

Synergistic trade-off between desertification and lake evolution in the eastern Qinghai Lake region since the late Last Glacial Interstadial: Evidence from aeolian sediments

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Abstract

Aeolian sediments in the eastern Qinghai Lake region, China serve as sensitive paleoclimate archives, offering an ideal window into past environmental conditions. This study investigated the Dashuitang (QDST) profile in the eastern Qinghai Lake region by integrating sediment grain size, chroma, and magnetic susceptibility (MS) proxies to reconstruct the regional environmental evolution since the Last Glacial Interstadial and to investigate its relationship with the water level fluctuations of Qinghai Lake. Grain size end-member modeling analysis (EMMA) identified three end-members: end-member 1 (EM1) represented fine-grained material transported over longer distances through mixing processes, which could reveal the regional moisture conditions; end-member 2 (EM2) primarily consisted of coarse-grained material from nearby sources transported via saltation or creep, indicating the intensity of the winter monsoon; and end-member 3 (EM3) mainly reflected deposition from dust storm events controlled by regional low-altitude wind systems. In addition, the regional environmental sequence demonstrated coherence with other records, collectively elucidating the sub-orbital-scale dynamics of the Asian monsoon. The environmental sequence was divided into four principal phases on the basis of sedimentary characteristics and climatic responses: the late Last Glacial Interstadial, Last Glacial Maximum, Last Deglaciation, and Holocene phases. Additionally, the results of this study revealed that there is a close linkage between desertification and lake evolution in the eastern Qinghai Lake region. Since the Last Glacial Interstadial, desertification and lake evolution processes have generally exhibited a trade-off relationship, wherein lake level decline and desert expansion exhibited a direct positive feedback. However, during the early period of the Late Holocene (approximately 2.80–1.50 ka BP), a synergistic response pattern emerged, characterized by relatively high lake levels alongside moderate desert

expansion, reflecting an asymmetric decoupling mechanism between the hydrological processes and aeolian dynamics during climatic transition periods. This study provides important insights for predicting the future evolution trends of lake-desert systems under climate change.

Full Text

Preamble

J Arid Land (2026) 18(3): 387-405 Synergistic trade-off between desertification and lake evolution in the eastern Qinghai Lake region since the late Last Glacial Interstadial: Evidence from aeolian sediments HU Mengjun , XU Aokang 1 College of Geography and Environmental Science, Northwest Normal University, Lanzhou 730070, China; Department of Geology, Northwest University, Xi' an 710069, China

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Keywords

desertification; aeolian sediments; late Last Glacial Interstadial; synergistic trade-off; end-member modeling analysis; Qinghai Lake Citation:

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1 Introduction

Qinghai Lake, situated on the northeastern margin of the Qinghai-Xizang Plateau, is the largest endorheic saline lake in China (An et al., 2012). Located at the convergence of the Asian monsoon and westerly circulation, and further modulated by the effects of the high altitude and complex topography, the lake serves as a sensitive archive of the paleoenvironmental dynamics (Chen et al., 2016; Xie et al., 2024). Qinghai Lake also serves as a critical ecological barrier restraining the eastward expansion of desertification from the Qaidam Basin. Nevertheless, the region's ecosystem remains structurally fragile and prone to degradation under both internal dynamics and external forcing, where frequent aeolian activities are closely associated with land desertification (E et al., 2019; Bai et al., 2020). Therefore, systematically unraveling the evolution of the desertification processes in the Qinghai Lake region during geological history carries significant scientific implications for regional ecological security and sustainable development.

Located in the eastern Qinghai Lake region, extensive aeolian deposits form a distinctive desert landscape that serves as a valuable archive of past climatic changes (Pullen et al., 2011; Liu et al., 2012; E et al., 2019). This desert system primarily comprises two mobile dune belts stretching from north of Gahai Lagoon to south of Haiyan Bay, along with a small active dune field in the northern area, covering a total extent of approximately 475 km (Wang et al., 2017). Radiocarbon and luminescence dating suggest that most of the aeolian sediments around Qinghai Lake were deposited during the Last Deglaciation and Holocene (Lu et al., 2011; Lu et al., 2015; Zhang et al., 2022). Only a few sections, such as the Niaodao (E et al., 2019) and Zhongyangchang (Liu et al., 2019) profiles, preserve sedimentary records extending back to the Last

Glacial Maximum or earlier. This sparse preservation may be attributed to post-depositional disturbances caused by glacial meltwater or monsoon precipitation, combined with generally unfavorable preservation conditions during the Last Glacial Maximum (Sun et al., 2007; Lai et al., 2009; Chen et al., 2016).

Climatic fluctuations during these periods triggered multiple phases of desert expansion and contraction (Rhode et al., 2010). As demonstrated by Xu and Xu (1983), desertification processes in the eastern Qinghai Lake region are closely linked to variations in the lake level. Lake-level regression exposed extensive lacustrine sediments to aeolian erosion and transport by westerly winds, supplying substantial source materials for the development of the eastern sandy lands (Xu and Xu, 1983). Paleobathymetric reconstructions indicate that lake depths of merely 3.00–5.00 m occurred during the Last Glacial Maximum (Liu et al., 2015), less than 10.00 m in the Early Holocene (Kelts et al., 1989; Wang et al., 2017), and reached maximum levels during the Middle Holocene, approximately 9.10 m higher than at present (Liu et al., 2015), compared with the modern average depth of approximately 22.00 m. This hydrological record provides key constraints for reconstructing paleo-shoreline evolution and lake basin development.

