

Article

The Sulfur Isotopic Characteristics of Evaporites in the Yarkand Basin of Xinjiang Province in the Paleocene and Its Paleoenvironmental Evolution

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Abstract: The Yarkand Basin, located in the southwest of the Tarim Basin, is a northeastern part of the eastern Paratethys ocean in the Paleocene, and a significant amount of evaporites, with gypsum, anhydrite, and halite as the main types, were developed in this area. These evaporites record the sedimentary environment at that time. A study was conducted on the sulfur isotopic composition of gypsum in the Paleocene of the Yarkand Basin to explore the origin of the evaporites and interpret the sedimentary environment. The experimentally measured sulfur isotope $\delta^{34}\text{S}_{\text{CDT}}$ values of 187 gypsum samples ranged from 6.69‰ to 25.92‰ with an average value of 18.64‰. The overall trend of the Paleocene gypsum sulfur isotopic curve is consistent with the global seawater sulfur isotopic curve, which shows a decreasing trend. In the early and middle Paleocene, the curve shows four stages of sulfur isotope increase, indicating that the sedimentary environment during that time was mainly influenced by bacterial reduction and a relatively open sedimentary environment, while the late period shows a decreasing trend, suggesting that the late period may be primarily influenced by terrigenous freshwater. In addition, the sulfur isotope value has the characteristics of decreasing from northwest to southeast of the basin, which may indicate that the sedimentary environment of Paleocene evaporites in the Yarkand Basin may also be related to paleotopography and distance from the estuary, resulting in differences in sedimentary environments. The mainly original sulfur isotope values of the Paleocene evaporites in the Yarkand Basin should be in the range of 18‰–20‰, which is a supplement to the Paleocene global paleoseawater and is of great significance for the reconstruction of the marine transgressive–regressive cycle and sulfur isotopic composition of the eastern Paratethys ocean during this period.

Keywords: Yarkand Basin; gypsum; sulfur isotope; sedimentary environment; Palaeocene; eastern Paratethys



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1. Introduction

Evaporite, a type of chemical sedimentary rock, serves as a valuable archive for paleoenvironmental information in basins. It not only contains significant records of paleoseawater and paleoclimate, but also acts as a sensitive indicator of sedimentary environments and climate conditions [1–4]. Sulfur isotopic techniques have been widely used to study evaporites in saline lakes in recent years [5], as they allow for regional and even global comparison of marine sedimentary layers due to their highly regular distribution in sulfate. Especially under complex conditions, analyzing the distribution of sulfur isotopes provides substantial evidence for reconstructing paleogeographic sedimentary environments and understanding the genesis of evaporites [6–9]. The sulfur isotope composition of marine evaporites records the evolutionary history of seawater sulfates in different geological

periods. By studying sulfates in evaporites, deep-sea barites, and carbonate minerals, it becomes possible to reconstruct a time record curve of $\delta^{34}\text{S}$ values [10–15].

Evaporites are closely related to geotectonic activities and marine transgression–regression cycles [16]. Massive evaporite sequences generally occur at the end of global geotectonic cycles, often associated with global marine regression [17]. The Yarkand Basin, located in the northeastern region of the eastern Paratethys ocean, was intermittently intruded by the Paratethys seawater during the Paleocene, so providing abundant provenance for the evaporite sequences. Evaporitic deposits are controlled by seawater during marine transgression–regression cycles, leading to continuous shifts in the depositional scale and concentrated centers of the evaporite formation [18]. The minerals found in the Yarkand Basin evaporites primarily include halite, gypsum, anhydrite, polyhalite, glauberite, and syn-genite. The Yarkand Basin underwent at least five stages of transgression–regression cycles during the Paleocene, resulting in the gradual evaporation and concentration of seawater in the basin [19]. This process led to the formation of a thick sequence of evaporites, known as the Aertashen Formation, which consists of thick gypsum layers interbedded with limestone and shale [20]. This evaporite sedimentary sequence is controlled by the transgressive–regressive cycle caused by the Tethys tectonic event and, thus, records the evolutionary history of Tethys seawater, especially the changes in sulfur isotopic composition.

Many studies have been made on evaporite distribution, horizon, mineral assemblage, potassium-forming prospect, tectonic activity, range of marine transgression, and evolution of ancient bay in the Yarkand Basin [21–30]. However, the sedimentary environment of evaporites has been less studied. Cao (2021, 2022) used gypsum sulfur isotopes to mainly explain the Paleocene marine environment of the Yarkand Basin [19,20]. Some gypsum samples from the Aertashen and Dashankou profiles in the Yarkand Basin were selected for sulfur isotope analysis, and the $\delta^{34}\text{S}$ in gypsum ranged from 16‰ to 21‰ (essentially a marine depositional environment) and 14‰ to 21‰ (an interactive marine depositional environment), reflecting the difference in the source of evaporite material [31]. Wang and Cao (2022) reconstruct and complement changes in the sulfur isotopic composition of the Paleocene seawater sulfates [32]. However, the samples in the above study are not sufficient and most of them are from outcrop profiles, which are easy to be weathered, so it is insufficient to discuss the sulfur isotopic composition and evolution rule of the Paleocene seawater systematically and entirely in the Yarkand Basin. The general trend difference of gypsum sulfur isotope in the Yarkand Basin and its causes are not clear; accordingly, the global data of sulfur isotopic composition in the Paleocene are relatively rare, which cannot limit the stratigraphic evolution of marine sulfur isotopic composition well. This paper aims to study the sulfur isotope of evaporative gypsum to explore the evolution of the Paleocene sedimentary environment in the Yarkand Basin and establish the Paleocene sulfur isotopic variational curve. It is important for revealing the evolution of seawater in the eastern Paratethys ocean and can provide a valuable addition to the global sulfur isotopic record.

2. Geological Setting

The Yarkand Basin, located in the southwestern area of the Tarim Basin, was a fore-land basin that has undergone late tectonic activities after being formed on a prehistoric crystalline basement [33,34]. The area consists of a piedmont thrust belt that runs from the West Kunlun piedmont to the basin's interior, a central sag (divided into the Kashgar and Yecheng-Hotan sags), the Markit slope belt, and the Bachu frontal uplift zone [35,36] (Figure 1). The basin was an inherited strike-slip graben basin during the early Cretaceous. The palaeolandscapes of this basin during the Late Cretaceous–Palaeocene period were consistent with their Early Cretaceous counterparts, and the basin entered a stage of fore-land basin development during this time. The subsidence and deposition of the basin were distributed along the West Kunlun and South Tianshan piedmont [37]. Since the Cenozoic, the basin has been influenced by the far-field effect of the collision between the Indian and Eurasian plates, resulting in the development of several sedimentation centers and a vast

sedimentary cover [38]. The sedimentation centers have gradually migrated from the West Kunlun front to the Yecheng–Kashgar line [39].

