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Quaternary International ▮ (▮▮▮▮) ▮▮▮–▮▮▮

Dry late-glacial and early Holocene climate in arid central Asia indicated by lithological and palynological evidence from Bosten Lake, China

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Abstract

Stratigraphical and chronological investigations of four sediment cores from Bosten Lake, the largest inland freshwater lake in China, provide a reliable regional environmental evolution record since the late-glacial. The stratigraphy of the four cores has been well correlated according to their lithology and chronology (OSL and ^{14}C dates). Pollen and grain size data from Bosten Lake show evidence for a dry regional climate during late-glacial and early Holocene (16–8 cal ka BP) indicated by a thick layer of aeolian sand deposit (>100 cm). Although the climate became humid after 8 cal ka BP, analysis of pollen assemblages (pollen A/C ratio and *Ephedra* percentage) also indicates that the climate was relatively dry in the Bosten Lake area between 8 and 6 cal ka BP, while afterwards more humid conditions (ca 6–1.5 cal ka BP) are assumed. Comparison with other lake records from arid central Asia influenced by the westerly winds generally supports the assumption of late-glacial to early Holocene dry climates in westerly dominated regions. Hence, they contrast the Holocene climate development in monsoon Asia. Relatively wet conditions during the late Holocene (6–1.5 cal ka BP) might be induced by stronger westerly circulation.

1. Introduction

The oxygen isotopes of the speleothems from Dongge Cave (Yuan et al., 2004; Wang et al., 2005) and Shanbao Cave (Shao et al., 2006) suggest that the climate became quite humid at the beginning of the Holocene in the Asian monsoon area with a strong summer monsoon and weak winter monsoon (Yancheva et al., 2007). Early Holocene high precipitation is also inferred based on the organic carbon isotopic record from Hongyuan peatland (Hong et al., 2003) and pollen records from lakes in the marginal modern monsoon area (e.g. Liu et al., 2002; Li et al., 2004). Evidence suggests that the Holocene Asian monsoon intensity variation generally follows insolation variations, although with some thousand years of lag (Kutzbach, 1981; COHMAP members, 1988; Wang et al., 2005).

However, the early Holocene climate in the regions of central Asia, which are influenced by westerly climate patterns (such as Xinjiang, western China) is still a debatable topic. The palynological, geochemical and isotopic records from Manas Lake in Northern Xinjiang (Rhodes et al., 1996), oxygen isotopic record from Guliya ice core near southern Xinjiang (Thompson et al., 1997) and pollen records from Lake Grusha and Lake Akkol in the Altai Mountains (Blyakharchuk et al., 2004) suggest that the climate was quite humid during the early Holocene to middle Holocene (11–6 cal ka BP). In western Mongolia, the lacustrine records have shown complex results with asynchronous high lake levels (Grunert et al., 2000). Moreover, based on published lake level reconstructions in north-western China (mostly an arid area today) Yu et al. (2000) indicated that the regional lake levels were much higher from 13 to 6 ka BP than after 6 ka BP by 20%. Therefore, the inferred early Holocene humid climate supports the hypothesis of asynchronous monsoon variations during the Holocene, i.e., the early Holocene was humid in the monsoon margin, presently an arid area, with strong summer monsoon (An et al., 2000). On the other hand, some review papers summarized several published

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doi:10.1016/j.quaint.2007.10.002

Please cite this article as: Huang, X.Z., et al., Dry late-glacial and early Holocene climate in arid central Asia indicated by lithological and palynological evidence from Bosten Lake,.... Quaternary International (2007), doi:10.1016/j.quaint.2007.10.002

Holocene sequences in this area and pointed out that the early Holocene climate was generally dry and optimal conditions prevailed during the mid-Holocene (Feng et al., 2006; Herzschuh, 2006), which generally follows the hypothesis of a 'mid-Holocene climate optimum' proposed by Li (1990) and Shi et al. (1993) which ascribed the mid-Holocene (8.5–3 ka BP) humid climate to the penetration of the Asian monsoon in this region. Mischke and Wünnemann (2006) attributed the higher moisture availability in the early mid-Holocene to a strong climatic influence of the Indian monsoon and its interplay with the westerly winds.

