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Holocene environmental changes around Xiaohe Cemetery and its effects on human occupation, Xinjiang, China

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Abstract: The Xiaohe Cemetery archaeological site (Cal. 4–3.5 ka BP) is one of the most important Bronze Age sites in Xinjiang, China. Although the surrounding environment is an extremely arid desert now, abundant archaeological remains indicate that human occupation was common during certain periods in the Holocene. Field investigations and laboratory analyses of a sediment profile near the Xiaohe Cemetery indicate that while the regional environment was arid desert throughout the Holocene there were three episodes of lake formation near the site in the periods 4.8–3.5 ka BP, 2.6–2.1 ka BP and 1.2–0.9 ka BP. Geomorphic and hydrological investigations reveal that a lake or lakes formed in a low-lying area when water was derived initially from the Kongque River and then shunted into the Xiaohe River basin. Low amounts of active chemical elements in lacustrine sediment between 4.8–3.5 ka BP indicate abundant and continuous water volume in the lake; the content of active chemical elements increased between 2.6–2.1 ka BP but was still at a relatively low level, suggesting a declining amount of water and diminished inflow. Between 1.2–0.9 ka BP there was a very high content of active elements, suggesting decreased water volume and indicating that the lake was stagnate. In contrast, the general climate condition shows that there had a warm-humid stage at 8–6 ka BP, a cool-humid stage at 6–2.9 ka BP and a warm-dry stage at 2.9–0.9 ka BP in this region. The hydrological evolutions around Xiaohe Cemetery did not have one-to-one correspondence with climate changes. Regional comparison indicates that broad-scale climatic conditions played an important role through its influences on the water volume of the Tarim River and Kongque River. But, the formation of the lakes and their level were controlled by geomorphic conditions that influenced how much water volume could be

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shunted to Xiaohe River from Kongque River. Human occupation of the Xiaohe Cemetery and nearby regions during the Bronze Age and Han-Jin period (202 BC–420 AD) corresponded to the two earlier lake periods, while no human activities existed in the third lake period because of the decreased water volume.

Keywords: human-environment interaction; Xiaohe Cemetery; Holocene; environmental change; sedimentary sequence

1 Introduction

In recent years the close relationship between paleoenvironmental changes and ancient cultural evolution has been repeatedly demonstrated (Sandweiss *et al*., 1999; Mo *et al*., 2010; Berglund, 2003; Kuper and Kropelin, 2006; Guo *et al*., 2013; Li *et al*., 2014). With detailed case studies from different archaeological sites and ancient cultures in diverse geographic regions, scholars have recognized there are many ways that humans are affected by the environment. While climate changes have been widely accepted as an important influence on cultural evolution in many areas (Gupta *et al*., 2004; Piao *et al*., 2010; Chen *et al*., 2015), other environmental processes, such as changing fluvial regimes (Zong *et al*., 2007; Kidder *et al*., 2012; Li *et al*., 2014), or the rise and fall of lake levels (Nunez *et al*., 2002; Canellas-Bolta *et al*., 2013) are understood to have equally important effects. Similarly, vegetation changes (An *et al*., 2014; Li *et al*., 2015; Yue *et al*., 2015) or altered geomorphic conditions (Wu *et al*., 2014; Zhou *et al*., 2014) must be considered. An important challenge for paleoenvironmental researchers is to sort out the cause-and-effect relationships among and between the many possible factors that affect human social and cultural development. Thus, while climate change may be important, its effects may be mediated through other physical processes that must be understood in regards to how humans respond to the environment.

The Xiaohe Cemetery archaeological site (Figure 1, Cal. 4–3.5 ka BP; Li *et al*., 2013), has attracted considerable attention because its exceptionally preserved mummified human remains and abundant cultural relics (Xie *et al*., 2007; Li *et al*., 2011; Qiu *et al*., 2014; Yang *et al*., 2014; Yang *et al*., 2014; Mai *et al*., 2016). The Cemetery was extensively investigated by the Xinjiang Cultural Relics and Archaeology Institute, Urumchi, China (henceforth, XCAI) in 2002. The site is a human-made mound constructed on a natural dune and standing about 7.75 m tall. At least 167 boat-shaped coffins, deposited in five layers, were discovered in the cemetery. All coffins were made of populus wood and some were wrapped in cowhide and covered with mud. Mummified human remains inside the coffins were wearing felt caps, fur coats, leather boots, and fur cloak wrappings. Artifacts associated with mummies included straw baskets, some copper and jade ornaments, and feathers; large quantities of wood items, especially Ephedra and Tamarix twigs, were also found in the coffins. Grains of bread wheat (*Triticum aestivum*) and broomcorn millet (*Panicum miliaceum*) were found in straw baskets in most coffins (XCAI, 2004, 2007; Yang *et al*., 2014).

An environment suitable for cultivation of these crops clearly existed for the people who buried their dead at Xiaohe Cemetery. The inhabitants lived on a mixed diet of hunting and gathering supplemented by growing wheat and millet and herding cow and sheep. Today, the area around Xiaohe Cemetery is extremely dry and is in a barren desert; sand dunes, dry wadis and desiccated playas are common in the region. No human live here now (Wang *et al*., 2008) and the area is known as "dead land" in historical records and foreign adventurers' writings (Bergman, 1939). Clearly, the environment that supported such a sophisticated culture has changed significantly over the past 4000 years.

Palynological analysis shows that reed (*Phragmites sp.*), Typha, lovegrass (*Eragrostis*) and Aster-type Asteraceae were present in the mud wrapping applied to the coffins (Li *et al.*, 2013). These are the only paleoenvironmental data for the Xiaohe Cemetery, and they indicate that there was a well-watered oasis near the site at the time it was occupied. Our analysis focuses on understanding the evolution of this oasis and why it eventually dried up. In addition, we are interested in understanding how the evolution of the oasis affected human cultural occupation at Xiaohe and in the nearby region. We conducted a hydrological and geomorphic survey in research area and apply laboratory analyses of sediment sequences to understand the history of Holocene environmental changes and their influences on culture occupation in the area.

