Environmental Evolution Recorded by Sediment Grain Size Since 33.9 ka BP in the Lop Nur Region, Xinjiang

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Abstract

The evolution of the mid-latitude westerly climate system is of great significance for revealing the mechanisms of high–low latitude climate interactions. The Tarim Basin, located in the mid-latitudes of the Northern Hemisphere, is a typical arid region strongly influenced by the westerly circulation, and its climate change makes it a key area for understanding the coupled relationship between the North Atlantic and the Asian monsoon system. At present, the hydrothermal configuration pattern of this region and its co-evolution with the global climate system remain controversial. Sediment samples from 0.00–16.10 m of core ZK0205 in the Luobei Depression, Lop Nur, Xinjiang, were analyzed, and three grain-size components sensitive to environmental change were identified: clay (<5 μm), silt (5–63 μm), and sand (>63 μm). Combined with catchment sedimentation patterns and modern observations, the three components indicate runoff variation, intensity of aeolian dust activity, and hydrodynamic conditions, respectively. Based on an accelerator mass spectrometry radiocarbon chronology, an environmental evolution sequence of the study area since 33.9 ka BP was reconstructed. The results show that: (1) the Lop Nur region was relatively humid during Marine Isotope Stage 3, shifted to arid conditions during Marine Isotope Stage 2, and was generally warm and dry during the Holocene, revealing a phased transformation of hydrothermal combinations since the Late Pleistocene. (2) Comparison between variations in grain-size components and oxygen isotope ratio records from the North Greenland Ice Core Project ice core indicates that the region responded well to millennial-scale climate events in the Northern Hemisphere, and that its response pattern underwent systematic shifts with changes in the climatic background. (3) Lop Nur is located at the junction between the core area and marginal transition zone of the westerlies; its climate evolution was not only constrained by the global climatic background but also jointly modulated by the westerly and monsoon systems, resulting in a highly complex regional climate pattern.

Full Text

Environmental Evolution Recorded by Sediment Grain Size Since 33.9 ka BP in the Lop Nur Region, Xinjiang

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Abstract: The evolutionary process of the westerly climate system in the mid-latitudes is of great significance for revealing mechanisms of interaction between high- and low-latitude climates. The Tarim Basin, located in the Northern Hemisphere mid-latitudes, is a typical arid region strongly influenced by the westerly circulation; its climatic changes are a key area for understanding the coupling relationship between the North Atlantic and Asian monsoon systems. At present, the hydrothermal configuration pattern of this region and its co-evolution with the global climate system remain controversial. Sediment samples from 0.00–16.10 m of core ZK0205 in the northern depression of Lop Nur, Xinjiang, were analyzed, and three grain-size components sensitive to environmental change were identified: clay (<5 μm), silt (5-63 μm), and sand (>63 μm). Combined with patterns of catchment sedimentation and modern observations, the three components respectively indicate changes in runoff, intensity of dust activity, and hydrodynamic conditions. Based on an accelerator mass spectrometry radiocarbon dating framework, an environmental evolution sequence for the study area since 33.9 ka BP was reconstructed. The results show that: (1) the climate in the Lop Nur region was relatively humid during Marine Isotope Stage 3, shifted to arid during Marine Isotope Stage 2, and was generally warm and dry throughout the Holocene, indicating staged transitions in the hydrothermal combination since the Late Pleistocene. (2) Comparison between grain-size component changes and the North Greenland Ice Core Project ice-core oxygen-isotope ratio record shows that the region responded well to Northern Hemisphere millennial-scale climate events, and that its response mode shifted systematically with the climatic background. (3) Lop Nur lies at the boundary between the core zone of the westerlies and the marginal transition zone; its climatic evolution was not only constrained by the global climatic background, but also jointly regulated by the westerly and monsoon systems, resulting in a highly complex regional climate pattern.

Keywords: Lop Nur; lacustrine sediment; grain-size analysis; stratigraphic composition; Central Asian arid region

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Northwest China is located in the eastern part of the world's largest mid-latitude arid region[1]. This region connects the low-, middle-, and high-latitude climate zones[2] and co-evolves with the Asian monsoon system; consequently, its formation and evolutionary process have long been a focus of geological research[3-4]. Eastern Xinjiang, as one of the core areas of the Central Asian arid region, is climatically controlled mainly by the westerlies and is also influenced by the East Asian summer monsoon[5], making it sensitive to changes in both major circulation systems[6-7]. A deeper understanding of the patterns of paleoenvironmental evolution in this region is of important guiding significance for improving the current ecological fragility of the area. Therefore, obtaining high-resolution climate records in this region and systematically revealing the details of aridification processes and their driving factors are particularly necessary.