Because of the poor understanding of the regional early Holocene climate, this study uses the lithological and palynological evidence of the well-dated sediment cores retrieved from a large freshwater lake, Bosten Lake. The aim is to provide an independent record to further analyze early Holocene climate in the arid central Asian region and discuss environmental factors influencing regional humidity variations during the early to middle Holocene (between 8 and 3 cal ka BP).

2. Regional setting

Bosten Lake (41°56′N–42°14′N; 86°40′E–87°26′E) is located on the southern slope of Tienshan Mountains and lies in the southeastern part of Yanqi Basin between Tienshan Mountains and Taklimakan Desert. The Yanqi Basin borders the Tienshan Mountains in the north and west and the Kuruktag Mountains in the south. Bosten Lake (1048 m a.s.l.) is the largest inland freshwater lake in China with a surface lake area of ca. 1000 km^2, maximum water depth of 16.2 m and an average depth of 8 m (Cheng, 1995). Zhong and Shu (2001) investigated a Holocene profile from the western shore of the lake, which demonstrated the potential for reconstructing the past climate history of the atmospheric westerlies. Bosten Lake is hydrologically open with 13 rivers flowing into the lake, of which the four major rivers, including the largest, the Kaidu River, account for 96% of the total water input. Water leaves the lake via the Kongque River, which flows to Lop Nur (Fig. 1).

Bosten Lake is in a continental setting and its climate reflects a typical temperate arid region influenced by westerlies. The meteorological station of Yanqi County records a mean annual precipitation of 70 mm and mean annual evaporation of 2000 mm, which are mainly contributed by the summer season. The dry climate leads to a simple vegetation community composed of high-altitude alpine meadow, steppe, desert steppe and desert with no distinct forest. In addition, some intrazonal vegetation is widely distributed, e.g. small areas of *Picea schrenkiana* forest stands on the shaded slopes or valleys, while some Ulmaceae trees grow in valleys and some halophyte vegetation occurs on alkaline soil. It is also notable that a large area of *Phragmites* and *Typha* plants grows in the swamp on the western side of the Bosten Lake (Xu et al., 1996; Huang et al., 2004).

3. Materials and methods

3.1. Field methods

In the past few years, a series of sediment cores (four long cores) were retrieved from Bosten Lake (Fig. 1) by using a piston corer. This paper will focus on the BST04H core, which was drilled from the center of the lake with

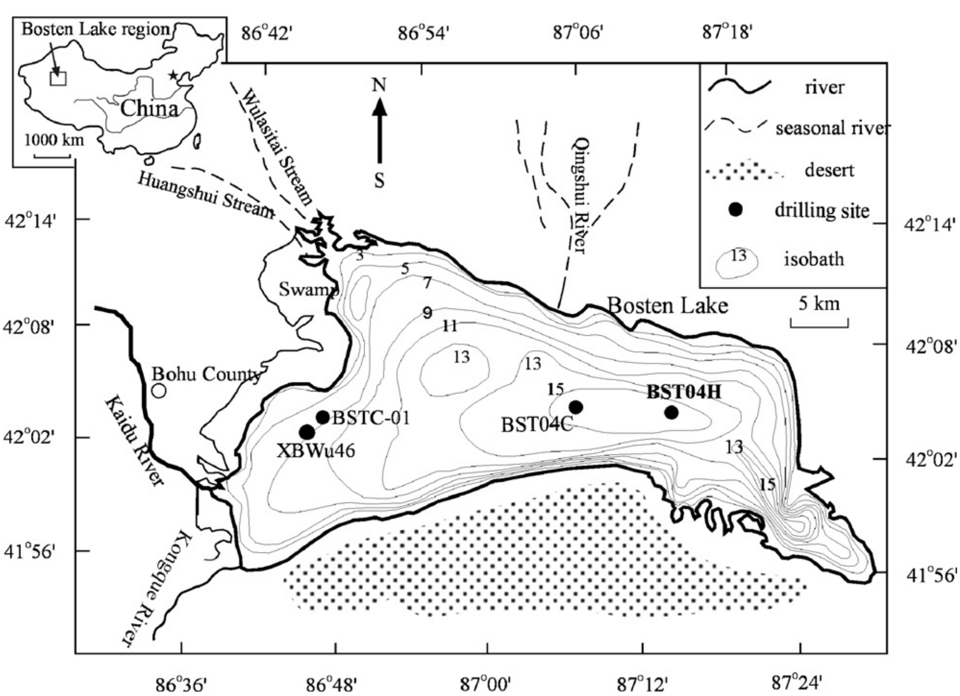

Fig. 1. Bosten Lake isobaths, rivers and the distribution of drilling sites. On the top left, the small figure shows the position of Bosten Lake in China.

