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Late Pleistocene paleoclimatic history documented by an oxygen isotope record from carbonate sediments in Qarhan Salt Lake, NE Qinghai–Tibetan Plateau

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ABSTRACT

Late Pleistocene paleoclimatic variability on the northeastern Qinghai–Tibetan Plateau (NE QTP) was reconstructed using a chronology based on AMS ^{14}C and ^{230}Th dating results and a stable oxygen isotopic record. These are derived from lake carbonates in a 102-m-long Qarhan sediment core (ISL1A) collected from the eastern Qaidam Basin. Previous research indicates that the $\delta^{18}O$ values of lacustrine carbonates are mainly controlled by the isotopic composition of lake water, which in turn is a function of regional P/E balance and the proportion of precipitation that is monsoon-derived on the NE QTP. Modern isotopic observations indicate that the $\delta^{18}O$ values of lake carbonates in hyper-arid Qaidam Basin are more positive during the warm and wet period. Due to strong evaporation and continental effect in this basin, the positive $\delta^{18}O$ values in the arid region indicate drier climatic conditions. Based on this interpretation and the $\delta^{18}O$ record of fine-grained lake carbonates and dating results in ISL1A, the results imply that drier climatic conditions in the Qarhan region occurred in three intervals, around 90–80 ka, 52–38 ka and 10–9 ka, which could correspond to late MIS 5, middle MIS 3 and early Holocene, respectively. These three phases were almost coincided with low lake level periods of Gahai, Toson and Qinghai Lakes (to the east of Qarhan Lake) influenced by ASM on the orbital timescales. Meanwhile, there was an episode of relatively high $\delta^{18}O$ value during late MIS 3, suggesting that relatively dry climatic condition in this period, rather than “a uniform Qarhan mega-paleolake” spanning the ~44 to 22 ka period. These results insight into the understanding of “the Greatest Lake Period” on the QTP.

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1. Introduction

The northeastern Qinghai–Tibetan Plateau (NE QTP) (Fig. 1A) is located at a triple junction of influences from the southeast Asian monsoon, the southwest Indian monsoon and the Westerlies (Bryson, 1986), which makes it sensitive to global climatic changes. The Qaidam Basin is the largest arid basin in this region, covering an area of 1.2×10^5 km^2. It was surrounded by the Kunlun Mountains to the south, the Altun Mountains to the west and the Qilian Mountains to the north and east. Under “higher mountain and lower basin” circumstances (Yuan et al., 1983), it has developed 27 salt lakes, many of which were once linked into a “mega-paleolake”, and deposits of thick salt beds and abundant brine resources are common (Chen and Bowler, 1986; Zhang, 1987).

Over the past thirty years, significant research efforts have been directed towards investigating halite mineral, brine resources and the evolutionary history of salt lakes in the Qaidam Basin (Chen and Bowler, 1986; Chen et al., 1990; Huang and Chen, 1990; Huang et al., 1991; Liang and Huang, 1995; Liu et al., 2008; Li et al., 2010; Wang et al., 1986; Yang et al., 1995; Zhang, 1987; Zhang et al., 1993, 2007; Zhao et al., 2007); however, the late Pleistocene paleoclimatic variation in the eastern Qaidam Basin is still largely unclear due in part to limited numbers of long-sequenced paleoclimatic records. Most of extant records extend back only to the late glacial or early Holocene (Liu et al., 2008; Zhao et al., 2007, 2008), although there are a few low resolution paleoclimatic records extending back to the last glacial or late Pleistocene (Chen and Bowler, 1986; Chen et al., 1990; Huang and Chen, 1990; Zhang et al., 1993; Yang et al., 1995). Beyond some paleoclimatic records of sediment cores in the Qarhan Salt Lake area, the Shell Bar, located in the southeastern margin of Qarhan Salt Lake, has been regarded as a better geomorphical evidence to reflect the evolution

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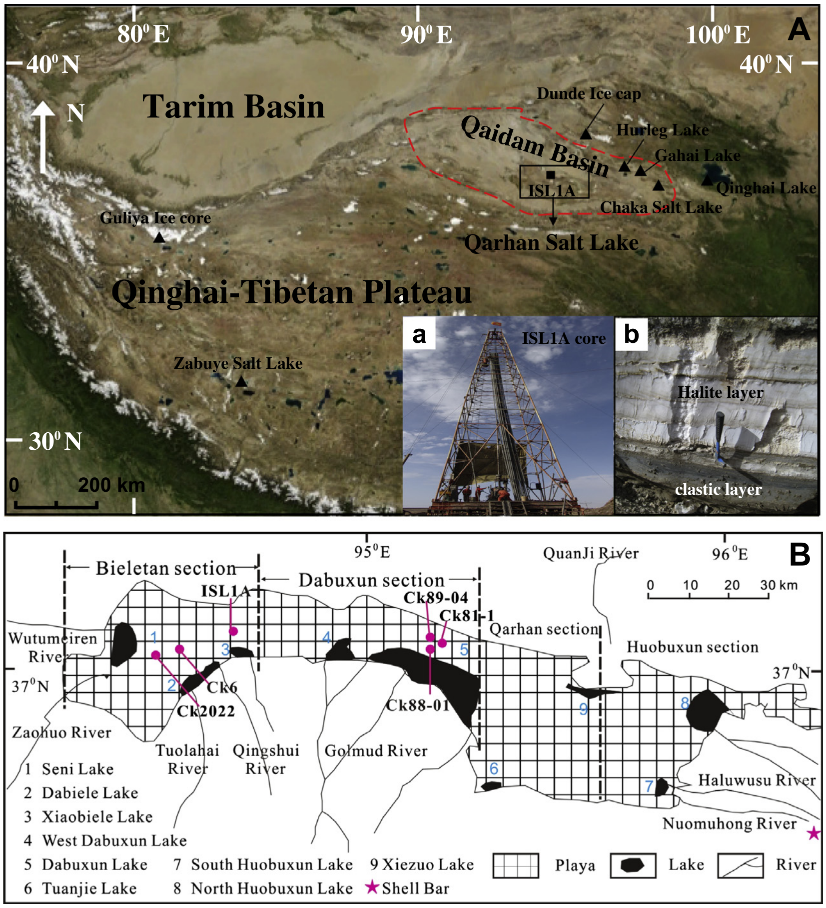

