Grain size and surface micro-texture characteristics and their paleoenvironmental significance of Holocene sediment in southern margin of the Gurbantunggut Desert, China Postprint

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Abstract

The southern margin of the Gurbantunggut Desert, China, is characterized by alternating layers of aeolian and alluvial deposits. Investigation of arenaceous sediment characteristics in this area is crucial for understanding interactive processes of wind and water forces, as well as sediment provenance. However, current investigations on such sediment characteristics remain relatively limited. In this study, we examined three aeolian-alluvial interactive stratigraphic profiles and different types of surface sediment in the desert-oasis transitional zone along the southern margin of the Gurbantunggut Desert. Based on optically stimulated luminescence (OSL) dating of aeolian sand and analyses of quartz sand grain size and surface microtextures, we explored Holocene aeolian-alluvial environmental changes along the southern margin of the desert, as well as sediment provenance. Results indicate that the grain size characteristics of different sediment types in the stratigraphic profiles were similar to those of modern dune sand, interdune sand, muddy desert surface soil, and riverbed sand. Their frequency curves exhibited unimodal or bimodal distributions, while cumulative probability curves displayed two- or three-segment patterns, dominated by suspension and saltation loads. The quartz sand in sediments along the southern margin of the desert has experienced alternating modifications by various exogenic processes, with limited transport distances and durations, and the depositional environment was relatively humid. During the Holocene, the southern margin of the desert was dominated by braided river deposits, and during intermittent periods of fluvial activity, aeolian deposits such as sand sheets, stabilized dunes, and mobile dunes also occurred. Provenance of Holocene alluvial deposits along the southern margin of the desert remained relatively constant, with detritus from the Tianshan Mountains representing the primary source. Aeolian sand primarily represents near-source replenishment, formed through in situ deposition of fluvial or lacustrine materials transported by wind erosion from the southern margin of the desert, and its provenance likewise derived from weathered Tianshan Mountain debris. In addition, sand from the desert interior may be transported at the desert scale by northwesterly winds, thereby influencing dune development along the southern margin of the desert. These results provide insights for understanding the composition and provenance changes of desert sand in the context of global climate change.

Full Text

Preamble

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Grain size and surface micro-texture characteristics and their paleoenvironmental significance of Holocene sediment in southern margin of the Gurbantunggut Desert, China

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Abstract: The southern margin of the Gurbantunggut Desert, China, is characterized by alternating layers of aeolian and alluvial deposits. Investigating the characteristics of arenaceous sediment in this area is of significant importance for understanding the interactive processes of wind and water forces, as well as the provenance of sediment. However, there are relatively few investigations on the characteristics of such sediment at present. In this study, we researched three aeolian-alluvial interactive stratigraphic profiles and different types of surface sediment on the desert-oasis transitional zone of southern margin of the Gurbantunggut Desert. Based on the optically stimulated luminescence (OSL) dating of aeolian sand and analyses of quartz sand grain size and surface micro-texture, we explored the aeolian-alluvial environmental change at southern margin of the desert in Holocene, as well as the provenance of sediment. The results indicated that the grain size characteristics of different types of sediment in the stratigraphic profiles were similar to those of modern dune sand, interdune sand, muddy desert surface soil, and riverbed sand. Their frequency curves were unimodal or bimodal, and cumulative probability curves were two-segment or three-segment, mainly composed of suspension load and saltation load. The quartz sand in the sediment at southern margin of the desert had undergone alternating transformation of various exogenic forces, with short transportation distance and time, and sedimentary environment was relatively humid. In Holocene, southern margin of the desert primarily featured braided river deposits, and during intermittent period of river activity, there were also aeolian deposits such as sand sheet deposits, stabilized dune deposits, and mobile dune deposits. The provenance for Holocene alluvial deposits at southern margin of the desert remains relatively constant, with the debris of the Tianshan Mountains being the primary provenance. Aeolian sand is mainly near-source recharge, which is formed by in situ deposition of fluvial or lacustrine materials in southern margin of the desert transported by wind erosion, and its provenance was still the weathered debris of the Tianshan Mountains. In addition, the sand in interior of the desert may be transported by northwest wind in desert-scale, thus affecting the development of dunes in southern margin of the desert. The results of this study provide a reference for understanding the composition and provenance changes of desert sand in the context of global climate change.

Keywords: aeolian-alluvial deposition; grain size; surface micro-texture; sedimentary environment; Holocene

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Introduction

Deserts represent significant geographical units in arid and semi-arid regions, formed through the interaction of various factors including landform, climate, and hydrology (Lancaster, 1995; Pye and Tsoar, 2009). The formation and development of deserts exert substantial influence on the evolution of regional land surface processes and even global climate change (Goudie and Middleton, 2006; Yang et al., 2012). Desert margins exist within zones of interaction among various surface layers (Yang and Eitel, 2016), where exogenic forces are particularly active. Typically, sedimentary strata in these areas consist of alternating aeolian and alluvial sequences (Goudie, 2002; Parsons and Abrahams, 2009), making them ideal archives for reconstructing desert paleoenvironments. Consequently, understanding the characteristics of aeolian-alluvial sediment at desert margins is crucial for comprehending the processes of exogenic force interaction and tracing sand provenance.

Grain size constitutes a fundamental characteristic of sediment, serving as an indicator of transport medium and energy while reflecting deposition processes and sand provenance (Team Northern Shannxi of Chengdu Institute of Geology (TNSCIG), 1978). Quartz sand is widely distributed, relatively hard, and chemically stable; however, it undergoes mechanical abrasion and chemical dissolution in different environments, retaining distinct micro-textures on its surface. These micro-textures make quartz sand widely applicable in paleoenvironmental studies (Krinsley and Doornkamp, 1973; Dai, 1988). Therefore, comprehensive analysis of grain size and quartz sand surface micro-texture contributes to deeper exploration of sedimentary environmental changes at desert margins and sand provenance.