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a Kullenburg-type piston corer, and integrate the stratigraphical changes and chronological data of all cores to explore the regional environmental and climate changes.

3.2. Dating methods

AMS ^{14}C dates were generated from samples of plant remains and also total organic carbon (TOC) samples. The TOC samples were 1-cm interval bulk samples. All the AMS ^{14}C samples were prepared with the standard pretreatment (alkali–acid–alkali) and then measured in the Radiocarbon Dating Laboratory of Kiel University in Germany and Peking University in China.

The OSL dating method was applied on the aeolian sand samples, within a depth interval of 5 cm, from the bottom of the cores (BST04C and BST04H) retrieved from the lake center. The samples were taken from a depth of 570–575 cm and 615–620 cm of the BST04C core and a depth of 557–562 cm and 678–690 cm of the BST04H core. Four OSL dating samples were prepared in a light-tight room with subdued red light of the OSL laboratory of Chinese Academy of Science. OSL was dated with the RisØ DA-15 OSL/TL reader with a 90Sr/90Y beta source, and the luminescence signal was good which indicates that the samples are suitable for OSL dating (Fan and Zhao, unpublished communication).

3.3. Grain-size analysis

Grain size was analyzed on the core samples at a 4 cm resolution. The grain size of the lake sediments was measured with a Malvern MS 2000 laser grainsizer after standard treatment with 10% H_2O_2 and 10% HCl and dispersed with sonication (Peng et al., 2005). This pretreatment removes the dissolvable salt and organic matter, with the remains generally representing the size of terrestrial debris. The error of the average grain size is less than 2%.

3.4. Pollen analysis

Pollen type was determined for core samples at an 8 cm resolution. The pollen preparation procedures follow the standard methods (Moore et al., 1991). Approximately 5 g of sediment was digested with 10% HCl, 40% HF and filtered with 7 μm sieve mesh. Before the chemical procedure, one tablet of *Lycopodium* spores (about 12,524 spores per tablet) was added to each sample for calculation of the pollen concentration. More than 500 pollen grains have been counted and identified to genus and family level per sample.

4. Results

4.1. Stratigraphy and lithology

The Holocene sediment cores taken from the different water depth have been correlated on a basis of their lithological changes (Fig. 2). The BST04H core (Chen et al., 2006) is 690 cm long, divided into two different parts: the upper part (0–556 cm) is carbonate rich mud and silt clay, with white gray to black gray color; the lower part (556–690 cm) is fine to coarse sand with gray to yellow color.

The BST04C core was retrieved from a water depth of 15.5 m, and its stratigraphy is also divided into two parts: 520 cm consists of lake sediments and while at the bottom >100-cm-thick aeolian sand with yellow colors.