The paleoclimate evolution of Central Asia, especially its hydrothermal combination pattern, has long attracted scholarly attention. As early as the 1990s, Li Jijun[8] proposed that environmental change in northwestern China since the

Late Pleistocene followed the general rule of the westerly belt in which "the cold period and rainy period are synchronous." Subsequent studies based on Lop Nur lacustrine sediments and sporopollen[2,9-11] further supported the view that since the Late Pleistocene, this region has mainly exhibited a "cold-wet—warm-dry" combination pattern, reflecting that the climate may have been out of phase with that of the monsoon region. However, in recent years, multiple studies have challenged this pattern, suggesting that during certain periods of the Late Quaternary the Central Asian arid region may have displayed climatic characteristics similar to those of the monsoon region[1,12-13]. These debates indicate that the hydrothermal combination pattern of the Central Asian arid region in the Late Quaternary and the mechanisms by which its moisture spatial distribution responds to millennial-scale climate events still require further investigation. Based on grain-size indicators from lacustrine sediments in Lop Nur, Xinjiang, this paper reconstructs the hydrological variation sequence of the region since the Late Pleistocene, providing higher-resolution evidence for studies of Central Asian paleoclimate dynamics and offering a new perspective for understanding the above controversies.

Sediment grain size is a commonly used sensitive indicator for reconstructing paleoclimate change.

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indicator that can reflect information such as sediment provenance, transport mechanisms, depositional environment, and paleoclimate changes[^14]. Because this indicator is easy to measure and relatively low in cost, it has been widely applied in paleoclimate studies[^15–17]. In lake sediments, coarse–fine changes in sediment grain-size composition can effectively indicate regional hydrodynamic conditions[^18]; meanwhile, as an important source of lake sediments in northwestern China, windblown dust inputs, and changes in their specific grain-size fractions, are often used to reflect the evolution of regional wind strength[^1,^19]. However, even within the same region and time interval, interpretations based on this indicator may still differ, partly because secondary minerals such as sulfates may not have been fully removed during sample pretreatment[^20]. Therefore, this study optimized the grain-size pretreatment method and, on this basis, systematically analyzed grain-size records since the Late Pleistocene in the Lop Nur region, revealing the pattern of climate change and characteristics of environmental evolution in this region since the Late Pleistocene, and providing more accurate data support for paleoclimate reconstruction.

1 Materials and methods

1.1 Overview of the study area

Lop Nur (39°–41°N, 88°–92°E) lies in the center of the Eurasian continent and is located in a secondary tectonic depression in the eastern part of the Tarim Block. To its south and north, respectively, lie the Altun Mountains and the Kuruktag Mountains (Fig. 1)[^21]. Overall, the terrain is higher in the southeast and lower in the northwest. The region has a typical continental arid climate, with scarce precipitation, intense evaporation, and an extremely dry climate[^22]. As a typical region controlled by the westerlies[^15,^23–24], Lop Nur most likely dried up completely between the late 1930s and early 1940s; thereafter, only seasonally very small water bodies remained[^25]. Even so, the sedimentary sequence in this region is complete and preserves abundant information on geological, hydrological, and environmental evolution[^26], providing an important carrier for paleoclimate research.

1.2 Research methods

Borehole ZK0205 (40°53$ '18.73' 'N, 90°51' 35.90'' $E) is located in the Luobei Depression in the northern part of Lop Nur, Tarim Basin, Xinjiang (Fig. 1), with a collar elevation of 790 m. The total length of the borehole is 90.18 m. In the core, salt beds dominated by thenardite are clearly visible, mainly concentrated in the middle and upper parts; the remaining intervals are mostly silty clay layers containing gypsum or thenardite, and the top is a halite layer. This paper focuses on the upper 16.10 m of the borehole core. According to characteristics such as mineral composition, color, structure, and grain size of the sediments, it is divided into eight lithologic intervals; the lithologic characteristics of each interval are shown in Table 1.

In this study, 295 sediment samples were systematically collected from the 0.00–16.10 m borehole core at 5 cm intervals for grain-size analysis. Grain-size testing was completed using a Mastersizer 2000 laser particle-size analyzer from Malvern, UK, with a measurement range of 0.002–2000 μm and a relative error of less than 3%. The salt-lake sediments of Lop Nur are rich in sulfate minerals such as gypsum and thenardite[^27–28]. Such minerals grow together with detrital particles in cemented form and directly affect the accuracy of grain-size measurements. When predecessors treated sediments such as loess[^29–31], the hydrochloric acid added could not effectively remove sulfate minerals. Therefore, referring to previous studies and in combination with the Lop Nur region

Fig. 1 Schematic diagram of the study area

Table 1 Description of lithostratigraphy of core ZK0205 in the Lop Nur

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Tab. 1 Description of lithostratigraphy of core ZK0205 in the Lop Nur

Depth/m	Lithostratigraphy
0.00~1.54	Light grayish-yellow fine-grained halite aggregates containing a small amount of fine sand; loose accumulation; halite crystals are colorless and transparent.
1.54~3.54	Light-gray fine-grained gypsum aggregates containing a small amount of silty sand; gypsum crystals occur as grayish-white fine acicular aggregates arranged in clusters.
3.54~4.54	Grayish-yellow massive silty sand containing a small amount of gypsum cryptocrystalline material; occasional halite.
4.54~5.42	Grayish-white massive silty sand containing fine-grained halite and a small amount of clay.
5.42~6.72	Grayish-black massive clay containing silty sand and a small amount of fine-grained gypsum.
6.72~11.96	Dark-gray massive fine-grained glauberite containing silty glauberite; crystals occur as gray scaly and flaky aggregates, cemented with silty sand, with a few pores visible. In the 9.21~11.00 m interval, the contents of silty sand and fine grains increase.
11.96~15.85	Dark-green massive clay containing a small amount of silty sand, with occasional glauberite cryptocrystals. After 15 m, the glauberite content gradually increases and the color changes to grayish yellow.
15.85~16.10	Grayish-green massive fine-grained glauberite-cemented silty sand; the structure is hard and compact.

