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Holocene Abrupt Climate Shifts and Mid-Holocene Drought Intervals Recorded in Barkol Lake of Northern Xinjiang of China

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Abstract: Study results in this paper have indicated that the Holocene climate in Xinjiang, Northwestern China has been alternating between wet and dry conditions, and was punctuated with a series of abrupt climate shifts. A sediment core taken from Barkol Lake in the northern Xinjiang of Northwest China was analyzed at 1cm interval for grain-size distribution. Abrupt climate shifts revealed by the grain-size proxy occurred at ca 1.4, 3.0, 4.3, 5.6, 8.0 cal kyr B.P., which were well correlated to both the abrupt shifts recorded in the North Atlantic Ocean (NAO) and the Holocene sea surface temperature (SST) cooling events in the Arabian Ocean. The correlation indicated that the climatic changes in the extreme arid Northwest China were associated with the NAO, probably via the North Atlantic Oscillation-affected westerly winds. The strength and position of westerly winds probably modulated the Siberian-Mongolian high-pressure system (winter monsoon), and played an important role in climate change of Northwest China. Moreover, an evident drought interval during the middle Holocene was also revealed by grain-size proxy.

Keywords: abrupt climate shifts; grain size; Holocene; Barkol Lake; Xinjiang

1 Introduction

Evidence from Greenland ice cores has indicated stability within the Holocene climate records and instability within those of the glacial climate, including abrupt shifts from the late glacial to the post-glacial period (<50yr) (GRIP members, 1993). Much more attention is currently being paid to abrupt climate shifts and millennial-scale climatic cycles, since these sub-periodicities are useful for investigating the causes of abrupt climate changes and the influence they could have on future climate (Zhou et al., 2002). O'Brien et al. (1995) demonstrated that the Holocene atmospheric circulation above the ice cap was punctuated by a series of millennial-scale shifts by the measurements of soluble impurities in Greenland ice core. Subsequently, the Holocene climatic instability has been reported in many places (Bond et al., 1997; Bianchi and McCave, 1999; Enzel et al., 1999; Luckge et al., 2001; McDermott et al., 2001; Baker et al., 2001). Based on an investigation in the high-latitude North Atlantic Ocean (NAO), Bond et al. (1997) concluded that the Holocene deep-sea sediments from the NAO recorded fingerprints of the Holocene climate instability with a cyclic periodicity of 1500yr. Bond et al. (2001) also attributed the documented lower amplitude of the Holocene climatic variations to the lack of amplifier of North American ice cap that dominated the last glacial. In China, great advancement in the understanding of the Holocene climate has occurred in recent decades (Yao and Thompson, 1992; Wang et al., 1996; Guo et al., 2000; Zhou et al., 2002; Chen et al., 2003). However, the recognition of short time-scale climatic events during the Holocene depends on relatively high sedimentation rates and precise dating. Except ice core, the high-resolution studies and reliable dating are scarce.

In this paper a sediment core taken from Barkol Lake in the northern Xinjiang of Northwest China was analyzed for grain-size distribution. Owing to its structure

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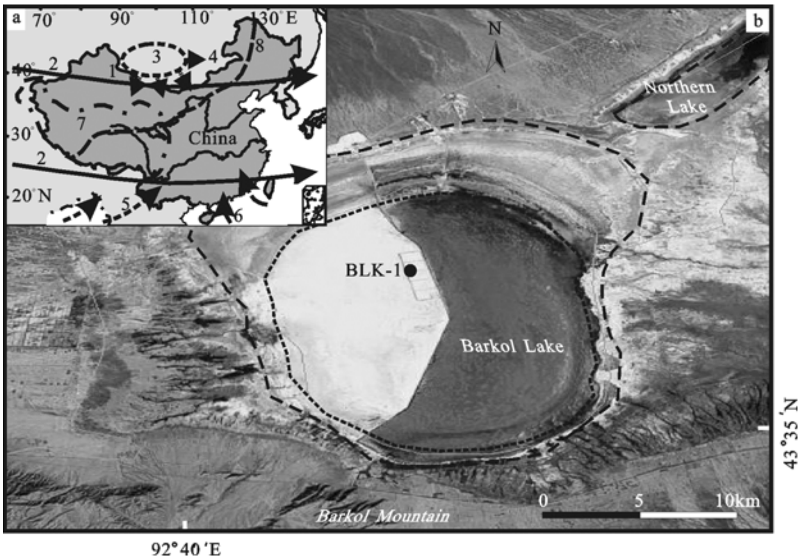
and geographical location, Barkol Lake could provide a high-quality proxy record of the Holocene climatic changes. Here, we presented a high-resolution Holocene grain-size record from the lake, trying to reveal the characteristics of the Holocene climate and enhance our understandings of the global Holocene climatic instability.