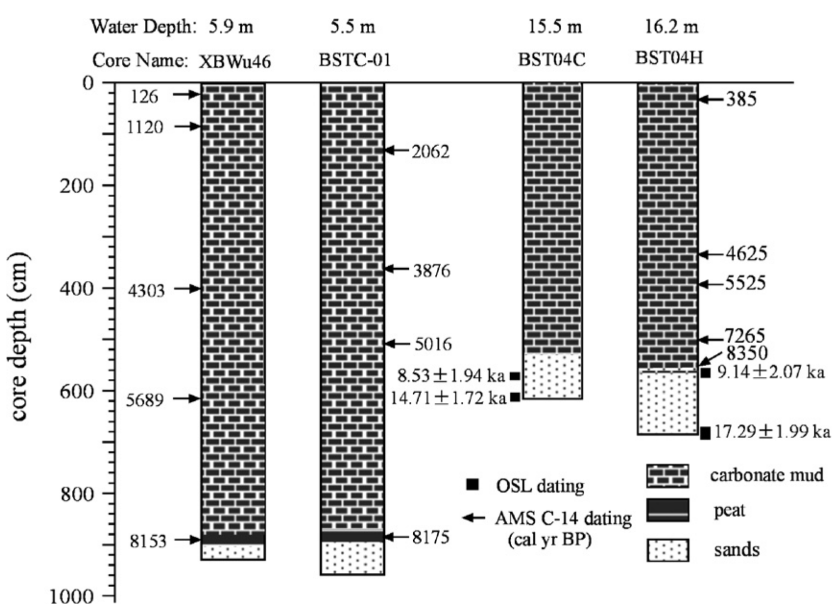

Fig. 2. Correlation of the cores from Bosten Lake based on the stratigraphy and chronology (*Note*: the chronology of BSTC-01 and XBWu46 core is after Zhang et al., 2004 and Wünnemann et al., 2003, respectively).

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The BSTC-01 core and XBWu46 core were drilled from the western part of the lake, with a water depth of 5.5 and 5.9 m, respectively. The BSTC-01 core is 952 cm long and the XBWu46 core (Wünnemann et al., 2003, 2006; Mischke and Wünnemann, 2006) is 924 cm long, with 863 and 880 cm long lake sediment records respectively, and both bottoms of the cores are coarse sand and a thin layer of peat sediment above it (see Fig. 2). Both cores were stopped at the layer of sand because it is impossible to penetrate the sand layer by using a piston corer. The difference between the cores is the thickness of the lake sediments in the shallow lake water area (5–6 m depth) being ca 4 m thicker than that in the deeper part (15–16 m depth), probably caused by higher sedimentation rates in shallow water close to the Kaidu River delta.

4.2. Dating results

Nineteen AMS ^{14}C samples have been dated along the BST04H core and eight of them are shown in Table 1 and Fig. 2. Among these five AMS ^{14}C dates of BST04H core, two of them are dated with TOC at depth of 31 and 556 cm, and other three are dated with 'terrestrial plant remains' (TPR) from depth of 335, 396, and 502 cm. At the same depths, three bulk TOC samples were also dated with the AMS ^{14}C method and revealed age deviations of 1245, 1020 and 1153 years indicating an average reservoir effect of roughly 1140 years. Although the reservoir effect might be changeable with time, it is treated here as constant, considering the relatively small variations of the differences for the three groups of parallel samples. Therefore, the average 1140-year age difference has been treated as the reservoir effect of the Bosten Lake. Moreover, extrapolation of the ^{210}Pb dates/sedimentation rate down to 31 cm, by comparing the ^{210}Pb dating results with the ^{14}C date at 31 cm (1470 ± 40 BP), the 1140-year reservoir effect is also reasonable (Chen et al., 2006). After removing the carbon reservoir effect of TOC dated ^{14}C ages, all the ^{14}C dates of the BST04H core have been calibrated to calendar ages with software OxCal-3.10 (Bronk Ramsey, 2005), and can be correlated with the ^{14}C dated leaves of the BSTC-01 core. For the age model of the BST04H core, the interval between the dating points was calculated. According to the dating results of the BST04H core, it can be inferred that the lake sediments started accumulating in the lake at approximately 8400 cal yr BP.

Based on the OSL dates of the sand layer of the BST04H and BST04C cores (see Fig. 2), the sand layer formed at least between 16 ka BP and around 8–9 ka BP. The OSL dates are comparable to the AMS ^{14}C dates of the lake sediments, confirming their reliability.

The calibrated AMS ^{14}C dates of core XBWu46 (Wünnemann et al., 2003, 2006; Mischke and Wünnemann, 2006), and the dates of BSTC-01 core (Zhang et al., 2004) are shown in Fig. 2 with detailed information in Table 1. All these AMS radiocarbon dates were measured on plant remains and seem to be reliable. For the peat layers in BSTC-01 core, a mean age of 8175 cal yr BP was calculated, slightly different from the date reported by Wünnemann et al. (2006) (see Fig. 2).