Nevertheless, systematic investigation of the coupling mechanisms between the water level dynamics of Qinghai Lake and eastern desertification processes remains insufficient. The unique coupled lake-desert system offers a natural laboratory for examining feedback mechanisms between paleo-hydrological changes and aeolian sedimentary responses.

Moreover, multiple aeolian sedimentary records from the region indicate that intensified aeolian activity occurred during the Early Holocene, suggesting relatively arid climatic conditions (Lu et al., 2015; E et al., 2019). In contrast, paleopedological evidence from the Halali profile on the southern shore of Qinghai Lake reveals well-developed paleosol layers, indicating the occurrence of warm and humid conditions during the same period (Chen et al., 1991). This apparent discrepancy may reflect spatial heterogeneity of the regional climate system, or alternatively, the different sensitivities of various environmental proxies to moisture variations.

Therefore, additional records are required to refine the paleoenvironmental sequence in the Qinghai Lake region.

This study examined a typical cyclic sedimentary profile composed of aeolian sand and weak sandy paleosol in the eastern Qinghai Lake region. Notably, a gravel layer discovered at the base of the profile may indicate the initial formation period of desertification in the eastern Qinghai Lake region (dated to the late Last Glacial Interstadial in this study). By integrating grain size, magnetic susceptibility, and chromaticity indicators, we reconstructed environmental records since the late Last Glacial Interstadial. Furthermore, through integration of existing research, this study assessed the contemporaneous extent of Qinghai Lake and found that there has been a synergistic trade-off relation-

ship between lake-level fluctuations and eastern desert evolution.

This investigation not only elucidates the formation and evolution mechanisms of the eastern sandy lands but also has scientific significance for understanding water-sand coupling processes in the fragile ecosystem on the northeastern Qinghai-Xizang Plateau. 2 Study area and profile Qinghai Lake is situated in the northeastern Qinghai-Xizang Plateau ($36^{\circ} 15'N$, $-100^{\circ} 16'E$), at the junction of Gangcha, Gonghe, and Haiyan counties (Fig. 1 [Figure 1: see original paper]). This intermontane basin, formed by tectonic fault depression, is surrounded by mountains and exhibits a topography that is higher in the northwest and lower in the southeast. The region experiences a typical semi-arid continental plateau climate, characterized by long cold winters and short cool summers. The mean annual precipitation is approximately 400 mm, and the mean annual temperature ranges from $-1.1^{\circ}C$ to $0.3^{\circ}C$. As an endorheic system, the lake is primarily recharged by several rivers, including the Buha River, the Shaliu River, and the Haergai River. The major vegetation types comprise forests, shrublands, grasslands, and desert grasslands. The soil types distributed from northwest to southeast include meadow soil, chestnut soil, and aeolian soil.

The QDST profile ($36^{\circ}29'N$, $100^{\circ} E$; 3449.68 m) is situated on a sheep-breeding farm east of Qinghai Lake. It constitutes a wind-eroded residual hill trending from northwest to southeast (Fig. 1a and b). Flanked by wind-eroded valleys on both sides, the hill exhibits clear evidence of sand movement within these valleys. The profile has a total thickness of 10.00 m and represents a typical cyclic sedimentary sequence composed of alternating aeolian deposits and weakly sandy paleosol layers (Fig. 1c). The QDST profile can be divided into nine distinct stratigraphic units from top to bottom on the basis of the sediment color, texture, structure, and interlayer contacts (Table 1). 3 Materials and methods

3.1 Materials

The QDST profile was continuously sampled at 10, 5, 2 and 5 cm within the 0.30-3.70, 3.70-5.30, 5.30-7.60, and 7.60-10.00 m depth intervals, respectively. A total of 232 samples were obtained. In addition, we collected ten optically stimulated luminescence (OSL) dating samples from key stratigraphic horizons based on the distinct soil characteristics.

3.2.1 OSL dating

The measurements were performed at the Center for Groundwater Mineral Water and Environmental Monitoring, Ministry of Land and Resources, using a Daybreak 1100 OSL system (Daybreak Nuclear and Medical Systems, Inc., New Haven, the United States). Under safe red-light conditions in a darkroom, the sample was extracted from its sampling tube, sieved, and transferred to a beaker. Prior to measurement, the following pretreatment was performed: organic matter and carbonates were removed by adding 40.00% Hydrogen Peroxide (H_2O_2) and

30.00% Hydrogen Chloride (HCl) solutions, respectively. The 4-11 μm grain size fraction was then separated via static water sedimentation (Stokes' law). The samples were well sealed, so the measured water content was taken as their original in situ water content at the time of deposition

Geographical location of Qinghai Lake and profile information. (a), location of Qinghai Lake in Qinghai sampling point in Qinghai Lake region; (c), field profile from Qinghai Lake and its correlation with sedimentary records from Lu et al. (2015) and Bai et al. (2020). The colors in the profile column match the actual colors of the sediment strata. OSL, optically stimulated luminescence; KTS, Ketusha; DST3, Dashuitang3; DST4, Dashuitang4; QDST, Dashuitang (eastern Qinghai Lake region, this study). The profiles of DST3 and DST4 are derived from Bai et al. (2020), and the profile of KTS is derived from Lu et al. (2015). and was corrected using the method proposed by Fleming (1970). Finally, equivalent doses were determined using the simplified multiple-aliquot regenerative-dose (SMAR) method and the Daybreak 1100 OSL system. Equivalent dose values were obtained from 4-8 aliquots per sample.