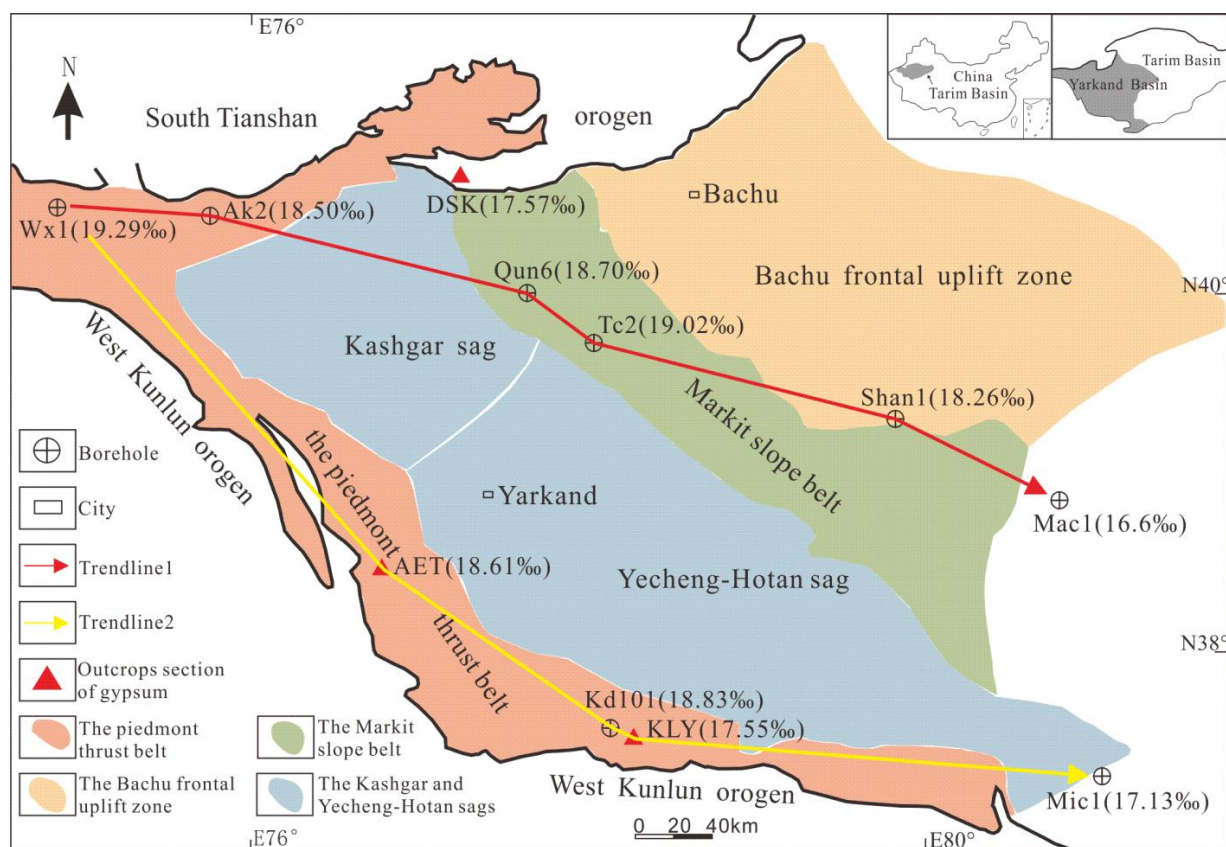


Figure 1. The location of drilling holes, evaporite outcrops, secondary tectonic units, and variation of sulfur isotope means in Yarkand Basin. The yellow trendline represents the average value of sulfur isotopes decreasing southeastward along the West Kunlun Mountains. This red trendline indicates that the average value of sulfur isotopes decreases from the junction of the West Kunlun Mountains and the South Tianshan Mountains towards the Markit slope belt.

During the Early Cretaceous, seawater intruded into the Yarkand Basin from the southwestern Tarim Basin in a west-to-east direction. The transgression continued to increase during the Paleocene era [40]. The sediment sources in front of the South Tianshan Mountains and the West Kunlun Mountains controlled the deposition in the Yarkand Basin during the Early Cretaceous. The extent of deposition distributed along the western Kunlun front showed a long strip in the NW-SE direction, and the sedimentary thickness gradually decreased from west to east [41]. In the Late Cretaceous, the basin experienced successive development of sedimentary facies, including a braided river delta, a supratidal evaporative sand–mud flat, a carbonate platform, and a salt–gypsum flat [42]. During the early Paleocene–Eocene, the basin was a semi-closed estuarine and lagoon environment, with terrestrial clastic deposition playing a significant role in the development of clastic rocks, gypsum rocks, and carbonate rocks [30]. These developments were influenced by subtropical arid climate conditions [43]. Multiple large-scale marine transgressive–regressive cycles occurred in the basin during the Late Cretaceous–Paleocene [19]. The Paleocene Aertashen Formation was deposited in a lacustrine sedimentary environment. It primarily consists of thick to massive gypsum, anhydrite layers interbedded with mudstone (or sandstone), and limestone (or argillaceous limestone). The contact between the Aertashen Formation and the underlying Late Cretaceous Tuyiluohe Formation is characterized as conformity [44]. As the extent of marine transgression increased, the bay waters deepened, and the salinity

of the water body normalized. This led to the development of thick deposits of shallow marine platform facies, including limestone, mudstone, and marly limestone [20].