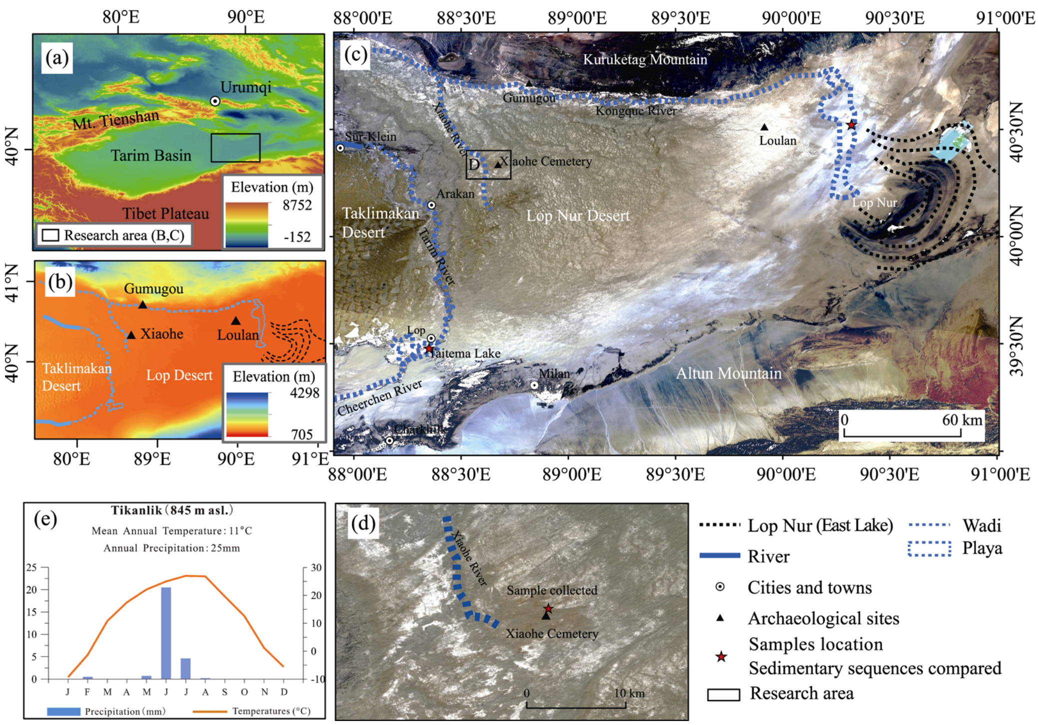

Figure 1 The location of Xiaohe Cemetery in Xinjiang, China
(a) Black rectangle marks the location of research area b and c. (b) The elevation of the research area based on DEM data (resolution of the Digital Elevation Model data is 90 m). (c) The geomorphic situation of the area based on satellite map (the map was created by merging bands 1, 2, and 3 of four 30 m-resolution Landsat-5 pictures). (d) Samples' location and the landscape around Xiaohe Cemetery. (e) The modern monthly changes of temperature and precipitation, observed by the Tikanlik meteorological station (2013).

2 Study area

2.1 Environmental and geographical setting

The Xiaohe Cemetery is located in the Lop Nur Desert (Figure 1b), which is in the eastern part of the Tarim Basin, Xinjiang (Figures 1a–c). The Lop Nur Desert is the lowest area of the Tarim Basin and is very flat, with an elevation of 790–810 m asl (Figure 1b). The lower channels of the Tarim River and Kongque River flow along the western and northern margins of the Lop Nur Desert and end at Taitema Lake and Lop Nur (Figure 1c), respectively. These two rivers flow along the edges of an extensive alluvial fan located between the Kuruketag Mountains on the north and the Taklimakan Desert to the west, and Altun Mountains on the south (Figure 1c). Because of the low gradient of the fan and the significant amount of sediment carried by these rivers as they emerge from the mountains the channels of the Tarim and Kongque rivers have freely migrated across the fan and are interlaced in the area from Yuli to Su-Klein. Channel switching of the two rivers has been common through time (Wang, 1996; Fan *et al*., 2006; Xia *et al*., 2008; Han and Xie, 2010). The Xiaohe River (Small River) is a distributary of Kongque River that flows from northwest to southeast ending in the desert (Figure 1c). The paleochannel of the Xiaohe River is 5 km away from the west side of Xiaohe Cemetery (Figure 2b). Today, these rivers and lakes are drying up.

The climate of the Lop Nur Desert belongs to a temperate continental type. Precipitation is about 20–30 mm per year and summer-winter temperature differences are considerable (Figure 1e). Meteorological records (1961–1990) at Lop Nur reveal that the average evaporation rises to 2902 mm per year and windy days occur one-third of the year (Luo *et al*., 2008). Plants mainly grow in the middle reaches of the Tarim River and along both sides of the Cheercheng River today. Existing vegetation is dominated by *Populus euphratica* and *Tamarix chinensis*. However, almost nothing grows within the Lop Nur Desert.

2.2 Archaeological background

No Neolithic archaeological sites have been found in the Lop Nur Desert. The Xiaohe Cemetery is one of the most important archaeological sites of Bronze Age in Xinjiang and also the earliest archaeological relics discovered to date within the Xiaohe River basin. After the Xiaohe Cemetery was abandoned, human vacated the Xiaohe River basin until the Han Dynasty. Archaeological sites, graves, artifacts and other relics dating to the Han and Jin dynasties (202 BC–420 AD) have been discovered within the Xiaohe River basin. An ancient city site radiocarbon dated to ca. 440–500 AD was found at about 6.3 km to the northwest of the Xiaohe Cemetery (Lv *et al*., 2010). Following this occupation, no human settlements existed until the modern era.

The Gumugou Cemetery (ca. 3.8 ka BP), situated 50 km to the north is contemporary with Xiaohe Cemetery (Figure 1b). In the Han and Jin Dynasty periods (202 BC–420 AD), Loulan City (Figure 1b) was one of the centers of trade and exchange in the area. Other major sites, such as Milan City site (Milan, Figure 1c) and Qieerqiduke City site (near the Charkhlik, Figure 1c) were abandoned at latest in the Tang Dynasty (618–907 AD) (Wang, 1998; Han and Xie, 2010).