The Gurbantunggut Desert, covering approximately 5.63$×10^{4}$ km^2, is the second largest desert in China (Zhu et al., 1980). Previous research has extensively investigated grain size and surface micro-texture characteristics of sediment within the desert interior and surrounding areas, yielding valuable insights into sedimentary environments and sand provenance. For instance, Huang and Zhou (2000) analyzed grain size and quartz sand characteristics in borehole sediment from the interdune region south of the desert, observing significant variations in sand grain size and various features of wind, water, and chemical effects on quartz sand surfaces, which enabled identification of three climate fluctuation events since the late Pleistocene. Shi and Xu (2007) studied sand features of alluvial sediment in the southern desert margin using grain size analysis and scanning electron microscopy, finding that its grain composition resembled dune sand, with poorly rounded quartz sand and widespread traces of aeolian and fluvial erosion. They suggested that the alluvial plain at the southern desert margin experienced aeolian deposition during dry climate periods in the Holocene. Huang (1996) and Qian and Wu (2010) investigated sand features in borehole sediment from the northern and southern parts of the desert, with results indicating that Holocene sandy sediment had finer grains and better sorting, with more pronounced traces of glacial, fluvial, and chemical effects on quartz sand surfaces. Recent studies on surface sand characteristics in the Gurbantunggut Desert also showed that dune sand in the southern margin was notably influenced by wind-driven sorting, tended to be finer, exhibited significant mechanical and chemical effects on quartz sand surfaces, and displayed a rich variety of sand provenance (Liu, 2020; Zhao, 2020; Zhu et al., 2021; Gao et al., 2022a).

In light of these preceding studies, it is evident that current research on sand characteristics of the Gurbantunggut Desert during the Holocene remains relatively limited, with results focusing on either single surface sediment or stratigraphic sediment, lacking comparative studies. Furthermore, the southern margin of the Gurbantunggut Desert, adjacent to the Tianshan Mountains, experiences significant wind and water effects in the desert-oasis transition zone. The sedimentary environment is unique and sand provenance is complex, yet few studies have revealed the dynamic changes of sedimentary environment and sand provenance at the southern desert margin through analysis of aeolian and alluvial stratigraphic sediment characteristics. Given these circumstances, we systematically investigated the characteristics of grain size and quartz sand surface micro-textures of Holocene sediment in the southern margin of the Gurbantunggut Desert to reveal Holocene sedimentary environmental changes and sand provenance, and to provide a scientific basis for predicting long-term desertification trends in the study area.

Study Area

The study area is situated at the convergence of the Gurbantunggut Desert and the alluvial plain in the northern piedmont of the Tianshan Mountains, China (Fig. 1 [Figure 1: see original paper]). The Junggar Basin is deeply nestled within the Asian continent, with a blocked terrain that is higher in the northeast and lower in the southwest (Wu, 1962). The Gurbantunggut Desert within it is significantly influenced by westerly circulation, boasts relatively good vegetation coverage, and represents the largest fixed and semi-fixed desert in China (Chen, 1963; Zhu et al., 1980; Wu, 2009). The desert experiences a temperate continental arid climate with an average annual precipitation of 120 mm and an annual average temperature ranging from 4℃ to 7℃ (Yang et al., 2004; Qian and Wu, 2010). Due to the unique topographical layout, westerlies enter the basin from the western Alataw Pass, the Emin River valley, and the northern Irtix River valley (Xinjiang Expedition of Chinese Academy of Sciences (XECAS), 1978; Yin, 1987), forming west and northwest winds near the surface (Fig. 1).

Surface water is scarce in the study area, with most rivers originating from the Tianshan Mountains and fed by glacial meltwater (Qian and Wu, 2010). These rivers run parallel, converging at the margin of the desert (Li et al., 2020), carrying debris resulting from glacial abrasion and frost weathering to form alluvial plains (XECAS, 1978; Zhu et al., 1980). In low-lying areas, water accumulates into lakes, forming shallow wetlands and marshes (Zhu et al., 1980). The desert hosts a diverse range of plant species, with higher vegetation coverage on gentle dune slopes and interdunes (Chen, 2010; Qian and Wu, 2010). Vegetation coverage is relatively poorer on dune tops, forming the primary areas for wind erosion and accumulation.

Fig. 1 Overview of the study area and sampling locations. XM, MG, and XQ are three study profiles.

Profile Overview and Sample Collection

The study profiles are located in the transitional zone between the southern margin of the Gurbantunggut Desert and the oasis (Fig. 1). Sedimentary sequences of the study profiles are primarily composed of alternating alluvial and aeolian layers, with aeolian dunes covering the top. Lithologic characteristics of each profile are shown in Table 1 . Three profiles were selected: MG, XM, and XQ profiles. The MG profile (45°03 16 N, 86°14 06 E), with a thickness of 365 cm, consists of diluvial deposits, floodplain deposits, and aeolian deposits (Fig. 2a

[Figure 2: see original paper]). The XM profile (45°07 19 N, 85°58 23 E), with a thickness of 355 cm, consists of floodplain deposits, diluvial deposits, stabilized dune deposits, and mobile dune deposits (Fig. 2b). The XQ profile (44°25 44 N, 88°22 26 E), with a thickness of 425 cm, consists of aeolian deposits, diluvial deposits, limnic deposits, and riverbed deposits (Fig. 2c).

Table 1 Lithologic characteristics of study profile

Profile	Depth (m)	Color	Granularity	Structure
	Reddish-brown	Silty clay	Massive structure	
	Reddish-brown, pale-yellow	Silty clay, silt	Massive structure	
	Grey-yellow	Very fine sand	Cross-bedding	
	Grey-yellow, reddish-brown	Very fine sand, silty clay	Horizontal bedding	
	Reddish-brown	Silty clay	Massive structure	
	Light-yellow	Clayish silt	Wavy bedding	
	Reddish-brown	Silty clay	Massive structure	
	Light-gray		Horizontal bedding	
	Light-green	Fine sand	Asymmetrical ripple, cross-bedding	
	Dark-yellow, purple-red	Very fine sand, clayish silt	Horizontal bedding, massive structure	
	Gray-green	Fine sand	Sandy iron-manganese rusty spot, Trough cross-bedding	

Fig. 2 Photos and lithological columns of study profiles. (a), MG profile; (b), XM profile; (c), XQ profile. OSL, optically stimulated luminescence.

Given that optically stimulated luminescence (OSL) dating technology has the best effect on aeolian sand (Aitken, 1998; Stokes et al., 2004; Robins et al., 2021), OSL dating samples were collected under dark conditions in aeolian sand layers after removing surface weathering materials from the profiles (Lai and Ou, 2013). Environmental proxy samples were collected at irregular intervals ranging from 5 to 10 cm apart, totaling 166 samples across the three profiles. Building upon on-the-spot investigation and considering the natural geographical characteristics of the study area, we collected different types of surface sediment from the southern margin of the Gurbantunggut Desert and the northern piedmont of the Tianshan Mountains, totaling 30 samples. The main sand types included dune sand, interdune sand, muddy desert surface soil, and riverbed sand (Fig. 1).

