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EDITED BY

Ramanathan Alagappan,
Independent Researcher, Tiruchirapalli, India

REVIEWED BY

Arif Husain Ansari,
Birbal Sahni Institute of Palaeosciences
(BSIP), India
Igor Hamid,
Federal University of Ceara, Brazil

*CORRESPONDENCE

Haowen Deng,
✉ haowendeng2025@163.com

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High-resolution carbon and oxygen isotope records in the Chang 7 organic-rich shale of the Yanchang formation, Ordos Basin, China and their geological significance

Haowen Deng*

College of Geosciences, Northeast Petroleum University, Daqing, China

The Late Triassic Chang 7 Member lacustrine organic-rich shale in the Ordos Basin is the most significant source rock for the Mesozoic oil system in the basin. This study utilizes high-resolution source rock samples to systematically analyze the organic carbon isotopes and carbonate carbon-oxygen isotopes of the Chang 7 Member source rocks. The results indicate that the average $\delta^{13}\text{C}_{\text{carb}}$ values for the Chang 7₁ to Chang 7₃ sub-members are 0.17‰, 0.33‰, and -2.8‰, respectively, and the average $\delta^{18}\text{O}_{\text{carb}}$ values are -14.1‰, -14.3‰, and -16.0‰, respectively. The Chang 7₃ sub-member exhibits anomalously low $\delta^{13}\text{C}_{\text{carb}}$ and $\delta^{18}\text{O}_{\text{carb}}$ values due to the influence of volcanic and hydrothermal activity. The carbon-oxygen isotopes, together with other element proxies, indicate that the Ordos Basin had semi-closed to semi-open hydrological conditions during the depositional periods of Chang 7₁ and Chang 7₂, with an overall warm and humid climate. The climate during the Chang 7₂ depositional period was relatively stable, while the Chang 7₁ period showed a trend towards increasing aridity. The lake during the Chang 7 depositional period had high paleo-productivity, with sedimentary organic matter being of mixed origin, primarily from aquatic organisms with some contribution from C3-type terrestrial higher plants. The findings of this study provide support and reference for research on paleoclimate, paleoenvironment, and organic matter enrichment mechanisms in the region.

KEYWORDS

triassic, carbon and oxygen isotope, organic matter, paleoproductivity, paleoclimate, source rocks

1 Introduction

Paleolake sediments contain abundant and valuable records of environmental conditions, often recording local and regional responses to climate (Alonso-Zarza, 2003; Jin et al., 2004). Stable carbon and oxygen isotopic composition of lake sediments (including lacustrine authigenetic carbonate and organic matter) is one of the most widely used indicator, which can be used in paleohydrology (e.g., closed or open lake, the change of water level and the source of lake water) and

paleolake hydrochemistry (e.g., salinity), paleoclimate (e.g., temperature, precipitation and their seasonal variation) and lake paleoproductivity (Wang and Zhang, 1999; Khadkikar et al., 2000; Nordt et al., 2002; Budd et al., 2002; Leng and Marshall, 2004; Retallack, 2005; Cai et al., 2009; Breecker et al., 2010; Hong and Lee, 2012; Li et al., 2013; Arefev et al., 2015). These paleoenvironmental and paleoclimate informations are important for understanding the abundance, biochemical degradation and preservation of organic matter in sedimentary rocks of petroliferous basins (Liu et al., 2001; 2004).

The Chang 7 lacustrine organic-rich shale of the Upper Triassic Yanchang Formation is the most important oil source of the Mesozoic petroleum system in the Ordos Basin, Central China (Qiu et al., 2014; Yuan et al., 2017; Yuan et al., 2019a; Yuan et al., 2019b; Yuan et al., 2020). Previous studies on the stratigraphic sequence, lithofacies paleogeography, element and organic geochemistry characteristics of the Chang 7 Member have been carried out (Yang and Zhang, 2005; Qiu, 2011; Yang and Deng, 2013; Qiu et al., 2014; 2015; Yuan et al., 2015; Zhang et al., 2015; He et al., 2016; Li et al., 2017; Wang et al., 2017; Yuan et al., 2017; Yuan et al., 2019a; Yuan et al., 2020), however, the characteristics of stable carbon and oxygen isotopes remain uninvestigated. Their analysis can provide potential new insights in comparison with existing studies. Therefore, it is necessary to systematically analyze the carbon and oxygen isotopic characteristics of the Chang 7 Member, further to reconstruct the local and regional paleoclimate during the deposition of the Chang 7 organic-rich shale and provide geochemical evidence for the correct understanding of the sedimentary evolution of the study area.

In this paper, a large number of high-resolution carbon and oxygen isotope data from bulk carbonates and organic matters in the Chang 7 Member lacustrine sediments are provided, and many data of DOP_T , $\text{C}_{\text{org}}:\text{P}$, CIA and AI contents of the Chang 7 shale are collected from previously published literature (Yuan et al., 2017; Yuan et al., 2019a; Yuan et al., 2020). We mainly attempt to study the stable carbon and oxygen characteristics and changes of paleoproductivity, paleoclimate and paleoenvironment during the Chang7 sedimentary period.

2 Geological setting

The Ordos Basin of central China (Figure 1) is a prolific petroliferous basin consisting of six tectonic units: Yimeng uplift, West margin thrust belt, Tianhuan depression, Yishan slope, Jinxi flexure belt, and Weibei uplift (Figure 1) (Yang and Deng, 2013; Qiu et al., 2014; Yuan et al., 2017; Yuan et al., 2019a; Yuan et al., 2020). The basin formed on Paleozoic strata of the North China Craton (Figure 2) (Wan et al., 2013; Qiu et al., 2014; 2015). The tectonic evolution of the Ordos Basin during the Triassic was tied to the Indosinian Orogeny, which comprises two episodes: the Early Indosinian Orogeny corresponding with the end of Middle Triassic and the Late Triassic Late Indosinian Orogeny (Yuan et al., 2019a; Yuan et al., 2020). The Ordos Basin during Early-Middle Triassic time was part of the North China intracratonic depression (Qiu et al., 2014; 2015). By Late Triassic time, the Ordos Basin had evolved to an intracontinental foreland basin characterized by an asymmetric

cross-section comprising of low-gradient northeastern and high-gradient southwestern flanks (Qiu et al., 2014; 2015). Rapid uplift of the Qinling Mountains bordering the basin to the south was accompanied by subsidence of the southern Ordos Basin coincident with the onset deposition of Chang 7 Member (Qiu et al., 2014; 2015; Yuan et al., 2019a; Yuan et al., 2020). Evidence of enhanced tectonic activity documented from the Chang 7 Member include inferred seismites (Li et al., 2008; Qiu, 2011; Xia et al., 2007; Yang et al., 2010), volcanic ash deposits (Qiu, 2011; Zhang et al., 2009; Yuan et al., 2019a), and mineral concentrations (e.g., pyrite veins, marcasite, gypsum, and manganese nodules) attributed to hydrothermal fluid movement (Qiu, 2011; Zhang et al., 2010; Yuan et al., 2017).

The Upper Triassic Yanchang Formation, 1000–1300 m of terrigenous deposits (Qiu et al., 2015), comprises 10 members (Chang 10–Chang 1 from bottom to top) distinguished on the basis of marker beds, sedimentary cycles, and/or lithological association (Qiu et al., 2014; 2015). Peak lake level coincided with deposition of the Chang 7 Member (Yang and Deng, 2013), which is dominated by lacustrine and deltaic sedimentary facies (Yuan et al., 2015). The Chang 7, which includes three sub-members (Chang 7₁, Chang 7₂, and Chang 7₃), comprises 100–130 m of siltstone, mudstone, black shale, and tuff intervals (Figure 3). The organic-rich shale, the principal source of hydrocarbon source rock of the Mesozoic petroleum system of the Ordos Basin, is distributed over much of the southwest Yishan slope and southern portion of the Tianhuan depression (Figure 1), covering an area of more than 10⁵ km² (Qiu et al., 2015). The Chang 7 shale is strongly enriched in TOC content, mostly kerogens of type I or II₁, indicating that the organic matter mainly came from the aquatic plants (Zhang et al., 2015).

3 Materials and methods

Forty-eight organic-rich shale samples used in this study were collected from the Well Yan 56 core, which lies at the periphery of Ordos Basin (Figure 1), covering a thickness of ~122 m (2956–3078 m), including 20 Chang 7₁ samples, 15 Chang 7₂ samples and 13 Chang 7₃ samples. Tuff intervals, pyrite veins and visible phosphate nodules were carefully avoided in the sampling. The total of 48 shale samples were powdered (<200 mesh) in an agate mortar.