Fig. 1. (A) Map showing the location of Qarhan Salt Lake, eastern–central Qaidam Basin and palaeoclimatic recording sites. a – is the drilling picture and b – is the picture of surface sediments in Qarhan Salt Lake. (B) Map of drilling cores and salt lakes in Qarhan Salt Lake area.

history of Qarhan paleolake (Chen et al., 1990; Ma, 1996; Zhang et al., 2007). The lake level history and climatic change of Qarhan paleolake had been reconstructed based on 42 ^{14}C dating results (including of 20 conventional ^{14}C ages and 22 AMS ^{14}C ages) and multi-proxies analysis of 2.6-m-long section in the Shell Bar (Chang et al., 2008; Zhang et al., 2007, 2008a, 2008b). However, new studies from the Shell Bar have argued that the bar dates to MIS 5 (Lai et al., 2013) and is, regardless of its age, not related to a lake but rather to a stream deposit (Mischke et al., 2013).

These low resolution paleoclimatic records of lacustrine deposits extending back to before the last glacial, together with differently geomorphic and sedimentological explanations for the Shell Bar raise a number of questions: (1) how did the Qarhan mega-paleolake form and evolve during the late Pleistocene? (2) the Qaidam Basin is an extremely arid region on NE QTP at present, which form an obvious contrast with the mega-paleolake during the late Pleistocene. What are possible mechanisms of paleoclimatic changes in the eastern Qaidam Basin? (3) the timing of a mega-paleolake on NE QTP is controversial, with a "Greatest Lake Period" alternatively hypothesized to date to MIS 3 or MIS 5 (Chen and Bowler, 1986; Colman et al., 2007; Fan et al., 2010, 2012a; Lai et al., 2013; Liu et al., 2010; Ma, 1996; Madsen et al., 2008, 2013; Rhode et al., 2010; Zhang et al., 2007). To answer these questions above mentioned, we present a stable oxygen isotope record of lake carbonates from a 102-m-long core in Qarhan Salt Lake area, eastern Qaidam Basin. The paleoclimatic changes since the late Pleistocene will be discussed in this study.

2. Description of the study area

Qarhan Salt Lake (36°37′36″–37°12′33″N, 94°42′36″–96°14′35″E) is the largest playa in the Qaidam Basin (Fig. 1B). The length from west to east is about 168 km and the extent from north to south is 20–40 km, covering an area is about 5856 km^2 (Huang and Han, 2007). It distributes 10 brine lakes around this playa, such as Seni Lake, Dabiele Lake, Xiaobiele Lake, Dabuxun Lake, Tuanjie Lake, Xiezuo Lake and Huobuxun Lake and so on (Fig. 1B). These brine lakes occupied an area of 500 km^2 and total dissolved solids (TDS) are more than 300 g/L (Yu et al., 2009). There are both thick halite layers and liquid beds of enriching K^+ and Mg^{2+} deposited in the Qarhan Salt Lake (Chen and Bowler, 1986; Zhang, 1987). These halite layers mainly contained halite and poor gypsum minerals (Li, 1987; Gao, 1987). The mineral components are relatively simple (Zhang et al., 1993). Most of brines in this region are enriched in K^+, which is the largest liquid bed and base for potassium fertilizer production in China. From east to west in this playa, four sections (Huobuxun, Qarhan, Dabuxun and Bieletan section) are divided in the Qarhan Salt Lake (Fig. 1B). The Bieletan section, located at the westernmost of the Qarhan Salt Lake, contains a complete sequence of the evaporite deposition. The thickness of halite layers are up to 70 m thick with an area of 1500 km^2. The Dabuxun and Qarhan section is located at the central of the Qarhan Salt Lake. The thickness of halite layers are up to 35–55 m with an area of 1120–1250 km^2. The Huobuxun section, located at the easternmost of the Qarhan Salt Lake, is the minimum sub-playa. The thickness of halite layers are up to 15–20 m with an area of 835 km^2 (Zhang, 1987; Yu et al., 2009). Field investigations indicate that there are 18 rivers originated from eastern Kunlun Mountain to supply into the Qarhan Salt Lake area, with the annual average runoff of 19.2 × 10^9 m^3 (Yu et al., 2009).

