper were collected from well J305 in the Jimsar Sag, Junggar Basin. A total of 27 gray and dark gray source rock samples were collected. Among them, 15 samples were from the lower section of the Lucaogou Formation and 12 samples were from the upper section. In this paper, trace element geochemical analysis and total organic carbon (TOC) content analysis were carried out on 27 hydrocarbon source rock samples, and major element geochemical analysis was carried out on 12 samples.

3.2 Major and trace element analyses

The major and trace elemental analysis was carried out at the Oil and Gas Research Center of the North-west Institute of Ecology, Environment and Resources, Chinese Academy of Science (CAS). The samples were first dried in an oven at 105°C for 24 h. After the samples had cooled, 0.5 g of the powder was weighed and mixed with $Li_2B_4O_7$ in a 5:1 ratio to make molten glass beads. The concentrations of the major elements were determined using a Phillips PW 1500 X-ray fluorescence (XRF) spectrometer. The accuracy of XRF analysis was higher than 1% for all major oxides. Trace elements were determined using a Nu Attom inductively coupled plasma mass spectrometry (ICP–MS) instrument. A standard curve was established for the concentration of each element in the standard sample, and the analytical error was less than 2%. In this paper, the elemental abundance of North American shale (NASC) was selected as the reference for comparison (Haskin and Haskin, 1966), and the rare earth elements were standardized to chondrites to investigate the elemental contents of the samples. The elemental content of a sample in the study area was divided by the corresponding elemental abundance in the standard, and a ratio greater than 1 was considered to be relatively enriched, while a ratio less than 1 was considered to be deficient. δCe* was defined as $\delta Ce^* = 3 \times Ce_N/(2La_N + Nd_N)$ for the Ce anomaly, and the Eu anomaly was calculated as Eu/Eu^* (δEu^*) $= Eu_N/(Sm_N \times Gd_N)^{1/2}$, where N is the normalized value for chondrites (Boyton, 1984).

3.3 Total organic carbon (TOC) content analysis

The TOC content analysis was conducted at the Oil and Gas Research Center of the North-west Institute of Ecology, Environment and Resources, CAS. The TOC was tested using a carbon and sulfur analyzer (LECO CS-230). First, to remove inorganic carbon, a powder sample of 300 mg was weighed and subsequently placed in a permeable crucible at 40°C in a beaker with 5% hydrochloric acid for 24 h. Afterward, the sample was washed in the crucible to neutralize it and finally dried. Detailed processing steps follow Shi et al. (2001).

4 Results

4.1 Major and trace elements

The major elemental components of the Lucaogou Formation samples are SiO_2, Al_2O_3, CaO, and MgO, with total mass fractions ranging from 64.76% to 74.80%, of which SiO_2 has the highest mass fraction, with an average of 45.56%. Al_2O_3 and CaO have comparable contents, with averages of 8.87% and 9.24%, respectively, and MgO has a lower mass fraction, with an average of 5.33%. There are also small amounts of Fe_2O_3, TiO_2, MnO, Na_2O, K_2O, and P_2O_5. For the contents of major elements, the samples are higher in Na_2O, MgO, and CaO and lower in Al_2O_3, SiO_2, P_2O_5, K_2O, Fe_2O_3, MnO, and TiO_2 compared with NASC (Fig. 2).

The concentrations of Sr, V, Ni, and Rb in the samples are highly variable (the concentrations are 150.15−870.96 ppm (parts per million), averaging 522.92 ppm; 48.1−110.51 ppm, averaging 76.39 ppm; 9.5−41.74 ppm, averaging 26.54 ppm; and 32.65−108.93 ppm, averaging 65.63 ppm, respectively), with Sr higher than the NASC concentration and V, Ni, and Rb lower than the NASC concentration. The higher concentration of Sr may be due to the higher calcite content in the carbonates. In addition, Mo is relatively enriched compared to NASC, whereas the remaining elements are more deficient (Fig. 2).

The rare earth elements (REE) plots of the samples reveal that the fluctuation trends of the curves are similar. The total rare earth elements (∑REEs) range from 107.94 to 257.17 ppm, with an average content of 161.42 ppm. Light rare earth elements (LREEs) and heavy rare earth elements (HREEs) show divergence. The distribution curves both show a right-tilted distribution pattern, and the LREEs are more enriched than the HREEs. The La–Sm curve is slightly steeper, and the Dy–Lu curve is gentler. These features reflect the typical rare earth distribution characteristics of sedimentary rocks and have similarities with the rare earth element distribution patterns of sedimentary rocks in passive terrestrial source areas. δEu shows obvious negative anomalies (δEu* = 0.5−0.64 with an average value of 0.55). The δCe* values range from 0.92 to 1.11, with an average value of 1.03 and no obvious anomalies (Fig. 3).