The irradiation dose rate from the ^{90}Sr - ^{90}Y β source was approximately 0.103871 Gy/s. The age calculation is as follows:

$$ED/AD = a \cdot t, \quad (1)$$

where t represents the ages (ka BP); ED is the equivalent dose (Gy); and AD is the annual dose (Gy/ka).

Chroma The naturally dried samples were ground into a homogeneous powder using an agate mortar and

Stratigraphy of Dashuitang (QDST) profile Number Stratigraphic type Depth (cm) Characteristic QDST1 Topsoil Gray-yellow and loose, with plant roots QDST2 Aeolian layer Grayish-white and medium fine sand, with few plant roots QDST3 Weak sandy paleosol layer sand, relatively compact, pseudomycelium QDST4 Aeolian layer Light gray and medium fine sand, with apparent eolian accretion QDST5 Weak sandy paleosol layer Dark grey and fine sand, firm QDST6 Aeolian layer Grayish white and fine sand, loose QDST7 Weak sandy paleosol layer Dark brown, silty, firm, and white mycelium present QDST9 Weak sandy paleosol layer Clay and cement compact were sieved through a 200-mesh screen. Prior to measurement, the CM-5 spectrophotometer (Konica Minolta Sensing, Inc., Osaka, Japan) was calibrated with a zero-calibration whiteboard.

Each prepared sample was then placed in a petri dish and measured three times. The average of these three readings was taken as the final chroma value.

Grain size Prior to analysis, all of the samples were subjected to the same pretreatment procedure as described for OSL dating. Subsequently, 10 mL of 0.05 mol/L sodium hexametaphosphate ((NaPO₃)₆) solution was added to each sample as a dispersant. The mixtures were then ultrasonicated for 7-8 min using an ultrasonic bath (frequency: 40.00 kHz; power: 120 W) to ensure complete dispersion of the particles. The grain size distribution was measured using a

Mastersizer 3000 laser particle size analyzer (Malvern Panalytical, Malvern, the United Kingdom). Each sample analyzed three times, and the average value was utilized. All of the chroma and grain size measurements were conducted at the Laboratory of Soil Geography, Northwest Normal University, China. The grain size data were analyzed using the parameterized Weibull end-member modeling algorithm as implemented by Paterson and Heslop (2015). The analysis was conducted by iteratively testing end-member numbers from 1 to 10. The optimal number of end-members was determined on the basis of the following criteria: a coefficient of determination (R^2) of greater than 0.80, an angular deviation of less than 5° , and a low inter-end-member correlation.

Magnetic susceptibility (MS) MS was measured using a Bartington MS-2 (Bartington Instruments Ltd., Oxford, the United Kingdom) at the Key Laboratory of Western Environment of the Ministry of Education, Lanzhou University, China. Air-dried samples were gently ground in an agate mortar and packed into standardized plastic sample boxes. After compaction and sealing, we recorded the mass of each sample to calculate the bulk density. Each sample was measured three times at both low (0.47 kHz) and high (4.70 kHz) frequency MS, and the average values were used for the subsequent analysis. Mass-specific magnetic susceptibility (MS/m) was calculated as follows: $MS/m = \frac{MS_{low}}{m}$, (2) where MS_{low} denotes the low-frequency magnetic susceptibility; and m denotes sample mass (kg/m³). Correlation analysis In this study, correlation analysis was performed using Origin software v.9.8.5.204 (OriginLab Corporation, Massachusetts, USA) on grain size components, end-members, chroma, and MS from the QDST profile. A correlation heatmap was subsequently generated to visually illustrate the strength of relationships among these variables. This approach effectively reveals the intrinsic associations between different sedimentary proxies.

4.1 Chronological framework

The OSL dating results for the QDST profile are presented in Table 2, with no age reversals observed in the sedimentary sequence. The chronological framework indicated that the bottom of the profile had an age of 31.90 (± 1.30) ka BP, i.e., the late Last Glacial Interstadial (Fig. 2 [Figure 2: see original paper]).

Further analysis revealed that the sedimentation rate was relatively low during about 8.74–4.59 ka BP (corresponding to depths of 5.30–5.96 m). This feature was also present in the KTS, DST3, and DST4 profiles from the eastern Qinghai Lake region (Fig. 1c). Comprehensive analysis suggests that the lower sedimentation rate during 8.74–4.59 ka BP may have been due to the relatively humid climate, higher vegetation coverage, and reduced surface erosion during the Middle Holocene. Furthermore, the KTS, DST3, and DST4 profiles, which all span the Holocene, exhibit a sedimentary facies transition from sandy paleosol to aeolian sands. As noted by Lu et al. (2015), the main period of paleosol development in the Qinghai Lake Basin occurred between 9.50 and 4.00 ka BP, which aligns well with the findings of this study, further supporting the reliability of the established chronological framework. The formation of the profile can

be divided into four stages on the basis of the sedimentary facies and chronological results: Stage I—late Last Glacial Interstadial (31.90–23.12 ka BP); Stage II—Last Glacial Maximum (23.12–15.79 ka BP); Stage III—Last Deglaciation (15.79–9.52 ka BP); and Stage IV—Holocene (<9.52 ka BP).