3 Materials and methods

3.1 Sedimentary sequence and sampling

Fluvio-lacustrine sediments of wadi and playa are present around the site today (Figures 2a–b). In 2010 a 3-m deep trench (labeled XH-N, Figure 2c) was excavated into the playa bed ~800 m north of the Xiaohe Cemetery (Figure 1d). The profile (Figure 2c) was divided into six strata based on physical and visual characteristics of the sediment (Table 1). We collected 55 sediment samples at 5 cm interval and obtained 7 chronological samples (6 for OSL and 1 for radiocarbon dating) (Figure 2).

Table 1 Sedimentary sequence of the XH-N profile

Stratum No.	Depth (cm)	Sedimentary description
1	0–15	Fluvio-lacustrine sediment, light greyish clayey silt with plant rootlets
2	15–40	Greyish fine sand with some silt layers, laminar structure
3	40–50	Fluvio-lacustrine sediment, light greyish clayey silt
4	50–90	Yellowish grey fine sand mixed with coarse sand, laminated and yellow rust spots
5	90–110	Fluvio-lacustrine sediment, light greyish silty clay with snail shells in the bottom
6	110–275	Brownish fine sand and medium sand, laminar structure

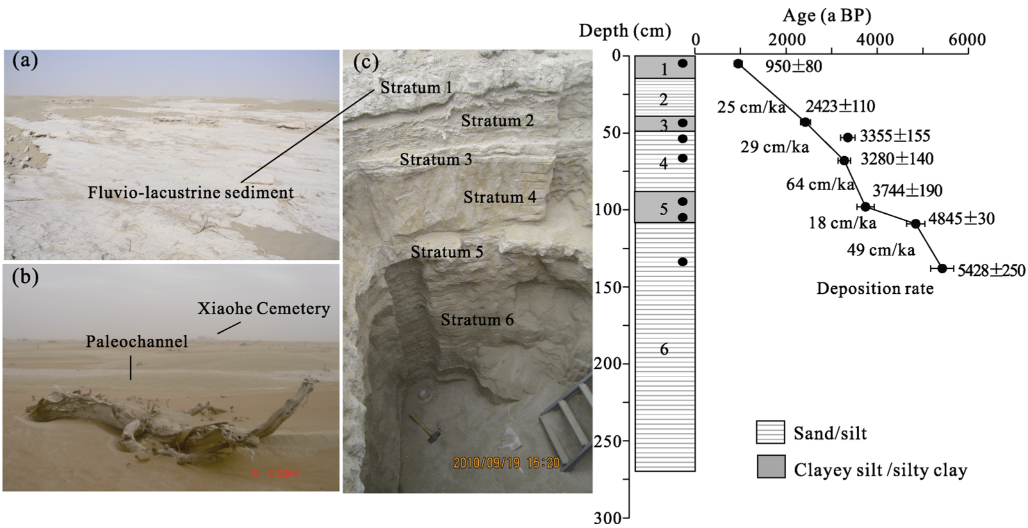

Figure 2 The environment around Xiaohe Cemetery (a and b) and the stratigraphy of the XH-N profile with ages (c)

3.2 Laboratorial analysis of the samples

Chronological research was conducted in the Technology Archaeology Laboratory of the School of Archaeology and Museology, Peking University. We chose 7–11 μm-sized quartz grains as the OSL material to ensure the luminescence signal was exposed before deposition. The radiocarbon date was obtained from snail shell and the result was calibrated using OxCal v3.10 (Ramsey, 2005). All chronological data were unified to be relative to AD1950 (referred to as “a BP”).

Fifty-five samples from the XH-N were analyzed for grain size and geochemical elements in the Laboratory for Land Surface Processes, Peking University and the Laboratory for the Orogenic Belt and Tectonic Movement, Peking University, respectively. Grain size was obtained by the Laser Particle Analyzer (Mastersizer 2000 manufactured by Malvern Company). Geochemical elements were investigated by using X-ray fluorescence spectroscope and the analytical results are reported as oxide compound form and percentage (10% is equivalent to 100 mg/g). The deviation based on repeat sample analysis was between 3% and 5%.

4 Results

4.1 Stratigraphy and chronological dating

Seven chronological samples (Table 2) were taken at 10–15 cm, 45–50 cm, 55–60 cm, 70–75 cm, 95–100 cm, 100–105 cm and 135–140 cm below the ground surface. The ages are in stratigraphic order except for sample XHB-3 (Figure 2 and Table 2). The data indicate an average sedimentation rate of 37.4 cm/ka for this profile (Figure 2); strata 2, 4 and 6, which are mainly composed of silt and sand, have a faster deposition rate than the fluvio-lacustrine strata 1, 3 and 5. The two data from stratum 4 are reversed, but the age differences are within the error ranges. This inversion may be because stratum 4 has the fastest deposition rate of the whole profile (64 cm/ka, Figure 3), resulting in incomplete exposure of quartz grains.

Table 2 Detailed information of every chronological sample

Sample No.	Stratum No.	Depth (cm)	Dating method	Dating material	Age
XHB-1	1	10–15	OSL	Silty clay	950±80 a BP
XHB-2	3	45–50	OSL	Clayey silt	2423±110 a BP
XHB-3	4	55–60	OSL	Silt and sand	3355±155 a BP
XHB-4	4	70–75	OSL	Silt and sand	3280±140 a BP
XHB-5	5	95–100	OSL	Silty clay	3744±190 a BP
XHB-6	5	105–110	^{14}C, AMS	Snail shell	4845±30 Cal. a BP
XHB-7	6	135–140	OSL	Silt and sand	5428±250 a BP

With the deposition rate in different stratum (Figure 2), we defined the age range of each stratum of the XH-N profile. The bottom of the stratum 6 presumably reaches to ~8 ka BP of the late early-Holocene or early middle-Holocene. So, the XH-N profile involves the Holocene sediment between 0.9–8 ka BP and the age intervals of each stratum are: (1): 0.9–1.2 ka BP; (2): 1.2–2.1 ka BP; (3): 2.1–2.6 ka BP; (4): 2.6–3.5 ka BP; (5): 3.5–4.8 ka BP; and (6): 4.8–8 ka BP. The Xiaohe Culture period corresponds to stratum 5.