2 Study Area and Methods

2.1 Study area

Barkol Lake (43°36′–43°43′N, 92°43′–92°51′E, 1580m a.s.l) lies about 15km west of Barkol County seat (Fig. 1). It once had a maximum area more than 800km^2 before and was reduced to only 100km^2 or so in 2005. The lake has a maximum water depth of about 1.1m and a mean depth of about 0.6m. The area of the catchment of the lake is 4514km^2, with two small rivers entering the lake, whereas no rivers drain the lake (Han, 1992; Yuan et al., 1998).

Barkol Lake is located at the arid area in the middle temperate zone of Northwest China (Fig. 1). Mean annual temperature is about 1.1℃. Mean annual precipitation is 202.3mm, whereas mean annual evaporation reach as high as 1638mm. The lake is primarily supplied by melt water from snow and glaciers in the surrounding mountains. At present, large area of the lake basin is covered with glauberite and saline pan deposits of halite with minor amounts of gypsum and exposed mudflat.



1. the study area; 2. the westerly winds at an altitude of about 3000m; 3. the Siberian-Mongolian High Pressure; 4. the winter monsoon; 5. the Indian monsoon; 6. the East Asian summer monsoon; 7. the Qinghai-Tibetan Plateau with an elevation of 3000m a.s.l.; 8. the modern summer monsoon limitation. BLK-1 is the sediment core site

Fig. 1 Climatic systems of China (a) and location of Barkol Lake in Northwest China (b)

2.2 Sampling and analysis methods

A sediment core (BLK-1) with a thickness of 251cm was extracted in Barkol Lake in July of 2004 (Fig. 1). In the field, this core was cut at 1cm interval for grain-size distribution and other laboratory analyses. Sediment materials are mostly composed of homogeneous silt and silty clay, with the exception of several intercalations of sand and granules in the middle part of the core. Seven bulk samples were obtained for conventional radiocarbon (^{14}C) dating from the sediment core.

Grain-size distribution of the sample was determined with a Malvern Mastersizer2000 Laser Analyzer with a measurement range of 0.02–2000μm. Before grain-size measurements, chemical pretreatment is essential to isolate discrete particles of the sample and to provide an evenly dispersed suspension of individual particles (Lu and An, 1997). The procedure can be described as follows: 1) All samples were pretreated with 10–20ml of 30% H_2O_2, heated at 80℃ to remove organic materials, and treated with 10ml of 10% HCl to remove carbonates. 2) About 2000ml of distilled water was added, and the sample solutions were soaked for 12 hours to remove any remaining acid. 3) The sample residue was finally treated with 10ml of 0.5M $(NaPO_3)_6$ on an ultrasonic vibrator for 10 minutes to facilitate dispersion before grain-size analysis. The Malvern Mastersizer2000 Laser Analyzer automatically measures the median diameter and the percentages of the related size fraction of a sample with a relative error of less than 1%.

3 Results

3.1 Chronology of sediment core

Seven radiocarbon samples of BLK-1 core were dated using the conventional method at the National Laboratory of Western China's Environmental Systems, Lanzhou University (Table 1, Fig. 2). A half-life of 5568yr was used for the calculation, and the conventional ages were converted to calibrated ages using the CALIB5.0 radiocarbon calibration program (Stuiver et al., 2005). The evident linear age-depth relationship has a correlation coefficient of 0.994, indicating that the dating results are statistically significant. The regression line between depth and ^{14}C age shows that reservoir effect affected by the dead carbon in Barkol Lake could be 750yr, therefore we subtracted 750yr from all ^{14}C ages then converted these ages to calendar year ages using the CALIB5.0 radiocarbon calibration program. The ages of sampled horizons were derived by liner interpolation, and the bottom of BLK-1 core was determined to be about ca 9400 cal yr B.P. Based on the average sedimentation rate, the resolution of this core is about 38yr/sample.