Optically stimulated luminescence (OSL) dating from QDST profile Test index Number Depth (m) Grain size (ka BP equivalent dose annual dose Gy/ka after content Note: Mean±SE. U, uranium; Th, thorium; K, potassium.

4.2 Chroma analysis

In the QDST profile, the a values ranged from 4.75 to 6.32, with a mean of 5.46. Vertically, the higher a values correspond to the weak sandy paleosol layers, while the lower values correspond to the aeolian layers. Overall, the a record exhibited a clear decreasing trend with notable stratigraphic variability (Fig. 3 [Figure 3: see original paper]).

4.3 Grain size feature

The QDST profile was predominantly composed of sand (>250.00 μm ; 17.40%), fine sand (50.00–250.00 μm ; 77.04%), followed by silt (5.00–50.00 μm ; 4.22%) and clay (<5.00 μm ; 1.34%). As shown in Figure 3, the vertical variations in the grain size components reveal an inverse relationship between the medium sand and fine sand. In contrast, both the silt and clay contents generally decrease up-section. The average grain size (M_z) serves as a proxy for the

Chronological framework of QDST profile. The colors in the profile column match the actual colors of the sediment strata.

Vertical variation characteristics of grain size and chroma in QDST profile. (a), clay; (b), silt; (c), fine sand; (d), coarse sand; (e), average grain size); (f), silt plus clay divided by sand (SC/D); (g), redness (a). The colors in the profile column match the actual colors of the sediment strata. winter monsoon intensity, with coarser values indicating a stronger wind strength. The of the QDST profile was 180.86 μm and exhibited a variation trend consistent with that of the medium sand fraction.

The silt plus clay divided by sand ratio (SC/D) is used to amplify the proportional relationship between the fine fraction (silt and clay) and sand in sediments, thereby providing a more sensitive indicator of the past aeolian activity intensity. Lower SC/D values indicated a stronger winter monsoon and enhanced aeolian transport, whereas higher values reflect weaker aeolian activities or pedogenesis. SC/D values ranged from 0.00 to 0.14, closely tracking the combined

variations in the clay and silt content. Overall, the ratio exhibits a gradual decreasing trend up-section (Fig. 3).

4.4 End-member modeling analysis (EMMA)

Following the criteria of high (>0.80), low angular deviation ($<5^\circ$), and low inter-end-member correlation, three end-members (end-member 1 (EM1), end-member 2 (EM2), and end-member 3 (EM3)) were identified as the most constrained and well-fitted solution (Fig. 4 [Figure 4: see original paper]).

End-member modeling analysis (EMMA) result of QDST profile. (a), determination coefficient (R^2); (b), angle deviation; (c), frequency distribution curves of end-members (c1) and average frequency distribution curves of each sedimentary layer (c2); (d), ternary diagram of three end-members of QDST profile. EM1, end-member 1; EM2, end-member 2; EM3, end-member 3. The blue boxes in figure a and b represent the 25 and 75 interquartile, illustrating the dispersion of the data.

The three end-members all exhibited a unimodal distribution with sharp peaks (Fig. 4c). EM1 had a modal grain size of $97.40 \mu\text{m}$, spanning a relatively wide grain size range. EM2 and EM3 displayed modal sizes of 175.70 and $243.00 \mu\text{m}$, respectively, and represented saltation and creep transport components. The average relative contributions of EM1, EM2, and EM3 were 15.54% , 64.09% , and 20.37% , respectively, further confirming the dominance of fine sand in the profile.

As shown in Figure 5 [Figure 5: see original paper], EM1 and EM2 exhibited mirror-image distribution patterns: EM1 generally

decreased up-section, while EM2 increased up-section. EM1 was most abundant in the weak sandy paleosol layers, while EM2 predominated in the aeolian layers. In contrast, EM3 exhibited significant fluctuations, particularly after approximately 2.78 ka BP in the Late Holocene.

4.5 MS variations

As shown in Figure 5, the MS parameters of the QDST profile varied as follows: the high-frequency magnetic susceptibility (M_{HF}) ranged from 5.48 to 12.85 , the low-frequency magnetic susceptibility (M_{LF}) ranged from 5.62 to 13.62 , and M_{MS} ranged from 0.86×10^2 to $2.7 \times 10^3 \text{ kg}^{-1}$. The variations in M_{HF} , and M_{LF} exhibited generally consistent trends, showing an overall decrease up-section. Moreover, the higher MS values correspond to the weak sandy paleosol layers, while the lower values are associated with the aeolian layers.

Vertical variation characteristics of end-members and magnetic susceptibility (MS) in QDST profile. (a), EM1; (b), EM2; (c), EM3; (d), high-frequency magnetic susceptibility (M_{HF}); (e), low-frequency magnetic susceptibility (M_{LF}); (f), mass-specific magnetic susceptibility (M_{MS}). The colors in the profile column match the actual colors of the sediment strata.

5.1 Information carried by end-members

The distinct linkage between end-members and strata implied that each end-member corresponded to a specific depositional regime. This interpretation was consistent with physical models of dust transport, which establish that there are inverse relationships between the transport distance and the grain size and peak height, i.e., coarser grains and higher peaks signify a proximal source (Qin et al., 2009). Furthermore, the strong negative correlation between EM1 and EM2 provided direct evidence that at least two dominant transport dynamics governed the sediment accumulation (Fig. 6 [Figure 6: see original paper]).