3. Methods

A total of 187 gypsum samples were selected from six boreholes (Wx1, Ak2, Kd101, Qun6, Tc2, and Shan1) (Figure 1) of the Paleocene Aertashen Formation in the Yarkand Basin (see Figure 2 for hand specimens of some samples). Then, all samples were ground to 200 mesh, and the analysis was carried out at the Analysis and Testing Center of the Institute of Nuclear Industry Geology in Beijing. A suitable amount of sulfate sample containing about 15 mg of sulfur was taken, and barium sulfate was extracted by the semi-melting method using a mixture of sodium carbonate and zinc oxide solvent. Barium sulfate, vanadium pentoxide, and quartz sand were mixed in the weight ratio of 1:3:3.5. The sulfur dioxide gas was oxidized by heating at 980 °C under near vacuum (2.0×10^{-2} Pa) to generate sulfur dioxide gas, which was collected by freezing method and analyzed for sulfur isotopic composition by Delta V Plus gas isotope mass spectrometry. CDT is used as the standard, and the calculated results are recorded by $\delta^{34}\text{S}_{\text{V-CDT}}$; the analytical accuracy is better than $\pm 0.2\text{‰}$. The sulfide reference standards are GBW-04414 and GBW-04415 silver sulfide, with $\delta^{34}\text{S}$ of $-0.07 \pm 0.13\text{‰}$ and $22.15 \pm 0.14\text{‰}$, respectively.

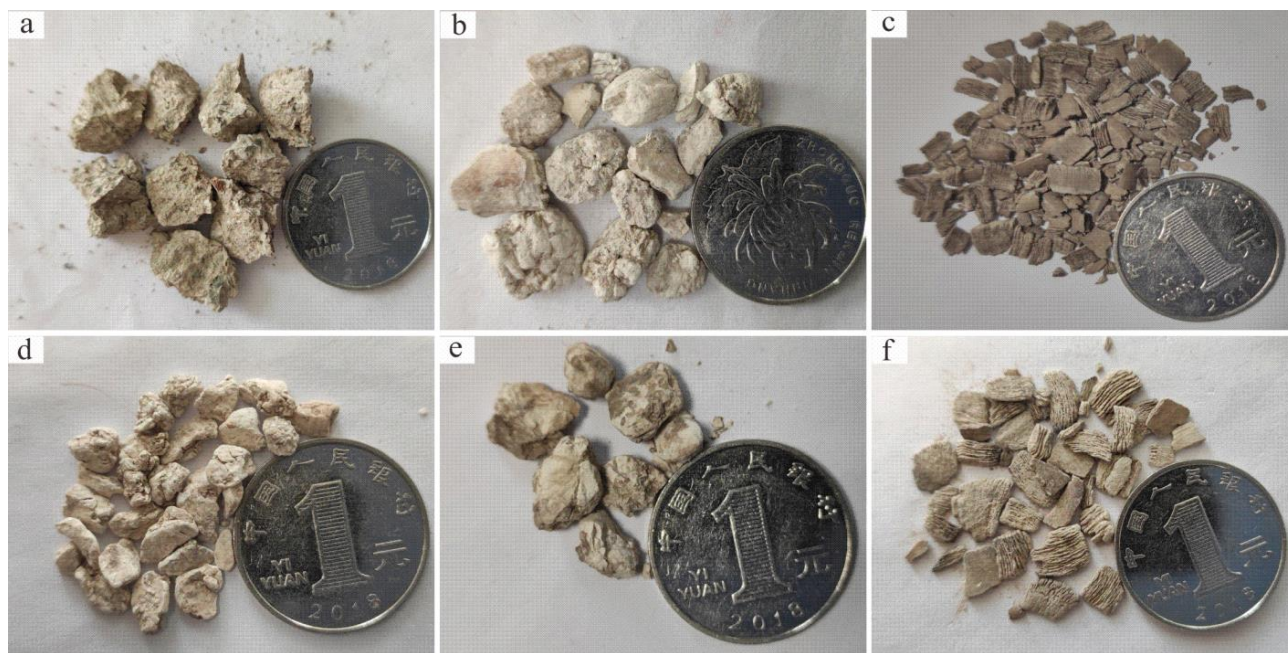


Figure 2. Pictures of partial gypsum samples: (a) gypsum of Ak2-1 at the 3902 m; (b) gypsum of Kd101-5 at the 2775 m; (c) gypsum of Qun6-5 at the 4594 m; (d) gypsum of S1-1 at the 664 m; (e) gypsum of Tc2-3 at the 4399 m; (f) gypsum of Wx1-21 at the 3630 m.

4. Results

The test results show that the distribution range of gypsum $\delta^{34}\text{S}$ values in different depth segments is large, with a range of 6.69‰–25.92‰, and an average of 18.64‰. The sample with a maximum of 25.92‰ was found at a depth of 2775 m (Figure 2b), and the sample with a minimum of 6.69‰ was found at a depth of 664 m (Figure 2d). The difference value between the maximum and minimum is 19.23‰. However, the distribution range is relatively concentrated, with 84.49% of them in the range of 18‰~20‰. All data are shown in Table 1, and distribution characteristics are shown in Figure 3.

Table 1. Gypsum sulfur isotope values of six boreholes in the Paleocene.