4.2 Grain size results

Grain size is generally interpreted as a proxy for past changes in transport and deposition dynamic (Zhang *et al*., 2010; An *et al*., 2012). We classified grain size using the Wentworth scale; sand composition was divided into fine sand (62.5–250 μm), medium sand (250–500 μm) and coarse sand (500–2000 μm). Md (median size) is the 50% value of the accumulation probability curve; the sorting index (So) is defined by the formula $(\phi_{84}+\phi_{16})/4+(\phi_{95}-\phi_5)/6.6$ (Folk, 1957; ϕ_{84} is the 84% accumulated value of the accumulation probability curves). Five representative types of accumulation probability curves of grain size (Figure 4) in different strata indicate the sedimentary process and grain source.

The results (Figure 3) of grain size analysis verify the characteristic of sedimentary changes we observed from the profile and that are indicated by the deposition rate changes: strata 1, 3 and 5 (and two samples at the bottom of stratum 6) are mainly composed of silt and clay (40%–60% and 10%–35%, respectively); strata 2, 4 and 6 are made up of relatively coarse grains of sand and silt (60%–80% and 10%–20%, respectively). The sand found in strata 2, 4 and 6 are mostly fine; medium sand comprises only 15%–20% in the middle of stratum 6 and coarse sand makes up only 10%–35% of strata 4 and 6.

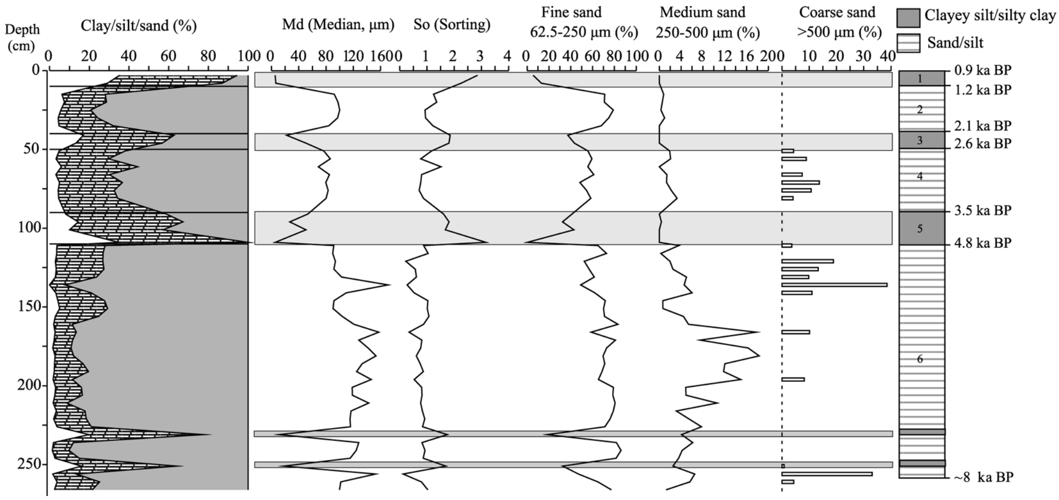

Figure 3 Variations of grain size parameters with the depth of the XH-N profile (Gray shading indicates the fine-grained strata)

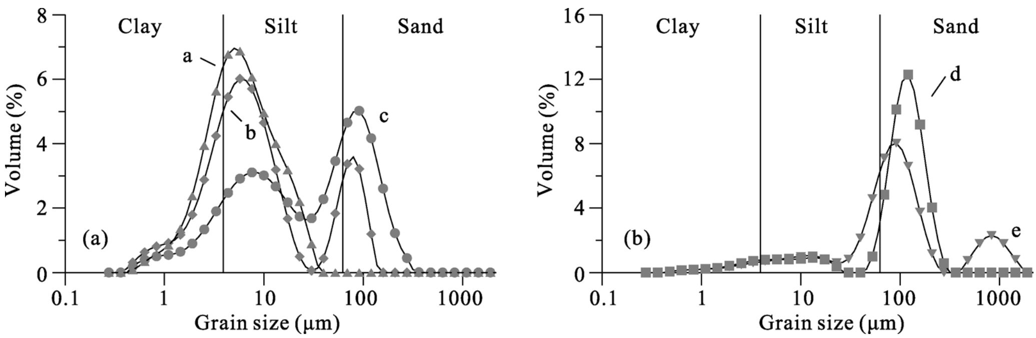

Figure 4 Five representative types of the frequency curves of grain size distribution in different strata

Frequency curve types a, b and c (Figure 4) are mainly present in strata 1, 3 and 5; two peaks are observed for types a and c, indicating two different sedimentary processes existed simultaneously. Frequency curve Type d (Figure 4) is present in strata 2, 4 and 6 and there is only one peak of the curve, indicating a single sedimentary process existed at that time. These differences can also be seen in the sorting index: the sorting value of strata 2, 4 and 6 is lower than in strata 1, 3 and 5 (So, Figure 3), revealing a relative well sorted single sedimentary process in these strata. The frequency curve of a few samples in strata 4 and 6 is Type e (Figure 4), which corresponds with the high values of coarse sand content in Figure 4. Type c is also present in the middle of stratum 2, indicating that there is some variability in the sedimentary processes that were occurring at this time.

4.3 Geochemical elements results

We tested for ten major geochemical elements (Figure 5). SiO_2 accounts for more than 60% of the total volume, on average, while MnO is the lowest, with no more than 0.1% of the total volume. The transport and gathering processes of the geochemical elements in the sediments are complex and the distribution of geochemical elements in different strata demonstrates various environmental characteristics and climate information (Zhong *et al*., 2005; Luo *et al*., 2008; Jia *et al*., 2012).

Most chemical elements have a close correlation with the changes in grain size indexes. Specifically, SiO_2, Al_2O_3, K_2O and P_2O_5 are strongly correlated (Figure 5). Al_2O_3 and K_2O have an obvious positive correlation with the fine-grain content and SiO_2 and P_2O_5 have a negative correlation in these strata. TiO_2 and Na_2O have a narrow range (Figure 5), but, TiO_2 has an obviously higher percentage composition in the middle of stratum 2, as do T-Fe_2O_3, MnO, CaO and P_2O_5. The percentage composition curve of Na_2O has a high value in stratum 1, and at the bottom of strata 3 and 4. The content changes of T-Fe_2O_3, MnO, CaO and MgO, which are generally higher in the upper ~70 cm and lower ~100 cm of the profile, correlate with episodes of fine-grain deposition. However, this correlation does not hold in the middle of the profile where these four chemical elements do not show a clear relationship with the fine-grain deposits of stratum 5.

