Holocene Environmental Evolution Recorded in Sediments from the Southern Margin of the Gurbantunggut Desert (Postprint)

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Abstract

The southern margin of the Gurbantunggut Desert is situated at the convergence zone of aeolian and fluvial processes, characterized by unique sedimentary environments and sensitive responses to climate change, making it an ideal region for investigating Holocene environmental evolution in the sandy lands of northwestern China. Three aeolian-fluvial interactive stratigraphic sections in the desert-oasis transition zone at the southern margin of the Gurbantunggut Desert were selected. Based on field observations of lithological characteristics and sedimentary sequences, a chronological framework was established through optically stimulated luminescence (OSL) dating. Combined with comparative analyses of grain-size parameters, magnetic susceptibility, and surface micromorphological characteristics of quartz grains, the evolution of sedimentary environments in the study area since the Holocene was comprehensively determined. The results indicate that the stratigraphic sequence primarily reflects the waxing and waning of fluvial and aeolian processes, exhibiting diachronous heterotopic characteristics. During approximately 11.8–10.2 ka, alluvial processes were active at the northern piedmont of the Tianshan Mountains, with braided rivers extending deep into the desert and localized development of fluvial deposits. During approximately 10.2–6.0 ka, the study area entered the Holocene Optimum, the desert retreated northward, and rivers, lakes, and wetlands were extensively developed. From approximately 6 ka to the present, alluvial processes have weakened, aeolian activities have become frequent, and desert and riverine environments have alternated. Over the past millennium, the sedimentary environment has exhibited enhanced aeolian activity and contracted fluvial deposition, with the Gurbantunggut Desert showing an overall trend of southward expansion. The emergence of Holocene humid environments in this region was primarily controlled by variations in the intensity and position of the westerly circulation. Furthermore, the coupling between Northern Hemisphere summer solar radiation and Tianshan glaciers, as well as climate fluctuations triggered by North Atlantic cold events, may also represent important factors influencing Holocene sedimentary environment changes in this region.

Full Text

Preamble

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Abstract: The southern margin of the Gurbantunggut Desert is located in the intersection area of wind-water forces with a unique sedimentary environment and sensitive response to climatic change. This makes the area ideal to study the Holocene environmental evolution of the northwest desert of China. Three aeolian-alluvial interactive stratigraphic profiles in the desert-oasis transitional zone of the southern margin of the Gurbantunggut Desert were selected. Based on field observation of the lithological characteristics and sedimentary sequences, the age scale was established using optically stimulated luminescence (OSL) dating. Herein, combined with the comparative analysis of particle size parameters, magnetic parameters, and surface micromorphology characteristics of quartz particles, the sedimentary environmental evolution process since the Holocene in the study area was comprehensively discriminated. The result showed that the stratigraphic sequences in the study area mainly reflect the prevalence and recession of river and wind-sand processes, exhibiting obvious characteristics of contemporaneous heterogeneity. Moreover, alluvial deposits were dominant in the northern piedmont of the Tianshan Mountains from 11.8 ka to 10.2 ka, and braided rivers penetrated the desert with local fluvial deposits. From 10.2 ka to 6.0 ka, the study area entered into the Holocene optimum, and the desert retreated northward with widespread lakes and wetlands. Furthermore, the study area has experienced weak alluvial deposits and frequent wind-sand activities from 6 ka to the present, and the desert environment alternated with the river environment. In the past millennium, the sedimentary environment of the study area has exhibited the characteristics of increased wind-sand activity and river alluvial atrophy, along with the Gurbantunggut Desert showing an overall trend of southward invasion and expansion. The change of strength and position of westerly circulation mainly controlled the emergence of the Holocene humid environment in the study area. Additionally, the coupling between the Northern Hemisphere summer insolation and the Tianshan Glacier and the climatic fluctuation caused by the Northern Atlantic ice-rafted debris event were crucial factors affecting the sedimentary environment of the study area in the Holocene.

Keywords: Holocene; sedimentary environment change; climatic evolution; aeolian-alluvial alternative deposition; Gurbantunggut Desert

Arid and semi-arid regions worldwide cover approximately 40% of the Earth’ s land surface. In addition to widespread aeolian dunes, alluvial and lacustrine deposits are also common in desert margins and interiors, serving as important geological archives for reconstructing Quaternary paleoenvironments in arid and semi-arid regions. Desert deposits also record key processes of dust transport and play an important role in global biogeochemical cycles. With global climate changes since the Last Glacial Maximum, the distribution range and activity characteristics of major deserts worldwide have changed significantly. Similarly, the distribution and activity characteristics of deserts and sandy lands in northern China have also undergone substantial changes during the Last Glacial Maximum and Holocene Optimum. However, due to differences in natural geographical environments among various desert regions in China, the stratigraphic sedimentary facies assemblages and proxy indicators show obvious spatial heterogeneity in their climatic characteristics and desert development processes during geological periods. Overall, deserts and sandy lands in central and eastern China generally experienced a humid climate period during the Holocene, with dunes becoming stabilized and desert range shrinking between 8-4 ka. As a major global dust source region, desert sediments also record key processes of dust transport, playing an important role in global biogeochemical cycles. However, regarding whether the timing and causes of humid periods in the Xinjiang desert region are consistent with the evolution sequence of deserts in the eastern monsoon region or exhibit uniqueness under the influence of westerly circulation, different viewpoints still exist.