OSL Dating

The equivalent dose (De) testing of OSL dating samples from the XM profile was carried out at the Luminescence Dating Laboratory, School of Geographical Sciences, Fujian Normal University, China. De was determined using the single aliquot regenerative-dose (SAR) protocol (Murray and Wintle, 2000; Wintle and Murray, 2006), and measurements were made using a Danish Risø luminescence reader (TL/OSL-DA-20C/D, DTU Nutech, Kongens Lyngby, Denmark). After pretreatment, we sent the samples to the China Institute of Atomic Energy for measurement of uranium (U), thorium (Th), and potassium (K) contents using neutron activation analysis. Water content of the samples was measured at approximately 5%, and we calculated the contribution of cosmic rays based on the sample’ s latitude, altitude, and burial depth, following Prescott and Hutton (1994). Environmental dose rate (D) of the samples was estimated accordingly. Burial age of the samples was determined using the age calculation formula: age (a) = equivalent dose (De) / environmental dose rate (D).

OSL dating of MG and XQ profiles was conducted at the Luminescence Dating Laboratory of the Institute of Crustal Stress, China Earthquake Administration. For the MG profile, samples MG1, MG3, MG4, and MG5 used 4–11 m fine quartz grains and were dated using the simple multi-aliquot regenerative-dose (SMAR) protocol (Wang and Lu, 2005) to obtain De. Sample MG2 and samples XQ1–XQ4 selected 90–125 m coarse quartz grains and were dated using the SAR procedure to determine De.

Grain Size Analysis

Grain size analysis was conducted using a laser diffraction particle size analyzer (Mastersizer 2000, Malvern Instruments, Malvern, UK) at the School of Geographical Sciences, Fujian Normal University, China. The instrument range spans from 0.02 to 2000.00 m. Prior to testing, we carried out repeatability tests, with measurement errors less than 1%. Grain size of the sediment was represented using Φ value ($\Phi = -\log_2 D'$, where D’ is the grain size in mm). We categorized grain size classes based on the Udden-Wentworth standard as follows: gravel ($< -1\ \Phi$), very coarse sand (-1–$0\ \Phi$), coarse sand (0–$1\ \Phi$), medium sand (1-2 Φ), fine sand (2-3 Φ), very fine sand (3-4 Φ), silt (4-9 Φ), and clay (>9 Φ). Mean grain size, sorting, skewness, and kurtosis were calculated using the Folk-Ward graphic method formula (Folk and Ward, 1957). Additionally, a granulometric end-member (EM) analysis was performed on the stratigraphic sediment using the algorithm proposed by Paterson and Heslop (2015).

Surface Micro-Texture of Quartz Sand Analysis

Observation of quartz sand morphology and surface micro-texture was conducted at the School of Geographical Sciences, Fujian Normal University, China, using a scanning electron microscope (JCM-6000Plus, JEOL, Tokyo, Japan). This study involved observation and statistical analysis of the morphology and surface micro-texture of a total of 992 quartz particles, comprising 13 stratigraphic samples and 12 surface samples. We carried out statistical analysis of quartz sand morphology and roundness according to the method proposed by Powers (1953), while the classification and interpretation of surface micro-texture followed the method presented by Krinsley and Doornkamp (1973).

Chronostratigraphy

Ages of OSL dating samples from the study profiles are presented in Table 2 . For most samples, OSL ages were consistent with the stratigraphic sequences, except for a slight inversion observed in the bottom alluvial layer samples from the MG profile. Age reversal may be attributed to differences in D caused by mineral composition. Compared with MG3 and MG4, D of MG5 was high (Table 2). XM and MG profiles at the southwestern margin of the desert represented mid to late Holocene deposits dating back to approximately 5.0 ka. The bottom sand layer in the XQ profile (at 4.25 m below the surface) had an OSL age of approximately 11.1 ka, indicating early Holocene sedimentation. In summary, these three profiles provided records of environmental information in the southern margin of the desert since the Holocene.

Table 2 Chronology and related parameters of the OSL (optically stimulated luminescence) dating samples in study profiles

Sample number	Depth (m)	U (µg/g)	Th (µg/g)	K (µg/g)	Water content (%)	Grain size (m)	Procedure	D (Gy/ka)	De (Gy)	Age (ka)
	2.60	1.44$±0.05|5.47±0.05|2.08±0.01|||*SAR*|3.00|1.37±0.05|4.74±0.05|||3.50|1.43±0.05|4.98±0.05|2.								

Note: U, uranium; Th, thorium; K, potassium; SAR, single aliquot regenerative-dose; SMAR, simple multi-aliquot regenerative-dose; D, environmental dose rate; De, equivalent dose. Mean±SE.

Surface Sediment

Different types of surface sediment in the study area exhibited a wide range of grain size distribution and significant differences in grain size composition (Fig. 3 [Figure 3: see original paper]). Muddy desert surface soil had the finest grain size, with the highest proportion of silt, followed by clay and very fine sand, along with some components of fine sand and medium sand. Interdune sediment was dominated by silt, with significant portions of very fine sand, fine sand, and clay, and lower content of medium sand. Dune sand was characterized by a predominance of fine sand, medium sand, and very fine sand, with very low contents of coarse sand, silt, and clay. Riverbed sediment displayed substantial internal variations, with most samples ranging from silt to coarse sand, and relatively higher content of fine sand and medium sand.

As shown in Figure 4a [Figure 4: see original paper], the frequency curves of dune sand displayed a unimodal distribution with a peak around 2.00–3.00 Φ. Most curves were sharp, with a few displaying slightly flatter profiles. Interdune sand showed a bimodal distribution with a narrow primary peak around 3.00–4.00 Φ and a broader secondary peak ranging from 8.00 to 9.00 Φ (Fig. 4b). Muddy desert surface soil exhibited a polymodal distribution with significant internal variability. There were two main patterns (Fig. 4c): one was bimodal with a sharp primary peak around 4.00–5.00 Φ and a distinct fine tail, while the secondary peak was less prominent with a peak around 1.00 Φ. The other pattern was trimodal with both primary and secondary peaks being relatively flat, forming a saddle-shaped distribution. Riverbed sand showed a unimodal distribution, and most samples had peaks ranging from 0.00 to 2.00 Φ, although there were some variations between individual samples (Fig. 4d).