4.2 Total organic carbon contents

The organic matter contents of the samples range from 2.66%−13.46%, with an average of 6.58% and a large vertical variation. The contents in the lower section of the Lucaogou Formation range from 2.66%−13.36%, with an average of 6.8%, and the values in the upper section of the Lucaogou Formation range from 2.83%−13.46%, with an average of 6.31%, with an overall high organic matter abundance.

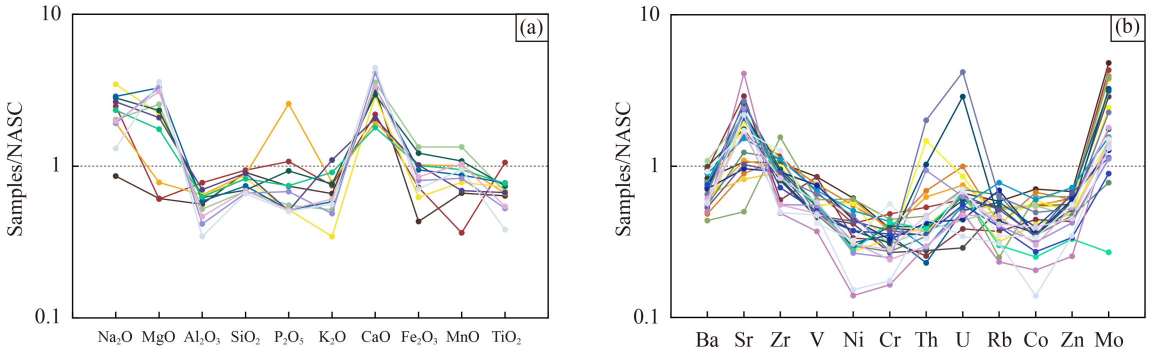

Fig. 2 Comparison of the major (a) and trace (b) element contents of the Lucaogou Formation with those of the North American shale (NASC).

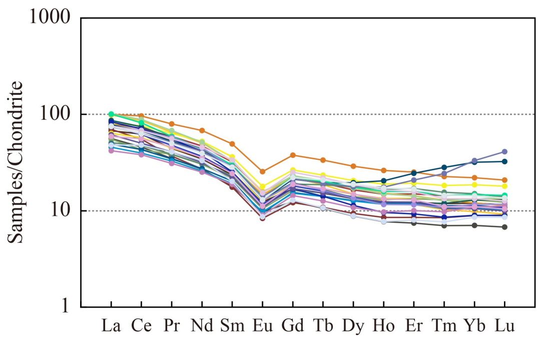

Fig. 3 Normalized rare earth element concentrations of the Lucaogou Formation normalized to chondrites.

5 Discussion

5.1 Temporal evolution of the sedimentary paleoenvironment in the Lucaogou Formation

5.1.1 Paleoclimate

The paleoproductivity of the lake and the supply of terrestrial materials are controlled by the paleoclimate; moreover, the paleoclimate affects the distribution of sedimentary elements and the mineral composition (Zhao, 1992). The elemental enrichment varies under different climatic conditions: elements such as Fe, Mn, Ni, Cr, Co, Cu, and Rb are more easily enriched in warm and humid environments, while elements such as Ca, Mg, Sr, K, Na, and Ta are easily enriched in dry and hot climates (Wang et al., 2014). The Sr/Cu ratio can indicate changes in the paleoclimate. Generally, Sr/Cu < 1 is not indicative, 1 < Sr/Cu < 10 indicates a warm and wet climate, and Sr/Cu > 10 indicates a dry and hot climate (Fan et al., 2012; Wang et al., 2017).

The Sr/Cu values of the lower section of the Lucaogou Formation range from 7.29 to 74.67, with a mean value of 30.19, indicating a hot and arid climate; the Sr/Cu values of the upper section of the Lucaogou Formation range from 4.41 to 31.08, with a mean value of 15.46, which is wetter compared to the lower section of the Lucaogou Formation. Overall, the hydrocarbon source rocks of the Lucaogou Formation were formed under arid paleoclimate conditions. Figure 4 shows that the Sr/Cu values fluctuate vertically. The Sr/Cu ratios are relatively low in the five high TOC-content intervals: interval 1 (depths of 3580–3574 m), interval 2 (depths of 3554–3540 m), interval 3 (depths of 3534–3526 m), interval 4 (depths of 3508–3498 m), and interval 5 (depths of 3448–3434 m). These results show that the high organic matter content is linked to wet climate conditions and that the low organic matter content is linked to an arid climate.