lake sediment characteristics, a saturated sodium carbonate solution was introduced during pretreatment to selectively remove sulfates[^20]. The specific procedure was as follows: take 10 g of sample, add 50 mL of saturated sodium carbonate solution, and stir at constant temperature on a magnetic stirrer for 50 h until the reaction is complete; subsequently add 50 mL of 10% hydrochloric acid, let it stand and react overnight, and then repeatedly rinse with deionized water to neutrality. If salts remain, repeat the above steps; add 50 mL of 10% hydrogen peroxide to remove organic matter, heat to remove residual hydrogen peroxide; before testing, add 5 mL of 0.05 $mol \cdot L^{-1}$ sodium hexametaphosphate dispersant, ultrasonicate for 3-5 min, and place in the laser particle-size analyzer for measurement. This method effectively removes the influence of sulfate minerals, so that the particle-size data obtained can more realistically reflect the dynamic characteristics of the sedimentary process[^20].

The dating of lake sediments usually uses radiocarbon (^{14}C) dating based on organic sediments[^32]. In the Lop Nur area, accelerator mass spectrometry radiocarbon dating (AMS^{14}C) has been widely applied and has yielded abundant research results[^33-35]. In this study, this method was used to carry out high-precision AMS^{14}C dating of organic sediments from the 0.00~16.10 m strata in the upper part of core ZK0205. A total of 9 samples were obtained, and all dating experiments were completed at the Xi' an Accelerator Mass Spectrometry Center.

2 Results and Analysis

2.1 Establishment of the age-depth model

Lop Nur is a closed, high-salinity lake. Its depositional system has a significant "old carbon" effect[^36], causing the ^{14}C ages of lake sediments to be older than the true depositional ages. In addition, the strata in this area are dominated by highly porous glauberite deposits[^37], and younger organic matter from later periods may have entered earlier sedimentary horizons with percolating water, further increasing the complexity of age identification. Therefore, when analyzing ^{14}C dating data, it is necessary to make a comprehensive judgment by combining lithological characteristics and referring to chronological frameworks previously established for the region[^38].

Since the Late Pleistocene, tectonic activity in the Lop Nur depression has tended to be stable[^39], and the climate also entered an extremely arid stage. The sedimentary environment of this area gradually evolved from a salt lake into a dry salt lake, accompanied by large-scale mineralization of potassium salts[^40-41]. Based on the above understanding, and after excluding inverted ages, this study used a total of 6 valid ^{14}C age data (Table 2), together with the AMS^{14}C dating conducted by Luo et al.[^42] on core ZK0807 in the same region (Fig. 1), to infer

Table 2 Results of AMS^{14}C dating and calibration of core ZK0205 in the Lop Nur

Tab. 2 Results of AMS ^{14}C dating and calibration of core ZK0205 in the Lop Nur

Laboratory no.	Sample no.	Depth/m	Material	Measured age/ka BP	Calibrated age/ka BP	Data quality
XA55102	ZK0205-5H-2	3.68	Organic sediment	10.200 ± 0.030	9.926 ± 0.073	Valid
XA55103	ZK0205-5H-7	3.98	Organic sediment	10.000 ± 0.030	9.860 ± 0.168	Excluded
XA50296	ZK0205-14C-2	5.24	Organic sediment	10.705 ± 0.030	10.763 ± 0.029	Excluded
XA55104	ZK0205-7H-5	5.67	Organic sediment	14.850 ± 0.040	16.220 ± 0.096	Valid
XA50297	ZK0205-14C-3	10.70	Organic sediment	23.170 ± 0.060	25.510 ± 0.185	Valid
XA50298	ZK0205-14C-4	11.20	Organic sediment	12.425 ± 0.040	12.639 ± 0.303	Excluded
XA55105	ZK0205-11H-29	12.60	Organic sediment	25.000 ± 0.040	27.352 ± 0.320	Valid
XA55106	ZK0205-12H-23	14.34	Organic sediment	28.095 ± 0.125	30.052 ± 0.324	Valid
XA50300	ZK0205-14C-6	15.98	Organic sediment	36.450 ± 0.150	34.580 ± 0.310	Valid

The measured surface age is approximately 3 ka; this result was used to construct a reliable age-depth model (Fig. 2).

Based on the distribution characteristics of the measured age data for each stratigraphic unit, linear regression equations were established using Grapher 10 software for the two depth intervals of 0.00–5.67 m and 5.67–15.98 m, respectively (Fig. 2). The interpolated ages of each stratum were calculated according to the corresponding regression functions, and the depositional age at 16.10 m in core ZK0205 was estimated to be approximately 33.9 ka BP.