The $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ of the bulk lacustrine carbonate in the samples were measured using an automated carbonate preparation device coupled to a Thermo Fisher MAT 253 isotope ratio mass spectrometer (IRMS) at the Analytical Laboratory of the Beijing Research Institute of Uranium Geology. CO_2 gas liberated from the carbonate was extracted by reacting ground samples with dehydrated phosphoric acid in a vacuum. The results are presented using the delta notation referred to the VPDB standard. Repeated measurements of a homogenized sample yields a standard deviation of $\pm 0.1\text{‰}$ for $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ measurements. The $\delta^{13}\text{C}$ of bulk organic matter in the samples were measured at the State Key Laboratory of Petroleum Resource and Prospecting, China University of Petroleum (Beijing). Approximately 100 mg of powder was gently leached using dilute HCl (hydrochloric acid) and rinsed with distilled water to remove inorganic carbon. After drying, the shale

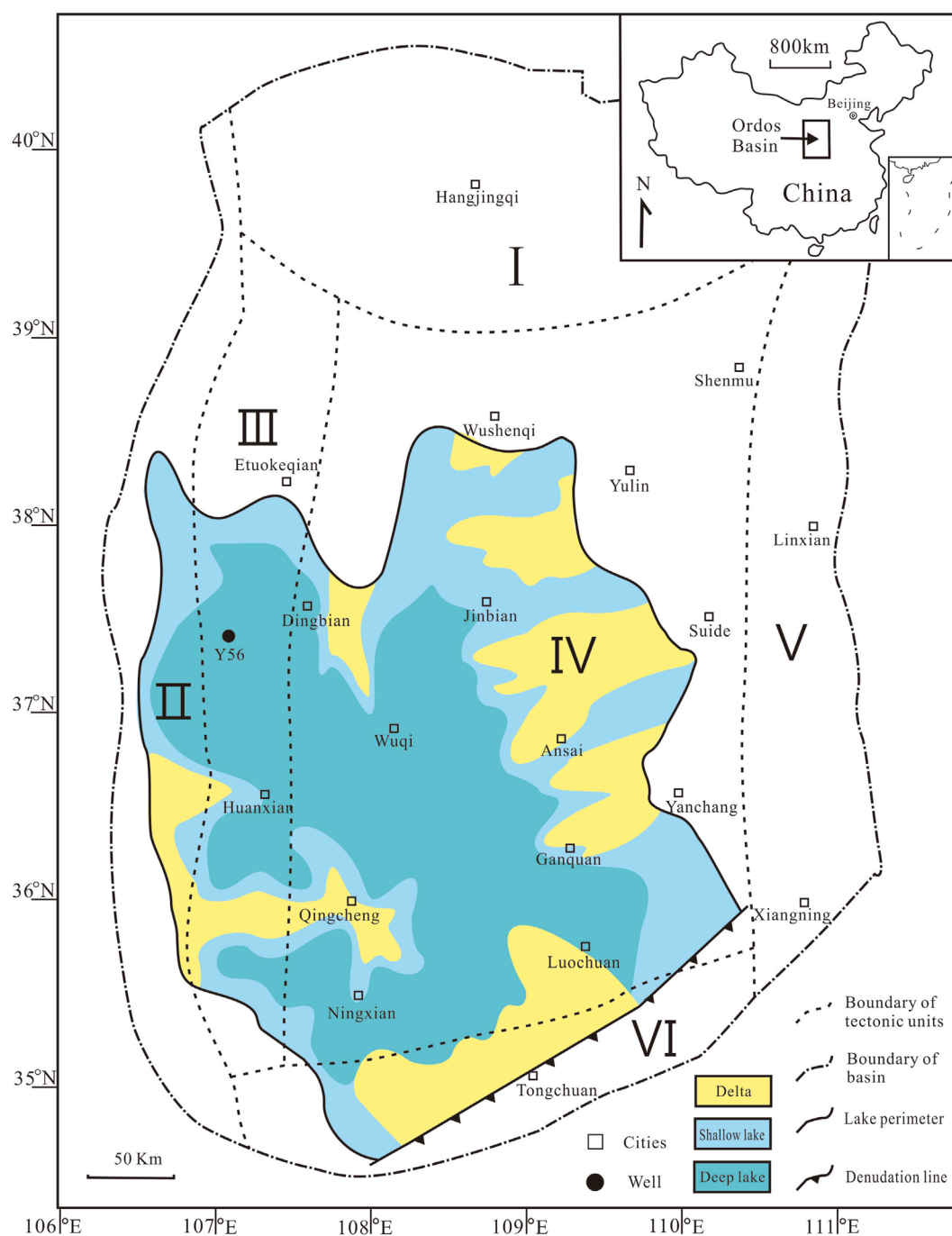


FIGURE 1

Location of the Ordos Basin, its tectonic division, and the location of sample well (after Yuan et al., 2017). I-Yimeng uplift; II-West margin thrust belts; III-Tianhuan depression; IV-Yishan slope; V-Jinxi flexure belts; VI-Weibei uplift.

powders were analyzed using a Finnigan MAT 253 IRMS connecting with Flash 2000HT elemental analyzer. The results are presented using the delta notation referred to the VPDB standard. The analytical precision was better than 0.1‰.

The data of DOP_T , $C_{org}:P$, CIA and Al contents of the Chang 7 shale are collected from publicly available scholarly articles

(Yuan et al., 2017; Yuan et al., 2019a; Yuan et al., 2020). DOP_T represents the ratio of pyrite Fe (based on total S) to total Fe, and $C_{org}:P$ means the molar ratio of organic carbon to total phosphorus (Yuan et al., 2017). $CIA = [Al_2O_3 / (Al_2O_3 + CaO^* + Na_2O + K_2O) * 100]$ in molecular proportions, where CaO^* represents CaO content of the silicate fraction (Nesbitt and Young, 1982).

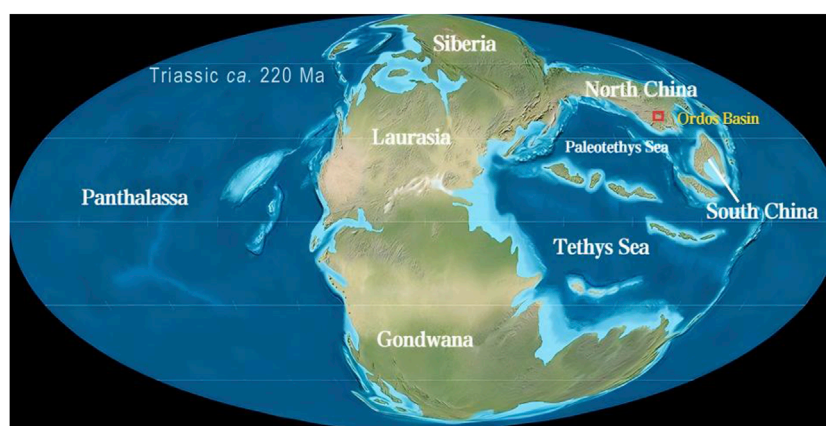


FIGURE 2
Global map of the Late Triassic and the location of the Ordos Basin.

4 Results

4.1 Carbon isotope values of bulk carbonate

The stable carbon isotope values of bulk carbonates ($\delta^{13}\text{C}_{\text{carb}}$) in the Chang 7 Member shale are presented in Table 1. The $\delta^{13}\text{C}_{\text{carb}}$ values in Well Yan 56 vary between -5.7‰ and 4.5‰ , with an average of -0.6‰ ($n = 48$). The $\delta^{13}\text{C}_{\text{carb}}$ values are relatively low and range from -5.7‰ to -0.9‰ (mean = -2.8‰) in the Chang 7₃ submember, showing decrease upward gradually to the middle (at ~ 3051 m) and then followed by an opposite trend (Figure 4). In the Chang 7₂ submember, the $\delta^{13}\text{C}_{\text{carb}}$ values vary between -4.4‰ and 4.5‰ (mean = 0.3‰), higher than that in the Chang 7₃ submember. The values show a general upward-decreasing trend, interrupted by a sharp positive excursion to 4.5‰ at ~ 3011 m. In the Chang 7₁ submember, the $\delta^{13}\text{C}_{\text{carb}}$ values change from -5.2‰ to 3.6‰ (mean = 0.2‰), showing twice obvious negative shifts at the bottom and middle.