In terms of cumulative probability curves, dune sand (Fig. 4e) consisted primarily of a two-segment pattern, except for samples M13-DS and XQ-DS which comprised a single segment (saltation load). The remaining samples were primarily composed of saltation load with a small amount of suspension load. Interdune sand (Fig. 4f) also exhibited a two-segment pattern, with a significant proportion of suspension load and a corresponding reduction in saltation load. Surface soil in muddy desert displayed a distinct inflection point at the beginning (Fig. 4g), corresponding to the third peak in the frequency curve, indicating the presence of a small amount of coarse traction load. Riverbed sand (Fig. 4h) also displayed a two-segment pattern, with saltation load being dominant and suspension load higher than that in dune sand.

As shown in Figure 4i, the mean grain size of surface sediment decreased from riverbed sand to dune sand, interdune sand, and muddy desert surface soil. Regarding sorting, dune sand exhibited good sorting with values ranging from 0.56 to 1.40 (Fig. 4j). Interdune sand and muddy desert surface soil showed poorer sorting with values ranging from 2.00 to 3.00. Riverbed sand sorting was inferior to dune sand, with values ranging from 0.44 to 1.76. In terms of skewness, dune sand displayed slight positive skewness, with values ranging from

-0.23 to -0.01 (Fig. 4k). Interdune sand and muddy desert surface soil generally exhibited negative skewness, with values ranging from -0.51 to 0.19. Riverbed sand skewness values ranged from -0.51 to -0.03, indicating marked negative values. Regarding kurtosis, dune sand exhibited moderate kurtosis with values ranging from 0.93 to 1.55 (Fig. 4l). Interdune sand and muddy desert surface soil generally had lower kurtosis values, with most samples ranging from 0.63 to 1.11, indicating slightly flat distributions. Riverbed sand kurtosis values ranged from 0.91 to 3.26, indicating sharp distributions.

Stratigraphic Sediment

Sediment grain size distribution within the study profiles was quite extensive, encompassing all grain size components from clay to coarse sand (Fig. 5 [Figure 5: see original paper]). The MG profile was primarily composed of silt, with lower proportions of clay and very fine sand. Diluvial deposits exhibited the highest content of silt, followed by clay. In the aeolian sand layers, there was a notable increase in very fine sand and fine sand, particularly at the depth of 135-185 cm. In the upper section of the XM profile (0-115 cm), both floodplain deposits and diluvial deposits contained high content of silt and clay. In the middle section (115-240 cm), the components of very fine sand and fine sand significantly increased. Below 240 cm, there was a distinct increase in sediment grain size, even including coarse sand components. The XQ profile displayed coarser sediment compared with MG and XM profiles. While diluvial and limnic deposits contained higher content of clay and silt, other layers contained substantial proportions of silt. Particularly at the bottom of the profile, riverbed deposits (305-425 cm) exhibited a sudden increase in grain size, with a majority of particles composed of fine sand and medium to coarse sand.

We executed the AnalySize EM analysis in MATLAB to fit 10 potential granulometric EMs based on grain size data from each profile (Fig. 6 [Figure 6: see original paper]). During the analysis, we determined the number of EMs for each profile based on linear correlation coefficient (R^2) and angular deviation. Generally, a higher R^2 (usually above 0.80) and a smaller angular deviation (usually less than 5) indicated better fit by EMs. Following the principles of EM selection, the number of granulometric EMs for the MG profile was determined to be 5 (Fig. 7a [Figure 7: see original paper]). Among them, EM1 and EM2 mainly dominated in diluvial deposits. EM3 was predominant in floodplain deposits, while EM4 and EM5 had higher proportions in aeolian deposits. A total of 5 granulometric EMs were extracted from the XM profile (Fig. 7b). EM1 mainly existed in diluvial deposits. EM2 occurred in floodplain deposits. EM3 had high content in stabilized dune deposits, while EM4 and EM5 accounted for a large proportion in mobile dune deposits. There were 6 granulometric EMs in the XQ profile (Fig. 7c). EM1 dominated in diluvial deposits. EM2 and EM3 were abundant in limnic deposits. EM4 was predominant in aeolian deposits, while EM5 and EM6 were concentrated in riverbed deposits.

Plotting the granulometric EMs reveals significant differences in their grain size compositions (Fig. 8 [Figure 8: see original paper]). In the MG profile, EM1 exhibited the highest proportion of clay (67.98%). EM2 and EM3 contained substantial amounts of silt (78.88% for EM2 and 84.46% for EM3, respectively). EM4 displayed relatively high levels of silt (51.58%) and sand (45.44%), while EM5 comprised a significant amount of sand (82.78%). Within the XM profile, EM1 was primarily composed of silt (59.46%) and clay (40.15%). EM2 contained a high proportion of silt (86.37%). EM3 still featured predominant silt (53.52%), but sand content (42.90%) had notably increased. EM4 and EM5 showed similar grain size compositions, with sand content reaching 97.08% and 97.88%, respectively. In the XQ profile, EM1 exhibited the highest clay content (56.24%), followed by silt (34.82%). EM2 showed the highest proportion of silt (86.55%). EM3 displayed relatively equal proportions of silt (54.49%) and sand (44.08%). EM4, EM5, and EM6 showed progressive increases in sand content (82.95%, 95.29%, and 99.35%, respectively), with significant decreases in silt content (10.33%, 1.47%, and 0.65%, respectively) and clay content (6.72%, 3.24%, and 0.00%, respectively).

Frequency curves of EM1 in the MG profile displayed a broad and gentle single peak (Fig. 9a [Figure 9: see original paper]). EM2 also showed a broad and gentle single peak, and the curve was coarse-skewed. EM3 was bimodal, with a primary peak exhibiting normal distribution and a faint secondary peak. EM4 and EM5 shared a similar bimodal pattern, with sharper primary peaks and flat secondary peaks. Within the XM profile, EM1 demonstrated a positively skewed, broad, and gentle single peak (Fig. 9b). EM2 displayed a nearly normal distribution but exhibited a notable fine tail. EM3 and EM4 shared similar curve shapes, featuring sharp primary peaks and less pronounced secondary peaks. EM5 showed a saddle-shaped double peak, with a wide span in the peak area. In the XQ profile, EM1 displayed a bimodal distribution (Fig. 9c), with the primary peak showing a positively skewed wide peak. EM2 showed a broad and gentle single peak, slightly positively skewed. EM3 showed a positively skewed single peak, and EM4, EM5, and EM6 were similar in curve shapes, both featuring sharp single peaks.