As can be seen from Fig. 2, the sedimentation rate of this borehole shows a clear correspondence with stratigraphic characteristics. In the lower interval (5.67–

16.10 m), lithologic variation is relatively small, the depositional environment is relatively stable, and the sedimentation rate is relatively high, about 600 mm $\cdot$ ka^{-1}. In the upper interval (0.00-5.67 m), lithologic variation is obvious; the composition of saline minerals indicates that desiccation of the lake basin had entered its late stage, and the sedimentation rate is relatively low, about 500 mm $\cdot$ ka^{-1}. Overall, strata with higher detrital mineral contents generally correspond to higher sedimentation rates, whereas strata dominated by saline minerals have relatively lower sedimentation rates.

2.2 Grain-size variation characteristics

The grain size of lacustrine sediments is an important proxy for paleoenvironmental reconstruction. Using 5 μm and 63 μm as the boundary values between clay/silt and silt/sand, respectively, the detrital particles in the sediments of core ZK0205 were divided into three fractions: clay (<5 μm), silt (5-63 μm), and sand (>63 μm). Their ranges of variation were obtained (Fig. 3), and sequences of percentage content versus depth were established for each fraction.

In the sediments of core ZK0205, the clay fraction content ranges from 4.70% to 91.44%, with an average content of 32.50%. At 11.96-15.85 m, the clay content increases markedly and fluctuates more strongly, reaching a maximum of 91.44%. The silt fraction content ranges from 8.57% to 77.60%, with an average content of 57.96%; it decreases markedly at 9.21-15.85 m, with a minimum of only 8.57%. The sand fraction content ranges from 0.00% to 84.01%, with an average content of 11.01%; at 0.80–1.54 m and 9.21-11.96 m, the sand fraction content increases sharply and then decreases, reaching a maximum of 84.01%; at 15.85-16.10 m, the sand fraction content increases, while it is generally higher in the remaining intervals.

The grain-size results show that, in the grain-size composition of sediments from the 0.00-16.10 m interval of core ZK0205, silt accounts for the largest proportion of the sediment particle-size fractions, followed by clay. The grain-size parameters of the sediments show that the mean grain size ranges from 2.04 to 235.11 μm, with an average value of 35.64 μm; the range of variation in mean grain size differs greatly among samples from different horizons (Table 3). The median grain size ranges from 0.79 to 220.00 μm, with an average value of 20.84 μm. The variation trends of the sand fraction, mean grain size, and median grain size are similar, indicating the influence of sand on the particle-size distribution characteristics of the sediments.

Fig. 2 Lithology and depth–age conversion diagram of core ZK0205 in the Lop Nur

Visible labels in Fig. 2:

- ZK0205 strata

Fig. 3 Vertical variation characteristics of grain size composition from borehole ZK0205 in the Lop Nur

Figure 2: Fig. 3 Vertical variation characteristics of grain size composition from borehole ZK0205 in the Lop Nur

- Top age: 3 ka
- Age/ka
- Depth/m
- Age = 2.2753 $\times$ depth + 2.6241
  Sedimentation rate = 500 mm $\cdot$ ka^{-1}
- Age = 1.6976 $\times$ depth $-$ 6.6132
  Sedimentation rate = 600 mm $\cdot$ ka^{-1}
- Age control points:
  - 9.926 $\pm$ 0.073 ka
  - 16.220 $\pm$ 0.096 ka
  - 25.510 $\pm$ 0.185 ka
  - 27.352 $\pm$ 0.320 ka
  - 30.052 $\pm$ 0.324 ka
  - 34.580 $\pm$ 0.310 ka
- Legend:
  - Halite
  - Gypsum-bearing silt
  - Gypsum-bearing silt
  - Halite-bearing silt
  - Clay containing silt with minor gypsum
  - Mirabilite-bearing silt
  - Clay containing silt

Fig. 2 Lithology and depth-age model of core ZK0205 in the Lop Nur

Note: MIS1 is the Holocene; MIS2 is Marine Isotope Stage 2; MIS3 is Marine Isotope Stage 3. The same below.

Fig. 3 Vertical variation characteristics of grain size composition from borehole ZK0205 in the Lop Nur

Table 3 Grain-size characteristics of sediments from borehole ZK0205 in the Lop Nur

Tab. 3 Grain-size characteristics of sediments from borehole ZK0205 in the Lop Nur

Depth/m	Mean grain size/μm	Median grain size/μm	Standard deviation/μm
0.00~1.54	18.30~115.00	6.24~20.50	0.833~1.361
1.54~3.54	9.17~41.10	4.90~12.60	1.112~1.521
3.54~4.54	7.43~40.60	4.84~29.20	1.008~1.447
4.54~5.42	8.48~17.60	4.88~9.97	1.147~1.436
5.42~6.72	10.50~26.50	5.44~12.80	1.113~1.286
6.72~11.96	8.98~235.11	5.08~220.00	0.876~2.191
11.96~15.85	2.04~158.00	0.79~173.00	0.945~1.947
15.85~16.10	14.00~75.20	15.90~16.10	0.970~1.333

The grain-size standard deviation reflects the sorting degree of sediments. The standard deviations of sediments in the 0.00–16.10 m interval of borehole ZK0205 show that most samples are poorly sorted, while a few are moderately sorted. Overall, the grain-size composition is complex, possibly reflecting the mixed effects of multiple transporting media such as wind and water. The grain-size compositional characteristics of sediments from different environments in the region also support the diversity of sediment sources or transport modes.