4.2 Oxygen isotope values of bulk carbonate

The stable oxygen isotope values of bulk carbonates ($\delta^{18}\text{O}_{\text{carb}}$) in the Chang 7 Member shale are listed in Table 1. The $\delta^{18}\text{O}_{\text{carb}}$ values of the Chang 7 Member in Well Yan 56 range from -18.6‰ to -11.8‰ , with an average of -14.7‰ . Specifically, the $\delta^{18}\text{O}_{\text{carb}}$ values change from -18.1‰ to -13.4‰ (mean = -16.0‰), from -15.7‰ to -12.2‰ (mean = -14.3‰), and from -18.6‰ to -11.8‰ (mean = -14.1‰) in the Chang 7₃, Chang 7₂, Chang 7₁ submember, respectively. Overall, there is a trend of gradual increase from the bottom to the top (Figure 4). Throughout the Chang 7 Member, the variation trend of $\delta^{18}\text{O}_{\text{carb}}$ values shows some similarity with that of $\delta^{13}\text{C}_{\text{carb}}$, with a moderate positive correlation between the two.

4.3 Bulk organic carbon isotope

The stable organic carbon isotope values of bulk rock ($\delta^{13}\text{C}_{\text{org}}$) in the Chang 7 Member shale are showed in Table 1. The $\delta^{13}\text{C}_{\text{org}}$ values of the Chang 7 member in Well Yan 56 range from -30.3‰ to -26.6‰ , with an average of -29.3‰ . Specifically, the $\delta^{13}\text{C}_{\text{org}}$ values vary from -30.1‰ to -26.6‰ (mean = -29.4‰), from -30.3‰ to -27.6‰ (mean = -29.5‰), and from -30.3‰ to -26.6‰ (mean = -29.4‰) in the Chang 7₃, Chang 7₂, Chang 7₁ submember, respectively. There is no significant difference among the three sub-members. Overall, most samples have $\delta^{13}\text{C}_{\text{org}}$ values around -29‰ , with distinct higher values observed in the middle of the Chang 7₃ sub-member, the middle of the Chang 7₂ sub-member, and the bottom and middle of the Chang 7₁ sub-member (Figure 4).

4.4 $\Delta^{13}\text{C}_{\text{carb-org}}$

The $\Delta^{13}\text{C}_{\text{carb-org}}$ represents the difference between the carbon isotope values of carbonate minerals and organic matter ($\delta^{13}\text{C}_{\text{carb}} - \delta^{13}\text{C}_{\text{org}}$). It primarily reflects the degree of carbon isotope fractionation between the organic and inorganic carbon reservoirs (Wang et al., 2014). A larger $\Delta^{13}\text{C}_{\text{carb-org}}$ indicates a stronger degree of fractionation. In the Chang 7 Member of Well Yan 56, the $\Delta^{13}\text{C}_{\text{carb-org}}$ values range from 23.2‰ to 34.5‰ , with an average of 28.7‰ . Specifically, the $\Delta^{13}\text{C}_{\text{carb-org}}$ values range from 23.8‰ to 28.6‰ (mean = 26.6‰), from 25.5‰ to 34.5‰ (mean = 29.8‰), and from 23.2‰ to 32.3‰ (mean = 29.2‰) in the Chang 7₃, Chang 7₂, Chang 7₁ submember, respectively. The lower $\Delta^{13}\text{C}_{\text{carb-org}}$ value in the Chang 7₃ sub-member is mainly related to the lower $\delta^{13}\text{C}_{\text{carb}}$ values during this period. Throughout the Chang 7 Member, the trend of $\Delta^{13}\text{C}_{\text{carb-org}}$ shows significant similarity to the $\delta^{13}\text{C}_{\text{carb}}$ values (Figure 4).

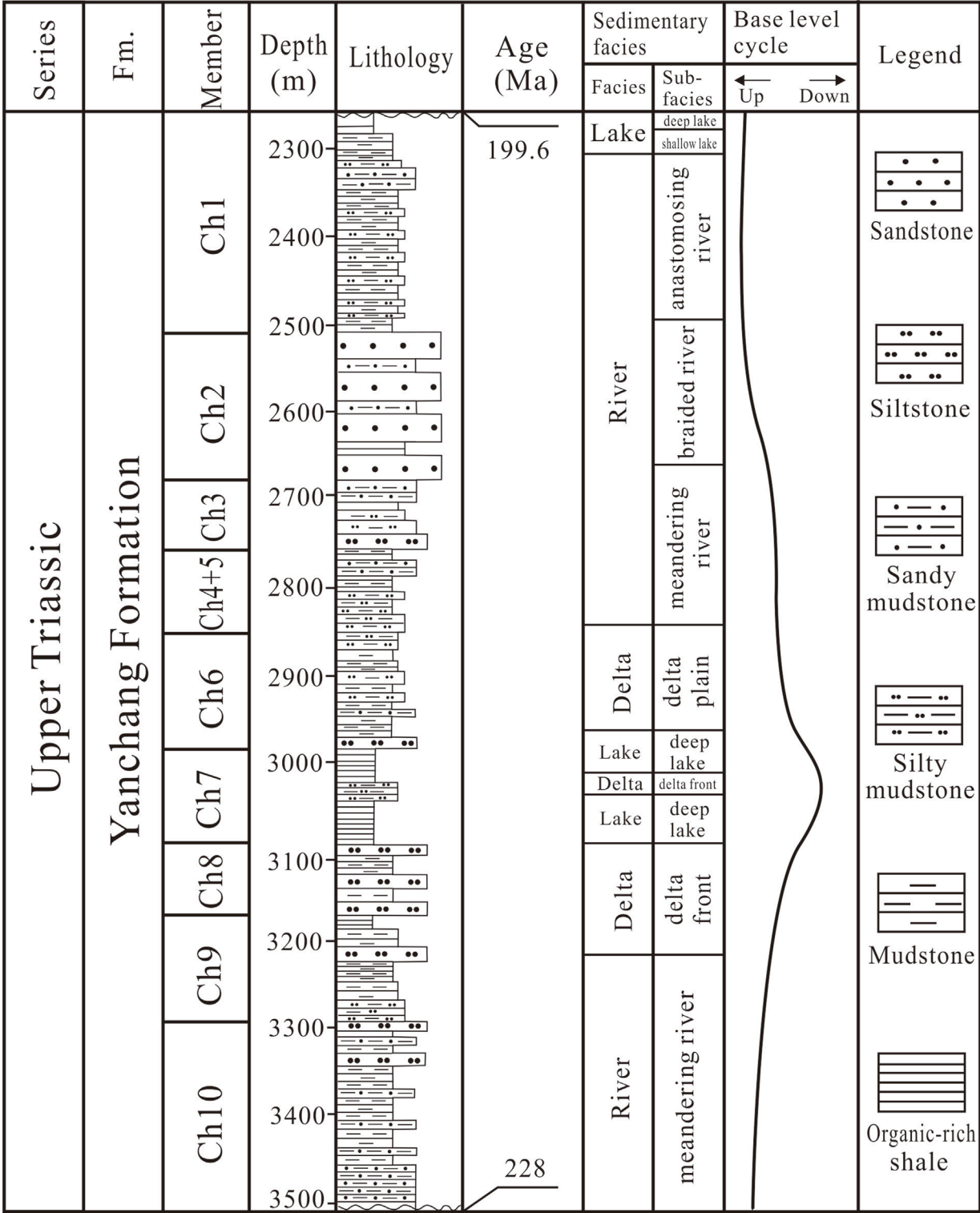


FIGURE 3
Integrated stratigraphic column of the Upper Triassic Yanchang Formation in Ordos Basin (after Yuan et al., 2017).

TABLE 1 Carbon and oxygen isotope values from bulk carbonates and organic matters in the Chang 7 source rocks of the Yanchang Formation, Ordos Basin.