The Qarhan Salt Lake area is in an extremely arid desert climate. Mean annual temperature is 5.33 °C, mean annual precipitation is about 24 mm, and the annual evaporation is about 3564 mm (Qarhan meteorologic station). The average wind speed is 4.3 m/s and relative moisture is 27.7% (Yu et al., 2009). Vegetation in the Qaidam Basin is characterized by shrub/semi-shrub desert vegetation, dominated by *Haloxylon ammodendron*, *Ceratoides lateens*, *Salsola* spp., *Ephedra przewalskii*, *Nitraria* spp., *Tamarix* spp., *Calligonum* spp. and *Artemisia* spp. (Hou, 2001).

3. Materials and methods

In June 2006, a 102-m long sediment core (ISL1A) was recovered from Qarhan Salt Lake, eastern Qaidam Basin (Fig. 1B). The lithologic and sedimentologic characteristics revealed that there were two large units in ISL1A. The upper part of ISL1A consists of white, white–gray halite layers, and silt sand and clay layers; the lower part of ISL1A consists of silt sand and clay with dark organic matter (Fig. 2). 110 sub-samples (including of silt, sand and clay deposits) were collected for stable oxygen isotopic analysis. All samples were soaked in deionized water for about 2 h, and then wet sieved with a 38 μm sieve. Material smaller than the 38 μm fine-grained fraction was centrifuged and oven dried at 40 °C. About 1 g sample was analyzed for ^{18}O/^{16}O at the Qinghai Institute of Salt Lakes, Chinese Academy of Sciences using a MAT-251 Isotope Mass Spectrometer. Results are expressed in delta (δ) notation relative to the V-PDB standard. Repeated analyses of laboratory standard carbonates with known δ^{18}O values were carried out to ensure instrumental accuracy. The analytical error of the laboratory standard is approximately ±0.2‰ for δ^{18}O value.

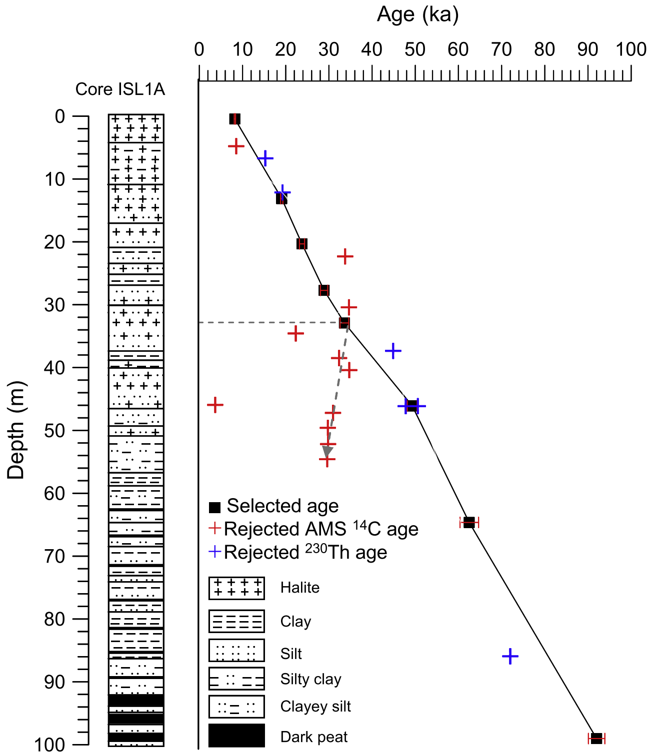

Fig. 2. Plot of ^{230}Th and AMS ^{14}C ages against the depth in ISL1A core in Qarhan Salt Lake area. The arrow shows that those AMS ^{14}C ages are unchanged and younger with increasing depth.

Twelve clay samples containing dark organic matter were collected from the upper 54.5 m core for accelerator mass spectrometry (AMS) ^{14}C dating. Eight halite samples were collected from the upper 46.0 m core for ^{230}Th dating. An assessment and comparison of these ^{230}Th and AMS ^{14}C ages have been discussed in another paper (Fan et al., 2014). In addition, three carbonate samples were collected from 64.5 to 98.9 m core for isochrone ^{230}Th dating. The impure carbonate samples were dissolved with 0.1 M HCl, 1 M HCl and HF–HClO$_4$, respectively, in order to obtain isochron ^{230}Th ages. Chemical procedures followed those described by Ma et al. (2004, 2010a,b). ^{230}Th ages of carbonate deposits were determined using an Octête® plus alpha spectrometer, with a vacuum of 20 mT and an energy resolution (FWHM) of about 25 keV at 5.15 MeV. Analyses were conducted at the U-series Dating Laboratory of Institute of Geology and Geophysics, Chinese Academy of Sciences.

4. Results

4.1. Chronology

Twelve AMS ^{14}C ages of total organic carbon (TOC) and eight ^{230}Th ages of halite in the upper 54.50 m sediment core of ISL1A have been compared and discussed (Fan et al., 2014). Three isochron ^{230}Th ages of lake carbonates from 64.5 to 98.9 m in ISL1A were measured using the isotopic ratios of U and Th among three fractions (including of leachates (L), residuals (R) and whole-samples (W)). In recent studies, a simple correction model has been applied successfully to test the sensitivity of ^{230}Th ages to detritus (Mallick and Frank, 2002; Hou et al., 2010; Li et al., 2010; Ma et al., 2011, 2012; Sanna et al., 2011). Here we employ this simple model to correct the initial ^{230}Th values of carbonate samples and calculated their ages by utilizing the ISOPLOT program (Ludwig, 1991). The details of ^{230}Th dating results are listed in Supplementary Tables 1 and 2. The results indicate that three isochron ^{230}Th ages of carbonate samples are in stratigraphic order, and the isotopic ratios of U and Th among L, R and W are almost linear relationship, suggesting that the correction model and isochron ^{230}Th ages in this study might be reasonable.