4.3. Grain-size analysis

The grain-size frequency distribution curve is an important indicator for evaluating the sedimentation environment and process (Sun et al., 2002). The grain-size curves generally could be divided into two stages above and below 550 cm (around 8 cal ka BP). Before 8 cal ka BP, the mean grain size of the sand layer is between 37 and 150 μm, averagely above 95 μm (Fig. 4a). There are generally two

Table 1
Dating results of BST04H core and BSTC-01 core (from Zhang et al., 2004) and BXBWu46 core (from Wünnemann et al., 2006)

Core name	LAB code	Depth (cm)	Material	C%	^{14}C age (yr BP)	Mean calendar age (⩾1 sigma)
BST04H	LAMS05084	31	TOC	5.524	1470 ± 40(*)	385
BST04H	LAMS05097	335	TPR	54.56	4105 ± 40	4625
BST04H	LAMS05091		TOC	2.986	5350 ± 40	
BST04H	LAMS05098	396	TPR	65.75	4780 ± 40	5525
BST04H	LAMS05092		TOC	2.901	5800 ± 40	
BST04H	KIA 25466	502	TPR	59.81	6337 ± 28	7265
BST04H	LAMS05094		TOC	2.757	7490 ± 40	
BST04H	LAMS05095	556	TOC	1.873	8650 ± 40(*)	8350
BSTC-01	KIA 18576	132	Plant	N/A	2099 ± 24	2062
BSTC-01	KIA 18575	366	Plant	N/A	3590 ± 27	3876
BSTC-01	KIA 18574	514	Plant	N/A	4426 ± 26	5016
BSTC-01	KIA 18573	846	Tree leaves	N/A	7364 ± 37	8175
XBWu46	KIA 13113	13	Organic matter	N/A	102 ± 24	126
XBWu46	KIA 13114	93	Plant	N/A	1207 ± 23	1120
XBWu46	KIA 13115	402	Plant	N/A	3866 ± 30	4303
XBWu46	KIA 13116	622	Plant	N/A	4949 ± 33	5689
XBWu46	KIA 13117	882	Plant	N/A	7368 ± 36	8153

TOC: total organic carbon, TPR: terrestrial plant remains, and samples marked (*) have reservoir effect.

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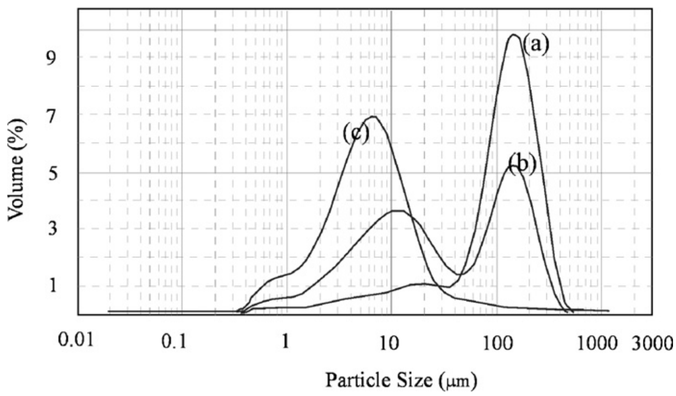

Fig. 3. Main types of grain-size frequency distribution curves along the BST04H core.

kinds of frequency distribution modes for the sand layer between 550 and 627 cm. The first type is shown as curve (a) in Fig. 3, which is the main mode of the grain-size distribution in the sand layer. This mode of the grain-size frequency distribution has one obvious peak at around 150 μm, and the other inconspicuous peak at around 15 μm. By comparing with the aeolian loess grain-size frequency distribution mode (Sun et al., 2002) and the modern airborne dust samples' grain-size distribution curve (Qiang et al., 2006), this mode typically represents an aeolian sand mode, and the aeolian sand at bottom of BST04H core more likely has come from the sand dunes nearby. The other mode of grain-size frequency distribution curve of the sandy sample consists of two obvious peaks at 15 and 150 μm representing two main components. One is the windborne coarse sand and the other is lake water sorted fine component, which might indicate a shallow water sedimentation environment. For the muddy lake sediments above 550 cm, the particle size distribution mode has one obvious peak at around 15 μm (Fig. 3c), which represents typical limnic environment in northwestern China.