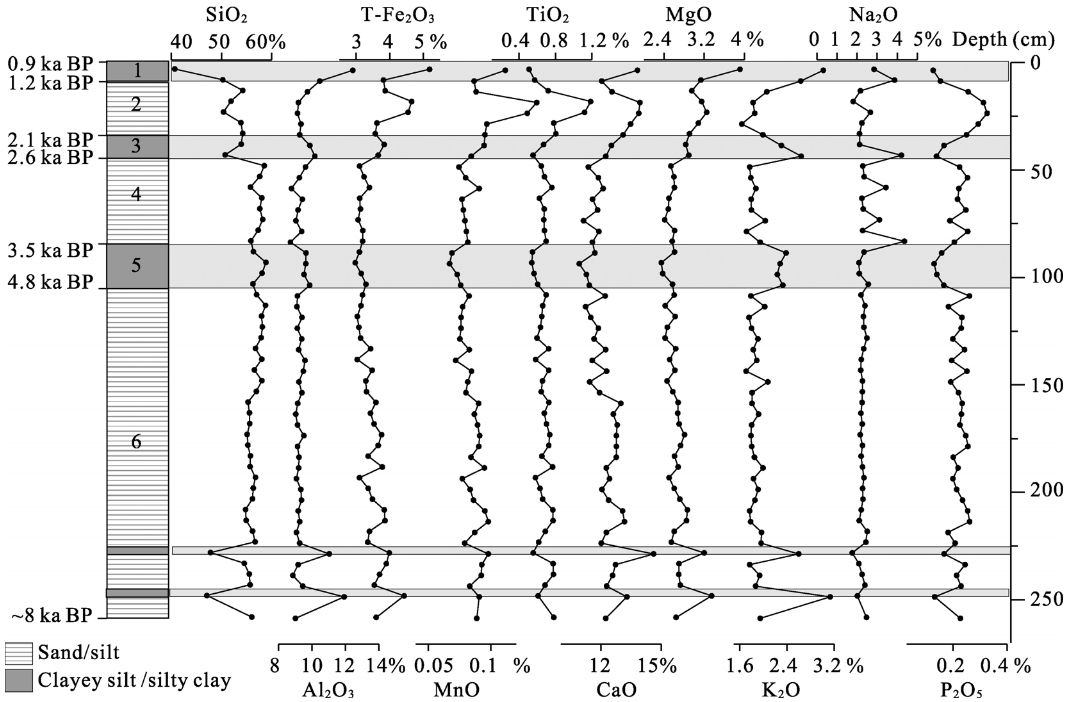

Figure 5 Variations of ten major geochemical elements with the depth of the XH-N profile (Gray shading indicates the fine-grained strata)

5 Discussion

5.1 Sedimentary facies and environmental interpretation

The deposition history around Xiaohe Cemetery as revealed by analysis of the XH-N profile varies between two facies: fine-grained and coarse-grained. We analyzed these changes from the bottom of the profile to the top.

Stratum 6 (~8-4.8 ka BP): Sediments in this stratum are primarily composed of sand (~ 70%) with low amounts of clay and silt (Figure 3). the main grain size frequency curve is Type d (Figure 4). The curve is well peaked and the peak value ranges between ~100 and

125 μm (very fine sand); this curve is similar to the grain size distribution of the sediments found in modern Taklimakan Desert sand (Yin *et al*., 2009) and in the fluvial sand of Tarim River (Feng *et al*., 1999). Stratum 6 has the highest Md value (Figure 3, 130–140 μm), the lowest clay and silt content (Figure 3, average 20%), and the best sorting (Figure 3, So < 1) of the profile; the sorting index here is close to the characteristic of aeolian sand. The high content of SiO_2 and relative lower percentage of T-Fe_2O_3 and Al_2O_3 indicate a weak weathering intensity, typical of an aeolian sand environment. Coarse sand was being transported by high-energy processes as indicated by the Type e curve (Figure 4), with a peak value ranging between ~750 and 1000 μm. In the Lop Nur, coarse sand in the sedimentary sequence is considered an indication of strong sand storms (Ma *et al*., 2008). The high percentage composition of coarse sand (Figure 3) at 120–140 cm (~5.2–5.8 ka BP) and 255–265 cm (approx. 8 ka BP), corresponds to periods of Holocene cold climate events (Bond *et al*., 1999). There are two stratigraphically brief episodes of fine-grain deposition in stratum 6, indicating periods of lesser aridity. However, the geochemical signatures of these events suggest that if there was standing water it was subject to high evaporation and would have been shallow and stagnant.

Stratum 5 (4.8–3.5 ka BP): Sediments of the stratum are composed of silt and clay (60%–80%) with relatively little sand (Figure 3). The grain size frequency curves are Types a and b (two peaks, Figure 4). The value of main peak ranges between 5 and 8 μm (fine silt), which we interpret as lentic sediments associated with a lake or standing water. The secondary peak of the frequency curves range between 90 and 100 μm and we interpret this peak to show that the lake environment was surrounded by desert at that time. The high percentage composition of Al_2O_3 is also attributed to the lake environment because the stable chemical element Al accumulates from strong weathering intensity (Zhang *et al*., 2008). Normally, lake environments in arid deserts are characterized by sediments that develop as carbonate and sulfate minerals precipitate out of solution as a result of evaporation. Ca, Mg and Na are very active chemical elements which are easily transported or leached by water flow (Sun *et al*., 2010). The gathering of active elements in lacustrine sediments indicates high concentration of minerals, and the lake would be shrinking with decreased water and/or enhanced evaporation intensity, high content of Na would be expected if the lake was nearly stagnant and endorheic. In stratum 5, however, low percentages of CaO, MgO and Na_2O suggest the abundant water in the lake with weak evaporation capacity at this time.