The Gurbantunggut Desert is located in the central Junggar Basin, in the eastern part of Central Asian arid regions, and in the transitional zone where North Atlantic climate signals are transmitted to the East Asian monsoon region. Previous studies on the Holocene environmental evolution of the Gurbantunggut Desert have yielded different conclusions. For instance, Huang et al. conducted comprehensive studies on borehole sediments from interdune areas on the southern margin of the desert and found that the marginal sedimentary sequences exhibited characteristics of aeolian-alluvial interaction, with a relatively humid climate fluctuation during the mid-Holocene. Chen et al. analyzed multiple environmental proxies from a sand ridge profile on the southwestern edge of the desert and concluded that the desert experienced multiple expansion and contraction processes since the Holocene, with its climatic and environmental change pattern consistent with the eastern monsoon region. Yang et al. utilized OSL dating, ground-penetrating radar (GPR), and indicators such as grain size and magnetic susceptibility to comprehensively study the paleoclimatic environment recorded in dune sediments from the southeastern part of the desert, pointing out that the early and late Holocene were the most arid periods with rapid dune accumulation, while the mid-Holocene saw increased humidity and dune stabilization. Recently, Zong et al. conducted systematic OSL dating of aeolian-alluvial interactive sequences on the southern margin of the desert, finding that the early Holocene was characterized by an arid climate with active wind-sand processes, while the mid-Holocene was the most humid period for the desert environment. In terms of humidity changes, the sedimentary records from the desert margin showed good consistency with surrounding lake and loess records. Overall, although increasing attention has been paid to desert margin areas where sedimentary environments evolve rapidly and are sensitive to climate change, and paleogeographic evolution information has been extracted through stratigraphic records, the paleoenvironmental evolution processes reflected by desert margin sedimentary sequences show obvious differences, and existing records are still insufficient to reveal the relationship between dune advance/retreat and alluvial prosperity/decline on suborbital to millennial scales and their formation mechanisms in the Gurbantunggut Desert.

This study selected three representative stratigraphic profiles from the desert-oasis transitional zone on the southern margin of the Gurbantunggut Desert. Based on field observations of lithological characteristics and sedimentary sequences, an age scale was established using OSL dating. Combined with comprehensive analysis of sediment grain size, magnetic susceptibility, and quartz particle surface micromorphology characteristics, this paper discusses the depositional processes and environmental evolution history of the desert-oasis transitional zone on the southern margin of the Gurbantunggut Desert since the Holocene, aiming to provide a scientific basis for predicting long-term desertification trends in the study area.

1.1 Study Area Overview

The study area is located in the intersection zone between the alluvial-proluvial plain of the northern Tianshan Mountains piedmont and the Gurbantunggut Desert [Figure 1: see original paper]. The Gurbantunggut Desert covers an area of 5.63\$×10^{4}\$ km^2, situated within the Junggar Basin. It is the second largest desert in China and the most significantly westerly-influenced desert, with fixed and semi-fixed dunes being absolutely dominant. The climate type is temperate continental arid climate, with an annual average temperature of 5-7°C and average precipitation of approximately 100-200 mm. Due to the injection of humid westerly airflow in summer bringing certain precipitation, and the influence of the Mongolian-Siberian High in winter causing cold wave and cold air intrusion that also brings precipitation, the desert has relatively good vegetation coverage, with natural landscapes different from other deserts in China. Since the Quaternary, with the continuous uplift of the Tianshan Mountains, the alluvial plain of the northern Tianshan Mountains piedmont has progressively advanced toward the Gurbantunggut Desert, forming a unique desert-oasis transitional zone with alternating aeolian and fluvial deposits. The main geomorphological types are river alluvial plains, with interbedded aeolian dunes and interdune alluvial corridors. As the terrain of the basin margin is higher in the south and lower in the north, rivers replenished by glacial meltwater and mountain precipitation mostly originate from the Tianshan Mountains and flow northward in roughly parallel courses into the desert margin. Therefore, the aeolian-alluvial interaction type in the study area is characterized as dispersed parallel drainage type, with each river depositional system being independent, relatively stable depositional processes, and basically no river capture or frequent migration of main channels. From west to east, the main rivers are the Manas River, Taxi River, Hutubi River, and Urumqi River.