4.4. Pollen analysis

The pollen assemblage data indicate a simple vegetation composition with only 30 different families/genera identified, while only 13 families/genera provide maximum percentages exceeding 1%, e.g. Chenopodiaceae, *Artemisia*, Gramineae, *Ephedra*, Compositae, Cyperaceae, Ulmaceae and others. The dominant pollen types in the assemblage are the Chenopodiaceae, *Artemisia* and Gramineae, which indicate plants that are capable of persisting in an arid environment. This is in general agreement with pollen assemblages identified in the Bosten Lake surface sediments (Huang et al., 2004). As the main components of the pollen assemblage, the pollen ratio of *Artemisia* to Chenopodiaceae (A/C ratio) can be used as a humidity proxy in arid, semi-arid areas (e.g. El-Moslinmany, 1990; Gasse et al., 1991; van Campo and Gasse 1993; Li et al., 2005). The higher A/C ratio means larger steppe component in regional vegetation and higher humidity. The pollen A/C ratio is lower at depth of 430–550 cm (average value is 0.82), and increases at depth of 430–150 cm (average value is 0.93) (Fig. 4b). *Ephedra* is a desert plant, and its pollen's percentage increases with decrease of precipitation in the surface pollen assemblages in China (Li et al., 2005) and in other regions of the world (Williams et al., 2006). The *Ephedra* percentage gradually decreases as one moves up the BST04H core, from high values of ~14% at 430 cm depth down to low values of ~2% at the core top (Fig. 4c). Both the lower A/C ratio and higher *Ephedra* percentage at depth of 550–430 cm (about 8–6 cal ka BP) suggest lower humidity compared to the upper sediment record (430–150 cm depth; about 6–1.5 cal ka BP). Almost no pollen grains were found in the sandy layer below 550 cm depth.

5. Discussion

5.1. Bosten Lake palaeoclimate

The dating results and lithological analysis show that the central part of Bosten Lake basin was covered by meters of aeolian sand between the late-glacial and 8.4 cal ka BP (Fig. 4a), then a layer of dark peat formed around 8.2 cal ka BP in shallow area (Wünnemann et al., 2003, 2006), and after 8 cal ka BP a stable lake formed in the basin. As pollen grains could not be found in the sand layer, either they disappeared by oxidation within the yellow sand or they were completely absent. The deposition of aeolian sand is attributed to at least dry climate conditions under a very low or even desiccated lake.

After 8.2 cal ka BP and peat formation, the lake sediments record a regional vegetation history characterized by a high percentages of *Ephedra* (Fig. 4c) and a low A/C ratio during 8–6 cal ka BP (Fig. 4b), which may indicate the relatively dry climate in this period compared to the higher humidity during 6–1.5 ka BP as higher pollen A/C ratio indicates. However, the dry period (8–6 cal ka BP) cannot be confirmed by the ostracod assemblages and isotope geochemistry as reported by Mischke and Wünnemann (2006), but they did reconstruct higher water salinity during this period.

5.2. Dry early Holocene climate in central Asia

Many lacustrine records from central Asia also support the hypothesis of a dry climate during the early Holocene in this area. Boomer et al. (2000) reconstructed the lake level changes of the Aral Sea, showing that lake level was much lower in the early Holocene than that in the middle Holocene (8–3 cal ka BP) (Fig. 4d). Both the Caspian Sea (Rychagov, 1997) and Lake Van (Landmann et al., 1996; Wick et al., 2003) have experienced low levels during the early Holocene. Moreover, in the Lake Van area, the pollen recorded vegetation variations indicate that the