Stratum 4 (3.5–2.6 ka BP): Sediments of this stratum are mainly composed of sand (around 65%) and have low clay and silt content (Figure 3). The sedimentary characteristics of this stratum are similar to those found in stratum 6. The main grain size frequency curve is Type d (Figure 4), indicating that an aeolian sand environment was dominant at this time. The high percentage composition of SiO_2 and the low content of Al_2O_3 and T-Fe_2O_3 confirm this interpretation. The high content of coarse sand (Figure 3) that appears at 75–85 cm (~3–3.5 ka BP), along with short-lived but relatively large changes in elements such as AL_2O_3, MnO, K_2O and Na_2O, suggest a brief but intense cool-dry episode at this time (Bond *et al*., 1999).

Stratum 3 (2.6–2.1 ka BP): Sediments of the stratum are mainly composed of silt and clay (60%) with a low content of sand (Figure 3). The grain size frequency curves are Types b and c (Figure 4). The fine-grained sediments and relatively high percentage composition of

Al_2O_3 and T-Fe_2O_3 indicates that a lake emerged at this time, similar to what was seen in stratum 5. However, increasing percentage composition of CaO and MgO indicates the decreased water and relatively enhanced evaporation capacity. A high value of Na_2O content presents in the bottom of the stratum and a low one after that shows that the lake was relative stagnant compared to the lake that emerged in stratum 5.

Stratum 2 (2.1–1.2 ka BP): Sediments of this stratum are predominantly sand (around 65%) with modest clay and silt content (Figure 3). The primary grain size frequency curve is Type d (Figure 4) but samples in the middle of stratum 2 are Type c. The sedimentary characteristics are largely similar to strata 6 and 4 but the geochemical data suggest a more humid situation than in earlier times. The peak value of P_2O_5 indicates well vegetated conditions because the elevated concentration of P is associated with the deposition of organic materials (Costa *et al.*, 2013). The high percentage composition of T-Fe_2O_3 and CaO reveal a lakeside or fluvial environment with high evaporation intensity. Considerable environmental variation is suggested by the varying signals suggesting both more humid conditions but also the presence of aeolian sand encroaching on the profile area around 1.5 ka BP.

Stratum 1 (1.2–0.9 ka BP): Sediments of this stratum are dominated by silt and clay (90%) with little sand (Figure 3). The grain size frequency curves are Types a and b (Figure 4). The fine-grained sediments and the relative high quantities of Al_2O_3 and T-Fe_2O_3 indicate that there was a standing lake, somewhat similar to what we saw in strata 5 and 3. In stratum 1, however, the very high percentage composition of CaO and MgO indicates the reduced water volume and strong evaporation capacity. The high value of Na_2O shows that this lake was shallow and stagnant compared to the lakes that developed in strata 5 and 3.

5.2 Regional differences and affect factors of environmental changes

Interpretation of the grain size and chemical element data indicates that the environment around Xiaohe Cemetery was mainly a desert throughout the Holocene but that it was punctuated with three episodes of lake/oasis formation ca. 4.8–3.5 ka BP, 2.6–2.1 ka BP and 1.2–0.9 ka BP (Figure 6g). The lake that emerged at ca. 4.8–3.5 ka BP had relative abundant and continuous water, and water inflow exceeded evaporation in a long time; the lake that formed ca. 2.6–2.1 ka BP had a relative higher evaporation capacity and reduced more water volume than the previous one; and the one that emerged ca. 1.2–0.9 ka BP, was very shallow and stagnant with strong evaporation capacity.

5.2.1 Climate background

Climate in the research area is dominated today by westerlies (Chen *et al.*, 2008; Zhao *et al.*, 2015). The $\delta^{18}O$ record from Guliya ice core (Figure 6a) indicates rising temperatures beginning ca. 8 ka BP, which corresponds to increasing solar insolation (Figure 6b). The Arid Central Asia (ACA) moisture index (Chen *et al.*, 2008) shows a rising trend from 8 ka BP (Figure 6c). The central part of the Bosten lake basin was cover by meters of aeolian sand then a layer of dark peat formed around 8.2 ka BP (Mischke and Wunnemann, 2006); after 8 ka BP, a stable lake formed in the basin (Huang *et al.*, 2009). The low value of Si/Fe ratio in our XH-N profile also reveals strong weathering intensity in the Early Holocene (Figure 6d). These indicators suggest that climatic conditions in eastern Xinjiang were relatively warm and humid in the early to middle Holocene.