1.2 Profile Description

Xiquan Profile (XQ) (44°25 44.39 N, 88°22 26.42 E) is located north of Fukang City in the southeastern part of the desert, collected from interdune areas of sand ridges near the terminal ancient channels of the Ganhezi River and Baiyang River downstream. The profile has a large exposed thickness, good horizontal stratigraphic continuity, and no obvious sedimentary facies changes. The lithological characteristics of each profile [Figure 2: see original paper] are described as follows:

The **Xiquan Profile** can be divided from top to bottom into: 0-30 cm: light yellow clayey silt layer with slightly wavy bedding; 30-115 cm: light reddish-brown sub-clay layer with horizontal bedding; 115-145 cm: grayish-white silt layer with slightly horizontal bedding, containing a thick layer of approximately 10 cm of light reddish-brown clayey silt at the bottom with micro-horizontal bedding; 145-240 cm: light gray-green silt layer, with superimposed wavy bedding and asymmetric current ripples in the upper part, and cross-bedding with a dip angle of about 10° in the lower part; 240-355 cm: blue-gray fine sand layer containing medium and coarse sand, developing low-angle cross-bedding.

The **Xigucheng Profile (XG)** (45°07 19.93 N, 85°58 23.71 E) and **Manas Forest Farm Management Station Profile (MG)** (45°03 16.15 N, 86°14 06.13 E) are located in the Mosuowan area in the southwestern part of the desert [Figure 45: see original paper]. These two profiles belong to the Taxi River and Hutubi River depositional systems, respectively, with modern sand ridges developed on the top. The **Xigucheng Profile** can be divided from top to bottom into: 0-70 cm: dark yellowish-orange very fine sand layer with slightly horizontal bedding; 70-130 cm: light reddish-brown sub-clay layer and grayish-yellow silt layer with interbedding, containing clay balls about 1 cm in diameter; 130-185 cm: grayish-yellow very fine sand layer with cross-bedding, with clay fragments in the upper part showing superimposed wavy bedding; 185-235 cm: grayish-yellow silt layer interbedded with light reddish-brown sub-clay layer, with a small amount of reddish-brown rust spots at the top; 235-295 cm: dark yellowish-orange very fine sand layer interbedded with light reddish-brown sub-clay layer, with horizontal bedding and slightly wavy bedding; 295-365 cm: light reddish-brown sub-clay layer with massive structure.

The **Manas Forest Farm Management Station Profile** can be divided from top to bottom into: 0-40 cm: dark purplish-red clayey silt layer with massive structure; 40-55 cm: dark yellowish-orange very fine sand layer with slightly horizontal bedding; 55-78 cm: dark purplish-red clayey silt layer with massive structure, containing uneven gray-green masses; 78-112 cm: dark yellowish-orange very fine sand layer with slightly horizontal bedding; 112-142 cm: dark purplish-red clayey silt layer with massive structure; 142-164 cm: grayish-white silt layer with a large number of reddish-brown rust spots and grayish-brown sandy lens rust spots, with a thick layer of about 10 cm of purplish-gray clayey silt in the upper part, wavy undulating and interbedded with grayish-white silt; 164-305 cm: blue-gray fine sand layer, mainly fine sand in the upper part, medium sand in the lower part, containing coarse sand, developing trough cross-bedding; 305-425 cm: grayish-yellow silt layer interbedded with light reddish-brown sub-clay layer.

2.1 Sample Collection

Based on the sedimentary facies and sequence changes of the three profiles, environmental proxy samples and OSL dating samples were collected at intervals of 5-10 cm from top to bottom. For proxy sample collection, following the sampling specifications and considering that OSL dating works best for aeolian sand layers, efforts were made to collect dating samples from aeolian sand layers after removing weathered material from the profile surface. A total of 4 OSL samples were collected from the XQ profile at depths of 0.66 m, 1.26 m, 2.75 m, and 3.00 m; 5 samples from the MG profile at depths of 0.55 m, 1.55 m, 2.50 m, 2.75 m, and 3.10 m; and 4 samples from the XG profile at depths of 0.66 m, 1.26 m, 3.25 m, and 4.05 m.

2.2 Experimental Methods

OSL Dating: OSL dating samples were completed at the OSL Dating Laboratory of the Institute of Crustal Stress, China Earthquake Administration. Fine-grained quartz (4-11 m) used the simplified multiple aliquot regenerative dose (MAR) protocol to measure equivalent dose values. Coarse-grained quartz (63-125 m) from samples MGOSL1, MGOSL3, MGOSL5 and XQOSL1-XQOSL4 used the single aliquot regenerative dose (SAR) protocol to measure equivalent dose values. The measurement instrument was a TL/OSL-20C/D type luminescence measurement system from Denmark. After sample pretreatment, they were sent to the China Institute of Atomic Energy for neutron activation analysis to measure uranium (U), thorium (Th), and potassium (K) content. Water content was uniformly set at 5$±$2%, and the environmental dose rate was estimated accordingly. Finally, the burial age was calculated using the formula:

Age = Equivalent Dose / Environmental Dose Rate.