EM1 had a modal grain size of 97.40 μm , characterized by a broad peak and a wide grain size distribution. It was the only one of the three end-members that contained silt-sized particles, with a minimum grain size of 18.14 μm . Generally, fine grains smaller than 20.00 μm can be lifted to heights of several thousand meters under strong winds and can undergo long-distance suspension

Correlation analysis of grain size components, end-members, chroma, and MS in QDST profile. (a), population correlation; (b), Stage I correlation; (c), Stage II correlation; (d), Stage III correlation; (e), Stage IV correlation; (f), comparison of frequency curve between EM2 and aeolian sediment in eastern Qinghai Lake region (Bai et al., 2020). Larger bubble sizes indicate stronger correlations. <0.050 level; <0.010 level; <0.001 level. transport via upper-level air currents (Pye, 1987). Even under weak storm conditions, the fine silt components in Loess Plateau sediments can be transported over medium- to long-distances (Vriend et al., 2011). This study found that EM1 contained not only fine-grained components that are susceptible to long-distance transport but also coarse-grained components that are typically transported over shorter distances. Patterson and Gillette (1977) suggested that 20.00–100.00 μm dust grains can undergo short-distance suspension transport under strong winds. Therefore, the fine silt in EM1 may represent meso-distant fine grains transported by the winter monsoon, while its coarser silt fraction likely originated from near-source sands carried by the same system. In addition, EM1 exhibited significant negative correlations with the sand content and , and positive correlations with the clay content, a , and the SC/D (Fig. 6a). Given that and SC/D can serve as proxy indicators of the winter monsoon intensity (Xu et al., 2024), and a qualitatively reflects the degree of pedogenic development (Giosan et al., 2002), the above relationships suggested that EM1 may represent a relatively warm-humid regional environment.

Therefore, lower EM1 values corresponded to a stronger winter monsoon and colder and drier climate. Thus, EM1 was interpreted as a proxy for regional moisture variability and also reflected the intensity of aeolian activity to a certain extent.

EM2 had a modal grain size of 175.70 μm and constituted the primary sedimentary component throughout the profile. It exhibited a narrow peak distribution, predominantly consisting of fine sand. Pye (1987) summarized the dynamic

conditions and the transport modes, elevation, and distances involved in aeolian processes and reported that 70.00–500.00 μm coarse grains can be transported via saltation or creep under the influence of the winter monsoon. Similarly, the 140.00–250.00 μm fraction in aeolian sediments in the Qaidam Basin has been used as a proxy

indicator for the winter monsoon intensity (Wang et al., 2023). Physical modeling of dust transport processes further suggested that EM2 was transported over a shorter distance and was closer to the source than EM1. Comparison with typical aeolian sediments east of Qinghai Lake, Bai et al. (2020) revealed that EM2 exhibited good sorting and high kurtosis (Fig. 6f), indicating a limited transport distance and elevation. In addition, EM2 was positively correlated with the sand content and negatively correlated with EM1, a , and SC/D. In conclusion, EM2 was interpreted as representing near-source coarse-grained material that was mainly transported via near-surface saltation or creep under high-energy conditions, and it was considered a robust proxy for reconstructing variations in the regional winter monsoon.

EM3 had a modal grain size of 243.00 μm , representing the coarsest end-member component in the sedimentary profile. It was primarily composed of fine to medium sand and exhibited good sorting. There were positive correlations between EM3 and the sand content and a , suggesting that it was linked to variations in the winter monsoon intensity. The relative abundance of EM3 in the stratigraphic sequence was generally low, but it exhibited marked fluctuations, particularly after approximately 2.80 ka BP. Qinghai Lake, situated in the northeastern Qinghai-Xizang Plateau, experiences frequent strong winds and dust storm events (Yang et al., 2021). Under such conditions, coarse-grained sediments are often transported and deposited rapidly via dust storms, leading to episodic influxes of proximal material. Therefore, EM3 was interpreted to be indicative of dust storm-driven sediment transport governed by regional near-surface wind systems. 5.2 Paleoenvironment sequence in the eastern Qinghai Lake region Stage I: the late Last Glacial Interstadial (31.90–23.12 ka BP) corresponds to the weak sandy paleosol layer at 7.70–10.00 m in the profile. During this period, the was relatively fine, while EM1, a , and MS all remained at elevated levels, reflecting relatively strong pedogenesis (Fig. 7 [Figure 7: see original paper]). Notably, the SC/D sequence exhibited significant fluctuations and a positive correlation with EM3, suggesting that its variations were likely primarily controlled by the near source dust input represented by EM3. This implies that the study area may have experienced unstable dust storm events during this interval. Concurrently, the low soot flux in Qinghai Lake (Hao et al., 2020), the higher pollen concentration in the southern Qinghai-Xizang Plateau (Zhu et al., 2009), and the verall negative δO excursions in Hulu Cave (Wang et al., 2008) collectively indicate the occurrence of a relatively strong Asian summer monsoon and a comparatively warm-humid climate during this phase. Furthermore, from a global process perspective, the more northerly position of the Intertropical Convergence Zone (ITCZ) (Deplazes et al., 2013) provides additional support for the intensified summer monsoon system.