The modal characteristics of sediment frequency distribution curves are an important basis for judging the form of sedimentary processes[^43]. As shown in Fig. 4, the grain-size frequency curves of the sediments in this interval are mostly polymodal. For a closed lake, this indicates that the depositional process may have been affected simultaneously by wind and flowing water. The figure shows the measured grain-size distributions of three peak-shaped samples and the grain-size distributions of multiple grain-size components calculated by separation. The analysis indicates that almost all samples contain a fine clay component of 0.56 μm (Fig. 4a), which may represent chemical precipitates in a closed lake[^44]. In sample ZK0205-11H-39 from the blackish-green massive clay layer at 11.96–15.85 m, the content of its clay component (3.56 μm) reaches 62.72% (Fig. 4b). This component is fine-grained, well sorted, and has a relatively wide distribution range, and is mostly suspension deposition under weak lake-water dynamics. In contrast, in sample ZK0205-11H-3 from the same interval, the sand component (200.00 μm) accounts for 84.70% (Fig. 4d); the other components have low contents, with coarse grain size, poor sorting, and a relatively narrow distribution range, and are mostly products transported by strong hydrodynamics[^44]. In sample ZK0205-5H-5 from the grayish-yellow massive silty sand layer at 3.54–4.54 m (Fig. 4c), the silty sand component (39.90 μm) accounts for 65.61%, and is usually formed by short-distance wind transport[^19]; the clay component (5.64 μm) accounts for 28.68%, and its characteristics are similar to those of the clay component in ZK0205-11H-39, indicating that this sample was likewise affected by the mixing of multiple transport modes.

2.3 Environmental implications of each grain-size component

Sediments in closed lakes in arid–semiarid regions are mainly composed of terrestrial clastic materials within the watershed[^19,^45] and exogenous aeolian dust materials[^46–^47], and their grain sizes are ⋯

(a) Grain-size frequency distribution curves of borehole ZK0205 (0.00–16.10 m)

(b) ZK0205–11H–39

- Fitted curve
- Fine clay component (0.56 μm, 30.49%)
- Clay component (3.56 μm, 62.72%)
- Silt component (28.30 μm, 6.80%)

(c) ZK0205–5H–5

- Fitted curve
- Fine clay component (0.56 μm, 5.70%)
- Clay component (5.64 μm, 28.68%)
- Silt component (39.90 μm, 65.61%)

(d) ZK0205–11H–3

- Fitted curve
- Fine clay component (0.56 μm, 1.64%)
- Clay component (5.02 μm, 5.43%)
- Silt component (22.40 μm, 8.23%)
- Sand component (200.00 μm, 84.70%)

Fig. 4 Grain-size distribution curve of borehole ZK0205 (0.00–16.10 m) in the Lop Nur

influenced by lake hydrodynamics

48

and regional aeolian-sand activity

49–50

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Lop Nur was once the terminal catchment area of the Tarim River and the Kongque River

51

. The sediments in the Tarim River basin are dominated by silt

19, 52

; therefore, it can be inferred that the sediments transported into Lop Nur are also dominated by silt and clay. Studies of borehole KY01 in the Xinhudistrict of Lop Nur indicate that the 3.5–6.2 μm grain-size component is mainly the product of suspended particles from terrigenous clastic material within the basin, re-sorted and deposited by lake hydrodynamics

19

. Liu et al.

12

used the finest particle component in the KY01 borehole sediments (modal grain size 4 μm) to indicate fluctuations in inflow runoff to the lake. In borehole CK-2, located in the Luobei Depression, the <5 μm grain-size component was interpreted as the product of a weak hydrodynamic environment

2

. Borehole ZK0205 is located near the lake-center area of the Luobei Depression; its natural environmental conditions are similar to those of borehole KY01, its geographic position is close to borehole CK-2, and the 0.00–16.10 m interval generally contains a <5 μm clay component. It is therefore inferred that this component can be used to reflect fluctuations in runoff entering Lop Nur.

In arid–semiarid regions, the grain-size composition of sediments in closed lakes is the result of the combined action of regional aeolian-sand activity and lake hydrodynamics. In such lacustrine depositional systems, the silt-sized (5–63 μm) component is directly related to the transport of atmospheric dust and has a clear significance as an indicator of wind-derived deposition. The climate of the Tarim Basin is dominated by the westerly circulation; vegetation is sparse, surface materials are loose, and abundant material sources are provided for dust

53

. Modern observations of dust deposition in northwestern China show that dust grain sizes are mainly distributed within the range of 5–63 μm

12, 54

, overlapping strongly with the modal grain-size range (20–70 μm) of loess deposits in the basin, thereby confirming the sensitivity of this grain-size component to the intensity of regional wind fields

55–56

. Lop Nur is located on the eastern margin of the basin and is dominated year-round by northeasterly winds

19

. Its near-surface wind field is strongly influenced by topography and by the strength and position of the westerly circulation

57–58

, and is the key driving force transporting dust into the lake basin. Therefore, fluctuations in the content of the silt (5-63 μm) component in the sediments may represent dust particles transported directly into Lop Nur by the atmosphere and serve as an effective indicator of the intensity of regional aeolian activity.