Grain Size Analysis: Grain size analysis of sediments was completed at the State Key Laboratory of Subtropical Mountain Ecology, Fujian Normal University. Particle size measurement used a Mastersizer 2000 laser diffraction particle size analyzer. According to the Udden-Wentworth standard, grain size grades were divided, and the Folk and Ward graphical method was used to calculate the mean grain size (M__z), standard deviation (σ__i), skewness (Sk__i), and kurtosis (K__g) of the samples.

Magnetic Susceptibility: Low-frequency magnetic susceptibility (__{lf}) was measured using a Bartinton MS2 magnetic susceptibility meter.

Quartz Micromorphology: A Hitachi S-3000N scanning electron microscope was used to observe and photograph the surface morphology of quartz particles in typical horizon samples.

3.1 OSL Dating Results

The OSL dating results of profile samples are shown in . The bottom sand layer (3.55 m) of the XQ profile has an age of about 11 ka, representing early Holocene deposition, similar to the bottom sand layer of the Wutonggou borehole in the southeastern desert. The age of the aeolian sand layer at 2.75 m depth is about 5.7 ka, representing mid-Holocene deposition. The ages of aeolian sand layers at 1.26 m depth in the XQ and MG profiles are similar, both reflecting frequent environmental changes in the mid-to-late Holocene in the study area. The age of the bottom sand layer (4.05 m) of the XG profile is about 10.8 ka, representing early Holocene deposition. The age of the sub-clay layer at 1.26 m depth is relatively young, possibly due to frequent exposure of fine-grained sediments caused by water flow fluctuations in the river environment. The age of the bottom aeolian sand layer (4.25 m) of the MG profile is about 10.5 ka, representing early Holocene deposition. The age of the aeolian sand layer at 2.50 m depth is about 5.4 ka, representing mid-Holocene deposition. The age of the aeolian sand layer at 0.55 m depth is about 1.0 ka, representing late Holocene deposition since 1.0 ka. The dating results show that the time span of the sedimentary sequences of the three profiles covers the entire Holocene, recording environmental evolution information since the Holocene in the study area.

3.2 Sedimentary Structure Characteristics

Sedimentary facies are the most significant stratigraphic evidence reflecting sedimentary environments and paleoclimatic conditions, and are direct indicators for reconstructing paleogeographic environments. The upper section (above 164 cm) of the XQ profile mainly consists of interbedded dark yellowish-orange very fine sand layers and dark purplish-red clayey silt layers [Figure 3: see original paper]. The purplish-red clayey silt layers have massive structure without bedding, showing flood slack-water deposition characteristics. The very fine sand layers show slightly horizontal bedding and should be flood slack-water deposition substrates on which sand sheets (flat sand areas) developed. The color of these strata is reddish, collectively reflecting a hot and dry desert environment. The interbedded layers are underlain by grayish-green very fine sand layers with anaerobic reduction characteristics, belonging to water-formed products. The lower section (below 164 cm) transitions from grayish-white silt layers to blue-gray fine sand layers. The grayish-white silt layer [Figure 3: see original paper] contains a large number of reddish-brown and grayish-brown plant root channel rust spots, with several wavy alluvial layers interbedded within the layer, and underwater sand ripples developed at the bottom, representing floodplain wetland deposition with frequent water volume changes. The bottom sand layer of the profile [Figure 3: see original paper] is blue-gray in color with trough cross-bedding, showing riverbed deposition characteristics and should be common braided river deposits in alluvial plain sedimentary structures.

The MG profile mainly consists of sub-clay and clayey silt layers in the upper section and silt and fine sand layers in the lower section [Figure 3: see original paper], with sedimentary structures similar to the XQ profile. The upper section shows wavy-bedded clayey silt layers and horizontally-bedded sub-clay layers (0-30 cm) with alluvial characteristics, belonging to floodplain and flood slack-water deposits. The interbedded sub-clay and silt layers contain clay balls about 1 cm in diameter [Figure 3: see original paper], indicating that the water volume and external dynamic environment of the terminal water flow were constantly changing, causing frequent shifts between floodplain and slack-water deposition environments. The very fine sand layer at 130-185 cm depth in the profile develops cross-bedding, representing typical aeolian sand. The overlying silt layer [Figure 3: see original paper] has migratory superimposed wavy bedding with clay fragments, belonging to floodplain deposits, indicating that alluvial plains on the northern Tianshan Mountains piedmont widely developed such deposits through periodic rapid accumulation in the original river terminal reaches.

The lower grayish-white silt layer (115-145 cm) of the XQ profile shows superimposed wavy bedding and asymmetric current ripples at the top, indicating a wide and shallow intermittent water flow environment. The lower blue-gray silt and fine sand layer (145-355 cm) has cross-bedding with the same dip angle, representing typical aeolian deposits.