Stage II: the Last Glacial Maximum (23.12–15.79 ka BP) corresponds to the aeolian layer at 6.60–7.70 m in the profile, which records a regional shift toward cold and dry conditions. During this period, α and EM1 decreased markedly, while EM2 increased significantly, and EM3 exhibited more pronounced fluctuations than in Stage I. These patterns collectively indicate the occurrence of enhanced westerly circulation, which dominates the intensified near source aeolian activity. The persistently positive δ O values of stalagmites from Hulu Cave (Wang et al., 2008) further corroborate the occurrence of weakened Asian summer monsoon precipitation. The cold and dry climate substantially suppressed vegetation development, consistent with coeval records from the Loess Plateau (Lin et al., 1991). In a global context, a weakened Atlantic Meridional Overturning Circulation (AMOC) (McManus et al., 2004) and a southward shifted ITCZ (Deplazes et al., 2013) jointly reinforced the westerly intensity. Notably, the sedimentary MS remained relatively high during this phase and exhibited a significant negative correlation with EM1 (Fig. 6d). This apparent discrepancy can be explained by the following processes: (1) selective removal of fine magnetic particles by intensified winter monsoon winds, along with a lower sedimentation rate, may indicate secondary transport of fine-grained material; and (2) exposure of iron-rich magnetic sediments along the lakeshore due to declining Qinghai Lake water levels (Xie et al., 2024), which were subsequently transported by westerlies to the depositional site, thereby compensating for or even masking the original aeolian magnetic signal.

Comparison of the indices of QDST profile with the palaeoenvironmental records. (a), EM1; (b), EM2; (c), α^* ; (d), MS; (e), of the DST profile in the Qinghai Lake (Bai et al., 2020); (f), total organic carbon (TOC) in the Qinghai1 (QH1) hole sediments of Qinghai Lake (Shi et al., 2003); (g), organic carbon isotopes in Luochuan County profile (Luochuan County is located in the Loess Plateau) (Lin et al., 1991); (h), pollen density of Lake Chen Co (the lake is located in the southern Qinghai-Xizang Plateau) (Zhu et al., 2009); (i), soot flux in core 1Fs of Qinghai Lake (the core was obtained from the International Continental Drilling Program (ICDP) in 2005; Hao et al., 2020); (j), stalagmite oxygen isotopes (δ O) from Hulu and Sanbao Cave () (Wang et al., 2008); titanium (Ti) element content in the Arabian Sea (k; Schneider et al., 2014) and sediment total reflectance records from the Cariaco Basin (l; Deplazes et al., 2013) were used to reconstruct latitudinal shifts of the Intertropical Convergence Zone (ITCZ); (m), Atlantic Meridional Overturning Circulation (AMOC) intensity (McManus et al., 2004); (n), North Greenland Ice Core Project (NGRIP) δ O (Yao et al., 1997); (o), 65°N solar radiation (Berger and Loutre, 1991). The red dashed bars in Figure 7a and f represent the typical stages corresponding to EM1 and TOC; N and S letters in Figure 7k and l denote the northward and southward shifts of the ITCZ, respectively.

Although reduced evapotranspiration under low solar radiation would theoretically favor higher effective moisture (Hu et al., 2024), the actual regional moisture supply remained insufficient, resulting in overall arid conditions.

Stage III: the Last Deglaciation (15.79–9.52 ka BP) corresponds to the weak sandy paleosol layer at 6.20–6.60 m in the profile. However, the proxy indicators did not exhibit rapid changes during this period: a and EM1 only increased slightly, EM2 exhibited no significant variation, and EM3 displayed a declining trend, suggesting weakening of the westerly dust transport intensity, local weathering, and short range sediment transport. As previously noted, the relatively high MS during the glacial period may have been influenced by iron-rich lacustrine sediments; the slightly lower MS values during this phase likely reflect reduced near surface sand flux and a decline in the aeolian activity intensity. Integrating local and broader regional environmental records, several signals point to a modest improvement in hydrothermal conditions (Fig. 7h–m); however, the overall climate regime remained cold and dry. Notably, pollen records from the southern Qinghai-Xizang Plateau do not exhibit marked changes during this stage, a phenomenon that may be attributed to the relatively low resolution of the pollen sequence, which may not capture millennium scale environmental fluctuations.

Stage IV: the Holocene (since 9.52 ka BP) was characterized by alternating deposition of aeolian layers and weak sandy paleosol layer. This phase can be subdivided into three stages on the basis of sediment grain size characteristics and chronological framework: the Early, Middle, and Late Holocene stages. The Early Holocene stage (9.52–8.74 ka BP) inherited the transitional

climatic pattern of the Last Deglaciation. All of the environmental proxy indicators utilized in this study continued the slow changing trends observed in the previous phase. Although the AMOC strengthened (McManus et al., 2004) and the ITCZ shifted slightly northward (Schneider et al., 2014), the Asian summer monsoon intensity remained relatively limited. The regional climate maintained an overall cold-dry regime with relatively pronounced aeolian activity. The Middle Holocene stage (8.74–2.90 ka BP) was marked by significant increases in EM1 and a , as well as decreases in EM2 and EM3. Concurrently, the sediment in the eastern Qinghai Lake region became finer (Bai et al., 2020), the total organic carbon (TOC) content increased (Shi et al., 2003), and the pollen concentration in the southern Qinghai-Xizang Plateau also increased notably (Zhu et al., 2009). These regional lines of evidence align well with the pronounced negative δO excursions recorded in stalagmites from Sanbao Cave, which signal enhanced summer monsoon intensity (Wang et al., 2008). Strengthened AMOC (McManus et al., 2004) and northward migration of the ITCZ (Schneider et al., 2014) served as driving mechanisms that reinforced the Asian summer monsoon circulation, leading to significantly increased effective moisture and establishing a warm-humid climatic optimum. In the Late Holocene stage (<2.90 ka BP) another climatic shift occurred. a^* , MS, and EM1 decreased, while EM2 increased and EM3 exhibited pronounced fluctuations, reflecting a return to cold-dry conditions as well as intensified aeolian activity and a higher dust storm frequency. Concurrent weakening of the AMOC and southward shift of the ITCZ (McManus et al., 2004; Schneider et al., 2014) jointly contributed to the recession of the summer monsoon. The coarsening of the sediment, decrease