Table 1 Radiocarbon data and calendar age of BLK-1 section in Barkol Lake

Field number	Laboratory number	Depth (cm)	^{14}C age (yr B.P.)	Calibrated age (2σ) (cal yr B.P.)	Dating material
BLK-1-243-246	05-44-1	4–7	907±63	930–698	Organic matter
BLK-2-231-234	05-43	16–19	1590±65	1686–1344	Organic matter
BLK-3-198-200	05-42-1	50–52	2245±58	2350–2125	Organic matter
BLK-4-170-173	05-41-2	77–80	3422±60	3839–3486	Organic matter
BLK-5-142-145	05-40	105–108	4340±60	5266–4823	Organic matter
BLK-6-110-113	05-39	137–140	5166±65	6176–5742	Organic matter
BLK-8-040-035	05-37-1	210–215	8111±72	9280–8774	Organic matter

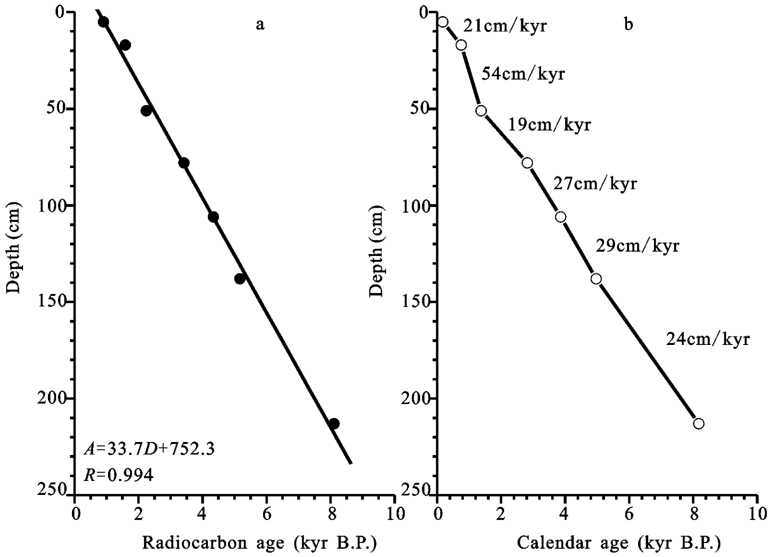
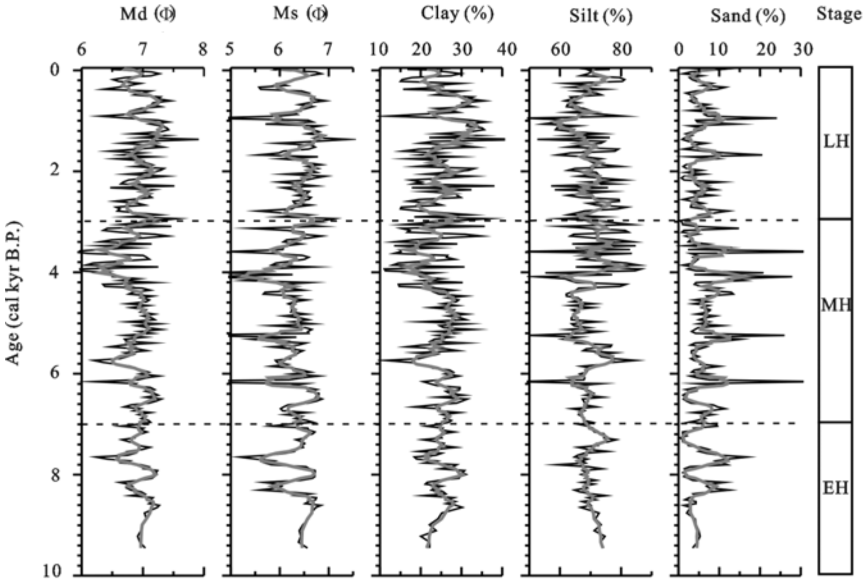