Cumulative probability curves of EM1 and EM2 in the MG profile consisted of suspension, saltation, and traction loads (Fig. 9d), with suspension load exceeding 95.000%. EM3 and EM4 exhibited a three-segment distribution, where saltation load was above 85.000%. EM5 was a two-segment distribution with saltation load representing about 80.000%. In the XM profile, EM1 was composed of suspension, saltation, and traction loads (Fig. 9e), with suspension load accounting for over 99.000%. EM2 and EM3 both showed three-segment distributions, with saltation load as the primary portion. EM4 was a two-segment distribution, with saltation load exceeding 95.000%. EM5 consisted of saltation and traction loads, with each accounting for 50.000%. In the XQ profile, EM1 followed a three-segment distribution (Fig. 9f), with a high proportion of suspension load. EM2 had saltation load representing more than 80.000%, followed by suspension and traction loads. EM3 was a three-segment distribution, with saltation load exceeding 95.000%. EM4, EM5, and EM6 were composed of suspension and saltation loads, and saltation load gradually increased from EM4 to EM6.

Mean grain size of granulometric EMs ranged from 1.00 to 9.00 Φ (Fig. 9g), with most EMs falling between 4.00 and 9.00 Φ. Sorting of each EM varied between 0.50 and 2.10; only EM4 in the XM profile and EM5 and EM6 in the XQ profile displayed relatively good sorting, with values lower than 0.71. Regarding skewness, except for EM1 in the XQ profile showing negative skewness with a value lower than -0.10, most other EMs ranged from -0.10 to 0.70, exhibiting nearly symmetrical to positively skewed distributions (Fig. 9h). The kurtosis of EMs varied widely, with values between 0.90 and 3.50, and most EMs displayed sharp or normal distributions (Fig. 9i). Through scatter plots of granulometric parameters, it was evident that sorting of EMs and mean grain size showed a certain positive correlation (R^2 = 0.41), indicating that as sediment grain size increased, sorting gradually improved. However, skewness (R^2 = -0.06) and kurtosis (R^2 = 0.01) did not exhibit significant correlation with mean grain size.

Morphology and Roundness

In surface sediment, the morphology of dune sand was predominantly circular (75.51%) and subrounded (46.00%) (Table 3). Compared with dune sand, interdune sand had a higher percentage of square particles (35.29%). The particles were mainly subangular (32.00%) and angular (30.00%). Muddy desert surface soil had higher content of square (34.00%) and rectangular (30.00%) sand, with angular particles (44.23%) being predominant. Square particles (44.55%) were more prominent, and angular particles (77.45%) overwhelmingly dominated in riverbed sand. Overall, the roundness of quartz sand in surface sediment followed the sequence from high to low: dune sand, interdune sand, muddy desert surface soil, and riverbed sand.

Table 3 Frequency of shape and roundness of quartz sand grains for surface sediment and stratigraphic sediment in study profiles

Sample type	Circular	Square	Rectangular	Triangular	Rounded	Subrounded	Subangular	Angular
MG diluvial sand								
MG aeolian sand								

Sample type	Circular	Square	Rectangular	Triangular	Rounded	Subrounded	Subangular	Angular
MG floodplain sand								
XM diluvial sand								
XM floodplain sand								
XM stabilized dune								
XM mobile dune								
XQ aeolian sand								
XQ diluvial sand								
XQ limnic sand								
XQ riverbed sand								

Note: DS, dune sand; IS, interdune sand; MD, muddy desert surface soil; RB, riverbed sand.

In the MG profile, aeolian sand exhibited the highest content of circular grains (38.24%) and the best roundness (37.50%). The roundness of floodplain sand was the poorest, with a square particle proportion of 44.12% and predominance of angular grains (62.16%). In the XM profile, both diluvial and floodplain sand showed poor roundness. In contrast, stabilized dune sand demonstrated better roundness, with predominant circular (41.18%) and subrounded (43.86%) grains. Mobile dune sand exhibited the best roundness, with over half being circular (58.00%) and a substantial proportion of subrounded (49.06%) grains. In the XQ profile, riverbed sand exhibited the best roundness, with a circular grain proportion of 68.09% and subrounded grain proportion (48.35%) exceeding nearly half. The aeolian sand had slightly lower roundness, with circular grain content of 54.05% and subrounded grain content of 43.28%. Both diluvial and limnic sand showed poor roundness, but the former was better than the latter.

Surface Micro-Textures

Typical aeolian features are products of high-energy wind environments, resulting from mutual collision of sand transported by wind. In surface sediment, aeolian features were very prominent on the surface of dune sand (Fig. 10 [Figure 10: see original paper]), with frequencies of each type of feature above 40% (Figs. 10a and 11). In interdune sand and muddy desert surface soil, there were also a certain number of aeolian features on the surface of quartz sand, with frequencies ranging from 30% to 50%. In the MG profile, pockmarked pits and dish-shaped pits on aeolian sand were significantly higher than those on diluvial sand and floodplain sand (Figs. 10b and 12), with frequencies exceeding 80%. In the XM profile, aeolian features were focused on stabilized dune sand and mobile dune sand (Figs. 10c and 12), especially on mobile dune sand. In the XQ profile, aeolian features on the surface of quartz sand in aeolian layers were not obvious (Figs. 10d and 12), but riverbed sand showed significant aeolian features, with frequencies approaching 70%, indicating that these sands have been subjected to strong wind action.

Fig. 10 Frequency of surface micro-texture of quartz sand grains for surface sediment and stratigraphic sediment in study profiles. (a), surface sediment; (b), MG profile; (c), XM profile; (d), XQ profile. 1, pockmarked pit; 2, circular and dish-shaped pit; 3, crescent-shaped impact crater; 4, sinuous ridge; 5, triangular pit; 6, V-shaped pit; 7, straight and bent impact groove; 8, subaqueous polished surface; 9, cleavage plane; 10, conchoidal fracture; 11, stria; 12, deep extrusion pit; 13, triangular and V-shaped flute; 14, siliceous sphere; 15, siliceous scale; 16, siliceous precipitation; 17, crack; 18, etch pit.

Fig. 11 [Figure 11: see original paper] Surface micro-textures of quartz sand grains for different types of surface sediment in the study area. The micro-texture type corresponding to the number is shown in Figure 10. (a1–a4), DS; (b1–b4), IS; (c1–c4), MD; (d1–d4), RB.