3.3 Grain Size Characteristics

Changes in sediment grain size reflect changes in depositional environments. Through grain size characteristic analysis, external force types and properties can be effectively identified, and relevant information about sedimentary environment evolution can be extracted. The grain size measurement results show that the sediments of the XQ and MG profiles are mainly composed of fine sand, very fine sand, and silt [Figure 4: see original paper], with low content of medium-coarse sand ($\Phi < 1$) and clay ($\Phi > 8$). Combined with the aforementioned sedimentary facies analysis, four depositional types can be identified [Figure 4: see original paper]: (1) Flood slack-water deposition, corresponding to the purplish-red clayey silt layer in the upper profile, with the finest sediment grain size in the entire profile. The positive-skewed wide peak reflects its water-formed nature, with larger δ values indicating poor sorting. (2) Sand sheet deposition, corresponding to the dark yellow sand layer in the upper profile, with grain size dominated by very fine sand and fine sand. The normal sharp peak and lower δ values indicate good sorting, belonging to aeolian deposits. (3) Floodplain wetland deposition, corresponding to the grayish-white silt layer in the lower profile, with a wide and flat peak and moderate sorting. (4) Riverbed deposition, corresponding to the blue-gray fine sand layer at the bottom of the profile, with high medium sand content, followed by fine sand and coarse sand. The positive-skewed sharp peak indicates relatively good sorting. Under fluvial action, fine-grained components are lost while coarse-grained components are significantly enriched. Additionally, the upward decreasing grain size of riverbed sand from the bottom is a typical depositional characteristic of alluvial fan sandy braided channels.

The grain size of the MG profile shows a binary cyclic structure composed of sub-clay and silt/very fine sand. From the frequency distribution curves of all samples [Figure 4: see original paper], the grain size peak appears in the silt fraction with Φ = 5-6, followed by the clay fraction with Φ = 7-8. The content of fine sand and very fine sand with Φ = 2-4 is not high, and medium-coarse sand components with $\Phi < 2$ are almost absent. Four depositional types can be identified [Figure 4: see original paper]: (1) Slack-water deposition, corresponding to the light reddish-brown sub-clay layer with high fine-grained component content, showing a positive-skewed wide peak [Figure 4: see original paper] and poor sorting. (2) Floodplain deposition, corresponding to the silt layer with wavy bedding in the middle profile, showing a negative-skewed wide peak and poor sorting. (3) Aeolian deposition, corresponding to the very fine sand layer with cross-bedding, with high fine sand and very fine sand content, showing a sharp peak and good sorting, but significantly negative-skewed. Fine clay can be seen at the tail end of the frequency curve, indicating that fine-grained components were trapped during aeolian deposition, possibly representing deposition in fixed and semi-fixed dunes with good vegetation coverage.

The grain size of the XG profile fluctuates greatly [Figure 5: see original paper], with high silt and very fine sand content, and a certain proportion of medium-coarse sand with $\Phi < 2$. The depositional types are similar to the MG profile. The upper clayey silt layer and sub-clay layer show negative-skewed wide peaks with poor sorting, reflecting a water-formed environment. The middle silt layer with high-angle cross-bedding shows a negative-skewed sharp peak with moderate sorting, similar to the aeolian sand layer in the MG profile, and should be fixed/semi-fixed dune deposits. The lower blue-gray fine sand layer with low-angle cross-bedding has increased coarse-grained components, good sorting, and should be mobile dune deposits. Additionally, the silt layer with wavy bedding has nearly identical grain size characteristics to the underlying aeolian sand layer, but with secondary sorting and reduced color, possibly indicating a transition from aeolian to fluvial environments.

3.4 Magnetic Susceptibility Characteristics

Magnetic susceptibility can typically serve as a proxy indicator for environmental changes and climatic processes. In terrestrial strata, studying the content of magnetic minerals in sediments helps reconstruct paleoenvironments and restore paleoclimates. Generally, in monsoon climate regions, sediment magnetic susceptibility is positively correlated with precipitation. When precipitation increases, pedogenesis strengthens, producing fine-grained strong magnetic minerals that enhance magnetic susceptibility. However, in arid desert regions with scarce precipitation, pedogenesis is weak, and magnetic susceptibility influencing factors become more complex. The magnetic susceptibility of the three profiles shows regular changes with depth, exhibiting peak-valley fluctuations in different sedimentary facies. High values appear in riverbed deposition layers and aeolian sand layers, while low values appear in flood slack-water deposition layers and floodplain deposition layers. This indicates that sediment magnetic susceptibility in the study area is positively correlated with particle size, with coarse-grained components having higher magnetic susceptibility and fine-grained components having lower magnetic susceptibility, basically consistent with magnetic susceptibility variation characteristics in arid region sediments. That is, arid regions are dominated by physical weathering, and sediment magnetic strength mainly reflects proximal primary magnetic minerals, which are greatly influenced by parent material and other factors. As weathering intensifies, magnetic susceptibility gradually decreases with decreasing particle size.