Samples	Depth (m)	$\delta^{34}\text{S}/\text{‰}$ (CDT)	Samples	Depth (m)	$\delta^{34}\text{S}/\text{‰}$ (CDT)	Samples	Depth (m)	$\delta^{34}\text{S}/\text{‰}$ (CDT)
S1-1	664	6.69	Kd101-1	2756	13.41	Wx1-20	3625	19.13
S1-2	666	15.11	Kd101-2	2763	14.11	Wx1-21	3630	19.83
S1-3	668	16.09	Kd101-3	2768	14.23	Wx1-22	3644	19.40
S1-4	670	17.50	Kd101-4	2771	19.66	Ak2-1	3902	18.17
S1-5	672	15.07	Kd101-5	2775	25.92	Ak2-2	3903	18.52
S1-6	674	14.80	Kd101-6	2777	25.40	Ak2-3	3904	18.63
S1-7	690	16.64	Kd101-7	2782	17.30	Ak2-4	3905	18.75
S1-8	694	16.13	Kd101-8	2783	18.34	Ak2-5	3906	18.76
S1-9	700	15.75	Kd101-9	2786	18.27	Ak2-6	3907	18.36
S1-10	708	14.79	Kd101-10	2789	18.76	Ak2-7	3908	18.42
S1-11	710	14.89	Kd101-11	2793	19.14	Ak2-8	3909	18.57
S1-12	712	15.43	Kd101-12	2796	18.95	Ak2-9	3910	18.67
S1-13	714	15.26	Kd101-13	2799	18.07	Ak2-10	3911	18.57
S1-14	716	16.27	Kd101-14	2803	18.48	Ak2-11	3912	18.81
S1-15	718	19.09	Kd101-15	2806	18.38	Ak2-12	3913	18.80
S1-16	720	15.93	Kd101-16	2807	18.09	Ak2-13	3914	18.47
S1-17	842	18.37	Kd101-17	2808	18.75	Ak2-14	3915	18.28
S1-18	844	18.55	Kd101-18	2809	18.85	Ak2-15	3916	18.60
S1-19	846	18.85	Kd101-19	2810	18.85	Ak2-16	3917	18.40
S1-20	848	18.57	Kd101-20	2812	19.00	Ak2-17	3918	18.11
S1-21	850	18.77	Kd101-21	2813	18.44	Ak2-18	3919	18.53
S1-22	852	18.54	Kd101-22	2814	18.39	Ak2-19	3920	18.96
S1-23	854	19.09	Kd101-23	2819	18.13	Ak2-20	3921	18.53
S1-24	856	18.56	Kd101-24	2823	18.15	Ak2-21	3922	18.22
S1-25	858	18.77	Kd101-25	2826	18.61	Ak2-22	3923	18.30
S1-26	860	18.82	Kd101-26	2829	19.03	Ak2-23	3924	18.27
S1-27	862	19.41	Kd101-27	2832	19.06	Ak2-24	3925	18.30
S1-28	864	18.61	Kd101-28	2833	18.55	Ak2-25	3926	18.01
S1-29	868	19.08	Kd101-29	2834	18.69	Ak2-26	3927	18.14
S1-30	870	19.10	Kd101-30	2836	18.61	Ak2-27	3928	18.15
S1-31	872	19.48	Kd101-31	2838	18.60	Ak2-28	3929	18.33
S1-32	874	19.46	Kd101-32	2839	19.50	Ak2-29	3930	18.16
S1-33	876	19.41	Kd101-33	2840	19.00	Ak2-30	3984	18.96
S1-34	878	18.78	Kd101-34	2841	18.51	Ak2-31	3987	19.15
S1-35	880	18.95	Kd101-35	2842	19.83	Ak2-32	4001	18.84
S1-36	882	19.36	Kd101-36	2848	19.15	Ak2-33	4007	18.59
S1-37	884	18.92	Kd101-37	2852	19.61	Ak2-34	4027	18.59
S1-38	886	19.11	Kd101-38	2853	19.61	Tc2-1	4394	18.87
S1-39	888	18.78	Kd101-39	2858	19.28	Tc2-2	4398	19.10
S1-40	890	18.85	Kd101-40	2859	19.41	Tc2-3	4399	19.20
S1-41	892	19.41	Kd101-41	2860	19.58	Tc2-4	4401	18.78
S1-42	894	19.25	Kd101-42	2864	19.60	Tc2-5	4402	19.19
S1-43	896	19.27	Kd101-43	2865	19.11	Tc2-6	4403	18.92
S1-44	898	19.23	Kd101-44	2870	20.14	Tc2-7	4404	19.09
S1-45	900	19.28	Wx1-1	3488	19.23	Tc2-8	4405	18.90
S1-46	902	18.95	Wx1-2	3521	19.02	Tc2-9	4409	18.86
S1-47	904	18.97	Wx1-3	3524	19.41	Tc2-10	4410	19.20
S1-48	908	18.24	Wx1-4	3530	18.59	Tc2-11	4411	19.18
S1-49	910	19.17	Wx1-5	3532	18.91	Tc2-12	4412	18.89
S1-50	912	18.55	Wx1-6	3538	19.19	Tc2-13	4413	19.12
S1-51	914	18.75	Wx1-7	3542	19.30	Tc2-14	4414	19.17
S1-52	916	18.46	Wx1-8	3548	19.02	Tc2-15	4415	18.87
S1-53	918	19.21	Wx1-9	3550	18.83	Tc2-16	4416	18.97
S1-54	920	18.74	Wx1-10	3567	20.33	Qun6-1	4581	18.85
S1-55	922	18.96	Wx1-11	3571	19.66	Qun6-2	4582	18.88
S1-56	926	19.02	Wx1-12	3575	19.23	Qun6-3	4585	18.96
S1-57	932	19.87	Wx1-13	3580	18.99	Qun6-4	4589	18.71
S1-58	934	19.35	Wx1-14	3584	18.95	Qun6-5	4594	19.06
S1-59	940	20.77	Wx1-15	3604	19.18	Qun6-6	4599	18.64
S1-60	942	21.34	Wx1-16	3610	19.24	Qun6-7	4602	18.64
S1-61	948	21.77	Wx1-17	3611	19.46	Qun6-8	4609	17.84
S1-62	950	22.17	Wx1-18	3615	19.92			
S1-63	956	22.04	Wx1-19	3620	19.45			

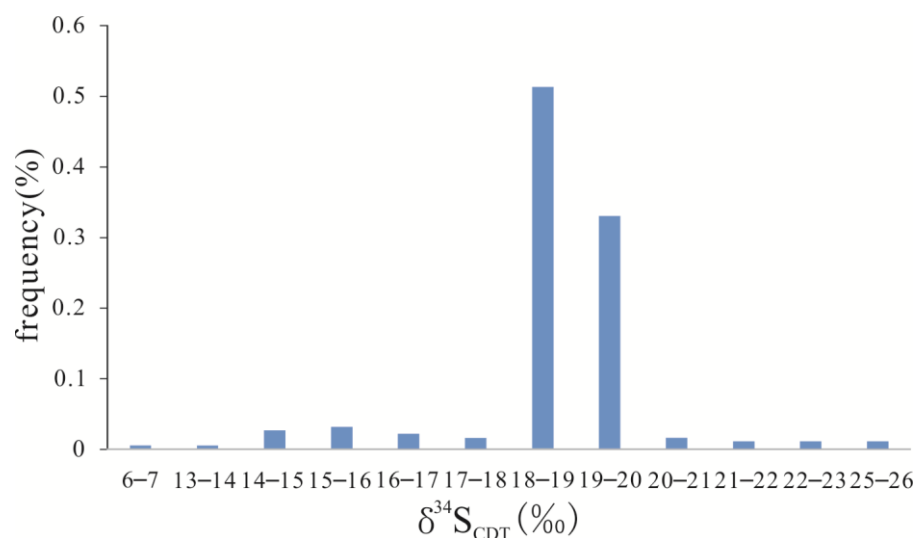


Figure 3. Distribution characteristics of gypsum sulfur isotopic values in Yarkand Basin.