Features such as triangular pits, straight impact grooves, and conchoidal fractures are products of high-energy fluvial environments, while long-term flow erosion leads to abrasion of sand, forming subaqueous polished surfaces. In surface sediment, besides abundant fluvial features on the surface of quartz sand in muddy desert surface soil and riverbed sand, such features were also observed on dune sand and interdune sand at frequencies of about 20% (Figs. 10a and 11). In the study profiles, frequencies of fluvial features on the surface of diluvial sand, floodplain sand, and limnic sand were high, ranging from 30% to 70% (Figs. 10b–d and 12). Similar to dune sand, fluvial features were present on the surface of aeolian sand in stratigraphic profiles, but frequencies were less than

20%. The fluvial features on riverbed sand in the XQ profile were much more significant (Fig. 10d). However, these features were fresh and superimposed on aeolian sand (Fig. 12 [Figure 12: see original paper]).

Fig. 12 Surface micro-texture of quartz sand grains for different types of sediment in study profiles. The micro-texture type corresponding to the number is shown in Figure 10. (a1–a6), MG profile; (b1–b6), XM profile; (c1–c8), XQ profile.

In glacial environments, due to strong extrusion, friction, and collision of solid materials, quartz sand retains micro-textures such as V-shaped flutes, cleavage planes, and conchoidal fractures on its surface. In surface sediment, glaciated features on the surface of quartz sand increased from dune sand to interdune sand, muddy desert surface soil, and riverbed sand (Figs. 10a and 11). In the MG profile, the sediment with the most glaciated features was floodplain sand, with frequencies between 20% and 50% (Figs. 10b and 12). In the XM profile, glaciated features on the surface of stabilized dune sand were relatively significant, with frequencies above 20% (Figs. 10c and 12). However, there were few glaciated features on the surface of mobile dune sand, with frequencies below 10%, indicating potential differences in provenance between the two dune deposits. In the XQ profile, glaciated features on the surface of quartz sand were not significant, with frequencies below 20% (Fig. 10d).

In desert environments, intense temperature changes and chemical dissolution usually result in cracks, etch pits, and siliceous precipitation on the surface of quartz sand. Among surface sediment, cracks were most developed on the surface of dune sand, with frequencies close to 80% (Figs. 10a and 11). Siliceous precipitation appeared on the surface of quartz sand in interdune sand and muddy desert surface soil, with frequencies exceeding 80%. Etch pits were most common on the surface of riverbed sand, with frequencies exceeding 40%. In the study profiles, cracks were most commonly observed on the surface of aeolian sand, with frequencies between 30% and 60% (Figs. 10b–d and 12). Siliceous precipitation on the surface of diluvial sand, floodplain sand, and limnic sand was widespread, with frequencies up to 60%. Etch pits on the surface of quartz sand in all profiles were relatively low, with an average frequency of around 30%.

Overall, whether in surface sediment or stratigraphic sediment, chemical features on the surface of quartz sand were quite significant, closely related to the relatively good vegetation cover in the Gurbantunggut Desert. The presence of mechanical impact features such as aeolian, fluvial, and glaciated features on particle surfaces indicated active exogenic forces in the study area, and sediment had undergone alternating transformation by various exogenic forces.

Sedimentary Environment Reflected by Grain Size EM and Surface Micro-Texture of Quartz Sand

Based on the aforementioned analysis, we found that MG profile EM1 and EM2, along with XM profile EM1 and XQ profile EM1, were predominantly present in diluvial deposits characterized by clay and silt, with a significant proportion of suspension load, akin to muddy desert surface soil. Previous studies have indicated that sediment grain size decreases gradually from upstream to downstream within fluvial dynamic systems, with suspension load mostly comprising clay and fine silt ranging from 10 to 15 mm (Sun et al., 2001). In the alluvial plain at the northern piedmont of the Tianshan Mountains, braided rivers experienced a decrease in gradient and flow velocity after emerging from the mountains, eventually flowing into the desert during flood periods, resulting in the development of diluvial deposits (Liu et al., 2018). Compared with modern river sand, quartz sand in diluvial deposits exhibited fewer fluvial features and better roundness, reflecting the weak hydrodynamic characteristics of distal reaches near the southern desert margin (Kang and Dai, 1988; Gao et al., 1995; Wu, 1995). Consequently, such EM represents low-flow suspended deposition in the distal reaches of braided rivers. However, due to weak hydrodynamic force and absence of visible bedding after deposition, such sediment more closely resembles stagnant water deposition (Jin et al., 2019; Yang et al., 2021).

MG profile EM3 and XM profile EM2 were primarily found in floodplain deposits, characterized by wavy bedding and dominated by silt with a significant proportion of suspension load. In the Junggar Basin, influenced by the swing of meandering rivers, when flood flow over the alluvial fan downstream of the braided river occurs, suspended and saltatory silts overflow to the convex bank, thereby forming fine-grained sediment on the river overbank (Xie and Yin, 2021). From the characteristics of quartz sand, the roundness of floodplain sand was relatively poor, with significant fluvial features, similar to quartz sand in muddy desert surface soil and modern riverbed sand, reflecting a mid- to high-energy flowing water environment. However, the frequent swing of braided rivers at the northern piedmont of the Tianshan Mountains led to their gradual transformation into meandering rivers (Tan et al., 2014; Han et al., 2023). Therefore, such EM represents floodplain sediment in the meandering segment downstream of the braided river, with significant changes in water volume after the river merged into the desert, resulting in a considerable proportion of fine-grained components in the sediment (Ren and Wang, 1981).

XQ profile EM2 and EM3 were primarily concentrated within limnic deposits, characterized by predominantly silt and clay, with a mixture of saltation and suspension load. The frequency curves exhibited a broad peak, indicating poor sediment sorting. From sediment structure, both EMs appeared gray-green, reflecting an anaerobic reducing environment due to prolonged waterlogging. However, the development of reddish-brown iron-manganese rusty spots within the layer suggested periodic fluctuations in water level (Ren and Wang, 1981). Apart from significant fluvial features, limnic sand also exhibited numerous chemical features, indicating that the sand had been in a humid environment for a long time after deposition (Vos et al., 2014). Such characteristics of quartz sand were not only commonly found in muddy desert surface soil and interdune sand but also prevalent in borehole sediment at the southern desert margin (Huang and Zhou, 2000; Qian and Wu, 2010). In summary, the two EMs represent lake and marsh wetland deposition in distal reaches of braided rivers with abundant water.