The paleoclimate characteristics can be indicated by the degree of chemical weathering of rocks. Strong chemical weathering usually occurs in tropical–subtropical climatic environments, which can respond to hot and humid climatic conditions to a certain extent. Moderate chemical

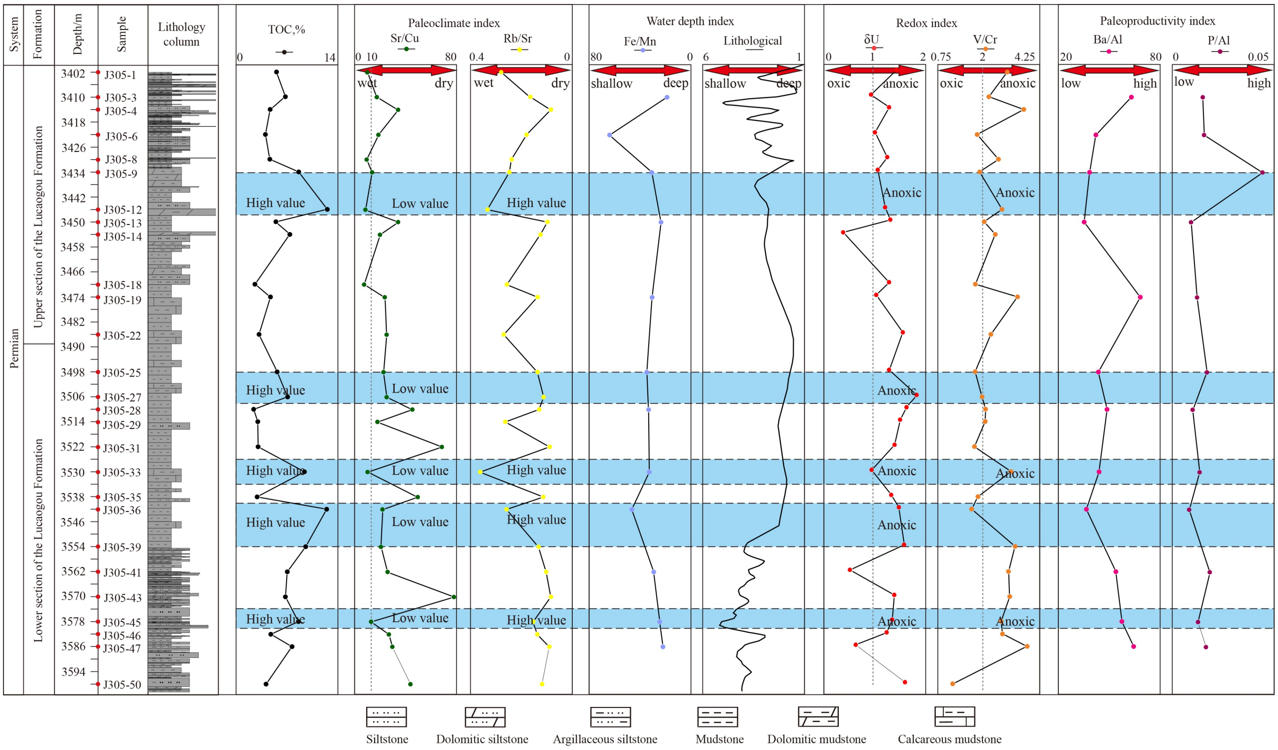

Fig. 4 Plot of TOC contents and indicators of paleoclimate, water depth, redox conditions, and productivity versus depth in the Lucaogou Formation in the J305 well.

weathering often occurs in warm and humid environments, while the degree of chemical weathering in cold and dry environments is usually low. Rb can be retained in source rocks for a long time and migrate slowly, while Sr is easily shed during chemical weathering, leading to a gradual decrease in the Sr concentration (Unkel et al., 2010). Therefore, the Rb/Sr ratio can be used to assess the degree of chemical weathering. Higher Rb/Sr ratios indicate stronger chemical weathering and a relatively warm and humid climate (Unkel et al., 2010; Yang et al., 2020). The Rb/Sr values of the lower part of the Lucaogou Formation range from 0.06 to 0.336, with a mean value of 0.128; the Rb/Sr values of the upper part of the Lucaogou Formation range from 0.059 to 0.307, with a mean value of 0.176, indicating that the paleoclimate transitions to relatively moist from the lower to upper part of the Lucaogou Formation. As shown in Fig. 4, the trends of Rb/Sr values and Sr/Cu values are basically consistent. The Rb/Sr values of the remaining high-TOC intervals are also relatively high, except for interval 4 (depths of 3508−3498 m), which may be caused by the inconsistent sensitivity of different elements to different climates. The overall indication is that the high organic matter content corresponds to a relatively humid climate.