No.	Well	Sub-member	Depth(m)	TOC (%)	$\delta^{13}\text{C}_{\text{carb}}$ (‰, V-PDB)	$\delta^{18}\text{O}_{\text{carb}}$ (‰, V-PDB)	$\delta^{13}\text{C}_{\text{org}}$ (‰, V-PDB)	$\Delta^{13}\text{C}_{\text{carb-org}}$ (‰, V-PDB)
1	Yan 56	Chang 7 ₁	2958.80	3.9	2.3	−11.8	−29.8	32.1
2	Yan 56	Chang 7 ₁	2960.60	3.8	1.8	−11.8	−29.5	31.3
3	Yan 56	Chang 7 ₁	2962.90	4.4	0.0	−13.5	−30.2	30.2
4	Yan 56	Chang 7 ₁	2965.05	1.0	−1.8	−15.2	−28.8	27.0
5	Yan 56	Chang 7 ₁	2967.30	3.3	1.0	−12.0	−29.9	30.9
6	Yan 56	Chang 7 ₁	2968.95	2.1	−1.8	−14.7	−30.0	28.2
7	Yan 56	Chang 7 ₁	2970.78	2.9	−0.1	−13.3	−29.2	29.1
8	Yan 56	Chang 7 ₁	2972.40	4.4	−0.1	−13.5	−28.9	28.8
9	Yan 56	Chang 7 ₁	2973.93	6.6	0.7	−13.6	−29.4	30.1
10	Yan 56	Chang 7 ₁	2976.90	4.0	1.7	−13.1	−26.7	28.4
11	Yan 56	Chang 7 ₁	2979.65	6.7	0.5	−14.4	−29.5	30.0
12	Yan 56	Chang 7 ₁	2983.50	0.5	−5.2	−16.3	−29.2	24.0
13	Yan 56	Chang 7 ₁	2986.40	5.9	0.5	−14.5	−29.5	30.0
14	Yan 56	Chang 7 ₁	2987.10	6.3	1.3	−14.6	−29.8	31.1
15	Yan 56	Chang 7 ₁	2988.80	5.5	1.8	−14.6	−29.6	31.4
16	Yan 56	Chang 7 ₁	2990.90	7.5	2.0	−14.7	−30.3	32.3
17	Yan 56	Chang 7 ₁	2992.90	3.0	−1.4	−14.0	−27.1	25.7
18	Yan 56	Chang 7 ₁	2993.00	4.7	0.9	−13.8	−30.0	30.9
19	Yan 56	Chang 7 ₁	2995.80	1.3	−4.4	−18.6	−27.6	23.2
20	Yan 56	Chang 7 ₁	2997.25	5.6	3.6	−14.4	−26.6	30.2
21	Yan 56	Chang 7 ₂	2998.80	6.9	0.9	−15.6	−29.6	30.5
22	Yan 56	Chang 7 ₂	3001.25	4.1	1.7	−13.9	−28.6	30.3
23	Yan 56	Chang 7 ₂	3003.50	5.2	1.7	−13.2	−29.3	31.0
24	Yan 56	Chang 7 ₂	3005.90	4.8	3.5	−13.8	−28.6	32.1
25	Yan 56	Chang 7 ₂	3008.20	5.3	4.5	−14.4	−30.0	34.5
26	Yan 56	Chang 7 ₂	3011.10	4.0	−4.4	−15.2	−29.9	25.5
27	Yan 56	Chang 7 ₂	3014.30	6.3	−1.9	−15.4	−29.8	27.9
28	Yan 56	Chang 7 ₂	3016.60	4.7	−1.1	−15.5	−29.6	28.5
29	Yan 56	Chang 7 ₂	3020.10	4.7	0.4	−14.0	−27.6	28.0
30	Yan 56	Chang 7 ₂	3020.50	3.7	−2.0	−13.6	−30.0	28.0
31	Yan 56	Chang 7 ₂	3021.60	3.8	−0.3	−15.7	−28.3	28.0

(Continued on the following page)

TABLE 1 (Continued) Carbon and oxygen isotope values from bulk carbonates and organic matters in the Chang 7 source rocks of the Yanchang Formation, Ordos Basin.

No.	Well	Sub-member	Depth(m)	TOC (%)	$\delta^{13}\text{C}_{\text{carb}}$ (‰, V-PDB)	$\delta^{18}\text{O}_{\text{carb}}$ (‰, V-PDB)	$\delta^{13}\text{C}_{\text{org}}$ (‰, V-PDB)	$\Delta^{13}\text{C}_{\text{carb-org}}$ (‰, V-PDB)
32	Yan 56	Chang 7 ₂	3024.25	5.6	0.1	−15.1	−30.3	30.4
33	Yan 56	Chang 7 ₂	3026.15	2.6	0.6	−12.2	−30.1	30.7
34	Yan 56	Chang 7 ₂	3029.30	3.7	−0.4	−13.5	−30.0	29.6
35	Yan 56	Chang 7 ₂	3036.30	4.1	1.6	−13.5	−29.9	31.5
36	Yan 56	Chang 7 ₂	3038.90	5.4	−1.7	−15.8	−29.8	28.1
37	Yan 56	Chang 7 ₃	3042.90	8.3	−2.0	−17.9	−30.0	28.0
38	Yan 56	Chang 7 ₃	3044.50	9.0	−0.9	−17.4	−28.4	27.5
39	Yan 56	Chang 7 ₃	3047.35	1.8	−2.2	−14.0	−29.7	27.5
40	Yan 56	Chang 7 ₃	3048.60	9.1	−2.5	−15.9	−29.8	27.3
41	Yan 56	Chang 7 ₃	3050.00	5.6	−1.0	−13.4	−29.5	28.5
42	Yan 56	Chang 7 ₃	3051.10	8.2	−5.7	−16.8	−30.0	24.3
43	Yan 56	Chang 7 ₃	3054.30	8.5	−5.2	−16.8	−29.8	24.6
44	Yan 56	Chang 7 ₃	3055.40	7.1	−5.3	−18.1	−29.7	24.4
45	Yan 56	Chang 7 ₃	3058.40	6.0	−2.8	−14.3	−26.6	23.8
46	Yan 56	Chang 7 ₃	3061.90	5.0	−3.1	−15.4	−30.1	27.0
47	Yan 56	Chang 7 ₃	3064.55	8.9	−0.9	−16.0	−29.5	28.6
48	Yan 56	Chang 7 ₃	3067.10	6.9	−3.3	−16.8	−29.9	26.6

TOC data are from [Yuan et al., 2017](#).

5 Discussion

5.1 Impact of volcanic and hydrothermal activity on carbon and oxygen isotope values

From the preceding data analysis, it is evident that the average $\delta^{13}\text{C}_{\text{carb}}$ values for the Chang 7₁ to Chang 7₃ sub-members in Well Yan 56 are 0.17‰, 0.33‰, and −2.8‰, respectively, while the average $\delta^{18}\text{O}_{\text{carb}}$ values are −14.1‰, −14.3‰, and −16.0‰. The Chang 7₃ sub-member exhibits relatively lower $\delta^{13}\text{C}_{\text{carb}}$ and $\delta^{18}\text{O}_{\text{carb}}$ values compared to the Chang 7₁ and Chang 7₂ sub-members. The carbon and oxygen isotope values of terrestrial or lacustrine carbonate rocks are primarily influenced by their sources and isotopic fractionation. Anomalies in these isotope values over short periods often reflect special geological events or changes in climatic conditions. Previous studies have shown that intense volcanic and hydrothermal activities, evidenced by diagnostic minerals (pyrite veins, marcasite, gypsum, siliceous rock, etc.) and element indicators (Al/(Fe + Mn), Al/(Al + Fe + Mn)), occurred in the Ordos Basin during the depositional period of the

Chang 7 member of the Yanchang Formation, especially during the Chang 7₃ sub-member ([Zhang et al., 2009; 2010; Qiu, 2011; Yuan et al., 2017; Yuan, 2018; Yuan et al., 2019b; Yuan et al., 2020; Yuan et al., 2022](#)). Core observations from Well Yan 56 revealed the presence of tuff (altered volcanic ash sediments) indicative of volcanic activity and carbonate veins indicative of hydrothermal activity in the Chang 7₃ sub-member ([Figure 5](#)). Therefore, the anomalously low $\delta^{13}\text{C}_{\text{carb}}$ and $\delta^{18}\text{O}_{\text{carb}}$ values in the Chang 7₃ sub-member may be influenced by volcanic and hydrothermal activities. Volcanic and hydrothermal activities release large amounts of CO₂, which typically has a lower $\delta^{13}\text{C}$ value (close to −5‰ to −8‰), significantly lower than the $\delta^{13}\text{C}$ values of seawater (about 0‰) and lake water. When this CO₂ dissolves in water and participates in the formation of carbonate rocks, it significantly reduces the $\delta^{13}\text{C}$ value of the carbonate rocks. Hydrothermal fluids also generally have lower $\delta^{18}\text{O}$ values, and under high-temperature conditions, the fractionation effect of oxygen isotopes (with heavy oxygen isotopes being largely lost in high-temperature environments) can also lead to a decrease in the $\delta^{18}\text{O}$ value of carbonate rocks ([Veizer et al., 1999; Chiodini et al., 2000; Wang et al., 2013](#)). For example, studies in southern Italy have shown that volcanic and hydrothermal activities