Notably, the magnetic susceptibility of the XQ profile in the southeastern desert margin is generally high, and the magnetic susceptibility values of sediments from the Wutonggou interdune borehole near the XQ profile are also generally high, indicating that provenance differences may be the main cause of primary mineral magnetic differences between the eastern and western margins of the desert. The magnetic susceptibility of sediments in the southeastern desert margin is significantly higher than that in the southwestern desert margin. From the perspective of magnetic susceptibility variation characteristics of aeolian deposits in the study profiles, high magnetic susceptibility in aeolian sand layers indicates a strong wind drought environment. This is because the magnetic susceptibility of aeolian deposits is mainly controlled by provenance, and magnetic susceptibility of aeolian deposits in the same region is relatively stable. Under this premise, the magnetic susceptibility of aeolian sand is positively correlated with particle size, and particle size also indicates wind strength during deposition. Therefore, changes in magnetic susceptibility of aeolian deposits can reflect changes in wind strength. The research results of this paper are generally consistent with the understanding of the relationship between grain size and magnetic susceptibility changes in sediments from the southeastern desert interdune borehole. However, although the bottom aeolian sand layer of the XQ profile has high medium-coarse sand content, its magnetic susceptibility is low, possibly because under the same volume, large amounts of quartz and feldspar are enriched while the content of strong magnetic minerals relatively decreases.

From the perspective of magnetic susceptibility variation characteristics of alluvial deposits in the study profiles, due to large differences in grain size composition between riverbed deposits and floodplain/flood slack-water deposits, there are significant differences in primary mineral magnetism. Riverbed deposits with larger particle sizes have higher magnetic susceptibility, while floodplain and flood slack-water deposits with finer particle sizes have lower magnetic susceptibility. Previous studies on magnetic susceptibility of ancient underwater sediments in the Alxa region also found that the magnetic susceptibility of 63-1000 m components is significantly higher than that of 0-63 m fine-grained components. Since the grain size composition of fluvial deposits is closely related to hydrodynamic conditions, the magnetic susceptibility differences caused by different primary magnetic mineral grain sizes can serve as a proxy indicator for hydrodynamic energy to some extent and become evidence for depositional dynamic environments. The grayish-white silt layer containing root channel rust spots in the lower section of the XQ profile has the lowest magnetic susceptibility in the entire profile. In addition to having more fine-grained components, long-term waterlogging under anaerobic conditions led to the reduction of ferromagnetic minerals into weakly magnetic goethite and lepidocrocite, which is an important reason for the low magnetic susceptibility. This not only indicates the weak hydrodynamic characteristics of terminal shallow water marshes but also reflects that there may have been a broad and stable water environment providing anaerobic reduction conditions during deposition.

3.5 Quartz Particle Surface Micromorphology Characteristics

During the transportation and deposition of clastic materials, quartz particles are affected by different external forces and post-depositional weathering dissolution, leaving different impact and dissolution traces on their surfaces. These traces are not only the main basis for judging the external forces acting on the sediments but also important references for reconstructing depositional environments. Sample XQOSL1 from the upper flood slack-water deposition layer of the XQ profile is sub-angular with low roundness. The particle surface has many V-shaped pits, deep large impact pits, and conchoidal fractures, indicating that it may have experienced early glacial transportation and later fluvial transportation processes. The irregular impact pits on the surface are relatively few, with relatively poor roundness, more or less bearing traces of glacial action, indicating that Tianshan glacial sediments may be an important provenance for sedimentary strata on the southern desert margin, and that sediments in both fluvial-lacustrine and aeolian environments have not undergone long-distance transportation. Additionally, most quartz particle surfaces have silica spheres and silica precipitation, indicating relatively humid depositional environments. Similar phenomena have been reported in previous studies on depositional environment of alluvial facies strata on the southern desert margin.

Sample XQOSL2 from the sand sheet deposition layer is aeolian sand with near-round shape, moderate roundness, and typical pitted surface structure. Deep large impact pits and V-shaped grooves indicate early glacial transportation, while slight cracks on the particle surface indicate that the post-depositional environment was arid with only a certain degree of weathering. Additionally, the poor roundness and few pitted pits reflect that the sediments were locally sourced and transported over short distances under wind action.

Sample XQOSL3 from the flood slack-water deposition layer has poor roundness, with numerous silica scales, silica spheres, and dissolution pits on the surface indicating humid depositional environments. Few impact pits indicate weak hydrodynamic conditions and no long-term transportation, with sediments being mainly proximal materials.

Sample MGOSL2 from the fixed/semi-fixed dune sand is sub-angular with relatively obvious conchoidal fractures, V-shaped pits, and not deep dish-shaped pits scattered with small pitted pits, reflecting compression during early glacial transportation and mutual collision during later wind transportation. The poor roundness indicates only brief transportation processes.