5.1.2 Paleobathymetry

Elemental geochemical studies have shown that sediments undergo regular dispersion and aggregation of certain elements during deposition, and these processes are related to mechanical partitioning, chemical partitioning, and biological partitioning (McLennan et al., 1995). Elements such as Mn and Al are more stable during migration and increase with increasing water depth; elements such as Fe and Mg are less stable, so Fe/Mn is commonly used to characterize the paleowater depth (Zhang et al., 2003). Some studies have shown that Fe/Mn values less than 100 indicate a deep lake, whereas values of 100−150 indicate a semideep lake, and values of more than 150 indicate a shallow lake environment (Wang et al., 2012). In addition, the variation in the grain size of clastic rocks can often be used to qualitatively determine the variation in the paleowater depth. In general, the finer grain size of clastic rocks indicates weaker hydrodynamic conditions and a deeper corresponding depositional environment. We numbered the lithologic grain size of the J305 wells from fine to coarse by 1−6 to serve as a proxy indicator of the paleowater depth. The specific numbering scheme is as follows: No. 1 represents mudstone, dolomitic mudstone, and gray mudstone; No. 2 represents silty mudstone; No. 3 represents muddy siltstone; No. 4 represents siltstone, dolomitic siltstone, and gray siltstone; No. 5 represents muddy fine sandstone; and No. 6 represents fine sandstone.

The Fe/Mn values in the lower part of the Lucaogou Formation range from 25.04 to 49.40, with a mean value of 34.86. The Fe/Mn values in the upper part of the Lucaogou Formation range from 21.75 to 66.81, with a mean value of 36.54. These results suggest that the Lucaogou Formation overall was deposited in a semideep lake to deep lake environment. The particle size variation in the clastic rocks shows that the mudstone content of the Lucaogou Formation gradually increases from the lower part of the Lucaogou Formation to the upper part of the Lucaogou Formation. The particle size curve indicates a trend of shallow–deep–relatively shallow water depth change. Overall, from the lower part of the Lucaogou Formation to the upper part of the Lucaogou Formation, the water body in the depositional environment had a tendency to become deeper (Fig. 4). The organic matter–enriched intervals generally correlate with deep paleodepths. For example, lower Fe/Mn ratios in stages 1, 3, 4, and 5 indicate a deep lake environment; the lithological index is relatively deep in the paleosols of stages 2, 3, 4, and 5 (Fig. 4). These values correspond to the paleoclimate indicators in Section 5.1.1.

5.1.3 Paleoredox conditions

According to the oxygen concentration at the bottom of the water column, redox conditions can be classified as oxic, suboxic, anoxic, and euxinic phases (Tyson and Pearson, 1991). Tribovillard et al. (2006) concluded that redox-sensitive elements, such as V, Cr, and Co, behave as soluble elements under oxic conditions and insoluble elements under reducing conditions in the sedimentary environment and are enriched autogenously in an oxygen-poor environment. Since the reduction of V occurs mainly in the lower part of the denitrification boundary, V is more likely to be adsorbed and precipitated by colloidal masses and clays in the reducing environment than Cr; therefore, its ratio can be used as an indicator of the oxidation–reduction state (Tribovillard et al., 2006). Generally, V/Cr values < 2 indicate oxidizing conditions, and ratios > 2 indicate anoxic conditions. In addition, previous studies have shown that, compared with Th, the migration ability of U is relatively strong, and the value of δU can be used to indicate changes in redox conditions in the depositional environment, with the expression $\delta U = 2U/(U + Th/3)$, in which $\delta U < 1$ is used for oxic environments and $\delta U > 1$ is used for anoxic environments (Jones and Manning, 1994).

The V/Cr values of the lower part of the Lucaogou Formation range from 0.96 to 3.52, with a mean value of 2.32; the δU values range from 0.77 to 1.44, with a mean value of 1.18. In the upper part, the V/Cr values range from 1.75 to 3.42, with a mean value of 2.42, and the δU values range from 0.70 to 1.31, with a mean value of 1.09. These results indicate that the Lucaogou Formation overall was deposited in an anoxic lake environment.