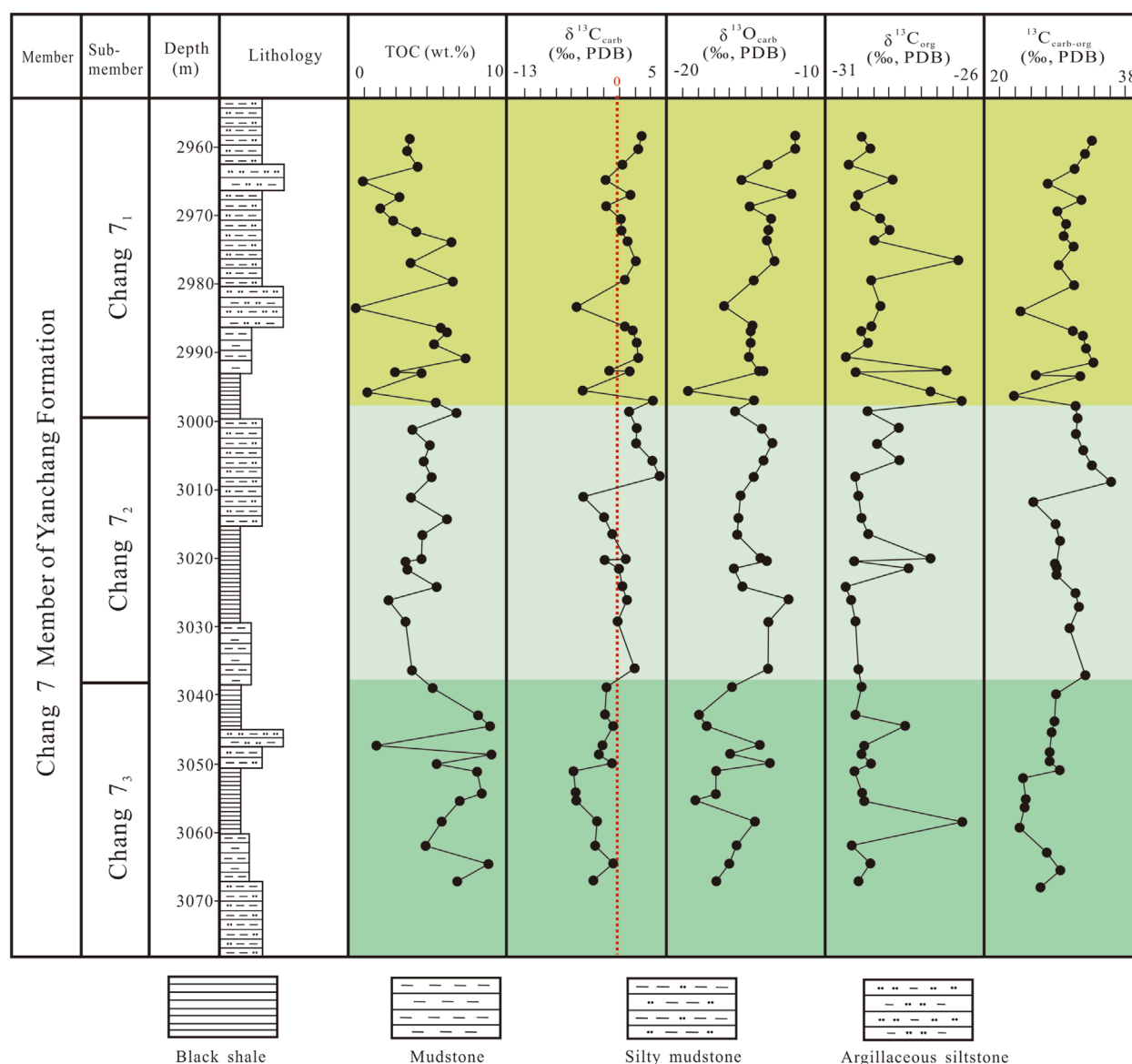


FIGURE 4
The $\delta^{13}\text{C}_{\text{carb}}$, $\delta^{18}\text{O}_{\text{carb}}$ and $\delta^{13}\text{C}_{\text{org}}$ records of carbonates and organic matter in the Chang 7 sediments for Well Yan 56, Ordos Basin. The data of TOC are from [Yuan et al. \(2017\)](#).

significantly reduce the $\delta^{13}\text{C}$ values of carbonate rocks, with the lowest values reaching -10‰ ; research in Yellowstone National Park in the United States indicates that hydrothermal activities reduce the $\delta^{18}\text{O}$ values of carbonate rocks by about 3‰ – 5‰ ([Veizer et al., 1999](#); [Chiodini et al., 2000](#)). Our preliminary studies also found that the carbon and oxygen isotopes of hydrothermal carbonate laminae in the Chang 7 source rocks of Well Wu 100 in the Ordos Basin exhibit anomalously low values, with $\delta^{13}\text{C}_{\text{carb}}$ and $\delta^{18}\text{O}_{\text{carb}}$ values of -8.2‰ and -20.0‰ , respectively ([Yuan, 2018](#)).

In summary, the intense volcanic and hydrothermal activities during the depositional period of the Chang 7₃ sub-member in the Yanchang Formation of the Ordos Basin caused the anomalously low carbon and oxygen isotope

values during this period. Therefore, in subsequent analyses of other aspects, we primarily utilize the carbonate carbon and oxygen isotope data from the Chang 7₁ and Chang 7₂ sub-members.

5.2 Is the lake open or closed?

Previous studies have analyzed the dynamic background and the bottom morphology of the lake basin during the Late Triassic Yanchang Formation depositional period in the Ordos Basin. These studies revealed that the southwestern part of the basin was relatively steeply inclined, while the northeastern part was relatively gentle, as a whole exhibited a northwest-southeast orientation, opening

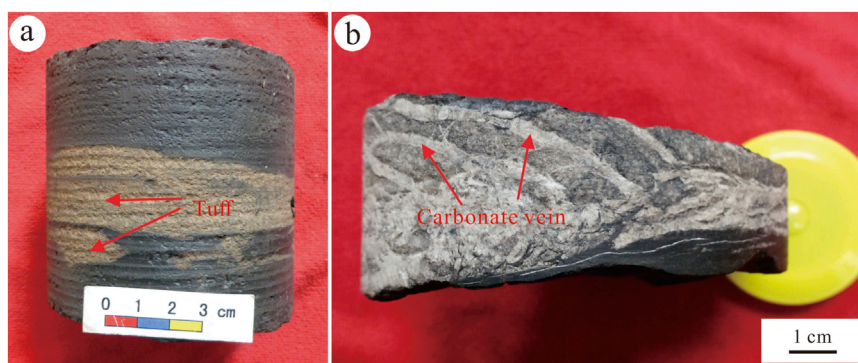


FIGURE 5
Core photographs from the Chang 7₃ sub-member of Yan 56 Well in the Ordos Basin. **(a)** Tuff, Chang 7₃, 3044.67 m; **(b)** Carbonate veins in the source rock, Chang 7₃, 3065.24 m (after [Yuan et al., 2022](#)).