In this study, we firstly selected those ages in stratigraphic order to establish the age-depth framework in ISL1A (Fig. 2). For upper 54 m sediment core in ISL1A, all AMS ^{14}C and ^{230}Th ages from upper 30 m sediment core are consistent, while AMS ^{14}C ages from lower 24 m sediment core are almost unchanged with increasing depth. All ^{230}Th ages from lower 24 m sediment core are increased with increasing depth. Therefore, those AMS ^{14}C ages from lower 24 m sediment core are rejected due to more than the upper limit of radiocarbon ^{14}C dating technique (Fan et al., 2014). For ^{230}Th ages from upper 54 m sediment core in ISL1A, they are in stratigraphic order (Fig. 2). Therefore, we selected those ^{230}Th ages of halite to reconstruct the age model in ISL1A. The lithology from 46.9 to 102.0 m consists of the silt, clay or dark peat layers. Therefore, these sediments were dated using the isochron ^{230}Th dating technique. Due to the U content of L fraction in sample ISL1A-38-1 is the lowest and the age of this sample is different from that of other two samples from 46.9 to 102.0 m. Therefore, we selected two isochron ^{230}Th ages of lake carbonates at 64.54 and 98.90 m to establish the age model. In general, the age model in ISL1A is more reasonable.

4.2. δ^{18}O record of lake carbonates in ISL1A

The δ^{18}O values of lake carbonates in ISL1A range between −8.43 and +2.53‰, with the mean value of −4.59‰ (Fig. 3b). Based on the age model of these sediments in ISL1A (Fig. 2), the δ^{18}O