The strata hosting MG profile EM4, EM5, and XM profile EM3 exhibited distinct cross-bedding, predominantly composed of sand and silt, displaying good sorting characteristics of aeolian sand. However, compared with modern dune sand, this type of aeolian sand tends to have finer grain size, a higher proportion of suspension load, and insufficiently developed aeolian features on sand surfaces along with numerous chemical features. Studies have shown that as mobile dunes tend to become stabilized, vegetation coverage increases and fine-grained sand increases significantly (Li and Fan, 2011; Lee et al., 2019). Moreover, during the process of dune stabilization, humidity conditions gradually improved, leading to the development of chemical features on sand surfaces. Therefore, such EM likely represents stabilized dune deposition. It is noteworthy that a certain number of fluvial features were observed on aeolian sand surfaces, indicating that it may have been formed by in situ sand accumulation of sediment carried and deposited by rivers at the southern desert margin (Qian et al., 2003; Zhu et al., 2014; Zhang et al., 2022). XM profile EM4 and EM5 are typical dune sand components, concentrated within the layer of mobile dune deposition, exhibiting characteristics consistent with modern dune sand. These sands had high roundness, significant aeolian features on the surface, but few chemical features, indicating that sand particles were transported by wind over long distances and then deposited in an arid environment (Dai, 1988). XQ profile EM4 was predominantly distributed within aeolian sand layers, composed of sand and a small amount of silt. The frequency curve exhibited a bimodal distribution, with saltation load higher than suspension load and good sorting. From sediment structure, the aeolian sand layers showed horizontal bedding, displaying characteristics of sand sheet deposition (Ren and Wang, 1981). However, due to the development of aeolian sand on the diluvial substrate, it was inevitable that adhesive diluvial sediment mixed with it, resulting in a minor peak and fine tail in the frequency curve (Li et al., 2021). This kind of aeolian sand was moderately rounded, with few aeolian features and a certain number of fluvial features, but chemical features were significant, indicating short transport distance and time, which also reflects the aeolian sand erosion and deposition process of in situ sand accumulation (Shi and Xu, 2007; Qian and Wu, 2010).

XQ profile EM5 and EM6 were primarily found within sand layers exhibiting trough cross-bedding, displaying characteristics of riverbed deposition (Ren and Wang, 1981). However, in terms of grain size characteristics, the main particle size of both EMs ranged from fine sand to medium sand, dominated by saltation load, with sharp peaks and good sorting, indicating aeolian sand characteristics. As previously mentioned, such sand had high roundness, with fluvial features superimposed on aeolian features on its surface, indicating that the two EMs represent aeolian sand modified by fluviation. The higher frequencies of fluvial features reflect abundant river water and strong hydrodynamic force. However, due to the relatively short flow path of rivers in the eastern Tianshan Mountains, the modification of sand by flow was limited, and aeolian features on sand surfaces remained prominent. In the downstream of the river in the arid desert, due to interaction between wind and water forces, transformation of sediment environment for sand grains was widespread. This can manifest as fluvial sand modified by wind action (Garzanti et al., 2022), or as aeolian sand modified by water action (Zhang et al., 2021).

In summary, during the Holocene, the desert-oasis transition zone at the southern margin of the Gurbantunggut Desert mainly developed a stratigraphic sequence alternating between braided river deposits and aeolian deposits. Influenced by climate, terrain, and variations in exogenic forces, the southern desert margin exhibited the development of braided river deposits, including low-energy suspended diluvial deposits, meandering channel floodplain deposits, limnic deposits, and riverbed deposits. Additionally, aeolian deposits including sand sheet deposits, stabilized dune deposits, and mobile dune deposits were prevalent. Considering the chronology of stratigraphy, from 11.8 to 10.2 ka, rivers in the southeastern desert margin had high discharge and strong hydropower. Frequent meandering of braided rivers led to the entrainment of aeolian sand along river banks, forming riverbed deposits. At the same time, glacial meltwater deposits developed in the interdune of the southeastern desert margin (Li and Fan, 2011), and a thick alluvial clay layer developed in the HG profile (Zong et al., 2022). Ebinur Lake also exhibited high water levels (Wu et al., 2003), indicating that alluvial deposits were prevalent on the desert margin at this stage. From 10.2 to 6.0 ka, braided rivers had abundant discharge, and the end of the river may have developed shallow wetlands in low-lying areas at the desert margin, resulting in limnic deposits. The increase of regional humidity during this period was also recorded by other sedimentary sequences at the desert margin. The FK profile was dominated by silty clay deposits (Zong et al., 2022). Clay mineral deposits developed in the lower reaches of the Manas River, China (Shi et al., 2007). The SFC profile in the lower reaches of the Hutubi River developed riverbed deposits and lacustrine deposits (Tan et al., 2023), and the water level of Ebinur Lake was also gradually rising (Wu et al., 1996). Since 6.0 ka, hydropower of braided rivers at the southern desert margin gradually weakened. This period witnessed the development of meandering channel floodplain deposits followed by low-energy suspended diluvial deposits in terminal river reaches. Meanwhile, intermittent enhancement of aeolian activity led to desert encroachment. Influenced by underlying topography and surface substrate, various aeolian deposits including aeolian sand sheets, stabilized dunes, and mobile dunes emerged. These aeolian deposits interacted and overlapped with river deposits, forming a complex alluvial-aeolian composite sequence. During this time, the MNS profile in the southwest of the desert recorded alternating changes of aeolian-alluvial processes (Zong et al., 2022), and the SFC profile reflected the interaction between river alluvial and aeolian accumulation (Tan et al., 2023). In addition, Dongdaohaizi Lake (Yan et al., 2004; Li et al., 2005; Ma et al., 2005) and Ebinur Lake (Wu et al., 1996) also experienced frequent variations in water level, reflecting fluctuations of aeolian and alluvial processes at the desert margin in mid- to late Holocene.