Fig. 2 Relationship between depth (*D*) and age (*A*) of BLK-1 sediment core (a) and calculation of sediment accumulation rate (b)

3.2 Grain-size distribution of core sediment

The Md (median grain size) of a sample is the diameter at the 50th percentile of grain-size distribution, whereas the Ms (mean grain size) is the quotient of dividing the sum of the diameters at the 16th, 50th and 84th percentiles by three. Data for the grain-size distribution (Md, Ms, clay content, silt content, and sand content) of BLK-1 core sediment since ca 9400 cal yr B.P. were plotted against calibrated radiocarbon ages (Fig. 3). High Md (Φ) and Ms (Φ) values correspond to fine particles, yet low Md (Φ) and Ms (Φ) values correspond to coarse particles respectively. As shown in Fig. 3, the Holocene grain-size distribution record is characterized by three stages: 1) Early Holocene (EH), before ca 7000 cal yr B.P., with the average Md of 6.96Φ; 2) Middle Holocene (MH), between ca 7000 and 3000 cal yr B.P., with the average Md of 6.79Φ; 3) Late Holocene (LH), after ca 3000 cal yr B.P., with the average Md of 6.97Φ.



Bold lines superimposed on the grain-size plots represent five-point running averages

Fig. 3 Time series of grain-size distribution record of sediment core in Barkol Lake in the Holocene

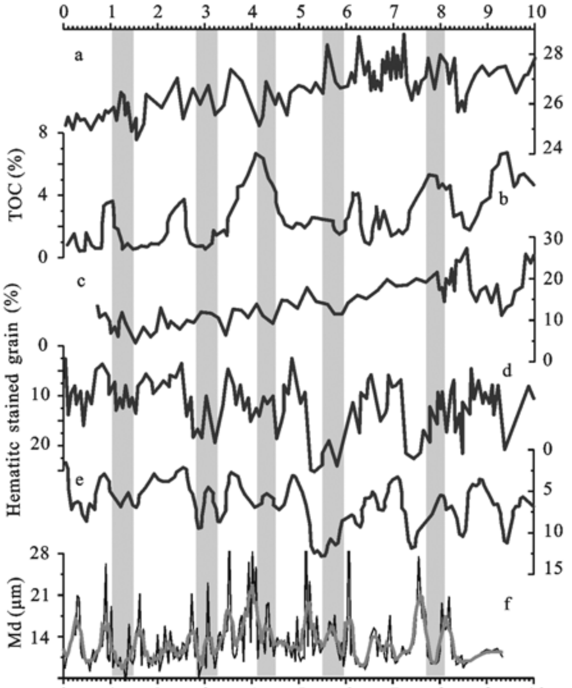
Before ca 7000 cal yr B.P., the Md and the clay-size fraction (<4μm) generally showed relatively higher values and varied within a narrow range. Three peaks of higher Md and clay-size fraction appeared at ca 8600, 8000 and 7400 cal yr B.P. From ca 7000 and 3000 cal yr B.P., the Md and the clay-size fraction maintained lower values and displayed high-frequency fluctuations. During this period, the Md and the clay-size fraction increased at ca 5600 cal yr B.P. and reached relatively higher values at 5400 cal yr B.P., then decreased at about 4700 cal yr B.P., until to 3900 cal yr B.P. reaching the lowest values. After ca 3000 cal yr B.P., the Md and the clay-size fraction increased steadily, but after 1600 cal yr B.P., they decreased.