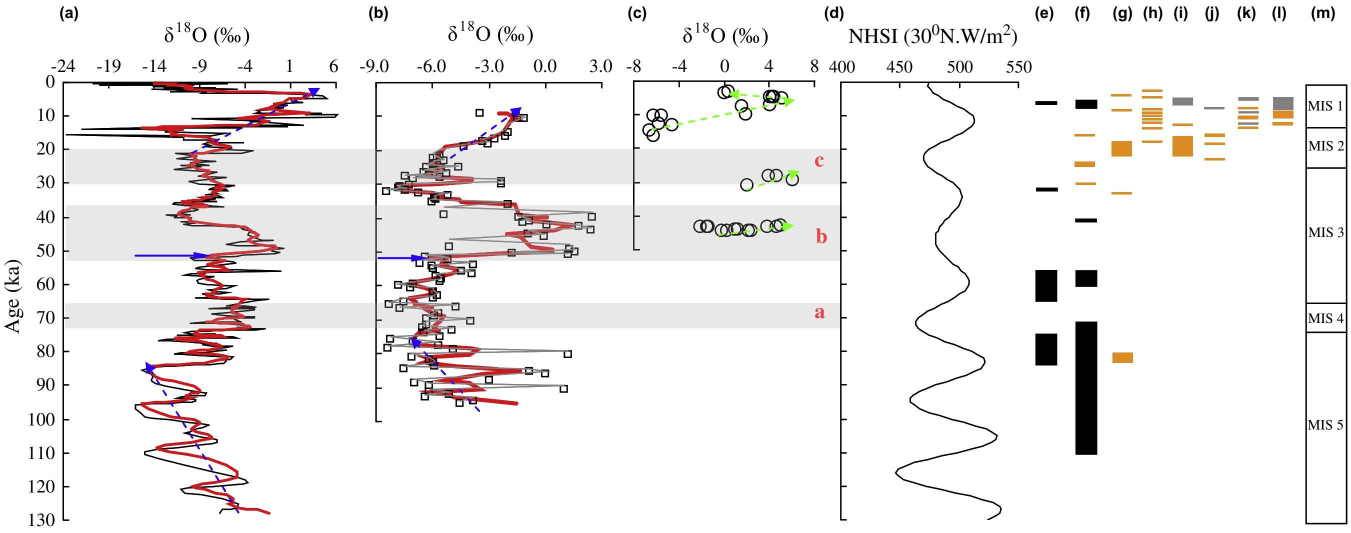

Fig. 3. Palaeoclimatic records of lake sediments and aeolian sands/loess on the Qinghai–Tibetan Plateau (QTP). (a) $\delta^{18}O$ of lacustrine carbonate from Zabuye Salt Lake (Zheng et al., 2007); (b) $\delta^{18}O$ of lacustrine carbonate from Qarhan Salt Lake (this study, the red line shows 3-point averages); (c) $\delta^{18}O$ of fluid inclusion brines from Qarhan Salt Lake (Zhang et al., 1993; Yang et al., 1995); (d) Northern Hemisphere solar insolation at 25°N (Berger and Loutre, 1991); (e) highstand phases of Gahai Lake and Toson Lake, northeastern Qaidam Basin (Fan et al., 2010, 2012a); (f) periods of paleohigh lake levels and sand wedges from Qinghai Lake (Porter et al., 2001; Madsen et al., 2008; Liu et al., 2010; Rhode et al., 2010); (g) aeolian records of southern QTP (Lai et al., 2009); (h) aeolian records of southern QTP (Péwé et al., 1995; Lehmkuhl et al., 2000; Sun et al., 2007); (i) sand and paleosol records of eastern Qaidam Basin (Zeng et al., 2003); (j) sand wedges and loess records of southern Qaidam Basin (Owen et al., 2006); (k) aeolian sand and paleosol records of Qinghai Lake (Lu et al., 2011); (l) aeolian sand and paleosoil records of eastern Qaidam Basin (Yu and Lai, 2012); and (m) marine oxygen isotopic records (Martinson et al., 1987). The letter of a–c shows the dry and cold climatic periods. The black bar in e and f records shows the high lake level phases. The orange bar in f, g, h, i, j, k, l and m records shows the period of aeolian sand/loess and ice wedges, while the gray bar in these records shows the relatively humid periods during Holocene. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

values between 94.7 and 9.0 ka are shown in Fig. 3b. The result indicates that the positive $\delta^{18}O$ values occurred at 90–80, 52–38 and 10–9 ka, respectively; while the negative $\delta^{18}O$ values occurred at intervening phases.

Zabuye Salt Lake, located in the southern QTP, is dominated by southwest Indian monsoon during interglacial or interstadial period. By comparison the $\delta^{18}O$ record of lake carbonates in ISL1A with that in Zabuye Salt Lake (Fig. 3a and b) (Zheng et al., 2007), we found that they are almost similar trending and synchronous pattern since late Pleistocene. The result implies that the age model in ISL1A is reasonable.

5. Discussions

5.1. The paleoclimatic interpretation of $\delta^{18}O$ value of fine-grained carbonate

5.1.1. Modern isotopic hydrology

In order to evaluate the variations in $\delta^{18}O$ and δD values of different fluids (including of lake water, interstitial brines and river water) in the Qarhan Salt Lake (Zhang, 1987), these values were projected into Fig. 4. We found that $\delta^{18}O$ values of lake water in the Qarhan Lake range between −4.96‰ and −8.48‰, which are obviously positive than those (from −11.81‰ to −8.81‰, $n = 15$) of river water (including of Golmud River and Nuomuhong River) inflowing to Qarhan Salt Lake. Meanwhile, the $\delta^{18}O$ values of lake water were positive than those (from −6.58‰ to −5.62‰, $n = 2$) of interstitial brines, and closed to the local evaporation line ($\delta D = 4.8\delta^{18}O - 17$) in the study area. Therefore, the more positive $\delta^{18}O$ values of lake water might be resulted from the strong evaporation and then enriched the heavier isotopes in the study area. Therefore, the precipitation and evaporation (P/E) balance or effective moisture might be a factor to control the hydrology and oxygen isotopes of lake water in the arid Qaidam Basin.

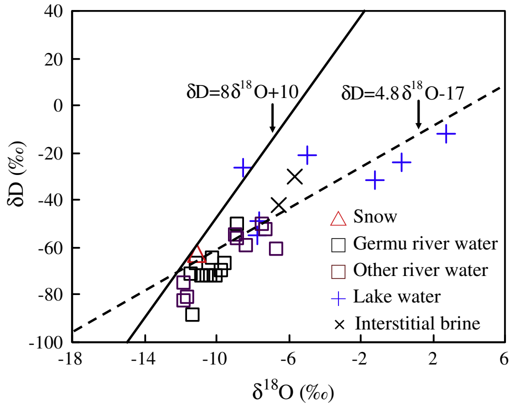

Fig. 4. The relationship between δD and $\delta^{18}O$ of lake water, interstitial brines and river water in the Qarhan region.

5.1.2. Paleoclimatic interpretation of $\delta^{18}O$ value of lacustrine carbonates

In order to eliminate the effect of biogenic carbonate and aeolian sediments on the analytical results, the fine-grained (<38 μm) fraction of samples were collected for the analysis of oxygen isotopes. The carbonate component in fine-grained samples was determined by X-ray diffraction method (XRD). The results show that the carbonate minerals are mainly dominated by calcite, and the dolomite is relatively low. The result implies that the fine-grained fraction in these samples contain large amount of authigenic carbonate precipitating from surface lake water.