towards the southeast, roughly parallel to the Qinling orogenic belt ([Qiu, 2011](#)). This suggests that the lake basin during this period had a certain degree of openness. The correlation between the $\delta^{13}\text{C}_{\text{carb}}$ and $\delta^{18}\text{O}_{\text{carb}}$ of lacustrine carbonate minerals can also be used to identify whether a lake was open or closed ([Talbot, 1990](#); [Li and Ku, 1997](#); [Leng and Marshall, 2004](#); [Li et al., 2013](#); [Hou et al., 2014](#)). In closed lake systems, intense evaporation and/or prolonged water retention can lead to the enrichment of heavy oxygen isotopes (^{18}O) in the lake water, while the equilibrium exchange between long-retained lake water and atmospheric CO_2 can increase the $\delta^{13}\text{C}$ value of dissolved inorganic carbon in the lake water ([Leng and Marshall, 2004](#); [Hou et al., 2014](#)). Generally, a high correlation between $\delta^{13}\text{C}_{\text{carb}}$ and $\delta^{18}\text{O}_{\text{carb}}$ values in lacustrine carbonate minerals is widely used as a paleohydrological indicator for closed lake systems. According to [Talbot \(1990\)](#), the square of the correlation coefficient (R^2) between $\delta^{13}\text{C}_{\text{carb}}$ and $\delta^{18}\text{O}_{\text{carb}}$ in closed lakes is typically greater than 0.5, whereas open lakes show weaker correlations and a smaller range of $\delta^{18}\text{O}_{\text{carb}}$ values ([Talbot, 1990](#); [Li and Ku, 1997](#); [Valero Garcés et al., 1997](#); [Alonso-Zarza and Calvo, 2000](#); [Li et al., 2013](#)). The correlation between $\delta^{13}\text{C}_{\text{carb}}$ and $\delta^{18}\text{O}_{\text{carb}}$ values in lacustrine carbonate minerals from the Chang 7 Member of the Yanchang Formation in the Ordos Basin is shown in [Figure 5](#). The samples from Well Yan 56 reveal two characteristics. Firstly, there is a weak to moderate correlation between $\delta^{13}\text{C}_{\text{carb}}$ and $\delta^{18}\text{O}_{\text{carb}}$ values ($R^2 = 0.31$, p -value < 0.05); Secondly, the $\delta^{18}\text{O}_{\text{carb}}$ values of the carbonate minerals are relatively dispersed (-18.6‰ to -11.8‰). These characteristics suggest that the hydrological conditions of the lake during the Late Triassic Chang 7 depositional period in the Ordos Basin were likely semi-open to semi-closed, which aligns with the findings of [Qiu \(2011\)](#). Furthermore, the correlation between $\delta^{13}\text{C}_{\text{carb}}$ and $\delta^{18}\text{O}_{\text{carb}}$ values in the Chang 7₂ sub-member is generally poor (R^2 values distributed around 0.16, p -value < 0.05), while the correlation in the Chang 7₁ sub-member is better ($R^2 = 0.46$, p -value < 0.05) ([Figure 6](#)). This indicates that the lake during the Chang 7₁ depositional period was relatively more closed, possibly due to the smaller lake area and shallower water depth during this time ([Yuan, 2018](#)).

5.3 Source of organic matter

The carbon isotope values of organic matter in sediments or sedimentary rocks are primarily influenced by the source of the organic matter, the depositional environment, and the degree of thermal evolution ([Yu et al., 2001](#)). During the Late Triassic Chang 7 depositional period in the Ordos Basin, the water bodies were mainly freshwater, and the overall thermal evolution degree of the Chang 7 source rocks did not vary significantly (with an average vitrinite reflectance of about 8.5%) ([Yuan, 2018](#)). Therefore, the $\delta^{13}\text{C}_{\text{org}}$ values of the shale in the Chang 7 section of Well Yan 56 are closely related to the source of the organic matter. Previous studies have shown that the $\delta^{13}\text{C}_{\text{org}}$ values of aquatic organic matter (Type I) are typically less than -28‰ , those of mixed organic matter (Type II) are usually between -28‰ and -25‰ , and those of terrestrial higher plant organic matter (Type III) are generally above -26‰ ([Schoell, 1984](#)). In subsequent research, [Huang \(1988\)](#) proposed a more detailed classification standard: Type I organic matter has $\delta^{13}\text{C}_{\text{org}}$ values $< -30\text{‰}$, Type II₁ organic matter has $\delta^{13}\text{C}_{\text{org}}$ values between -30‰ and -28‰ , Type II₂ organic matter has $\delta^{13}\text{C}_{\text{org}}$ values between -28‰ and -26‰ , and Type III organic matter has $\delta^{13}\text{C}_{\text{org}}$ values $> -26\text{‰}$. The $\delta^{13}\text{C}_{\text{org}}$ values of the source rock in the Chang 7 section of Well Yan 56 in the Ordos Basin range from -30.3‰ to -26.6‰ , with an average of -29.3‰ . As can be seen from [Figure 7](#), the organic matter types in the Chang 7 section of the Yanchang Formation in the study area are mainly Type I and Type II₁, indicating that the organic matter during the Chang 7 depositional period was primarily aquatic, with some contribution from terrestrial higher plant organic matter. This is consistent with previous research findings ([Yang and Zhang, 2005](#); [Zhang et al., 2008; 2015](#)).

Terrestrial plants can be classified into three major categories: C3, C4, and CAM plants, based on the number of carbon atoms in the primary products of photosynthesis ([Liu et al., 2005](#)). Due to significant differences in photosynthetic pathways, leaf structure, photorespiration, ecological adaptability, water use efficiency, and photosynthetic efficiency between C3 and C4 plants, their living environments and carbon isotope compositions also differ ([Liu et al., 2005](#)). C3 plants have lower photosynthetic

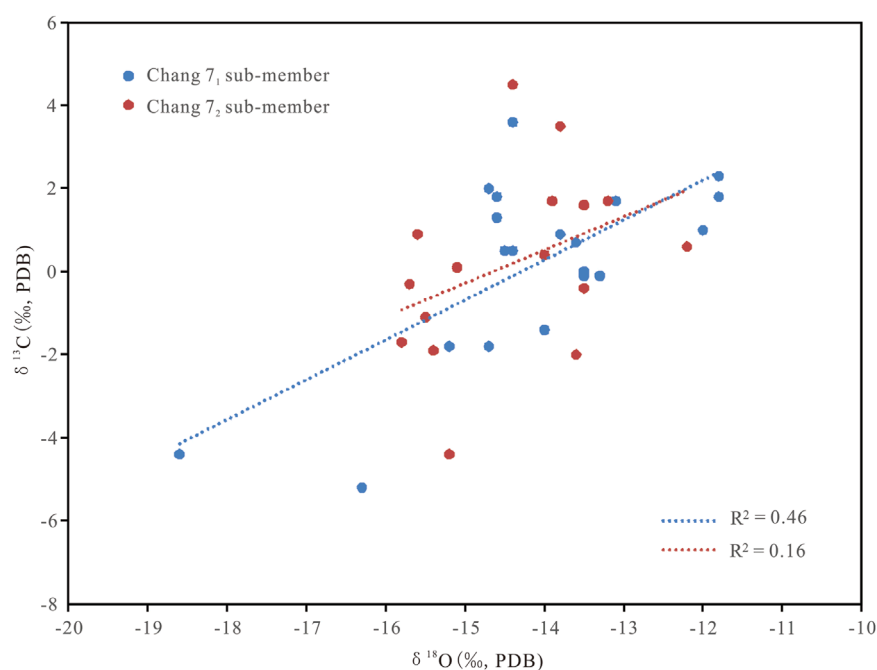


FIGURE 6
Correlation between $\delta^{13}\text{C}_{\text{carb}}$ and $\delta^{18}\text{O}_{\text{carb}}$ values of the Chang 7 carbonates in Well Yan 56, Ordos Basin.