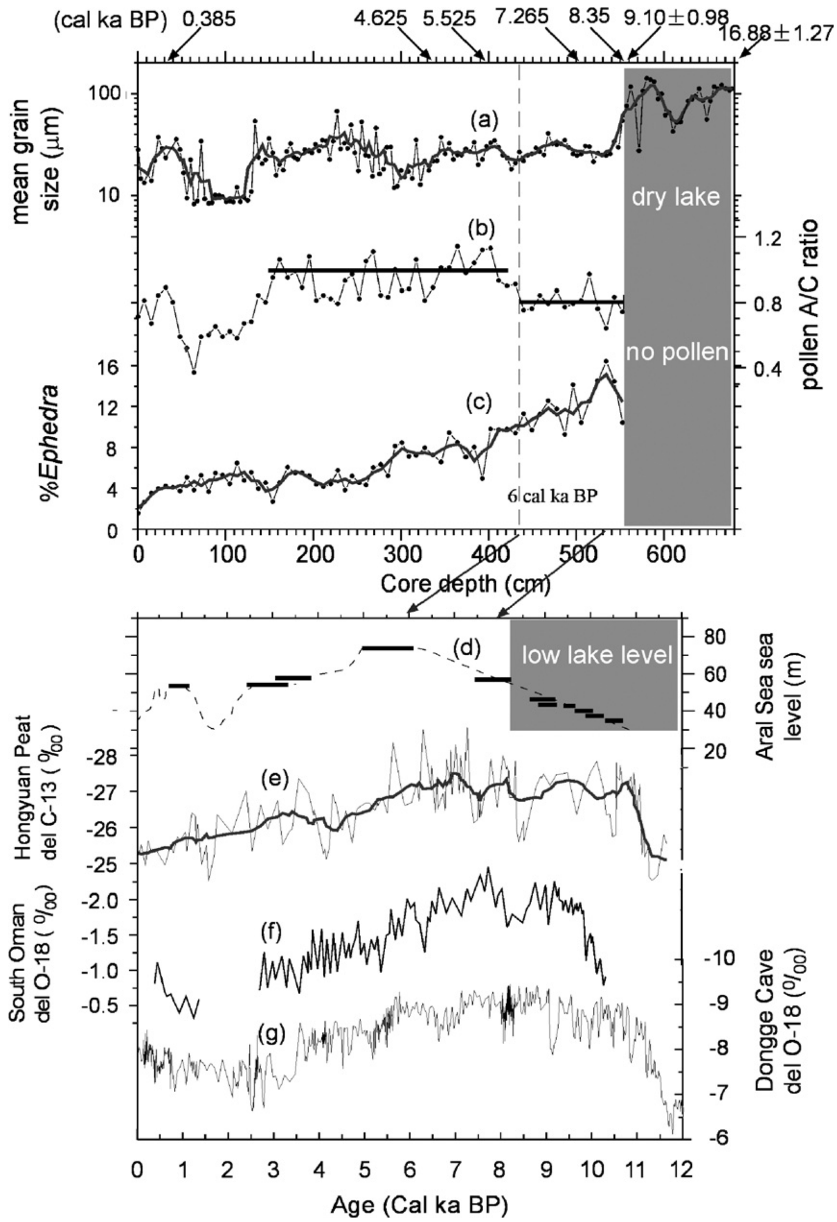

Fig. 4. Comparison of the proxy analyses results of BST04H core: curve (a) average grain size; (b) pollen A/C index; (c) *Ephedra* percentage from Bosten Lake and curve (d) Holocene lake level variations of Aral Sea (from Boomer et al., 2000, with minor changes of the chronology) with the Asian monsoon strength indicators. Curve (e) shows carbon isotopes of plant cellulose from the Hongyuan peat in Hong et al. (2003); (f) shows oxygen isotopic records of stalagmite from South Oman (Fleitmann et al., 2003), and (g) shows Oxygen isotopes of stalagmite from Dongge Cave (Dykoski et al., 2005) (*Note*: the coarse gray lines on the curve (a) and (c) are 10 points and 3 points adjacent averaging, respectively).

desert steppe in the early Holocene was replaced by forest vegetation in the middle to late-Holocene (Van Zeist and Woldring, 1978).

In northern Xinjiang, Wulungu Lake is regarded to have formed later than Bosten Lake, at around 7–8 cal ka BP, with pollen assemblages also indicating a dry climate prior to this in the early Holocene (Xiao et al., 2006). In the western part of Mongolia, the modern Lake Telmen only formed after around 7000 cal yr BP (Peck et al., 2002; Fowell et al., 2003). The large area of similar lake records in arid central Asia suggests that the lake evolution is controlled by the regional climate and all of these lakes' records show that this area was dry during the early Holocene and even late-glacial (16–8 cal ka BP).

On the other hand, as previously mentioned, monsoon Asian records provide different palaeoclimatic reconstructions at this time. Records from peat (Hong et al., 2003, 2005), speleothems (e.g. Fleitmann et al., 2003; Yuan et al., 2004; Dykoski et al., 2005; Wang et al., 2005; Shao et al., 2006), lakes (e.g. Li et al., 2004; Shen et al., 2005) and the Ocean (Gupta et al., 2003) provide Holocene Asian monsoon evolution records (Fig. 4e–g). These data suggest that the Asian monsoon was strong and the climate was humid during the early Holocene with peaks at

9–7 cal ka BP and later decreased stepwise after 7 cal ka BP. Therefore, we assume that the Holocene climate evolution history in arid central Asia is out of phase to the monsoon evolutions.