In recent decades, the $\delta^{18}O$ values of authigenic carbonate in the closed lakes is widely used as a proxy to reconstruct the climatic and environmental changes (Lister et al., 1991; Henderson et al., 2003, 2010; Anderson and Leng, 2004; Qiang et al., 2005; Xu et al., 2006; Liu et al., 2007; 2009; Holmes et al., 2007; Heikkilä et al., 2010; Anderson et al., 2011; Zhang et al., 2011; Li et al., 2012). In the closed lakes, the oxygen isotopes of lacustrine carbonates are influenced by the temperature and the isotopic composition of lake water at the time when carbonate precipitated in lakes (Leng and Marshall, 2004; Xu et al., 2006). In addition, other factors might also be important in controlling the oxygen isotopes of lake water. They could be (1) δ^{18}O changes of precipitation season (Fontes et al., 1996); (2) the δ^{18}O of the source waters (Holmes et al., 2007) as a result of atmospheric circulation changes (Henderson et al., 2010); and (3) a combination of both. Usually, the effect of water temperature on δ^{18}O values of carbonate is considered small because for every 1 °C increase in water temperature, there is a corresponding 0.24‰ decrease in the δ^{18}O value of carbonate (O'Neil et al., 1969). Due to less precipitation in the hyper-arid Qaidam Basin, the δ^{18}O changes of precipitation season might be relatively small. Therefore, the P/E balance and moisture source as a result of atmospheric circulation changes in the study area are main factors to control δ^{18}O variations in lake water as well as lacustrine carbonates. Modern observations show moisture sources influence the spatial distribution of stable isotopes of precipitation (Aizen et al., 2006; Tian et al., 2003, 2007). The result indicates that there is a positive correlation between δ^{18}O of precipitation and air temperature on seasonal to decadal timescales in the Westerlies region, including entire central Asia and the northern QTP, suggesting temperature plays a dominant role in controlling variations of precipitation δ^{18}O (Tian et al., 2003; Aizen et al., 2006). In contrast, there is a poor correlation between δ^{18}O of precipitation and air temperature on seasonal to decadal timescales in the Asian monsoon region (Yao et al., 1996; Tian et al., 2003). This is due to strong monsoon activity bringing much precipitation and more depleted heavy isotopes (Tian et al., 2003) into the lake catchments.

In general, the δ^{18}O values of lacustrine carbonates are mainly controlled by the isotopic composition of lake water, which in turn is a function of regional P/E balance and the proportion of precipitation that is monsoon-derived in the arid region (Lister et al., 1991; Henderson et al., 2003;Zhang et al., 2003, 2011; Anderson and Leng, 2004; Qiang et al., 2005; Liu et al., 2007; Jin et al., 2009; Anderson et al., 2011).

5.2. Paleoclimatic changes in the eastern Qaidam Basin, NE QTP

Late Pleistocene paleoclimatic variation in the eastern Qaidam Basin is still largely unclear due in part to limited numbers of long-sequenced paleoclimatic records. Qiang et al. (2005) used the δ^{18}O values of carbonate in Lake Sugan to discuss the effective moisture variation during the past 2 ka BP, and concluded that the climate was drier during the early-middle period of "Medieval Warm Period" (MWP). Wang et al. (2013) reported a 1700-year n-alkanes hydrogen isotope record of moisture changes in sediments from Lake Sugan in the Qaidam Basin, and reported that overall drier and wetter climate in the "Medieval Warm Period" and "Little Ice Age", respectively. These records demonstrate that the δ^{18}O values of lake carbonates in this basin are more positive during the warm period. According to the δ^{18}O values of river water, lake water and interstitial brine in the Qarhan Salt Lake (Fig. 4), the result indicates that the δ^{18}O values of river water are more negative than those of lake water. Therefore, the positive δ^{18}O values indicate that the existence of lacustrine phase, even though it was pretty saline under strong evaporation circumstances, while the carbonates with more negative δ^{18}O values probably precipitated in streams, flood plains and so on.

Based on this interpretation and the record of δ^{18}O values of lake carbonates in ISL1A, we inferred that lacustrine conditions of the Qarhan paleolake occurred in three intervals, around 90–80 ka, 52–38 ka and 10–9 ka, which could correspond to late MIS 5, middle MIS 3 and early Holocene, respectively. Although these lacustrine phases in the Qarhan region might have much precipitation being brought into Qarhan Lake catchments, however, the regional P/E balance in the Qaidam Basin is main factor to control the variation in δ^{18}O values of lake water as well as lake carbonates (Lister et al., 1991; Henderson et al., 2003; Zhang et al., 2003; 2011; Anderson and Leng, 2004; Qiang et al., 2005; Liu et al., 2007; Jin et al., 2009; Anderson et al., 2011). Qarhan Salt Lake is located in the eastern Qaidam Basin on the NE QTP, just beyond the northern limit of modern ASM influence (Winkler and Wang, 1993). Meanwhile, it is also one of the hyper-arid regions on the Northern Hemisphere at present. Modern observations of stable isotope composition in precipitation at Delinghga, eastern Qaidam Basin show that higher δ^{18}O values of precipitation are currently associated with warm periods, indicating a positive correlation between air temperature and δ^{18}O values of precipitation (Tian et al., 2003). Due to strong evaporation and continental effect, therefore, the positive δ^{18}O values of lacustrine carbonates indicate that the drier climatic conditions in the hyper-arid Qaidam Basin. This is because less precipitation and stronger evaporation will be concentrated the Qarhan paleolake and enriched more positive isotopes in the lakes.