Some samples indicate an oxic environment, reflecting the fluctuation of redox conditions in sedimentary water bodies. Within the five intervals with high TOC contents, both the δU and V/Cr values ndicate a more anoxic environment, except for interval 2 and interval 4, in which the V/Cr values indicates a weakly oxidizing–weakly reducing environment, indicating a general stratification of the water column. In general, the organic matter enrichment of the Lucaogou Formation occurred in an anoxic-prone environment.

5.1.4 Paleoproductivity

Rich sources of organic matter and good productivity conditions are the basis for organic matter enrichment. Ba is mainly derived from decaying phytoplankton organic matter and barite in the biological skeleton and to a lesser extent from terrestrial detritus and Fe–Mn compounds (Tyrrell, 1999). P is not only one of the essential nutrients for the survival of living organisms but also participates in most of the metabolic activities of living organisms and can be deposited into the sediment together with the remnants of extinct organisms. P is often used to characterize the productivity of a water body (Westermann et al., 2013). Al, Ti, and other elements are often used to indicate the input of terrigenous debris during the sedimentary period of marine/lacustrine sedimentary rocks (Calvert and Pedersen, 2007; Lézin et al., 2013). When assessing the level of paleoproductivity, Ba and P from terrigenous clastic minerals easily cause deviations in Ba and P contents in lake water. The Ba/Al and P/Al ratios are used to remove the influence of terrigenous debris. Therefore, in this paper, we select the Ba/Al and P/Al ratios as indicators for paleoproductivity reconstruction.

The Ba/Al values of the lower part of the Lucaogou Formation range from 28.65 to 62.47, with a mean value of 46.82. The P/Al values range from 0.008 to 0.018, with a mean value of 0.013. In the upper part of the Lucaogou Formation, the Ba/Al values range from 29.50 to 78.41, with a mean value of 49.63. The P/Al values range from 0.0089 to 0.044, with a mean value of 0.019. The productivity levels of the lower and upper sections of the Lucaogou Formation are comparable. Except for the P/Al value in interval 5, which indicates high paleoproductivity, the paleoproductivity indicators in the remaining high TOC intervals do not have obvious peaks. The paleoproductivity indicators do not correspond well with the TOC content and other proxies, which may indicate that the productivity was not coupled to climate and organic matter burial during the deposition of the Lucaogou Formation.

5.2 Relationship between the sedimentary paleoenvironment and organic matter enrichment

To decipher the relationship between the sedimentary paleoenvironment and organic matter enrichment, we performed a correlation analysis of the TOC content with the paleoclimate, redox conditions, paleobathymetry and paleoproductivity. The paleoclimate has a positive correlation with the TOC content ($R^2 = 0.2036$), and redox conditions have a slight trend correlated with the TOC content (Fig. 5). The other two indicators have no correlation with the TOC content. Combined with the vertical variation in paleoenvironmental indicators that is discussion above, it seems that the warm and humid climate, more anoxic environment, and high lake water depth were favorable for organic matter enrichment in the Lucaogou Formation. Below, we discuss multiple factors that potentially influenced organic matter burial.

The change in the climate from a dry state to a wet state directly affects the distribution and flourishing of biological populations and indirectly affects the sedimentary environment, such as the water salinity, redox conditions and material source input (Wittkop et al., 2020). On the one hand, warm and humid climatic conditions are favorable for life activities within the lake basin, which can promote the photosynthetic process and provide organic matter by increasing the level of primary productivity; on the other hand, the wet climate and abundant rainfall increase surface runoff, which provides debris and brings a large amount of nutrients. In addition, the relatively favorable climate may cause stratification of the water column and favor the preservation of organic matter. The Sr/Cu of the Lucaogou Formation correlates with the TOC content, with lower Sr/Cu values correlating to a higher organic matter content (Figs. 4 and 5), indicating that the paleoclimate may be one factor controlling organic matter enrichment in the Lucaogou Formation and that a warm and humid climate promoted organic matter burial.

Redox conditions are an important factor affecting the preservation of organic matter. An anoxic lake environment inhibits the degradation of organic matter and is conducive to the preservation of organic matter. During the depositional period of the Lucaogou Formation, the bottom of the water body was generally in an anoxic and therefore reducing environment, which was favorable for organic matter preservation. Furthermore, the intervals with high TOC contents tend to correlate with layers that formed under a more anoxic environment (Fig. 4). These results indicate that the anoxic environment was also a factor influencing organic matter enrichment.