By comparison, the environmental significance of the sand-sized (>63 μm) component is more complex. Traditional studies have held that the content of coarse particles in lacustrine sediments is closely related to hydrodynamic intensity

38

. Fine-grained deposition is often regarded as a marker of humid periods with high lake levels, whereas enrichment of coarse particles corresponds to arid stages with low lake levels

59

. However, recent studies have found that, in lakes of arid–semiarid regions, when the change in open-water level is relatively small, under the drive of strong hydrodynamics, coarse clastic material is more easily transported to the lake-center area; at this time, coarse particles

The enrichment of the material instead indicates a humid climate[^60]. Zhang et al.[^17], through rare-earth-element tracer analysis, found that some of the sand grains > 63 μm in the Lop Nur sediments may have originated from fluvial transport by the Tarim River and the Qarqan River, indicating strong hydrodynamic conditions. In addition, against the background of the distinctive strong wind field in the study area, coarse particles may also have an aeolian origin. Liu et al.[^12] suggested that sand-dust storm activity in this region was mainly driven by high-latitude cold events in the Northern Hemisphere and by low-level northwesterly airflow. As a huge dust source area, the Taklimakan Desert, under the action of extremely strong winds (dust-storm events), is fully capable of transporting coarse sand-sized particles near the surface to lake basins[^61–^62]. Therefore, when using the sand fraction (> 63 μm) to reconstruct paleoenvironmental conditions, aeolian and hydrodynamic origins must be distinguished comprehensively; in particular, during key intervals such as the Last Glacial Maximum, the dominant controlling mechanism should be clearly identified.

3 Discussion

3.1 Environmental evolution process in the Lop Nur region since 33.9 ka BP

Based on changes in sediment grain-size components, an environmental-evolution sequence for the Lop Nur region since 33.9 ka BP was reconstructed (Fig. 5). During late marine isotope stage 3 (MIS3) (33.9–29.0 ka BP), the clay fraction shows an increasing trend, while the silt fraction fluctuates markedly (first decreasing rapidly and then increasing). The sand fraction was relatively high during 33.9–32.5 ka BP, and then decreased rapidly and remained at a

Fig. 5 Comparison of sediment grain-size from Lop Nur since 33.9 ka BP with the NGRIP and the Kesang Cave ( )18O record

Figure 3: Fig. 5 Comparison of sediment grain-size from Lop Nur since 33.9 ka BP with the NGRIP and the Kesang Cave ( )18O record

stable low value. The lithology of the MIS3 stage is mainly dark-green massive clay, and the color may reflect relatively great water depth, with organic matter on the lake bottom not having completely decomposed and oxidized (Fig. 3). Overall, the climate during late MIS3 was comparatively humid.

In the early part of deep-sea oxygen isotope stage 2 (MIS2) (29.0–11.7 ka BP), the clay fraction fluctuated downward, while the silt fraction remained high. After entering the Last Glacial Maximum (26.0–19.0 ka BP), the clay fraction fluctuated upward; the silt fraction fluctuated downward and then upward; and the sand fraction fluctuated greatly and reached high values, after which it decreased rapidly and tended to stabilize. After entering the last deglaciation (19.0–11.7 ka BP), accompanied by rising temperatures in the Northern Hemisphere, the clay fraction increased slowly; the silt fraction decreased slightly compared with before but still remained high; and the sand fraction remained low and stable. The entire MIS2 stage exhibits distinct arid characteristics. This result is consistent with An et al.[^1] in their study of pollen from Lake Balikun [[unclear: continuation not visible on this page]].

Note: NGRIP $\delta^{18}O$ (‰, VSMOW) is the oxygen-isotope ratio from the North Greenland ice-core record; The Kesang record $\delta^{18}O$ (‰, VPDB) is the oxygen-isotope ratio from calcite in Kesang Cave; Is1-Is6 denote interstadials 1-6; YD denotes the Younger Dryas event; H1-H3 denote Heinrich events 1-3.

Fig. 5 Comparison of sediment grain-size from Lop Nur since 33.9 ka BP with the NGRIP and the Kesang Cave $\delta^{18}O$ record

The pollen record indicates a dry environment during 30.7-9.0 ka BP, consistent with this study area showing arid characteristics in MIS2, extending into the early Holocene.

In the early Holocene (MIS1; ca. 11.7-7.0 ka BP), the clay-component content increased, the silt-component content decreased, and the sand-component content remained at a stable low value. At this time, climatic conditions improved compared with the preceding period. As lake evolution entered its late stage[1], minerals indicative of arid environments, such as gypsum and halite, developed widely (Fig. 3). Subsequently, the silt-component content increased, and climatic conditions continued to develop toward aridity.

After 7.0 ka BP, the silt-component content decreased and the clay component increased; this lasted for roughly 1.0 ka, after which the sand component rose rapidly and reached a peak, suggesting that the climate briefly shifted toward

[1] 39,63

humid conditions. This stage continued until 4.2 ka BP, when the silt component increased rapidly and the sand component fell to an extremely low value. Until 3.0 ka BP, core ZK0205 no longer produced new lacustrine deposits, implying that severe drought may have occurred in the Lop Nur depression. The climatic characteristics of this extreme drought may ultimately have led to large-scale contraction of the Lop Nur lake basin, or even intermittent desiccation.