This conclusion has been verified by geomorphic and chronometric evidence at Gahai, Toson and Qinghai Lakes on the NE QTP. Gahai and Toson lakes are located in the Delinghga sub-basin on the northeastern edge of Qaidam Basin. In 2010, we investigated an outcrop along the east shore of Gahai Lake. A section comprising lacustrine and beach deposits was excavated and seven Optically Stimulated Luminescence (OSL) age samples were collected in this section. Geomorphic and OSL ages demonstrate that higher lake level periods of Gahai Lake occurred at 85–72 and 63–55 ka, corresponding to late MIS 5 and early MIS 3 (Fan et al., 2010, 2012a). Meanwhile, OSL dating and geomorphic interpretations of two sections (TSH1 and TSH2) from Toson Lake indicate that high lake level during MIS 3 and Holocene existed at 31 and 5.4 ka, respectively (Fan et al., 2012a). Qinghai Lake is located on the NE QTP margin east of Gahai Lake and has a lake history similar to that in the Delinghga sub-basin. A large number of high paleoshorelines have been identified along the southern margin of the lake, and OSL dating results suggest that high lake levels ~20 to 66 m above that of the modern lake occurred at ~110 to 75 ka (Madsen et al., 2008; Liu et al., 2010; Rhode et al., 2010). By comparison with lake level records at Gahai, Toson and Qinghai Lakes (Fig. 3b, e and f), we found that these drier climatic conditions inferred by δ^{18}O values of lacustrine carbonates in ISL1A are almost coincided with low lake level periods of these three lakes on the NE QTP.

If this conclusion is acceptable, drier paleoclimatic condition from lacustrine carbonates in ISL1A are inconsistent with high lake level period of Gahai and Qinghai Lakes during late MIS 5. The δ^{18}O values in ISL1A are variable and gradually negative from 90 to 80 ka along with decreasing Northern Hemisphere solar insolation (NHSI) (Fig. 3d), while the recently reported Tianmen (south-central QTP) (Cai et al., 2010) and Hulu (eastern China) stalagmite records (Wang et al., 2008) influenced by ASM all show the inverse δ^{18}O-NHSI relationship during late MIS 5, implying that stronger ASM induced by higher NHSI might bring much precipitation into lake catchments and more depleted heavy isotopes in the lakes. Therefore, the result is understandable that much precipitation induced by stronger ASM would be brought into Gahai and Qinghai Lakes, and develop higher lake level period of these lakes along with higher NHSI, while less precipitation and strong evaporation strengthened the shrinkage of Qarhan paleolake and enriched positive heavy isotopes along with higher NHSI during late MIS 5.

The second drier climatic condition in Qarhan region occurred at 52–38 ka. The result was confirmed by ostracode assemblages of a Luanhaizi Lake core from the Qilian Mountains indicate cold and dry conditions prevailed and a thick sequence of playa deposits accumulated after 45 ka (Mischke et al., 2005). The pollen record from Lanzhou also indicates that the pollen taxa decreased significantly in abundance at 46.0–39.0 ka (Jiang et al., 2011). Meanwhile, abundant and positive $\delta^{18}O$ of fluid inclusion brines from two sediment cores (Ck8904 and Ck8801) in the Qarhan Salt Lake were found (Zhang et al., 1993; Yang et al., 1995).

The third drier climatic condition in Qarhan region occurred at 10–9 ka. The result was confirmed by lower lake level of Toson Lake during early Holocene than that during mid-Holocene (Fan et al., 2012a). Similarly, abundant aeolian sediments have been reported in this period. We selected some loess/paleosol records and sand wedges from eastern Qaidam Basin (Fig. 3i, j and l) (Zeng et al., 2003; Owen et al., 2006; Yu and Lai, 2012) and Qinghai Lake (Fig. 3f and k) (Porter et al., 2001; Liu et al., 2012; Lu et al., 2011) on the NE QTP, and loess records from southern QTP (Fig. 3g and h) (Péwé et al., 1995; Lehmkuhl et al., 2000; Sun et al., 2007; Lai et al., 2009), and compared with the $\delta^{18}O$ records of lake carbonates in ISL1A. We found that the drier phase in Qarhan Lake was coincided with the formation of widespread aeolian sediments and sand wedges in the eastern Qaidam Basin and around Qinghai Lake (Porter et al., 2001; Zeng et al., 2003; Owen et al., 2006; Liu et al., 2012; Lu et al., 2011; Yu and Lai, 2012). Meanwhile, it is also synchronous with aeolian sediments in the southern QTP (Péwé et al., 1995; Lehmkuhl et al., 2000; Sun et al., 2007; Lai et al., 2009).

In general, all these records above mentioned demonstrate that paleoclimatic variation reconstructed from $\delta^{18}O$ values of lake carbonates in a 102-m-long sediment core (ISL1A) is acceptable. Meanwhile, the paleoclimatic interpretation of $\delta^{18}O$ values of lake carbonates in the arid Qaidam Basin is reasonable.