As discussed above, primary productivity is an important source of organic matter in mud shale, and organic matter enrichment may require high biological productivity to provide organic carbon. However, there seems to be no correlation between the paleoproductivity indices, Ba/Al and P/Al, and the TOC content, which implies that paleoproductivity plays a nonsignificant role in organic matter enrichment in the Lucaogou Formation,

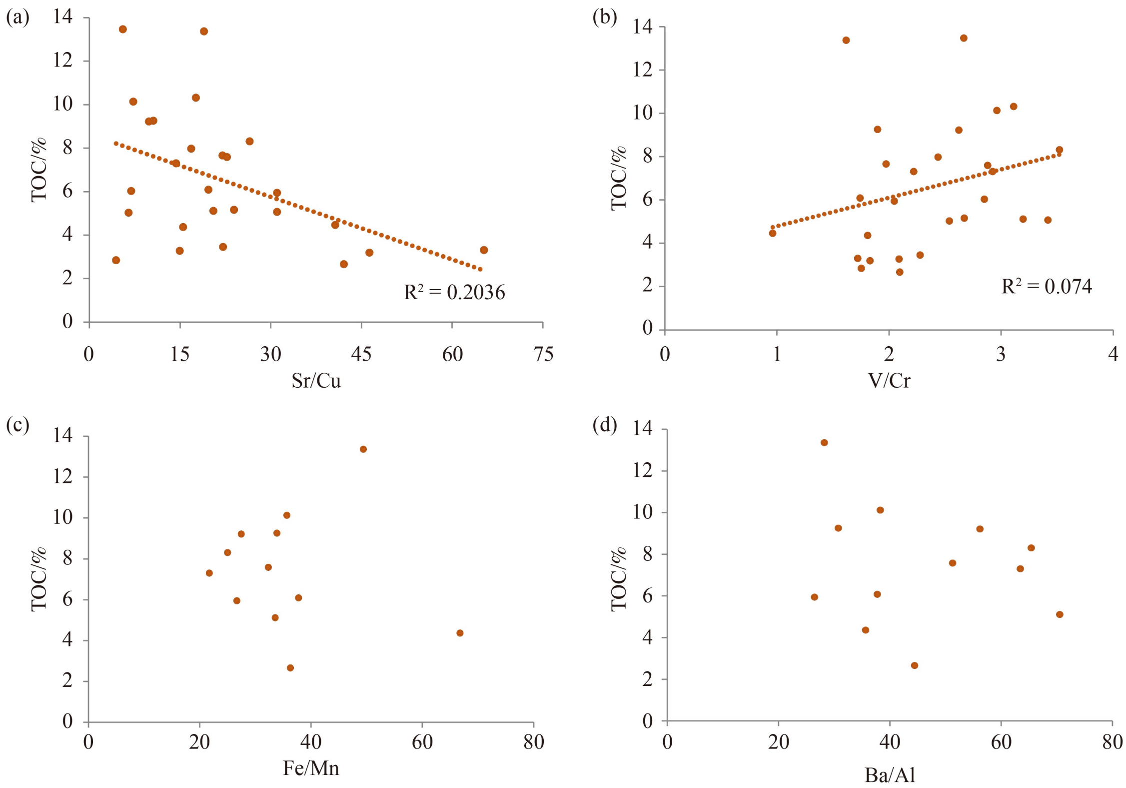

Fig. 5 Relationships between Sr/Cu ratios and the TOC content (a), V/Cr ratios and the TOC content (b), Fe/Mn ratios and the TOC content (c), and Ba/Al ratios and the TOC content (d).

although a low resolution of datapoints may cause bias in the interpretation.

Overall, we consider that the organic matter enrichment of the Lucaogou Formation is the result of the combined effect of paleoclimate, redox conditions and other factors. Primary factors include paleoclimate and redox conditions, and an overall arid climate and anoxic environment promoted organic carbon burial. In addition, temporal events of a more humid climate and more anoxic lake conditions induced an abrupt increase in the TOC content in the vertical section of the Lucaogou Formation.

5.3 Spatial variation in depositional environments in the Lucaogou Formation

A large number of previous studies have been performed on the depositional environment of the Lucaogou Formation in the Junggar Basin, but most of them have focused on one specific section or one well, and thus, a comprehensive and systematic regional comparison is lacking. A study of the spatial differences in the depositional environments of the Lucaogou Formation is important for understanding the evolution of the Permian sedimentary environment in the Junggar Basin. In the south-eastern Junggar Basin, the Lucaogou Formation is widely distributed in the Chaiwopu Sag, the Fukang Sag and the Jimsar Sag around the Bogda Mountains (Fig. 1). In this paper, a cross-sectional comparison is made between the Chaiwopu Sag, the Fukang Sag and the Jimsar Sag to discuss the spatial differences in the depositional environment of the Lucaogou Formation.