3.2 Response of the Lop Nur region to Northern Hemisphere millennial-scale climate events during the Late Quaternary

Climate change in the Lop Nur region shows a clear response to millennial-scale climate events in the Northern Hemisphere during the Late Quaternary[2]. This study compares the variation sequences of sediment components of different grain-size fractions with the oxygen isotope ratios of the North Greenland Ice Core Project ice core (NGRIP ice-core $\delta^{18}O$) record[3] (Fig. 5). In MIS3, during the warm events of interstadial 5 (Is5) and interstadial 6 (Is6), the silt content decreased, while clay and sand contents increased; during Heinrich event 3 (H3), however, the clay content increased and sand content was low. After entering MIS2 (29.0–14.7 ka BP), the response pattern to millennial-scale events, such as Heinrich event 2 (H2), Heinrich event 1 (H1), and the interstadial 2–4 (Is2–Is4) warm events, changed. During the Is2–Is4 warm events, the silt content increased, whereas during cold events (H2 and the Xian nü mu event), the sand content rose sharply. During the global 4.2 ka BP drought event in MIS1, the silt content increased rapidly while the sand content declined to an extremely low value, indicating an extremely arid environment that may have caused desiccation of the Lop Nur depression. The response pattern of this stage to short-term events was similar to that of MIS3.

Therefore, millennial-scale Northern Hemisphere climate events are well recorded in the sediments of Lop Nur, but their response pattern underwent systematic transitions with changes in the climatic background (warm periods MIS1/MIS3 and cold period MIS2). Since 33.9 ka, short-term climate variability from high latitudes has regulated climatic evolution in southeastern Xinjiang, indicating that the climate-driving mechanisms of millennial-scale climate events, such as Heinrich events, may have changed under different climatic stages.

3.3 Driving mechanisms of climate change in the Lop Nur region since 33.9 ka BP in the Late Quaternary

Lop Nur is located in eastern Xinjiang, China. Since the Late Quaternary, its climate change has mainly been controlled by the westerlies and influenced by

[2] 2,10,12,23
[3] 64-66

high-latitude atmospheric circulation[4]. Chen et al.[5] divided the boundaries of the westerly core zone, transition zone, and summer-monsoon region during the Holocene; Lop Nur lies in the westerly core zone and transition zone (Fig. 6). Its climate change was jointly affected by the westerlies and the summer monsoon, so the climatic-change pattern of this region is highly complex. During the warm phase of MIS3, overall Northern Hemisphere temperature was relatively high. At this time, the westerly circulation weakened and the influence of the East Asian monsoon strengthened[6], leading to increased regional precipitation and increased meltwater from snow and ice in the Kunlun Mountains. The amount of fluvial sand transported into the Tarim Basin increased, and the region as a whole was humid. Until the H3 cold event, with strengthening of the westerlies, hydrodynamic intensity weakened markedly, and the region gradually shifted toward aridity.

Entering the cold stage of MIS2, the overall Northern Hemisphere climate was cold and experienced multiple rapid cold–warm oscillations, such as the H1 and H2 cold events and the Is2–Is4 warm events. Strengthening of the Siberian High caused the westerlies to shift southward and intensify[7], and the westerly core zone may have expanded southeastward to the Lop Nur region accordingly. At this time, stalagmite δ^{18}O records from Kesang Cave shifted positive[8], indicating that the Lop Nur region was almost unaffected by the East Asian monsoon. After entering the last glacial maximum, sediment grain size increased markedly; especially during the H2 cold event, the sand component increased while the silt component likewise increased. This indicates that when high-latitude cold events occurred in the Northern Hemisphere, strengthening of the westerlies brought moisture, while enhanced low-level airflow supplied coarse-grained aeolian dust deposition. However, persistently low temperatures limited the efficiency of westerly moisture transport, while enhanced low-level wind fields more readily transported aeolian dust material. Therefore, the overall climatic conditions during the cold stage of MIS2 were characterized by a broad background of aridity.

Entering the Holocene, with the rise in global temperature, regional climatic conditions generally improved. However, as a large shallow lake, Lop Nur was extremely sensitive to temperature-related changes in evaporation[9]. Warming led to a significant increase in evaporation; when temperature exceeded a certain threshold, the lake level dropped and even the lakebed was exposed, and the silt component in the sediments increased correspondingly. Multiple studies have indicated[10] that, since the Holocene, lacustrine evolution in the Lop Nur region entered a declining stage and was overall characterized by an aridification trend.