5.3. Possible mechanism

There are several possible mechanisms to explain the dry early Holocene climate in arid central Asia proposed by different studies. Feng et al. (2006) suggested that the early Holocene dry climate might be induced by the delayed response of the low latitude oceans to the peak insolation at high latitudes, while Herzschuh (2006) made a hypothesis that the strong insolation enhanced strong air uplift on the Tibetan Plateau caused intensified descent of air masses and consequently increased aridity of the inland areas in the early Holocene. But both of them have ascribed the middle Holocene humid climate to the penetration of the Asian monsoon. As discussed above, the early Holocene was quite humid in monsoon Asia, but it is dry in the Eurasian continental interior. Since the strong monsoon did not make the central Asia humid during the early Holocene, how could it mainly contribute to the wetter climate in the remote Asia interior when it became weaker and weaker in the middle to late-Holocene?

The hypothesis suggested by Feng et al. (2006) should therefore be carefully evaluated, although it sounds reasonable. Vandenberghe et al. (2006) and Huang (2006) suggested that the westerly and monsoon system are in competition and the convergence zone of these two atmospheric circulation systems depends on their relative strength. During the early Holocene, the monsoon systems were strong and pushed the westerlies more northward (Qin and Yu, 1998), and central Asia was controlled by the end of the Asian monsoon with little water vapor (Herzschuh, 2006), at the same time, the stronger insolation led to higher temperature and stronger evaporation, and then caused aridity in this area. On the other hand, when the insolation decreased at around 8–6 cal ka BP, the North Atlantic area cooled down and the thermohaline circulation moved southward with negative North Atlantic Oscillation (NAO). The monsoon gradually retreated, and westerlies in this area became stronger, bringing more water vapor from middle latitude North Atlantic Ocean. Moreover, statistical analysis of the relationship between NAO anomalies and precipitation variations from more than 100 stations in mid-latitudes of central Asia shows that the negative NAO anomalies correspond to increased precipitation in the inland area of the mid-latitude Asia (Aizen et al., 2001). Therefore, the humid climate in continental inland during this period would not be affected by the penetration of the Asian monsoon system but more likely by stronger westerly circulation and lower temperatures. According to the Holocene humidity variation processes of central Asia and monsoon Asia, it also can be inferred that the regional climate is out of phase to the Asian monsoon variations.

6. Conclusions

The OSL dating results of the two sediment cores from Bosten Lake center and the grain-size analysis of BST04H core suggest that the lake catchment environmental conditions were not stable during the late-glacial, with evidence that parts of the lake basin was covered by a thick layer of aeolian sand. Moreover, the AMS ^{14}C dating results of the BST04H core, XBWu46 core and BSTC-01 core indicate that Bosten Lake formed at around 8 cal ka BP. The two AMS ^{14}C dates of the peat layer are similar, and both of the calibrated ages are 8175 ± 125 cal yr BP, suggesting the lake formed after 8 cal ka BP. Pollen analysis of the sediments indicates that regional climate was drier between 8 and 6 cal ka BP than that of mid- to late-Holocene, supporting other evidence of such an arid/dry climate in this region at this time. Bosten Lake also supports evidence of an out of phase climate compared to variations in the Asian monsoon region. Therefore, humidity variations in arid central Asia are more likely connected with the westerly evolutions. Although several possible mechanisms for interpreting the Holocene climatic pattern over central Asia have been discussed, the influence of northern hemisphere ice mass still has not been considered here, and the regional climate variability is still poorly understood as well.

Acknowledgments

Special thanks go to Dr. Zhang C.J., Chen Y.D., Xiao S., Lv Y.B., Yang X.L. and Shang H.M. who have contributed to the fieldwork or part of lab-work. We are also very grateful to Dr. Virginia Panizzo at ECRC, University College London, who has improved the English of the manuscript. This study was funded by NSFC Projects (Grant nos. 40701192, 90502008) and NSFC Innovation Team Project (grant No. 40421101).

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