5. Discussion

5.1. Characteristics of Sulfur Isotopic Composition

The $\delta^{34}\text{S}$ composition of marine sulfate is a crucial indicator of the global sulfur cycle throughout geological history. In contemporary seawater sulfate and evaporites of marine origin, the sulfur isotopic $\delta^{34}\text{S}$ values typically range from 19.0‰ to 24.3‰, with the majority clustering around 21‰ [45]. In addition, during the Paleocene period, seawater precipitation had $\delta^{34}\text{S}$ values ranging from 16‰ to 20‰ [15]. Most of the samples analyzed in this study exhibit $\delta^{34}\text{S}$ values within this range, indicating a similarity to the isotopic composition of Paleocene marine sulfates. This suggests that the formation of gypsum in the Yarkand Basin resulted from cycles of marine evaporation.

Table 2 lists the maximum, minimum, and average values of the measured sulfur isotopic $\delta^{34}\text{S}$ values of Paleocene gypsum and the statistics of samples in the Yarkand Basin. The $\delta^{34}\text{S}$ values of sulfur isotopes varied considerably, ranging from 6.69‰ to 25.92‰. The magnitude of variation varies among borehole sections; for example, the gypsum $\delta^{34}\text{S}$ value in the Shan1 borehole has the largest variation of 15.48‰, while the Tc2 borehole has the smallest variation of 0.42‰. Nonetheless, despite variations in gypsum $\delta^{34}\text{S}$ values among different drill holes, the average values generally fall within the range of 18.26‰ to 19.29‰, suggesting that relative stability in the Paleocene depositional environment of the Yarkand Basin as a whole.

Table 2. Maximum value, mean value, range of variation, and count of samples of gypsum sulfur isotope.

Borehole/m	Gypsum $\delta^{34}\text{S}$ (‰)			
	Min–Max	Mean	Rangeability	Count of Samples
Wx1 3488–3644	18.59–20.33	19.29	1.74	22
Ak2 3902–4027	18.01–19.15	18.50	1.14	34
Kd101 2756–2870	13.41–25.92	18.83	12.51	44
Qun6 4581–4609	17.84–19.06	18.70	1.22	8
Tc2 4394–4416	18.78–19.20	19.02	0.42	16
Shan1 664–956	6.69–22.17	18.26	15.48	63

5.2. Sulfur Isotopic Curve of the Paleocene

The sulfur isotopes present in seawater sulfate can serve as an important tool for stratigraphic correlation. Raw data on seawater sulfur isotopes preserved in evaporites, carbonate-associated sulfates, and marine barite from around the world are commonly used to reconstruct seawater sulfate's continuous sulfur isotopic curves for the Phanerozoic [8,10,15,46–49]. In particular, the Yarkand Basin, located in the northeast of the eastern Paratethys ocean, experienced numerous large-scale marine transgression–

regression cycles during the Late Cretaceous–Paleocene period, particularly in the western Tarim Basin [25]. These cycles led to the recurrent formation of evaporite deposits, with the well-known Paleocene Aertashen Formation being a notable example. Consequently, the region presents a unique opportunity to study the evolutionary history of sulfur isotopes due to the nearly continuous deposition of evaporites [50].

However, the strata where the boreholes are located may have undergone superimposed thickening or tip extinction due to the influence of multiple periods of transgressive–regressive events and later tectonic evolution in the Yarkand Basin during the Paleocene, which may destroy the complete sedimentary sequence of evaporite. It is impossible to reconstruct the Paleocene sulfur isotopic curve simply according to the depth of borehole samples. Therefore, it is necessary to reorder these boreholes according to the sequence of rocks formed by transgression and regression. For evaporite basins affected by the ocean, Cao (2022) identified five stages of transgressive–regression events through the evaporite–limestone sedimentary cycles in different areas of the basin and reconstructed the stages of marine transgressive–regression and the scope of each stage of the Yarkand Basin [19]. The stages and scopes of them are shown in Figure 4.