The Sr/Cu ratios in the Jimsar Sag are significantly higher than those in the Fukang and Chaiwopu Sags, indicating that the climate in the Jimsar Sag is drier than that in the other two sags (Fig. 6). The chemical index of alteration (CIA) is commonly used to indicate chemical weathering and paleoclimate (Getaneh, 2002; Algeo and Twitchett, 2010). The expression is as follows: CIA = $Al_2O_3/(Al_2O_3 + Na_2O + CaO^* + K_2O) \times 100$; all oxides are in molar units. CaO* represents the CaO in the silicate portion of the rock. The equation for CaO* is as follows (McLennan, 1993): $CaO^* = \min(CaO-10/3 \times P_2O_5, Na_2O)$. The CIA values of the samples from the Lucaogou Formation in the three sags are mostly between 50 and 65, indicating moderate weathering intensity in the area. Except for the Dalongkou section, the CIA values of the Lucaogou Formation in the Jimsar Sag are lower than those in the Fukang and Chaiwopu Sags, indicating weaker chemical weathering and a drier climate (Fig. 6). This difference may be attributed to the paleogeographic distribution of the three sags. During the deposition of the Lucaogou Formation, the Jimsar Sag was a closed lake basin, while the Chaiwopu and Fukang Sags were closer to the Tianshan Mountains. While the Tianshan Mountains impeded atmospheric water vapor transport,