[4] 10
[5] 53
[6] 67
[7] 68
[8] 69
[9] 70
[10] 39,60

Fig. 6 Spatial extent of the "westerlies-dominated climatic regime" during the Holocene

Figure 4: Fig. 6 Spatial extent of the "westerlies-dominated climatic regime" during the Holocene

During the global cold event around 8.2 ka BP, evaporation was suppressed and a brief humid phase appeared; afterward, the area returned again to a predominantly arid regime. Although Holocene climate change in the Lop Nur region is not fully consistent with the amplitude of effective-moisture changes in the Asian westerly region revealed by Chen et al.[11], the records of regional humidification are mutually consistent. This difference may be related to Lop Nur' s location in the westerly core ···

Fig. 6 Spatial extent of the "westerlies-dominated climatic regime" during the Holocene[53]

The location of the boundary between the core area and the transition zone is related to differences in the degree of influence exerted by the westerly and monsoon systems under different climatic backgrounds. The record from core ZK0205 shows that the Holocene wettest interval occurred during 4.0–7.0 ka BP, which is also consistent with the negative trend in the $\delta^{18}O$ records of Cheng et al.[69] from Kesang Cave stalagmites. The surface sediment age of core ZK0205 is 3.0 ka BP; Kesang Cave stalagmite records show an abrupt positive $\delta^{18}O$ excursion at this time, further indicating that, under a high-solar-radiation background, precipitation from the Asian summer monsoon, or the water vapor transported by it, may once have affected this region. This suggests that the Asian summer monsoon also exerted a certain modulating effect on the climate of the Lop Nur region.

In summary, the dynamical characteristics of climate change in the Lop Nur region since the late Late Pleistocene are as follows. **Switching of the dominant controlling factors:** Lop Nur lies near the boundary between the westerlies core area and the transition zone; its climate evolved over the waxing and waning of the two major systems, the westerly belt and the Asian summer monsoon. When the westerlies core area expanded, the westerlies occupied the dominant position and controlled regional precipitation in this area. When the westerlies core area contracted, changes in the strength of the Asian monsoon may have participated in regulating the water-vapor pattern of Lop Nur. **Combined effects of temperature and water vapor:** Regional dry–wet conditions are not determined solely by water-vapor transport; temperature plays an important role by influencing evaporation and atmospheric circulation (such as the strength and pathway of the westerlies). For example, even if enhanced westerlies may bring water vapor (as in the cold MIS2), long-term low temperatures likewise limit the atmospheric moisture content and the efficiency of moisture transport;

[11] 53

conversely, when higher temperatures cause evaporation to exceed water-source supply, the region may also shift toward drought (as in the Holocene). There is a significant threshold effect in the influence of temperature changes on regional humidity.

4 Conclusion

(1) This study obtained grain-size data for sediments from core ZK0205 (0.00-16.10 m) in the northern depression of Lop Nur. By analyzing the indicative significance of its three components—clay, silt, and sand—the environmental evolution process of the Lop Nur region since 33.9 ka BP was revealed.

(2) The environmental evolution process of Lop Nur since the late Late Pleistocene was as follows: during MIS3, the climate was relatively humid; during MIS2, it shifted to aridity, and this arid state continued into the Holocene; during MIS1, warm-dry characteristics were displayed.

(3) Comparison with the NGRIP ice-core δ^{18}O record shows that changes in the grain size of Lop Nur sediments clearly responded to millennial-scale climate events in the Northern Hemisphere, and that the response mode underwent systematic shifts with the climatic background. This indicates that precipitation changes in this region were constrained not only by the global climatic background, but also by changes in the strength and position of the westerly circulation, and were also influenced by the monsoon system during the global-warming stage.

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Grain-size record of environmental evolution in the Lop Nur in Xinjiang since 33.9 ka BP

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Abstract: The evolution of the mid-latitude westerly climate system is crucial for understanding interaction mechanisms between high- and low-latitude climate systems. The Tarim Basin, located in the typical arid to semiarid zone influenced by the Northern Hemisphere westerlies, serves as a key region for deciphering the coupling between the North Atlantic and Asian monsoon systems. However, debates remain regarding its moisture-heat configuration patterns and their co-evolution with global climate systems. This study analyzes grain-size fractions from 295 samples of the 0.00-16.10 m sediment core ZK0205 in the Luobei Depression of Lop Nur, Xinjiang, China. Three environmentally sensitive grain-size fractions are identified: clay (<5 μm), silt (5-63 μm), and sand (>63 μm), which are interpreted as indicators of runoff input, aeolian activity intensity, and strong hydrodynamics, respectively, based on sedimentary characteristics of arid lake basins and modern observational data. Supported by an AMS ^14C chronological framework, the environmental evolution of the study area since 33.9 ka BP was reconstructed. The main findings are as follows: (1) The Lop Nur region experienced humid conditions during MIS3, which shifted to arid conditions during MIS2. Overall, the Holocene was characterized by warm and dry conditions, revealing phased changes in moisture-heat configuration on a millennial scale. (2) Comparison between grain-size fraction variations and the Greenland NGRIP ice-core δ^18O record indicates that the region responded sensitively to Northern Hemisphere millennial-scale climate events. Notably, the response pattern shifted systematically with background climate states (warm periods MIS1/MIS3 against cold periods MIS2). (3) Located at the boundary between the core westerlies domain and its transitional margin, the climate evolution of Lop Nur was constrained by global climatic background conditions and jointly influenced by the westerlies and Asian monsoon systems. This interplay

results in high complex regional climatic variability.

Keywords: Lop Nur; lacustrine deposit; grain-size analysis; stratigraphic composition; arid Central Asia

Note: Figure translations are in progress. See original paper for figures.