in the TOC content, and changes in the soot flux in the eastern Qinghai Lake region (Shi et al., 2003; Bai et al., 2020; Hao et al., 2020) further corroborate the trend toward colder and drier conditions.

Analysis revealed that during this stage, the TOC and EM1 varied largely in phase, while the TOC lagged slightly behind EM1. This phase difference may reflect the delayed response of surface vegetation productivity to changes in the climatic aridity-humidity: the cold-dry shift indicated by the enhanced aeolian activity (rising EM2) requires a certain cumulative duration before it substantially suppresses vegetation growth and organic matter accumulation.

Notably, the North Greenland Ice Core Project (NGRIP) $\delta^{18}O$ record exhibits lower temperatures in each stage prior to the Last Deglaciation (Fig.7n), whereas the QDST profile indicates that the late Last Glacial Interstadial was significantly warmer than the Last Glacial Maximum. This discrepancy can be primarily attributed to the high-latitude location of the NGRIP, which may have experienced less pronounced regional climatic variability (Hu et al., 2024). During the Holocene, high-latitude records such as NGRIP more reliably capture post-glacial warming trends at the global scale. In contrast, although it may have experienced slightly lower absolute temperatures during the Holocene than during the late Last Glacial Interstadial due to its high altitude, the Qinghai Lake region exhibits more pronounced fluctuations in sedimentary proxies related to cooling and warming in the QDST profile. This suggests that the Qinghai Lake region responded more sensitively to Holocene climate changes than high-latitude areas.

5.3 Synergistic trade-off between desertification in the eastern Qinghai Lake region and lake evolution

Changes in water level of Qinghai Lake directly affect the material sources and depositional processes of the eastern desert by regulating the exposure of lakeshore sediments (Xu and Xu, 1983). Therefore, there was a close link between the desertification in the eastern Qinghai Lake region and lake evolution. This study explored the synergistic trade-off relationship between desertification in the eastern Qinghai Lake and lake evolution (), by integrating the desert extent from remote sensing imagery with existing studies on paleo deserts and lake level changes (Liu et al., 2015; Lu et al., 2015; Wang et al., 2017; Zhang et al., 2022). The term “trade-off” refers to a direct positive feedback between lake level decline and desert expansion: lowering water levels expose sediments, which are then transported by wind to the eastern Qinghai Lake region, promoting desertification. “Synergistic” indicates that the system is influenced by other

Comparison of the indices of the QDST profile with the Qinghai Lake water level. (a), EM1; (b), EM2; (c), lake level in the arid area of Middle East Asia (Zhang et al., 2021); (d), water level changes of the Qinghai Lake (Zhang et al., 1994); (e), level fluctuation curve of the Qinghai Lake (Liu et al., 2015); (f), negative correlation between EM1 and EM2 in the depth intervals of 0.30-2.00 and 3.50-10.00 m of the QDST profile; (g), positive correlation between EM1 and EM2 in the depth interval of 2.00-3.50 m of the QDST profile (ca. 2.80-1.50 ka BP). factors (e.g., human activities), leading to decoupling or even an

inverse relationship between the lake level and desert extent.

Previous studies on aeolian sediments in the eastern Qinghai Lake region have mostly been limited to profiles that do not extend to the basal deposits. In contrast, the QDST profile reaches a basal gravel layer, leading to the inference that the eastern desert of Qinghai Lake had formed by at least the late Last Glacial Interstadial (Hu et al., 2024). Meanwhile, research indicates that the lake level of Qinghai Lake was high during the late marine isotope stage 3 (MIS3), after which the lake generally retreated, though fluctuations in water level cannot be ruled out (Song et al.,

2020). Synthesizing available evidence, the lake level during the late Last Glacial Interstadial was considered to have been slightly higher than that of the Holocene (Long et al., 2012; Li et al., 2015). This hydrological pattern aligns with variations in EM1. As a proxy for the regional moisture conditions, EM1 fluctuates in response to lake level expansion and contraction.

Comparison with existing lake level reconstructions shows that EM1 exhibits consistent trends with multiple water level proxies (Fig. 8a [Figure 8: see original paper] , d, and e). Moreover, the rapid decline in EM1 during the Last Glacial Maximum corresponds to low lake levels (Fig. 8e). This demonstrates that the sedimentary sequence of the QDST profile provides an important archive for revealing the synergistic trade-off relationship in the lake-desert system since the late Last Glacial Interstadial.

However, the absence of direct sedimentary evidence of the eastern desert during the Last Glacial Interstadial currently limits the assessment of desert extent in that period (Wang et al., 2017).

Consequently, this study can only infer a relatively limited extent of the eastern desert during the Last Glacial Interstadial based on EM2, which reflects regional wind dynamics and aeolian sediment source characteristics.