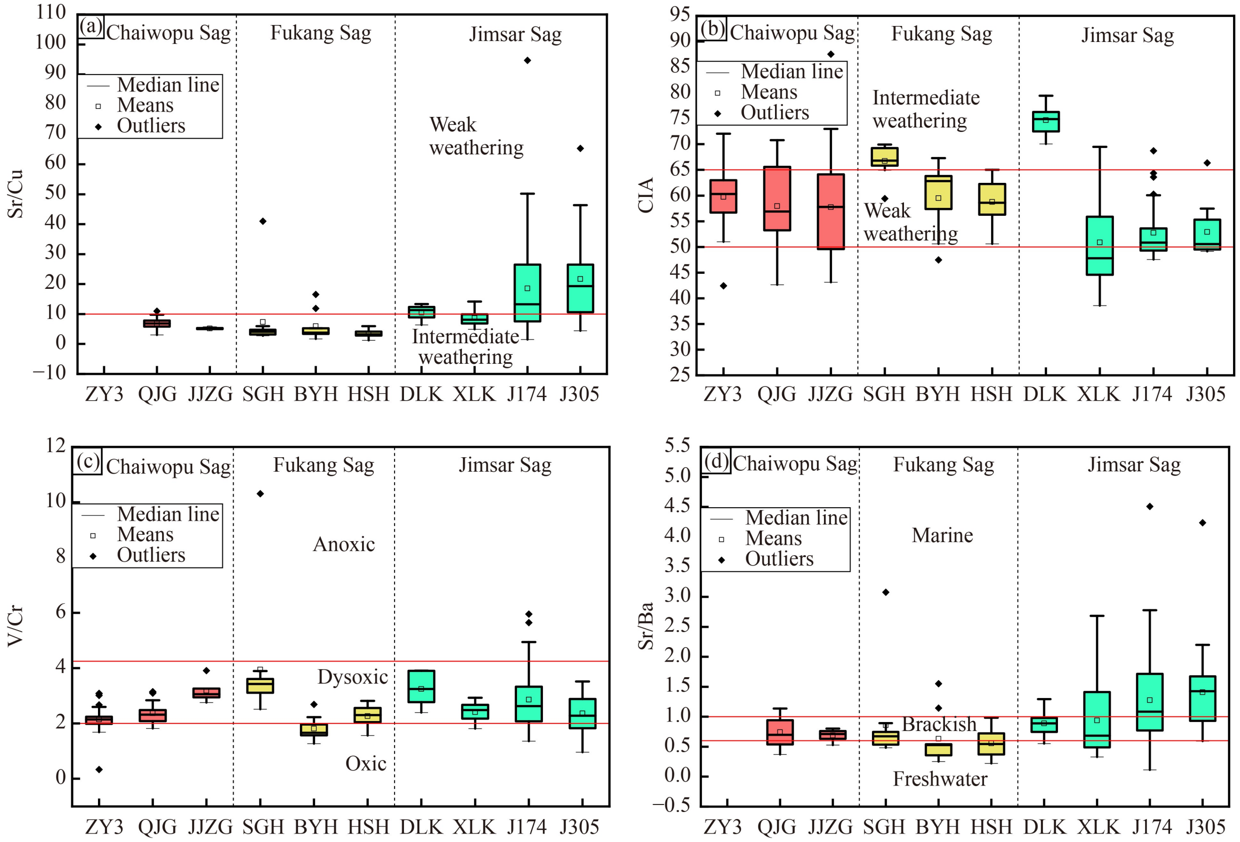

Fig. 6 Comparison of paleoclimatic and paleoenvironmental indicators among the Chaiwopu, Fukang, and Jimsar Sags in the south-eastern Junggar Basin. Abbreviations along the *x*-axis indicate multiple cores and outcrop sections, as shown in Fig. 1 (data of well ZY3 are from Chen et al. (2017); QJG is the Qijiagou section, and the data are from Liu et al. (2022a); JJZG is the Jingjingzigou section, and the data are from Cheng et al. (2022) and Lin et al. (2019); SGH is the Sigonghe section, and the data are from Shi et al. (2018); BYH is the Baiyanghe section, and the data are from Zhao (2016); HSH is the Huangshanhe section, and the data are from Li et al. (2016); DLK is the Dalongkou section, and the data are from Cheng et al. (2022) and Lin et al. (2019); XLK is the Xiaolongkou section, and the data are from Liu et al. (2022a); well J174 is located in the Jimsar Sag, and the data are from Tao et al. (2022)).

they caused cloud accumulation and triggered intermittent rainfall in the mountains. In arid mountainous areas, intermittent rainstorms are likely to cause floods; thus, fan-delta deposits formed at the spillway. This is confirmed by the development of coarse-grained fan-delta deposits in the Chaiwopu Sag (Liu et al., 2022a). In contrast, in the Jimsar Sag, which is farther away from the Tianshan Mountains, lacustrine deposits were mainly developed under less rainfall or flooding.

The V/Cr ratios of the three sags of the Lucaogou Formation are generally in the range of 2 to 4, indicating an anoxic environment (Fig. 6). This result is further supported by the extensive development of pyrite in the Lucaogou Formation (Wang et al., 2022). Compared to the Chaiwopu and Fukang Sags, the slightly higher V/Cr ratio in the Jimsar Sag indicates more reducing lake water conditions. Sr/Ba indicators can be a valid measure of the paleosalinity in fine-grained siliceous clastic deposits (McCulloch et al., 2005). The Sr/Ba ratios of the samples from the Chaiwopu Sag and the Fukang Sag are similar, ranging from 0.5 to 1, indicating that these sags were in a semisaline environment (Fig. 6). The Sr/Ba ratio of the Jimsar Sag is significantly higher than that of the Chaiwopu Sag and the Fukang Sag (Fig. 6), indicating that the paleolake in the Jimsar Sag had a higher paleosalinity. This is also consistent with the presence of gypsum pseudocrysts, which are indicative of high salinity and strong evaporation, as discovered by Wu et al. (2017) in the Lucaogou Formation in the Jimsar Sag.

The compilation of the spatial variation in paleoenvironmental indicators in the three sags indicates that the Jimsar Sag experienced a more arid climate and a more saline environment than the Chaiwopu and Fukang Sags during the deposition of the Lucaogou Formation. In addition, the TOC content of the Lucaogou Formation in the Jimsar Sag is higher than those of the other two sags and is especially higher than that of the Chaiwopu Sag (Zhang et al., 2018; Lin et al., 2019). By comparing the spatial differences in the depositional environments of the Chaiwopu Sag, the Fukang Sag and the Jimsar Sag and combining the TOC contents in the three sags, it can be concluded that a special paleogeographic location of the Jimsar Sag led to a more arid climate, a more saline depositional environment, and more anoxic lake conditions. These factors controlled the spatial variation in the TOC content in the south-eastern Junggar Basin.

6 Conclusions

By analyzing paleoenvironmental indicators based on the elemental compositions and TOC contents of the well J305 samples and compiling data sets from the Jimsar Sag and two adjacent sags, we discussed the temporal and spatial evolution of the sedimentary environment in the Lucaogou Formation in the south-eastern Junggar Basin and interpreted their implications for organic matter enrichment. Overall, the Lucaogou Formation was deposited under an arid climate and anoxic lake conditions, although fluctuating environments occurred. A spatial comparison of sedimentary environments in the three sags indicates that the organic matter-enriched Jimsar Sag experienced a more arid climate and a saltier and more anoxic lake environment during the deposition of the Lucaogou Formation due to its specific paleogeographic position. The spatially arid climate and anoxic environment induced organic matter burial in the Jimsar Sag, while temporal events of a more humid climate and more anoxic environment triggered organic matter-enriched intervals in the Lucaogou Formation.

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