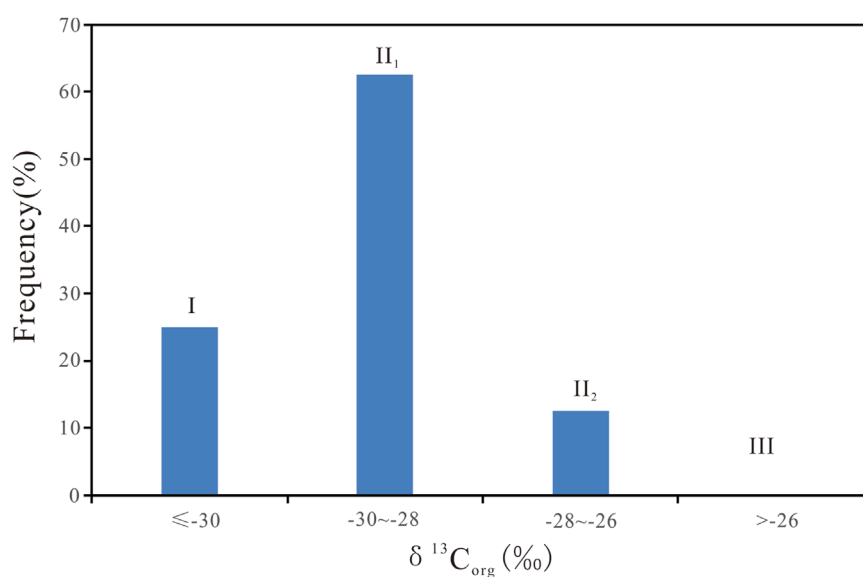
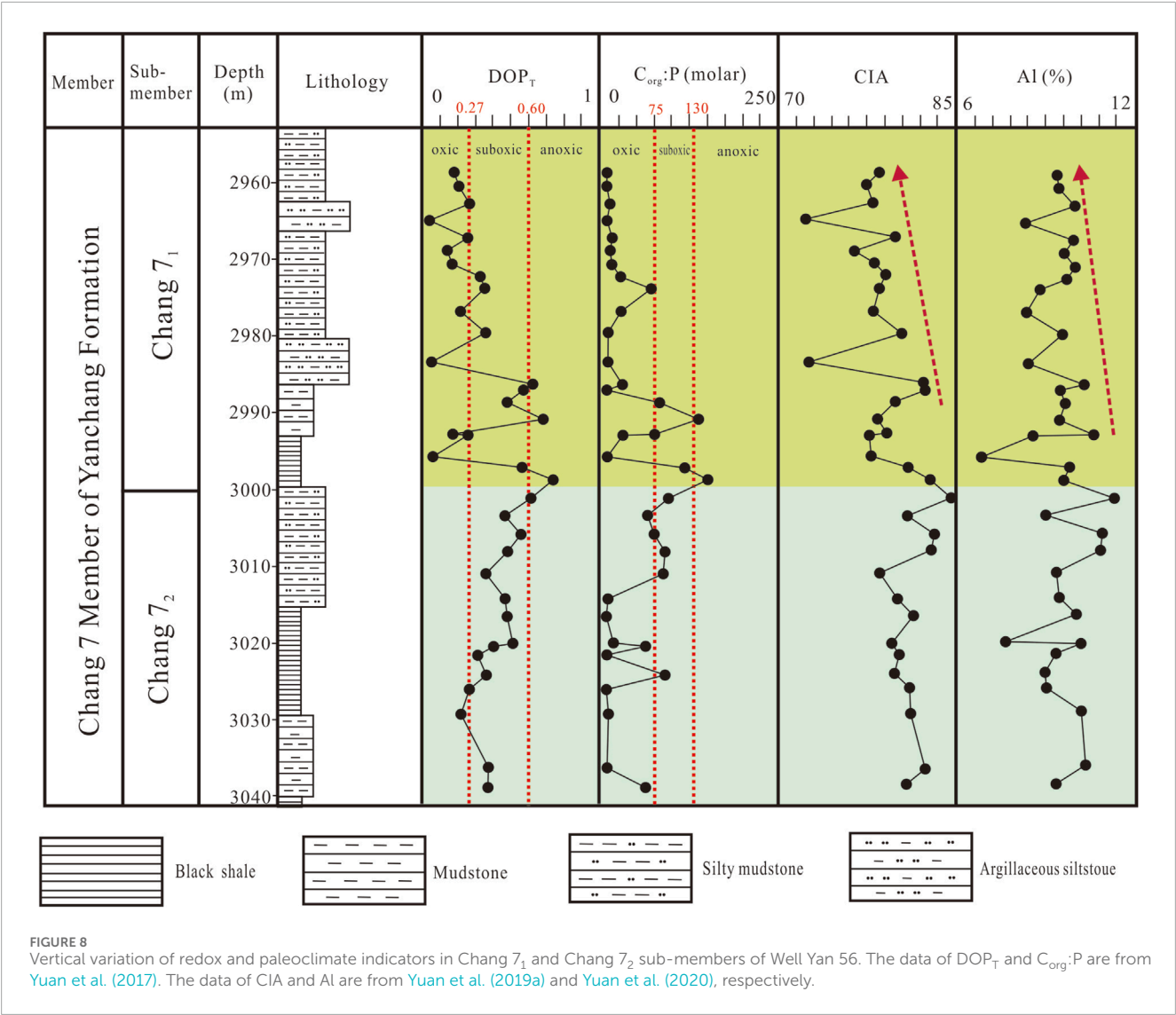


FIGURE 7
Frequency distribution diagram of organic carbon isotopes in the Chang 7 Member of Well Yan 56, Ordos Basin.

efficiency and lower water use efficiency, typically thriving in warm and humid environments, with carbon isotope compositions ranging from -22‰ to -34‰ , averaging -27‰ (Liu et al., 2005). In contrast, C4 plants exhibit higher photosynthetic efficiency and higher water use efficiency, usually found in hot and arid environments, with carbon isotope compositions ranging from -9‰ to -19‰ , averaging -13‰ (Liu et al.,

2005). The $\delta^{13}\text{C}_{\text{org}}$ values from the Chang 7 section of Well Yan 56 indicate that the terrestrial plants contributing to the sedimentary organic matter during that period were likely C3 plants. This further suggests that the climate conditions at that time were probably warm and humid, which aligns with the findings from paleomagnetic studies, pollen analysis, and elemental indicators (Yuan et al., 2019b).



5.4 Lake paleoproductivity

The carbon isotopic composition of lacustrine carbonate rocks is primarily controlled by the carbon isotopic fractionation during carbonate formation and the carbon isotopic composition of dissolved inorganic carbon (DIC) in the lake water (Chen et al., 2010). The carbon isotopic composition of lake water DIC is influenced by various factors, including the carbon isotopic composition of inflowing lake water, CO₂ exchange between the atmosphere and lake water DIC, the magnitude of lake palaeoproductivity, and the degradation of organic matter (Chen et al., 2010). However, significant positive shifts in the δ¹³C values of freshwater lacustrine carbonate rocks can only be attributed to the intense degradation of sedimentary organic matter by methanogenic bacteria during the diagenetic stage and the increase in lake palaeoproductivity (Zhang et al., 2013). Among these, the increase in δ¹³C values caused by the degradation of sedimentary organic matter by methanogenic bacteria is quite significant, often showing a positive shift of >4‰ (Garziane et al., 2004). In the study area, except for one sample from the Chang 7₂

sub-member (4.5‰), the δ¹³C_{carb} values in Well Yan 56 are mostly below 4‰, indicating that the variation in δ¹³C_{carb} values is not influenced by methanogenic bacteria. Redox conditions have been demonstrated to exert a significant influence on isotopic signatures, owing to the capacity of redox conditions to modify the isotopic fractionation of carbon, predominantly through the process of bacterial sulfate reduction. DOP_T and C_{org}:P suggest that the water column during the Chang 7₁ and Chang 7₂ depositional period was dominantly oxic-suboxic (Figure 8), suggesting that redox conditions had a limited influence on isotopic fractionation during this period. So, the δ¹³C_{carb} values of Chang 7 samples may be closely related to lake palaeoproductivity. When lake palaeoproductivity is high, aquatic organisms thrive and preferentially absorb ¹²C from the DIC in the water through photosynthesis, leading to a relative increase in the ¹³C content in the inorganic carbon pool (Liu, 1998). This increases the degree of carbon isotopic fractionation between the inorganic carbon pool and organic matter, thereby increasing the δ¹³C_{carb} and Δ¹³C_{carb-org} values. Therefore, the δ¹³C_{carb} and Δ¹³C_{carb-org} values can be used to analyze changes in lake palaeoproductivity.