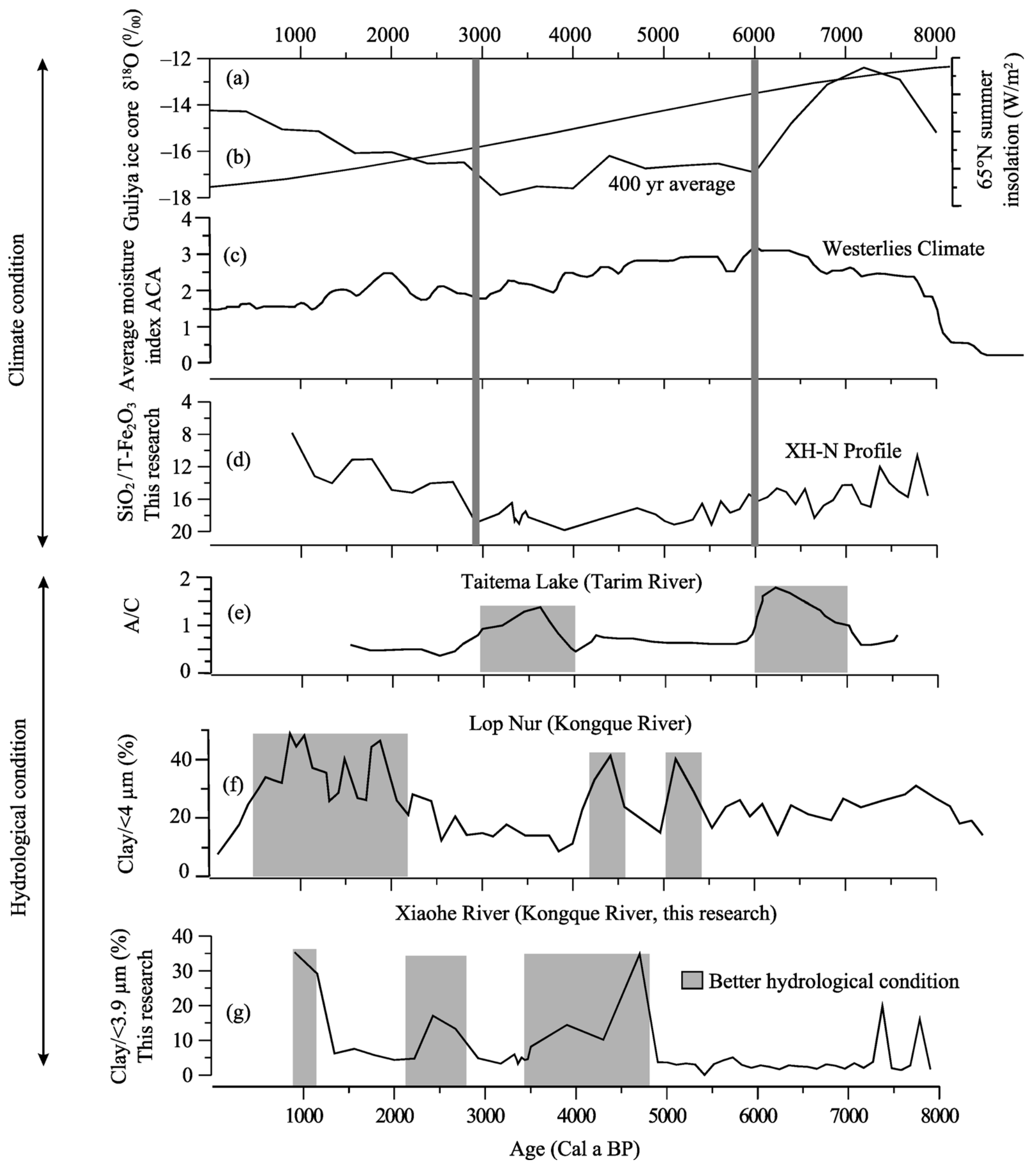

Figure 6 Comparisons of climate conditions and hydrological conditions of the indexes of the XH-N profile to the other researches, two periods of human occupation observed as black rectangles in bottom.
(a. $\delta^{18}O$ from Guliya ice core (Thompson *et al.*, 1999); b. 65° summer insolation (Berger and Loutre, 1991); c. Average moisture index in ACA (Chen *et al.*, 2008); e. A/C ratio of Taitema Lake (Zhong *et al.*, 2005); f: Clay content of Lop Nur (Ma *et al.*, 2008); d and g: This research)

Diminishing $\delta^{18}O$ values of Guliya ice core (Figure 6a), and decreased solar insolation (Figure 6b), suggest a cooler climate emerged following ~6.8 ka BP. The ACA moisture index (Figure 6c) declined slightly but was still above average. At Balikun Lake, the climate was generally cool and humid during this period, as indicated by lower carbonate content, higher organic content and relative high A/C ratio (*Artemisia* and *Chenopodiaceae*, An *et al.*, 2012). From 5.5–4 ka BP, the A/C ratio from Lake Sayram suggests that the humidity was generally high (Jiang *et al.*, 2013). The decreasing Si/Fe ratio in the XH-N profile indicates a lower weathering intensity (Figure 6d). The climate was relatively cool and humid in this period.

After 2.8 kaBP, the decreasing ACA moisture index (Figure 6c) indicates that climate conditions were trending towards increasing aridity. Palynological research indicates that the percentage composition of drought-resistant plants increases (Yao *et al*., 2015). The Guliya record shows a slow warming trend (Figure 6a) despite the fact that solar insolation was still declining (Figure 6b). The Bosten Lake record indicates rising temperatures, which are indicated by stronger evaporation as measured by an increase in carbonate content (Huang *et al*., 2009). The Si/Fe ratio in the XH-N profile shows that weathering intensity was growing (Figure 6d). The rapid increase in the Si/Fe ratio demonstrates the high evaporation of the lake environment seen in stratum 1. The climate was warm and dry through this period.

In light of the broad climate trends discussed here it is evident that the three episodes of lake formation around Xiaohe Cemetery did not occur when there were clear signals of humid climate conditions in the region. This is especially notable for the lakes that formed ca. 2.6–2.1 ka BP and 1.2–0.9 ka BP; these lakes developed at a time of regionally increasingly arid climatic circumstances. The desiccation of the lakes is also negatively correlated with regional climatic changes.

5.2.2 Regional comparison

From the above discussion it is evident that lake evolution in the Xiaohe Cemetery area was not directly driven by the regional climate. Instead, we argue that the Xiaohe Cemetery environment was affected more by local geomorphic circumstances than acted on by larger climate processes. The Xiaohe River is situated on the alluvial fan formed by the Tarim and Kongque rivers. The low gradient of this fan and the relatively coarse composition of the fan sediments encourage the formation of multiple braided channels with high rates of anastomization (Makasake, 2001). Water flow in the fan was evidently alternating back and forth as channels filled or cut into the fan surface. The proclivity for channel switching by the Tarim and Kongque rivers had been discussed before (Wang, 1996; Fan *et al*., 2006; Xia *et al*., 2008; Han and Xie, 2010). The river networks on the alluvial fan are sensitive to geomorphological changes and erosion, which could have substantially changed water allocation and distribution in the area.

The influence of local geomorphology and especially channel switching on the alluvial fan can be seen by comparing the Xiaohe Basin with Taitema Lake, which gets flow from the Tarim River, and Lop Nur, which receives its inflow from the Kongque River (Figures 6e and 6f). In the Early Holocene, Taitema Lake (Figure 6e) had good hydrological conditions and the environment was well vegetated, as indicated by the rising A/C ratio in early-mid Holocene, which reached its peak value ca. 7 to 6 ka BP. The Lop Nur had an increased clay content from 8 ka BP which then slowly dropped down after 7 ka BP (Figure 6f); the relative low percentage composition of clay indicates the hydrological conditions of Lop Nur were not as good as those in Taitema Lake. These data suggest the water from Tarim-Kongque River mainly flowed through the Tarim River into Taitema Lake; only a small quantity of water flowed into the Lop Nur, which is the downstream basin of the Kongque River. The environment around Xiaohe Cemetery was desert at this time because water barely flowed into Xiaohe River basin.