4 Discussion

Barkol Lake, an intermontane basin lake, is located in the arid region (Fig. 1). The area of the catchment in ancient time was about 30 times that of the modern lake. The mean annual evaporation is 8.1 times the mean annual precipitation. This region is affected by the mid-latitudes atmospheric westerly airflow, and studies have shown that since the late Pleistocene, climate change was predominated by alternations of warm/dry and cold/wet combinations and was different from that in the monsoonal eastern China (Li, 1990; Han, 1992). A synthetic analysis of multiple proxies has shown that sediment grain sizes are a more effective and sensitive proxy of climatic and environmental changes than other geochemical proxies (Chen and Wan, 1999). In general, larger sediment grain size is often interpreted to indicate dry climate during lower lake level while smaller sediment grain size implies wet climate during higher lake level (Hakanson and Jansson, 1983; Zhang et al., 1997; Chen and Wan, 1999). Zhong et al. (2004) demonstrated that during relatively cold (or cool)/wet periods, fine particles were likely carried to deposit in lake resulting from strengthened chemical weathering and increase in plant coverage protecting the surface from erosion, leading to increase in the Md values (corresponding to finer particles). Conversely, during relatively warm/dry periods, intensive physical weathering resulted in more clastic particles, plant coverage decreases, the surface materials are likely free from protection and coarse particles are easily carried to lake, leading to decrease in the Md values (Zhong et al., 2004). Based on these results, we infer that the grain-size distribution of the BLK-1 core can be linked predominantly with the hydrological cycles over the catchment: higher Md of clastic particles resulting from increase in the content of the clay-size fraction is generally related to the enhancement in the precipitation intensity in the catchment. We interpret the grain-size distribution of Barkol Lake sediment as a proxy index for past climatic changes.

Holocene climate change has been a topic of research in China for several decades (Shi and Kong, 1992). The $\delta^{18}O$ record from the Greenland ice core suggested a quite stable climate during the Holocene (GRIP members, 1993). Yet, O'Brien et al. (1995) measured soluble impurities from Greenland ice core, demonstrating that the Holocene atmospheric circulation above the Greenland ice cap was punctuated by a series of millennial-scale shifts. When elucidating the significance of the NAO, Visbeck (2002) proposed that the NAO dominated winter atmospheric variability in the extratropical Northern Hemisphere, which not only influenced the climates in the regions surrounding the North Atlantic, but also affected the strength of the westerly winds across the mid-latitudes. These westerly winds influence the climate of the Mongolian Plateau, which in turn affect the Siberian-Mongolian high-pressure system (winter monsoon), and thus affect the climate in China (Porter and An, 1995). As Barkol Lake is situated near the Siberian-Mongolian High (Fig. 1), if above hypotheses are correct, abrupt Holocene climate changes recorded in NAO might have left geological imprints in the study area. However, the previous studies on the Holocene climate in Barkol Lake did not find the abrupt climate shifts correlative to those revealed from the NAO.

The well-dated BLK-1 core showed abrupt climate shifts which were superimposed on longer timescale climatic changes. Several events indicated by grain-size proxy occurred at ca 1.4, 3.0, 4.3, 5.6, 8.0 cal kyr B.P., which were correlated to both the abrupt climatic shifts recorded in the NAO (Bond et al., 1997) and to those in the Zoigê Plateau (Zhou et al., 2002), the Qinghai-Tibet Plateau (Wang et al., 2004) and the SJC section in the Minqin Basin (Chen et al., 2001) in China (Fig. 4), and some of them were also correlated with Holocene SST cooling events in the Arabian Ocean (Sirocko et al., 1993). Our results also correspond well to the record of Gun Nuur Lake, northern Mongolia, where the Holocene climate was also unstable and characterized by alternating cold (or cool)/wet or warm/dry records (Wang et al., 2004). Based on the fact that Holocene climatic changes in the NAO, the Arabian Ocean and this study area, it is reasonable to deduce that these abrupt climate shifts during the Holocene have global significance.



a. in the Qinghai-Tibet Plateau (Wang et al., 2004); b. in the SJC section (Chen et al., 2001); c. in the Arabian Ocean (Sirocko et al., 1993); d. and e. in the NAO (Bond et al., 1997); f. in the Barkol Lake (this paper)

The grey strips represent abrupt climate shifts

Fig. 4 Correlations of climate shifts recorded by Md in Barkol Lake core with those recorded by different proxies in other regions

To further understand the significance of the Holocene climate change, we have used the Red-noise spectra analysis method (REDFIT) (Schulza and Mudelsee,