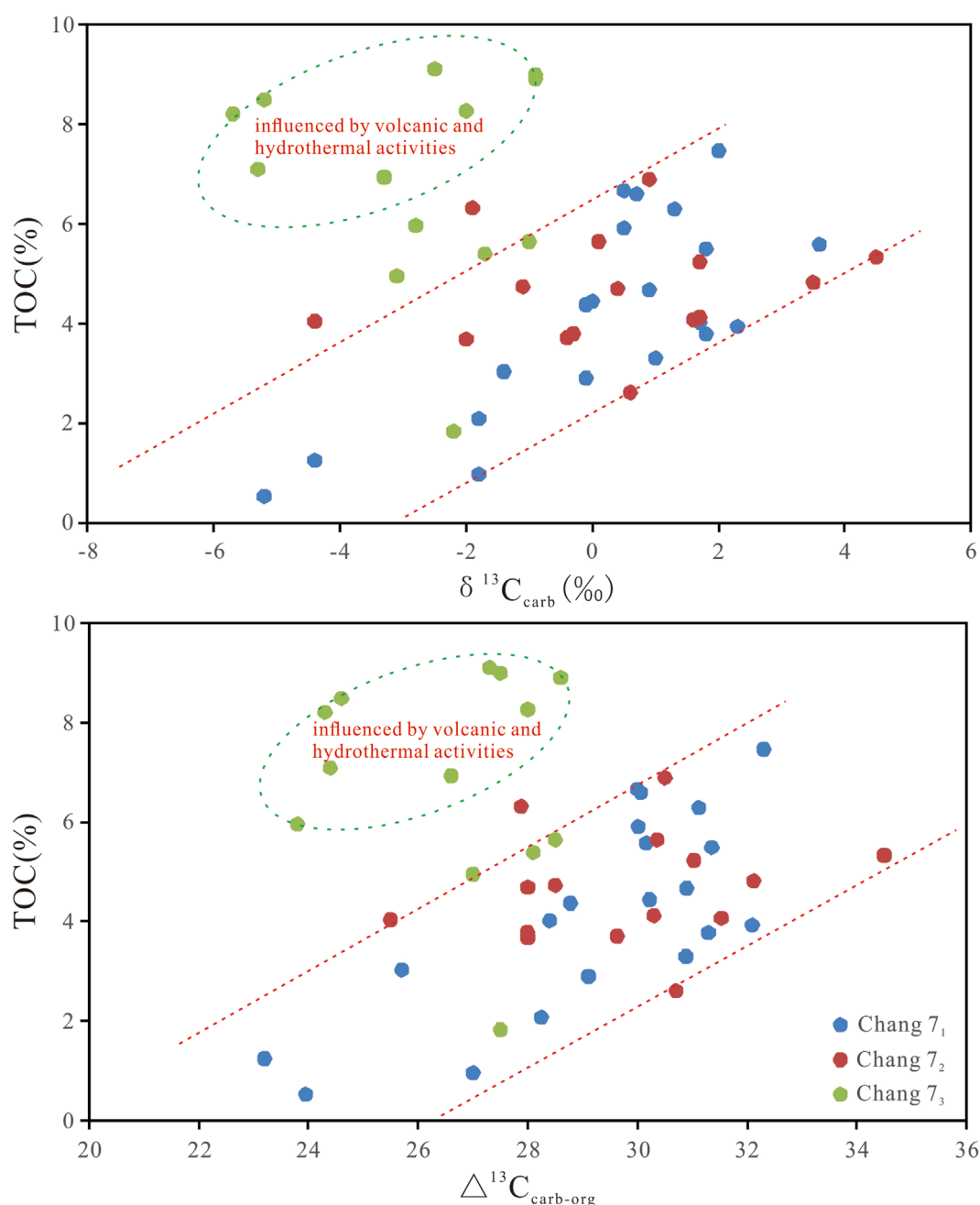


FIGURE 9
Relationship diagram of TOC content with $\delta^{13}C_{carb}$ and $\Delta^{13}C_{carb-org}$ values in the Chang 7 Member of Well Yan 56, Ordos Basin.

The mean $\delta^{13}C_{carb}$ values for the Chang 7₁ and Chang 7₂ sub-members in Well Yan 56 are 0.17‰ and 0.33‰, respectively, and the mean $\Delta^{13}C_{carb-org}$ values are 29.2‰ and 29.8‰, respectively, indicating that the lake palaeoproductivity during the Chang 7₂ depositional period was generally relatively high. From the vertical changes in $\delta^{13}C_{carb}$ and $\Delta^{13}C_{carb-org}$ values (Figure 4), the trends of both are very consistent, indicating that the palaeoproductivity of the Chang 7₁ and Chang 7₂ sub-members had periodic fluctuations. In the Chang 7₂ sub-member, two obvious cycles from large to small can be seen, and the $\delta^{13}C_{carb}$ and $\Delta^{13}C_{carb-org}$ values in

the upper cycle of the Chang 7₂ sub-member are larger than those in the lower cycle (Figure 4), indicating that the late Chang 7₂ depositional period had higher lake palaeoproductivity. The lake palaeoproductivity in the Chang 7₁ sub-member shows two cycles from large to small and then to large in the middle and lower parts, while in the upper part, it shows a gradually increasing trend (Figure 4).

In addition, as can be seen from Figure 9, except for the Chang 7₃ sub-member, which is affected by volcanic and hydrothermal activity, the TOC content in the Chang 7 Member of Well Yan 56 in

the Ordos Basin has a good positive correlation with the $\delta^{13}\text{C}_{\text{carb}}$ and $\Delta^{13}\text{C}_{\text{carb-org}}$ values, indicating that the enrichment of organic matter during the Chang 7₁ and Chang 7₂ depositional periods in the Ordos Basin was mainly controlled by lake palaeoproductivity. This can provide support for studying the enrichment of sedimentary organic matter or the formation of source rocks during this period.

5.5 Paleoclimate

The oxygen isotope composition of lacustrine carbonates is closely related to the oxygen isotope composition of dissolved oxygen in the water body at the time of carbonate formation. The oxygen isotope composition of the water body, in turn, is influenced by various factors such as the oxygen isotope composition of atmospheric precipitation and inflow runoff, evaporation intensity, and hydrological conditions of the lake (Chen et al., 2010). Therefore, the oxygen isotopes in lacustrine carbonates can often be used to qualitatively indicate paleoclimate information from the time of their formation. The size of the lake area, whether the lake is open or closed, the residence time of lake water, and the intensity of evaporation are the most important factors controlling the oxygen isotope composition of lake water (Liu, 1998). During the Chang 7 depositional period, the Ordos Basin was a large lake (Qiu, 2011). Even during the depositional periods of the Chang 7₁ and Chang 7₂ sub-members, when the hydrology was semi-closed to semi-open, the residence time of the lake water would still be relatively long, and the $\delta^{18}\text{O}$ of the lake water was mainly influenced by the precipitation/evaporation ratio (P/E) (Leng and Marshall, 2004). Therefore, $\delta^{18}\text{O}_{\text{carb}}$ can, to some extent, indicate the wet and dry changes in the lake area. Enriched $\delta^{18}\text{O}$ signatures (positive values) in climate archives typically reflect aridification, whereas depleted $\delta^{18}\text{O}$ (negative values) correlates with increased humidity (Leng and Marshall, 2004).

The mean $\delta^{18}\text{O}_{\text{carb}}$ values for the Chang 7₁ and Chang 7₂ sub-members in the Yanchang Formation of Well Yan 56 in the Ordos Basin are -14.1‰ and -14.3‰ , respectively, characterized by negative excursions, indicating that the overall climatic conditions during these two depositional periods were both humid, which aligns with the findings from paleomagnetic studies, pollen analysis, and C-value (Yuan et al., 2019b). From the vertical variation of $\delta^{18}\text{O}_{\text{carb}}$ values in Well Yan 56 (Figure 4), the $\delta^{18}\text{O}_{\text{carb}}$ values during the depositional period of the Chang 7₂ sub-member show two cycles of first increasing and then decreasing, indicating periodic changes in climate during this period. In contrast, the $\delta^{18}\text{O}_{\text{carb}}$ values during the depositional period of the Chang 7₁ sub-member show an overall increasing trend from bottom to top, indicating a gradual drying trend in the climate during this period. In addition, both the CIA (chemical index of alteration) values and AI contents of the Chang 7₁ samples exhibit a consistent downward trend from the base to the top of the section, indicating a progressive decline in chemical weathering intensity over time (Figure 8). The lithology of the Chang 7₁ sub-member also coarsens from bottom to top (Figure 4), and from the Chang 7₂ to the Chang 7₁ depositional period, the lake underwent a gradual shrinking process (Yuan, 2018), which aligns well with the climatic changes observed during this period.

6 Conclusion

1. The average values of $\delta^{13}\text{C}_{\text{carb}}$ in the Chang 7₁-Chang 7₃ sub-sections of Well Yan 56 in the Ordos Basin are 0.17‰, 0.33‰, and -2.8‰ , respectively, and the average values of $\delta^{18}\text{O}_{\text{carb}}$ are -14.1‰ , -14.3‰ , and -16.0‰ , respectively. The Chang 7₃ sub-section exhibits anomalously low values of $\delta^{13}\text{C}_{\text{carb}}$ and $\delta^{18}\text{O}_{\text{carb}}$ due to the influence of volcanic and hydrothermal activity.
2. During the depositional periods of Chang 7₁ and Chang 7₂, the Ordos Basin had semi-closed to semi-open hydrological conditions. The overall climate during these periods was warm and humid supported by carbon-oxygen isotopes and other element proxies (CIA and AI), with relatively stable climatic conditions during the Chang 7₂ depositional period, while the Chang 7₁ depositional period showed a gradual trend towards drier conditions.
3. The lake palaeoproductivity during the Chang 7 depositional period in the Ordos Basin was relatively high. The sedimentary organic matter was of mixed origin, primarily from aquatic organisms, with some contribution from C3-type terrestrial higher plants.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

HD: Writing – original draft, Writing – review and editing.

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Conflict of interest

The author declares that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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