Sample MGOSL4 from the mobile dune sand is near-round with relatively good roundness. Not deep dish-shaped pits and numerous pitted pits are typical features of wind transportation, while very few dissolution pits and silica precipitation reflect arid depositional environments.

4.1 Regional Sedimentary Environment Change Characteristics Recorded by Profile Stratigraphic Sequences

Based on the comprehensive analysis of the aforementioned sedimentary facies and environmental proxy indicators [Figure 8: see original paper], the stratigraphic sequences in the study area reflect frequent transformations of depositional environments among river-lake wetlands, desert dunes, and interdune lowlands during the Holocene. According to the XQ profile record, around 11.1 ka, river terminals on the northern Tianshan Mountains piedmont may have developed frequently migrating braided rivers with strong hydrodynamic forces and relatively stable fluvial deposition. In contrast, the adjacent MG profile reflects aeolian deposition environments. Around 10.8 ka, the XQ profile transformed into a floodplain wetland environment, but with fluctuating hydrodynamic forces. The adjacent XG profile recorded river activities appearing on the desert margin from 9.6-5.4 ka, reflecting alternating river and wind-sand environments, while the southern XQ profile reflected stable river-lake environments on the desert margin since the early Holocene. Around 5.8 ka, the XQ profile recorded floodplain wetland deposition with reduced water volume, beginning to show wind-sand activity, and the study area transformed toward a desert environment with sand sheet deposition. Subsequently, terminal rivers penetrated the desert margin, and flood overflow formed muddy deserts. Around 4.0 ka, the study area again experienced wind-sand activity, developing sand sheet deposition on the basis of flood slack-water deposition. Thereafter, the XQ profile alternated between flood slack-water deposition and sand sheet deposition until linear dunes expanded and invaded, becoming interdune lowlands and showing a stable desert environment.

The sedimentary sequences of the three profiles are mainly composed of interbedded alluvial and aeolian strata. The sediments may originate from upstream glacially ground debris, and the transportation and accumulation processes of aeolian deposits on the desert margin are frequently affected by water flow. Therefore, compared with typical aeolian sand quartz particles in the Gurbantunggut Desert, quartz particles in the study profiles retain traces of early glacial action and later fluvial and wind transportation, indicating that Tianshan glacial till may be an important provenance for sedimentary strata on the southern desert margin, and that sediments have not undergone long-term transportation.

The sedimentary environment of the study area alternates under the action of wind-water forces. In the past millennium, the sedimentary environment has shown characteristics of enhanced wind-sand activity and atrophied river alluvium, with the Gurbantunggut Desert showing an overall trend of southward invasion and expansion. By analyzing the Holocene sedimentary sequence changes of the three profiles and previous research profiles, the desert margin depositional environment exhibits characteristics of contemporaneous heterogeneity, but overall is dominated by the prevalence and recession of river and wind-sand processes. That is, since the mid-to-late Holocene, the southern desert margin has experienced enhanced wind-sand activity and dune development with desert expansion during cold and dry periods, while increased water volume in terminal rivers penetrated interdune lowlands on the desert margin and developed floodplain wetland deposition, suppressing wind-sand activity and dune deposition during humid periods.

4.2 Holocene Environmental Evolution of the Southern Margin of the Gurbantunggut Desert

Overall, the Holocene sedimentary environment changes in the study area are relatively sensitive to global climate change responses, with the sedimentary sequences reflecting the history of Gurbantunggut Desert advance/retreat and the expansion/contraction of the alluvial-proluvial plain on the northern Tianshan Mountains piedmont. Since the Holocene, driven by changes in solar radiation intensity, the strength and position changes of westerly circulation, and the coupling of alpine ice and snow melt, the sedimentary environment in the study area has undergone three main stages:

11.8-10.2 ka: In the early Holocene, the study area developed fluvial deposits, with quartz particle surfaces showing traces of glacial and fluvial transportation. At this time, the XQ profile in the southern desert was dominated by thick alluvial clay deposits, and glacial meltwater deposits appeared in interdune lowlands on the southeastern desert margin. Ebinur Lake sediment records show large water volume, indicating increased surface humidity in the study area. However, loess records on the northern Tianshan Mountains piedmont (LJW10) show the opposite, indicating an arid environment in the early Holocene. Related research points out that the early Holocene in Central Asian arid regions had relatively small precipitation, with weak westerly circulation, and was overall under arid climate control. Therefore, the local river environment presented in the study area during this period was not caused by changes in westerly circulation intensity. As the main source of surface moisture in low-altitude areas of Central Asian arid regions, water release from surrounding alpine glaciers determines the humidity degree within the basin. Thus, the appearance of river environments in the study area during the early Holocene may be due to enhanced Northern Hemisphere summer insolation causing Tianshan glacier melting, leading to increased local humidity in the desert-oasis transitional zone.