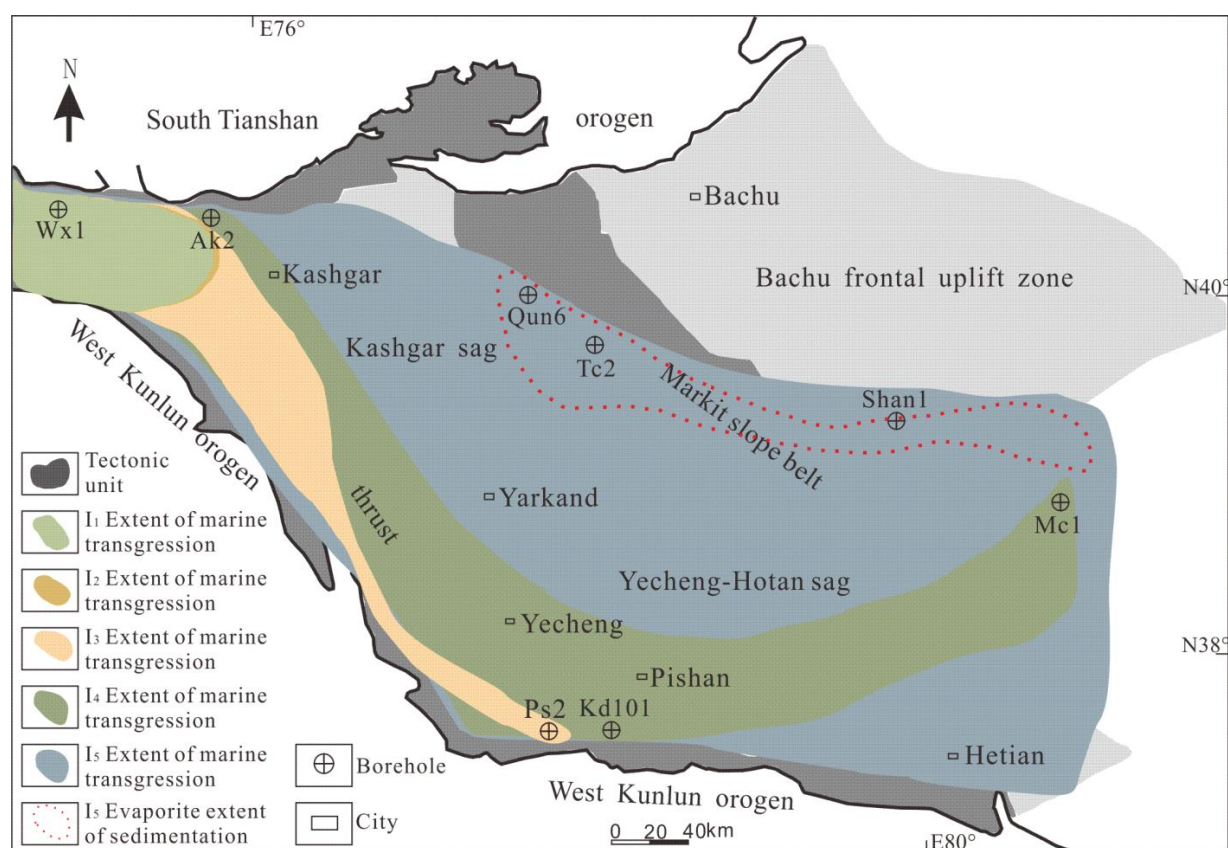


Figure 4. Characteristics of the extent of five Palaeocene transgressions in Yarkand Basin [19].

The first transgressive–regressive cycle (I_1) only affected the western Kunlun Mountains and the southern Tianshan Mountains in the northwest of Yarkand Basin. The extent of I_2 transgression is roughly the same as that of the I_1 cycle. The I_3 transgression extended southeast along the narrow riverway at the west Kunlun foothills to the area around the Ps2 borehole. The transgression degree of I_4 is greater than that of I_3 , covering the whole South Tianshan and West Kunlun Mountains, extending from the southeast of the West Kunlun Mountains to the southeast Markit slope belt, and reaching the vicinity of the Mc1 borehole. The I_5 transgression covered the whole Yarkand Basin. The evaporite deposition ranges of the four marine intrusions (I_1 , I_2 , I_3 , and I_4) are all roughly the same as the corresponding marine intrusion ranges, but the evaporite deposition range of the I_5 marine transgression

is concentrated in and around the Markit slope belt. Therefore, by combining the evaporite stratigraphic histograms of these six boreholes (Figure 5), it is possible to establish the temporal sequence of evaporite deposition in each borehole.

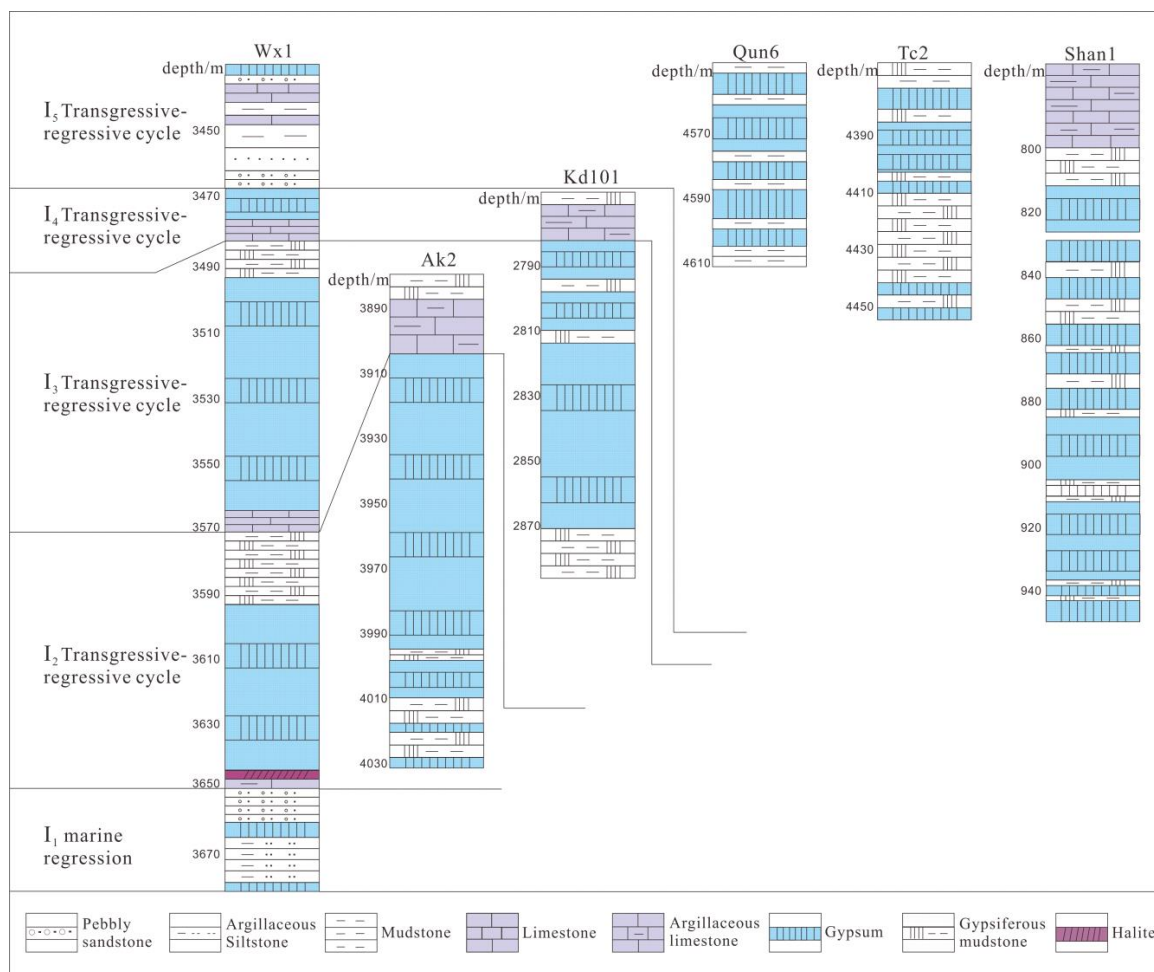


Figure 5. Comparison of transgression–regressive cycles of six boreholes in the Paleocene of the Yarkand Basin.