During the Last Glacial Maximum, the Qinghai Lake experienced a pronounced regression (marked by a significant decline in EM1), with its water level dropping to approximately 25.00 m below the modern level, leading to extensive exposure of lake bottom sediments (Liu et al., 2015). Intensified winter winds exacerbated the erosion and transport of the exposed sediments, providing a key dust source for the large-scale expansion of the eastern desert. Entering the last deglaciation, the climate underwent rapid oscillations such as the Bølling-Allerød events, causing frequent lake level fluctuations (Jin et al., 2015) and increasing uncertainty in the lake level reconstruction for this period. Although the increase in solar radiation and limited glacial melt contributed to a general increasing lake level trend during the transition to the Holocene, the Early Holocene water level remained about 20.00 m below the modern level (Liu et al., 2015).

Synthesizing available evidence, it is inferred that lake levels during the Last Deglaciation fluctuated within a range roughly 20.00-25.00 m below the modern

level. Regional sedimentary records also indicate that during the Last Deglaciation and Early Holocene, the extent of the eastern desert was smaller than during the Last Glacial Maximum (EM2 showed a modest decline), which was consistent with a relatively wetter climate and weakened aeolian activity (Lu et al., 2011; Liu et al., 2015; Lu et al., 2015).

During the Middle Holocene warm-humid period, the lower limit of the permafrost in the northeastern Qinghai-Xizang Plateau rose markedly (He et al., 2022), the regional lake levels were generally high (Zhang et al., 2021), with the water level of Qinghai Lake was approximately m above the modern level (Liu et al., 2010, 2015). During this phase, in the region, the aeolian activity and sediment-transport capacity significantly weakened, and the sedimentary facies gradually shifted from aeolian sand and loess deposition to paleosol development, reflecting suppressed aeolian activity (Rhode et al., 2010). However, in the early period of the Late Holocene (ca. 2.8 ka BP), EM1 and EM2 exhibited positive correlations within the 50 cm interval, suggesting that the classic trade-off relationship of the lake-desert system may have become decoupled. Specifically, both the EM1 and lake level reconstructions constructed by Liu et al. (2015) indicate that the Qinghai Lake maintained relatively high water levels, yet the extent of the eastern desert expanded slightly. This phenomenon can be attributed to cooling that significantly suppressed lake surface evaporation, coupled with local lake climate feedbacks, which together sustained relatively high water levels. Meanwhile, the intensified westerly circulation, combined with the inhibitory effect of the low temperatures on the vegetation, jointly promoted aeolian activity and desert expansion. Subsequently, from the late period of the Late Holocene onward (ca. 1.5 ka BP), the climate became colder and drier, and the control of the water level of Qinghai Lake over the eastern desert was re-established, primarily manifesting as a trade-off relationship between the declining lake level and desert expansion.

In summary, fluctuations in the water level of Qinghai Lake have played a significant role in the development of the eastern desert. The schematic diagram in Figure 9 [Figure 9: see original paper] illustrates the relationship between desertification in the eastern Qinghai Lake region and lake evolution since

Possible spatial patterns of desertification in the eastern Qinghai Lake region and lake evolution during different periods. (a), modern; (b), late Last Glacial Interstadial; (c), Last Glacial Maximum; (d), Early Holocene; (e), Middle Holocene; (f), Late Holocene. The possible spatial pattern of desertification in the late Last Glacial Interstadial period was not assessed. the late Last Glacial Interstadial. Specifically, since the Last Glacial Interstadial, the lake evolution and regional desertification have generally exhibited a trade-off relationship, with one advancing as the other recedes. However, during the early period of the Late Holocene, the two displayed a synergistic and decoupled pattern, reflecting the nonlinear and complex responses of surface processes driven by climatic system dynamics.

6 Conclusions

This study investigated the environmental evolution of the eastern Qinghai Lake region since the late Last Glacial Interstadial through grain size, chroma, and MS analysis of the QDST profile, and evaluated the synergistic trade-off relationship between the desertification and lake evolution in this region. The main conclusions were summarized below.

The grain size had three end-members. EM1 contains finer grains from the middle to upper layers and fine sand particles near the source, serving as an indicator of regional moisture fluctuations. EM2 represents near-source coarse grains transported mainly by saltation or surface creep under high-energy conditions and serves as a robust proxy for variations in the winter monsoon intensity. EM3 reflects short-range transport of sediments via dust storms controlled by near-surface wind systems. The environmental sequence was divided into four stages: late Last Glacial Interstadial, characterized by a weak winter monsoon and relatively humid conditions; the Last Glacial Maximum, marked by intensification of the winter monsoon and a cold-dry climate; the Last Deglaciation, during which the hydrothermal conditions improved slightly but the climate remained cold and dry; and the Holocene, during which early warming, a Middle Holocene thermal optimum, and late cooling occurred, reflecting a cyclical pattern of cold-warm fluctuations. There existed a close coupling relationship between the desertification and lake evolution in the eastern Qinghai Lake. Fluctuations in the lake level, driven by monsoon dynamics and climatic changes, directly modulate the expansion and contraction of the eastern

desert. Since the Last Glacial Interstadial, desertification and lake evolution in this region have generally exhibited a trade-off relationship. However, during the early period of the Late Holocene (ca. 2.80–1.50 ka BP), the two exhibited a synergistic relationship.

Conflict of interest The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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