10.2-6.0 ka: The study area entered the Holocene optimum period, with the desert retreating northward and widespread development of rivers, lakes, and wetlands. The XQ profile developed thick and stable floodplain wetland deposits, with sediments showing grayish-green reduced color and low magnetic susceptibility, reflecting long-term waterlogging environments. During the same period, the XG profile was dominated by alluvial sandy clay, silty fine sand, and sandy silt, while the MG profile was dominated by alluvial silt deposits. The Mosuowan sand ridge profile in the southwestern desert developed dense sandy paleosol layers [Figure 9: see original paper], and the Wutonggou sand ridge and interdune deposits in the southeastern desert showed decreased grain size and magnetic susceptibility, with slowed dune accumulation and tendency toward stabilization. In the surrounding areas, the Artemisia/Chenopodiaceae ratio (A/C) in Manas Lake sediments reflected a humid climate, Ebinur Lake expanded, Mogu Lake in the lower Manas River developed clay mineral deposits dominated by kaolinite, the Urumqi River source glacier melted extensively, and Barkol Lake water level gradually rose. Especially, loess deposits in surrounding mid-low mountain zones recorded the same humid trend as the arid basin, indicating that the increased humidity during this period may be due to enhanced westerly circulation increasing water vapor content and precipitation in the core area of Central Asian arid regions. It can be seen that against the background of gradually strengthening westerly circulation, the southern Junggar Basin region may have experienced a long period of climatic optimum during the early-to-mid Holocene.

6.0 ka to present: The study area mainly shows alternating alluvial and aeolian layers, reflecting alternating changes between humid and arid environments. During this period, the Mosuowan sand ridge in the southwestern desert developed interbedded paleo-aeolian sand and paleosol layers, the XG profile recorded environmental evolution processes with wind-sand deposits after 3.6-2.5 ka, and the Wutonggou sand ridge in the southeastern desert also experienced a fixation and contraction period after 2.5 ka. Additionally, Dongdaohaizi, Ebinur Lake, and Barkol Lake experienced frequent water level fluctuations. The Ebinur Lake area alternated between desert vegetation and grassland vegetation, and the Artemisia/Chenopodiaceae ratio (A/C) in Altai Mountain peat also reflected humidity fluctuations. Among them, the tree and shrub pollen content in Kanas Lake sediments in the southern Altai Mountains [Figure 9: see original paper] reflected a cold and dry climate period, roughly consistent with the development time of aeolian sand layers in the XQ profile, showing the sensitivity of the study area' s stratigraphic sections to regional humidity changes. Especially, the profile sections in the study area may have captured climate signals released by North Atlantic cold events. For example, the accumulation times of aeolian sand layers at 5.7 ka and 2.8 ka are close to the 5.9 ka and 2.8 ka ice-rafted debris events, respectively. Meanwhile, Tianshan glaciers in the northern piedmont experienced ice advances at 4.1 ka and 1.5 ka [Figure 9: see original paper], which correspond well with several wind-sand activities revealed in this study since the mid-to-late Holocene.

In summary, the stratigraphic sections in the study area record the prevalence and recession of river and wind-sand processes since the Holocene, reflecting the humidity evolution history of the southern margin of the Gurbantunggut Desert [Figure 9: see original paper]. Regional warming in the early Holocene caused extensive Tianshan glacier melting, leading to the appearance of river environments on the southern desert margin. In the mid-to-late Holocene, the gradual strengthening of westerly circulation interwoven with atmospheric fluctuations triggered by North Atlantic cold events may be the main drivers of river and wind-sand environment changes in this region.

5 Conclusions

1) Sedimentary facies and grain size characteristics reveal that the stratigraphic sections in the desert-oasis transitional zone on the southern margin of the Gurbantunggut Desert mainly consist of four depositional types: riverbed deposits, floodplain wetland deposits, flood slack-water deposits, and wind-sand deposits.

2) The magnetic susceptibility of sediments in the study area mainly reflects proximal primary magnetic minerals, is positively correlated with particle size, and is associated with external force transportation intensity. Therefore, its changes can be used to indicate depositional environmental changes.

3) Quartz particle surfaces in the profile sections retain traces of early glacial action and later fluvial and wind transportation, indicating that Tianshan glacial till may be an important provenance for sedimentary strata on the southern desert margin, and that sediments have not undergone long-distance transportation.

4) The stratigraphic sequences in the study area mainly reflect the replacement of river-lake and wind-sand environments. In the early Holocene, braided rivers penetrated the desert, and fluvial deposits developed on the southern desert margin. In the mid-Holocene, the desert retreated northward, and the study area transformed into a river-wetland environment. In the late Holocene, wind-sand activities were frequent, with wind-sand environments alternating with river environments. The emergence of humid environments in this region during the Holocene may be constrained by the strength and position changes of westerly circulation, as well as the coupling between Northern Hemisphere summer insolation and Tianshan glaciers. Additionally, the profile sections in the study area may have captured climate signals released by North Atlantic cold events in the mid-to-late Holocene, indicating that desert margin deposition is sensitive to regional cooling events.

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