As a result, a Paleocene evaporite sulfur isotopic curve in the Yarkand Basin is established (Figure 6). This curve fluctuates frequently, and five increasing (decreasing) fluctuation trends can be clearly seen in the figure. These trends are 19.40‰–20.33‰, 18.83‰–20.14‰, 19.11‰–25.92‰, 13.41‰–22.17‰, and 22.17‰–6.69‰ from right to left, respectively. In the realm of geological research, it is widely accepted that the sulfur isotope values found in marine evaporite gypsum typically fall within the range of 15‰ to 23‰, whereas the sulfur isotope values discovered in marine–terrestrial gypsum range from 10‰ to 15‰. Furthermore, the sulfur isotope values present in terrestrial gypsum are less than 10‰ [15,51–53]. During the early stages of development, the two fluctuation trends displayed a small variation range of 18‰–20‰, which likely indicates that the sedimentary environment during this time was relatively stable, primarily consisting of a marine sedimentary environment. In the middle period, the two rising fluctuation trends showed an increase from 19.11‰ to 25.92‰, followed by a decrease to 13.41‰, and then an increase to 22.17‰. This shift could suggest a transition from a marine sedimentary environment to a marine continental sedimentary environment and then back to a marine–sedimentary environment. In the later period, a decreasing trend emerged, ranging from 22.17‰ to 6.69‰, which may suggest a shift from a marine sedimentary environment to

a marine–continental sedimentary environment, eventually transitioning to a continental sedimentary environment.

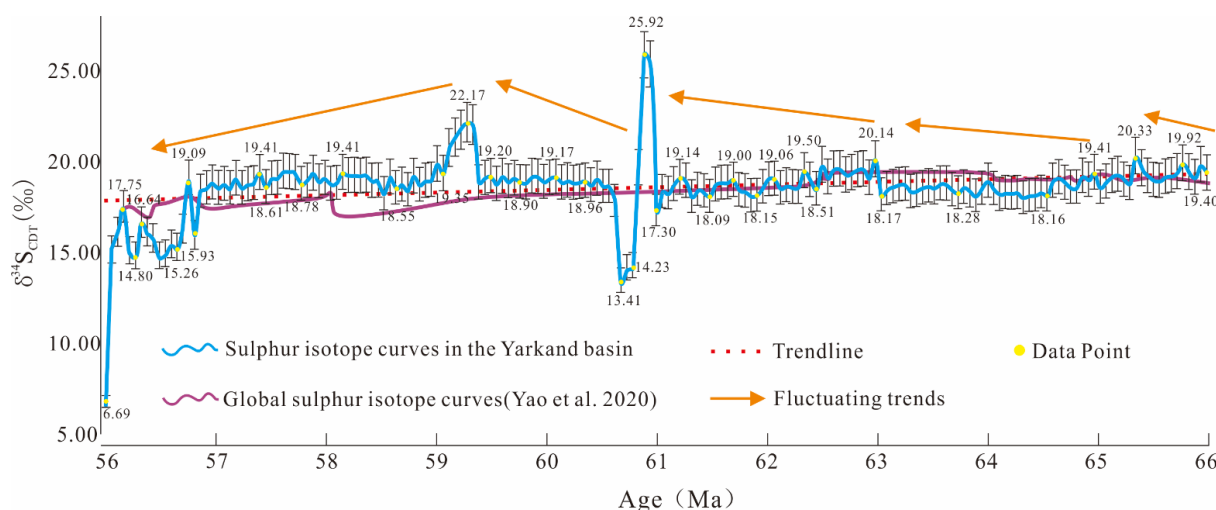


Figure 6. Paleocene sulfur isotope curves in the Yarkand Basin and the global Paleocene sulfur isotope curves. The purple LOWESS curve is constructed by utilizing the latest sulfur isotope data from 56 Ma to 66 Ma [15]. The blue curve is from the data of WX1, AK2, Kd101, Qun6, Tc2, and Shan1 boreholes of the Yarkand Basin during the Paleocene.

The Paleocene global sulfur isotopic curve is constructed by utilizing the latest sulfur isotope data from 56 Ma to 66 Ma [15] (Figure 6). Upon comparing this curve with the sulfur isotopic curve of the Yarkand Basin, it is evident that the latter also displays a general trend of decreasing $\delta^{34}\text{S}$ values over the Paleocene period. However, the evolution curve of Paleocene $\delta^{34}\text{S}$ values in the Yarkand Basin demonstrates a significant difference from the global curve. Specifically, the overall Paleocene $\delta^{34}\text{S}$ values in the Yarkand Basin are notably higher. Paytan et al. (2020) indicated that the global Paleocene sulfur isotope $\delta^{34}\text{S}$ ranged from 16‰ to 20‰, with an average value of 18.36‰ [15]. Consequently, it is reasonable to assume that the original sulfur isotope value of Paleocene evaporites in the Yarkand Basin was primarily within the range of 18‰ to 20‰, with an average value of 18.64‰.

5.3. Paleocene Evaporite Sedimentary Environment in the Yarkand Basin

During the Paleocene, the Paratethys seawater was introduced into the Yarkand Basin from the Alay graben located in the northwest of the Tarim Basin. The seawater was subsequently blocked by the middle-low hills of West Kunlun Mountain, finally leading to the formation of a lagoon [32]. The basin was influenced by land-derived clastic sedimentation and characterized by a semi-closed estuarine and lagoon environment during the early Paleocene–Eocene period [30]. Under the control of a subtropical arid climate, clastic rocks, gypsum rocks, and carbonate rocks were formed [43], and the Aertashen Formation underwent lagoonal and very shallow water evaporitic terrace phase sedimentation [54]. It is worth noting that evaporite rocks, such as gypsum and halite, are usually formed in closed or semi-closed basins and arid climates or strongly evaporated environments [55].

The process of evaporative precipitation of sulfate generally causes relatively tiny sulfur isotope fractionation, which can generally be ignored. As a result, the evaporatively precipitated sulfate is considered representative of the $\delta^{34}\text{S}$ values of seawater during the same period [56]. The fluctuations in $\delta^{34}\text{S}$ values are frequently caused by bacterial sulfate reduction or insufficient seawater replenishment in closed evaporite basins [1,44,57,58]. The $\delta^{34}\text{S}$ values of Paleocene gypsum sulfur isotopes in the Yarkand Basin exhibit frequent fluctuations, with four major upward trends identified. Especially in the Kd101 borehole, where unusually high sulfur isotope $\delta^{34}\text{S}$ values (25.40‰ and 25.92‰) were observed. The increase in sulfur isotope values reflects the enrichment of $\delta^{34}\text{S}$ in seawater sulfate, maybe

indicating the presence of bacterial reduction (BSR) of Paleocene seawater sulfate in the Yarkand Basin. Because BSR preferentially removes ^{32}S from dissolved sulfate, leading to the enrichment of ^{34}S in the residual brine [59,60].