5.3. The timing of a mega-paleolake on NE QTP

The timing of a mega-paleolake on NE QTP is controversial (Chen and Bowler, 1986; Colman et al., 2007; Fan et al., 2010, 2012a; Lai et al., 2013; Liu et al., 2010; Ma, 1996; Madsen et al., 2008, 2013; Rhode et al., 2010; Zhang et al., 2007). The $\delta^{18}O$ values in ISL1A are negative at 33–30 and 28–26 ka, while those are positive at 30–29 ka. Therefore, although there were two episodes of relatively negative $\delta^{18}O$ values and an intervening positive $\delta^{18}O$ values during late MIS 3, suggesting that dry/wet climatic fluctuation in this period, rather than "a uniform mega-paleolake in the Qaidam Basin" (Chen and Bowler, 1986; Ma, 1996; Owen et al., 2006; Zhang et al., 2008a). Geomorphic and chronometric evidence at Gahai Lake and Toson Lake in the northeastern Qaidam Basin indicate that no high beach sediments were found during late MIS 3. Only a single OSL age of 31 ka dates to the period and it was obtained from a lacustrine section (~4 m above modern lake surface), suggesting relatively low lake level during late MIS 3 compared to late MIS 5 (Fan et al., 2012a). Meanwhile, an integrated review from lake level records, glacial advances and lacustrine records on the NE QTP indicates that the effective moisture in this region was lower during MIS 3 (Fan et al., 2012b). Therefore, previously reported "a uniform mega-palaelake" spanning the ~44 to 22 ka period based on the conventional and AMS ^{14}C ages of Shell Bar (Chen and Bowler, 1986; Ma, 1996; Owen et al., 2006; Zhang et al., 2008a) did not exist in the Qaidam Basin, although there were two negative excursion of $\delta^{18}O$ in ISL1A during late MIS 3. Based on new OSL ages and stratigraphic interpretations from Shell Bar, Gahai, Da Qaidam and Qinghai Lakes, the timing of a mega-paleolake on the NE QTP occurred at MIS 5 or earlier (Madsen et al., 2008, 2013; Fan et al., 2010, 2012a; Liu et al., 2010; Rhode et al., 2010; Lai et al., 2013).

5.4. Possible forcing mechanisms of dry/wet changes

Lake and loess records indicate that the climatic system is interplayed between the Westerlies and ASM on the NE QTP during interglacial–glacial timescales (Vandenberghe et al., 2006; An et al., 2012). During the last glacial period, the influence of the Westerlies dominated, while during the Holocene, the dominant ASM influenced the paleoclimatic changes on the NE QTP (An et al., 2012). At present, we did not know that whether penetrate the ASM into the eastern Qaidam Basin during the last interglacial period? Geomorphic interpretations and OSL dating results indicate that the ASM might reach Gahai and Qinghai Lake catchments on the orbital timescales and develop higher lake level during late MIS 5. From Fig. 3b, we found that average $\delta^{18}O$ values of lake carbonates in ISL1A at 90–80 ka are lower than those at 52–38 and 10–9 ka, respectively. Under higher NHSI during the last interglacial period circumstances, the relatively lower $\delta^{18}O$ values imply that a little ASM might bring some precipitation into lake catchments of Qarhan paleolake.

During the last glacial period, higher $\delta^{18}O$ values in ISL1A and lower lake level of Toson and Qinghai Lakes in the study area implying drier climatic condition. This is possible that the weaker ASM and stronger Westerlies altered water balance of Qarhan paleolake. Meanwhile, the $\delta^{18}O$ of precipitation influenced by the Westerlies moisture source due to the low moisture or recycling from lakes might be relatively positive during the last glacial period. In overall dry climate, abundant aeolian sediments were deposited on the southeastern margin of Qaidam Basin and around Qinghai Lake (Porter et al., 2001; Zeng et al., 2003; Owen et al., 2006; Liu et al., 2012; Lu et al., 2011; Yu and Lai, 2012) accompanying with the west winds in this region. Until early Holocene, the climatic condition is also drier along with increasing NHSI. The increasing NHSI will strengthen the stronger evaporation of Qarhan paleolake due to less precipitation in the arid region.

Although we have not discussed those phases of more negative $\delta^{18}O$ values that might not be typically lacustrine conditions in ISL1A, three more positive $\delta^{18}O$ phases indicate the drier climatic conditions since late Pleistocene, which provides an evidence to discuss or interpretate lake-level changes of lakes based on discontinuously geomorphic features on the NE QTP, especially in the Qaidam Basin have limited numbers of long-sequenced paleoclimatic records.

6. Conclusions

Late Pleistocene paleoclimatic variability on the northeastern Qinghai–Tibetan Plateau (NE QTP) was reconstructed using a chronology based on AMS ^{14}C and ^{230}Th dating results and a stable oxygen isotopic record. These are derived from lake carbonates in a 102-m-long Qarhan sediment core (ISL1A) collected from the eastern Qaidam Basin. Previous research indicates that the $\delta^{18}O$ values of lacustrine carbonates are mainly controlled by the isotopic composition of lake water, which in turn is a function of regional P/E balance and the proportion of precipitation that is monsoon-derived on the NE QTP. Modern isotopic observations indicate that the $\delta^{18}O$ values of lake carbonates in hyper-arid Qaidam Basin are more positive during the warm and wet period. Due to strong evaporation and continental effect in this basin, the positive $\delta^{18}O$ values in the arid region indicate drier climatic conditions. Based on this interpretation and the $\delta^{18}O$ record of fine-grained lake carbonates and dating results in ISL1A, the results imply that drier climatic conditions in the Qarhan region occurred in three intervals, around 90–80 ka, 52–38 ka and 10–9 ka, which could correspond to late MIS 5, middle MIS 3 and early Holocene, respectively. These three phases were almost coincided with low lake level periods of Gahai, Toson and Qinghai Lakes (to the east of Qarhan Lake) influenced by ASM on the orbital timescales. Meanwhile, there was an episode of relatively high $\delta^{18}O$ value during late MIS 3, suggesting that relatively dry climatic condition in this period, rather than "a uniform Qarhan mega-paleolake" spanning the ~44 to 22 ka period. These results insight into the understanding of "the Greatest Lake Period" on the QTP.

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Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.jseaes.2014.02.003.

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