Provenance Indication of Grain Size and Quartz Sand Surface Micro-Texture

Previous studies have shown that sand provenance of the Gurbantunggut Desert mainly consists of clastic materials produced by weathering and erosion of rocks in surrounding mountains, as well as contributions from fluvial and lacustrine sediment at the desert margin and underlying sand in the basin (Zhu et al., 1980; Qian et al., 2001; Qian et al., 2003; Shi et al., 2006; Zhu et al., 2014; Huang et al., 2018; Zhang et al., 2022). As the southern desert margin is located at the convergence zone of wind and water forces, both exogenic forces exert a certain degree of modification on debris from surrounding mountains, making the sediment source more complex compared with other areas of the desert. In provenance analysis of desert sediment, abrasion of sand during transport by different exogenic forces often leads to differences in grain size characteristics, making them distinct from sediment in the source area (Jerolmack et al., 2011). Relying solely on grain size analysis may not be sufficient to accurately determine sand provenance (Gao et al., 2022b). However, features such as roundness and surface micro-textures of quartz sand can provide important references for provenance discrimination (Vos et al., 2014). Therefore, this study, based on grain size analysis, combines characteristics of quartz sand to explore the provenance of sediment at the southern desert margin.

Alluvial deposits at the southern desert margin were primarily formed by alluviation from rivers originating from the northern piedmont of the Tianshan Mountains and seasonal precipitation. Potential provenance of this material could be debris produced by glacial erosion and abrasion, as well as frost weathering in the Tianshan Mountains. In surface sediment, quartz sand in muddy desert surface soil and riverbed sand exhibited poor roundness, with numerous prominent fluvial features and significant glaciated features. These characteristics indicated that debris from the Tianshan Mountains was the main provenance of modern alluvial sand at the southern desert margin. Stratigraphic sediment, including diluvial sand, floodplain sand, and limnic sand, displayed similar features, suggesting that weathered debris from the Tianshan Mountains played a crucial role in supplying material to alluvial deposits at the southern desert margin during the Holocene. The interaction between rivers and dunes at the southern margin of the Gurbantunggut Desert represents a unique pattern, namely scattered by dune- and field-parallel drainage (Li et al., 2019). Various rivers originating from northern slopes of the Tianshan Mountains can transport debris generated by glacial abrasion and frost weathering without interfering with each other, depositing sand materials at the southern desert margin. Furthermore, during the Holocene, there have been no significant tectonic alterations in the Junggar Basin, confirming that alluvial deposits at the southern desert margin consistently originated from the Tianshan Mountains.

Grain size of surface sand in the Gurbantunggut Desert gradually decreases from northwest to southeast, with the finest sand observed in the south of the desert, primarily composed of very fine and fine sand, and exhibiting poor roundness (Qian and Wu, 2010; Zhao, 2020; Zhu et al., 2021; Gao et al., 2022a). However, results of this study showed that in modern dune sand at the southern desert margin, fine sand and medium sand were predominant, similar to characteristics of surface sand in the central desert. Additionally, there were clear aeolian features on the sand, with good roundness. This result suggested that under conditions of strong wind or dust storms, sand from the interior of the desert may be transported and subsequently accumulated at the southern margin (Pye, 1987). In the stratigraphic profiles, the sand layer at the bottom of the XQ profile was aeolian sand modified by fluviation, consistent with grain size characteristics of mobile dune sand in the XM profile. Predominant grain size components were fine sand and medium sand, with well-rounded quartz sand and significant aeolian features on the surface. Therefore, the source area may also be the interior of the desert. Aeolian sand of the MG profile, stabilized dune sand of the XM profile, and aeolian sand of the XQ profile exhibited finer grain size, similar to modern muddy desert surface soil and interdune sand. They all showed higher content of silt, along with poor roundness of quartz sand, and fluvial and glaciated features contributed significantly. These characteristics collectively reflect the proximal nature of such aeolian sand (Pye, 1987; Qian et al., 2000; Vos et al., 2014), indicating that they may have primarily originated from widespread alluvial deposits in the south of the desert. Current studies also suggest that fluvial and lacustrine deposits in the south of the desert served as a “transit station” for the transfer of weathered debris from the Tianshan Mountains. After being transported by wind erosion, they provided sand provenance for the development of dunes at the southern desert margin (Tursun et al., 2022; Zhang et al., 2022). Ultimately, regardless of how the sands were processed and modified, their provenance was still debris formed by glacial erosion and abrasion, and frost weathering from the Tianshan Mountains. However, recent studies have shown spatial heterogeneity in sand provenance of the Gurbantunggut Desert. In spring and winter, when dust storms occur frequently, weathered debris from the Altay Mountains can be transported to the central and eastern parts of the desert with prevailing winds, and sand in the western part of the desert comes from the Junggar Basin (Li et al., 2024). Under the action of strong wind, the southern part of the desert, which is located in the downwind direction of prevailing winds, may be affected by sand input. Therefore, the contribution of weathered debris from mountains around the Junggar Basin to the development of dunes at the southern desert margin remains to be further studied.

Conclusions

Based on analysis of OSL chronology, grain size, quartz sand morphology, and surface micro-texture, we explored sedimentary environmental change and sand provenance at the southern margin of the Gurbantunggut Desert during the Holocene. Around 11.8 to 10.2 ka, frequent swings of braided rivers on the southern desert margin led to the entrainment of aeolian sand along river banks, forming riverbed deposits. From 10.2 to 6.0 ka, braided rivers exhibited abundant water flow, resulting in the inflow of tail water into the desert fringe, forming limnic deposits. Since 6.0 ka, water in braided rivers diminished, leading to the development of meandering floodplain deposits and low-flow suspended diluvial deposits in tail water sections. During periods of enhanced aeolian activity, the desert encroached southward, and aeolian deposits formed on substrates of river deposits, overlapping with them. During the Holocene, alluvial deposits at the southern desert margin had a relatively stable provenance, consistently composed of debris transported by river flow and intermittent floods from the Tianshan Mountains. Aeolian sand was primarily supplied from proximal sources, formed by in situ deposition of fluvial and lacustrine sediment transported by wind erosion in the southern desert. Additionally, sand from the interior of the desert may have undergone transportation on a desert scale via strong winds such as dust storms, contributing to the development of dunes at the southern desert margin. These results provide a reference for studying the formation and evolution of the Gurbantunggut Desert and for preventing desertification in the future.

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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Author Contributions

Conceptualization: MA Yunqiang; Data curation: MA Yunqiang, TAN Dianjia, ZOU Xiaojun, TAO Tonglian; Methodology: MA Yunqiang, LI Zhizhong; Formal analysis: MA Yunqiang, TAN Dianjia, ZOU Xiaojun; Software: TAO Tonglian; Writing-original draft preparation: MA Yunqiang; Writing-review and editing: MA Yunqiang, LI Zhizhong, TAN Dianjia; Funding acquisition: LI Zhizhong. All authors approved the manuscript.

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