In addition, the degree of isotopic fractionation during the bacterial sulfate reduction process is significantly influenced by whether the system is open or closed. In an open system, sulfate is continuously replenished, and the sulfate concentration does not decrease with the reaction. At the same time, the reduced H_2S combines with metal ions to form sulfides, which are continuously removed from the system. As a result, the concentration of H_2S in the system does not increase with the reaction. In this scenario, provided environmental conditions remain relatively constant, the isotopic fractionation will remain within a certain range, and the isotopic fractionation coefficient is often a constant value [61]. The nearly semi-enclosed basin is continuously replenished with seawater, and the sulfur isotope composition remains stable. The rhythmical changes of lithology (gypsum interspersed with limestone and mudstone) and the periodic changes of gypsum sulfur isotope value in the Paleocene Aertashen Formation of the Yarkand Basin indicated that the Yarkand Basin was poorly sealed and often replenished by seawater or fresh water. Consequently, the evaporite sedimentary environment at this time was relatively open.

The depositional extent of Aertashen Formation evaporite spreads over almost the entire Yarkand Basin, but its thickness varies across the basin in the Paleocene. In general, the gypsum in this Formation is more developed in the West Kunlun Mountain Front, particularly in the area surrounding the Wb1/Wx1 borehole, which is a prominent depositional center. The depositional thickness and scale of gypsum gradually decrease from the West Kunlun Mountain Front to the north to the South Tianshan Mountain Frontal Zone and the east to the Markit slope belt [23]. The Paleocene gypsum sulfur isotopic $\delta^{34}\text{S}$ values in the Yarkand Basin decrease from the junction of the West Kunlun Mountains and the South Tianshan Mountains to the southeast, with a greater decrease observed at the Markit slope belt than at the front of the West Kunlun Mountains. This trend can be observed by combining the mean gypsum sulfur isotopic $\delta^{34}\text{S}$ values from various field outcrop profiles and boreholes [20,32], as depicted in Figure 1. Therefore, it can be inferred that the ancient seawater started from the junction of the West Kunlun and South Tianshan Mountains, first invaded the southeast along the West Kunlun Mountains, and then spread toward the Markit slope. This is consistent with the change in the extent of marine transgression predicted by Cao [19].

The topography of the ancient salt lake in Yarkand Basin exhibited a high eastern region and a low western region. In the early stage of evaporite sedimentation, the depositional center was concentrated in the drilled area west of the basin, distributed along the southern Tianshan and the western Kunlun Mountains in an elongated form. In the late stage of the Aertashen Formation, the transgression scope expanded to the Markit slope belt. Due to the relatively far extension of seawater, a shallow evaporation platform environment was formed, represented by substantial, thick gypsum–salt deposits. With the seawater extension, the influence of seawater on sedimentary basins gradually weakens. The ancient salt lake was more susceptible to other factors, as seen from the variation of gypsum sulfur isotope $\delta^{34}\text{S}$ in the Shan1 and Kd101 boreholes. Both the thickness of gypsum strata and the $\delta^{34}\text{S}$ value of the sulfur isotope of gypsum show such a similar rule, indicating that the sedimentary environment of Paleocene evaporite in Yarkand Basin may also be related to the paleotopography and distance from the estuary, resulting in the difference of sedimentary environment.

The late Paleocene gypsum sulfur isotope $\delta^{34}\text{S}$ values in the Yarkand Basin gradually decreased from 22.17‰ to 6.69‰ (Figure 6), probably reflecting the increasing influence of exogenous sulfur. The late sedimentary environment may have been mainly influenced by terrigenous freshwater. The low $\delta^{34}\text{S}$ value can be attributed to two possible reasons:

1. Low $\delta^{34}\text{S}$ value of sulfate from the provenance: The source material itself may have had a low $\delta^{34}\text{S}$ value, resulting in low $\delta^{34}\text{S}$ values in the sedimentary sulfate;

2. Constant supply of source material and high oxidation degree of water: The constant supply of source material, combined with high oxidation conditions in the water, can make it difficult for anaerobic bacteria to survive. As a result, there is almost no biological fractionation, and the $\delta^{34}\text{S}$ value of sulfate remains low.

When marine sedimentary sulfate is injected with fresh water from the perimeter, it can result in low $\delta^{34}\text{S}$ values relative to the $\delta^{34}\text{S}$ values of normal seawater sulfate during the same period. When the basin is affected by continental freshwater and seawater, the sulfur isotopic composition of sedimentary sulfate (mainly gypsum) often has these characteristics of them, with $\delta^{34}\text{S}$ values usually ranging from 10‰ to 15‰ [62]. The fluctuation trend from 22.17‰ to 6.69‰ in the late period likely reflects a transition from a marine sedimentary environment to a marine–continental sedimentary environment and eventually to a continental sedimentary environment. The presence of mud and gravel associated with evaporite provides strong evidence of a terrigenous freshwater supply. Sulfates in terrigenous fresh water feeding the evaporation basin should have lighter sulfur isotopes. Therefore, the light sulfur isotopic characteristics of evaporite gypsum in the Yarkand Basin are likely affected primarily by terrigenous freshwater recharge.

6. Conclusions

Analysis of the sulfur isotopes of 187 gypsum samples showed that $\delta^{34}\text{S}$ values ranged from 6.69‰ to 25.92‰, with an average value of 18.64‰. The overall trend of the Paleocene gypsum sulfur isotopic curve in the Yarkand Basin is consistent with the global seawater sulfur isotopic curve, which exhibits a decreasing trend.

A trend of increasing sulfur isotopes is observed in the four early and middle phases, suggesting that the early and middle phases may have been mainly influenced by bacterial reduction and a relatively open sedimentary environment. In contrast, the late stage shows a decreasing trend, indicating that the late phase may have been mainly influenced by freshwater of terrestrial origin. Additionally, the sulfur isotope values in the basin have the characteristic of decreasing from northwest to southeast, which indicates that the depositional environment of the Paleocene evaporites in the Yarkand Basin may also be related to the paleotopography and the distance from the estuary, resulting in the difference in the depositional environment.

The original Paleocene evaporites in the Yarkand Basin should have a main body range of sulfur isotope values from 18‰ to 20‰, which is a supplement to the sulfur isotope of the Paleocene Tethys global paleo-seawater.

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