2002) to further analyze the Md proxy index. From Fig. 5, we find several pronounced periodicities, such as 1667yr, 431yr, 200yr, 133yr, 108yr and 77yr (with 90% confidence level). The 1667yr periodicity (95% confidence level), which is similar to the 1600yr periodicity recorded by the Sanjiaocheng section in Minqin Basin, Gansu Province, Northwest China (Chen et al., 2001), probably corresponds to the well-documented Bond cycle (about 1500yr) of the North Atlantic ice rafting events (Bond et al., 1997), precipitation event (ca 1500yr) in western Canada (Campbeell et al., 1998), the dry/wet cycle related to the monsoon and the dust deposition (1450–1470yr) in the Arabian Sea (Sirocko et al., 1996). Hence this periodicity reflects a large-scale similarity and the Holocene climatic instability. The periodicity of 200yr coincides with the so-called Suess-cycle; and 133yr, 108yr and 77yr periodicities have been viewed to be related to solar modulation and Gleissberg period caused by solar activity (Stuiver and Braziunas, 1993; Gleissberg, 1994). The 431yr periodicity, for which we can not provide a reasonable explanation at present, is similar to the 427yr periodicity exhibited in the peat record in Zoigê Plateau (Zhou et al., 2002).

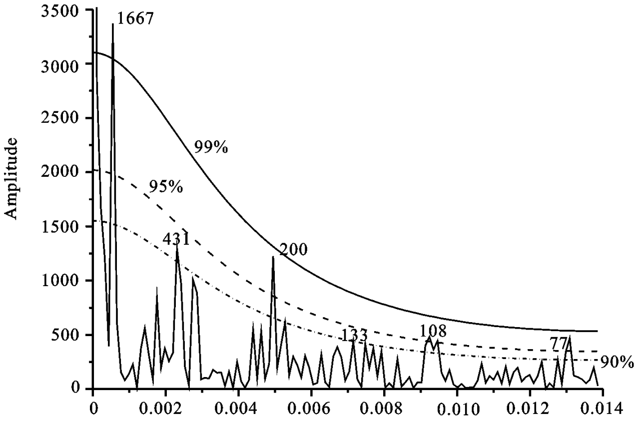


Fig. 5 Power spectrum of Md in BLK-1 sediment core based on Red-noise spectra analysis method (REDFIT) (Schulza and Mudelsee, 2002)

Previous study has suggested that the Middle Holocene was possibly a period of particularly profound change in low latitudes, with land air temperature apparently declining across much of the globe, and with regional differences in precipitation (Steig, 1999). Traditionally, the Middle Holocene in most parts of China was thought to be warmer with higher precipitation, resulting from a strong Asian summer monsoon (Shi and Kong, 1992). However, grain-size data of Barkol Lake differ from the above viewpoints. As shown in Figs. 3 and 4, during the middle Holocene (ca 7000–3000 cal yr B.P.), the average Md is generally lower than that in the early and late Holocene, with two minima at ca 6300–5200 cal yr B.P. and 4500–3500 cal yr B.P. Therefore, grain-size data in this paper indicate that during the middle Holocene, the precipitation decreased distinctly and the climate was very dry. In fact, the middle Holocene dry intervals have been documented in various records from other parts of Northwest China (Guo et al., 2000; Chen et al., 2003), which contrast with the so-called mid-Holocene Climatic Optimum in the eastern China (Shi and Kong, 1992). These drought events in the middle Holocene were suggested to be universal phenomena. We think that such drought in large regions of the central and western China may also explain the paradox of maximum dust flux in Pacific Ocean sediments (Rea and Leinen, 1988; Pye and Zhou, 1989) during the supposedly warm and humid Climatic Optimum (Shi and Kong, 1992) in Northwest China.

5 Conclusions

A high-resolution Holocene climatic record is revealed in Barkol Lake by grain size proxy in northern Xinjiang, Northwest China. The data from the BLK-1 core demonstrate that the Holocene climate was unstable and characterized by either a cold (or cool)/wet or warm/dry combination, being contrary to those reported in the eastern China. Data obtained in this study document the abrupt climatic shifts that were correlated to the ice rafting events in the high-latitude NAO, suggesting that the NAO might have affected the climate in Siberia and Notehwest China via influencing the strength of the westerly winds. Moreover, our results are generally inconsistent with the traditional concept of the global middle Holocene Megathermal or Climatic Optimum. The results indicate that the Barkol Lake has experienced two extreme dry intervals during ca 6300–5200 cal yr B.P. and 4500–3500 cal yr B.P.

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