A substantial oasis evolved in the Xiaohe Cemetery area at ca. 4.8–3.5 ka BP. This oasis could only develop if abundant water flowed into Xiaohe River basin and could only happen if the Kongque River carried substantial flow. At this same time, decreased A/C ratio (Figure 6e) and low percentage composition of clay (Figure 6f) reveals that hydrological conditions in Lop Nur and Taitema Lake were relatively poor. High A/C ratio in Taitema Lake ca. 4–3 ka BP indicates some amount of water flowed into the downstream basin of the Tarim River, but most of the water flow was in the Kongque River basin where a channel shift allowed it to be shunted into the Xiaohe River, thus allowing for the formation of lakes and an oasis. A gradual channel switch, perhaps caused by sediment accumulation near the head of the Xiaohe River, may be responsible for the desiccation of the lakes/oasis around Xiaohe Cemetery and thus the decline of Xiaohe culture. The rise in A/C ratio of Taitema Lake just prior to 3.5 ka BP corresponds with a decline in clay percentages in Lop Nur and indicates an increasing diversion of water flow from the Kongque to the Tarim River.

After ca. 3 ka BP, lakes formed around Xiaohe Cemetery at 2.6–2.1 ka BP and 1.2–0.9 ka BP but the water was relative shallow, with strong evaporation intensity; these poor hydrological conditions are especially seen in the lake that emerged around 1 ka BP. Clearly there was sufficient flow in the Xiaohe River to sustain lakes in these two periods. At the same time, desert vegetation was common around Taitema Lake, as indicated by an A/C ratio < 0.5 following 2.5 ka BP. In contrast, at Lop Nur, the percentage composition of clay increases considerably (Figure 6f) and snails and phytoliths were found in sediment layers dated to this time, indicating that this was a period of very good hydrological conditions (Ma *et al*., 2008). The <Shui Jing Zhu> (Li, ~400AD) records that the Lop Nur was a "very vast lake with a great amount of water" and noted that "the water quantity was big enough that the lake level didn't fall even when seasons shift". These data indicated that water mainly flowed in the Kongque River and that the Tarim River was relative dry or underfit. Despite the flow in the Kongque River, however, water was not regularly diverted into the Xiaohe, possibly because of siltation and gradient shifts.

Even though they were within the same watershed and were being affected by similar climatic circumstances through time, the hydrological evolution of the Xiaohe River Basin, Lop Nur, and Taitema Lake varied considerably. Clearly, climate was not the direct influence on the hydrological evolution in the research area. Modern precipitation in the research area is only 20–30 mm/yr but even increased moisture availability caused by the Holocene climatic optimum was not enough to trigger the change from desert to lake around Xiaohe Cemetery. Instead, river water in the Kongque and Tarim rivers was influenced by glacial melting, which was affected by climate change. However, the flow of water into the Xiaohe Basin was the direct result of channel switching upstream. When the Kongque was the primary drainage system water was shunted into the Kongque River but when the Tarim River captured the main flow the Kongque River and the Xiaohe River ran dry. In the very late Holocene when the Kongque had become the principal drainage, the Xiaohe did not reactive because of changes to the local geomorphic situation.

5.3 Environmental changes and human occupation

In an arid desert with a fragile ecosystem the presence or absence of surface water available for human use was a primary influence on the settlement pattern through time. In times when there was standing surface water we see significant cultural development around Xiaohe Cemetery. This is especially notable during the Xiaohe and Loulan (late Western Han) periods, when cultural developments were most notable and correspond with the formation of lake oases.

The lake/oasis at Xiaohe Cemetery first formed 4.8–3.5 ka BP; the lake supplied enough fresh water to sustain the Xiaohe culture's rise and development. A cool-humid climate also benefited the maintenance of the oasis. Human habitation expanded around 4 ka BP and people were able to practice agricultural activities in the flat plain among the rivers and lakes of the alluvial fan and to build the Xiaohe Cemetery on the dunes near the river. This situation lasted for about 500 years. Chronological and sedimentary evidence shows that lacustrine sediments were no longer being deposited after 3.5 ka BP. The desiccation of the lake and the reduction of the surface water resources correspond to the decline of the Xiaohe culture and the abandonment of the area. An arid environment existed between ca. 3.5–2.6 ka BP and standing surface water was minimal or absent; no human sites have been discovered in the downstream section of the Kongque River at this time (XCAI, 2008).

A lake re-emerged in the study area at 2.6–2.1 ka BP and some surface water for human use was still available for a short time up to ca. 1.5 ka BP. The development of this lake corresponds with the expansion of the Silk Road in Han times. Though the climatic condition was warm and dry, enough water inflow to Xiaohe River maintained the human activities here. After 2.1 ka BP, most of the water in the Kongque River gradually flowed to Lop Nur. Despite these environmental challenges, extensive human activities are documented around Xiaohe Cemetery and a prosperous culture developed around the nearby Loulan ancient city.

A shallow, stagnant lake was present between 1.2–0.9 ka BP. This lake was not a suitable environment for human use. Unsurprisingly, archaeological remains are absent at this time.

6 Conclusions

Analysis of the sediments in the XH-N profile reflects environmental changes around Xiaohe Cemetery over the period 8.2–0.9 ka BP: lakes formed as a result of steady fluvial input at 4.8–3.5 ka BP, 2.6–2.1 ka BP and 1.2–0.9 ka BP while a relative dry environment with weak fluvial activity predominated at other times. Geochemical analysis further demonstrates the environmental changes and indicates that the lake in the period 4.8–3.5 ka BP and 2.6–2.1 ka BP had better hydrological condition and the lake of 1.2–0.9 ka BP was shallow and stagnant.

The formation and transition of the hydrological environment in the research area was not solely affected by climate conditions. The formation of a lake and its associated environment depended on a continuous and abundant water supply, which was derived initially from the Kongque River and then shunted into the Xiaohe River basin. Climate change obviously controlled moisture availability at the broader scale, but suitable geomorphic and hydrological conditions dictated if water could flow into the Xiaohe River basin.

Abundant evidence indicates that the presence or absence of an oasis and available surface water had direct influence on the rise and development of culture during the Xiaohe and Han periods in the research area. These results suggest that even in extreme environments, climate change is not the sole driver of human occupation and land use. Archaeological and paleoenvironmental research must consider a wide array of factors when exploring the rise and fall of human cultures.

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