A 94–10 ka pollen record of vegetation change in Qaidam Basin, northeastern Tibetan Plateau

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ABSTRACT

Drill core (ISL1A) was obtained from the Qarhan Salt Lake in central eastern Qaidam Basin, northeastern Tibetan Plateau (NE TP). Fossil pollen and the lithology of the core sediment were analyzed in conjunction with AMS 14C and 230Th dating. The results indicated that Artemisia and Chenopodiaceae dominated the steppe/desert steppe vegetation developed around the lake between 94 and 51.2 ka, corresponding with the organic-rich silty clay deposited in the core sediments. Pediastrum continuously appeared in the core sediments between 94 and 51.2 ka, indicating freshwater to oligohaline conditions of the paleo-Qarhan Lake during the late marine isotope stage (MIS) 5, MIS 4, and early MIS 3. During the 51.2 to 32.5 ka period, Ephedra dominated shrub-desert vegetation expanded in the basin, while Pediastrum disappeared in the core sediments. The core sediments consisted of interbedded layers of halite silt and clay-rich halite between 51.2 and 32.5 ka, signifying a shift toward drier hydrologic conditions. Thus, the paleo-Qarhan Lake experienced periods of desiccation and shallow water levels. Artemisia and Chenopodiaceae dominated steppe/desert steppe vegetation appeared again from 32.5 to 25.3 ka, with clay-rich sediments in the core, thereby suggesting an increase of runoff from the lake under relatively wetter climatic conditions. Since 25.3 ka, however, pollen concentrations declined, corresponding with the amount of halite deposited in the core sediment and, suggesting a cold, dry climatic condition during MIS2. Our findings have important implications for understanding complex regional vegetation and climatic responses to large-scale forcings in the Qaidam Basin.

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1. Introduction

The northeastern Tibetan Plateau (NE TP), located at a triple junction of influences that include the Asian summer monsoon, the westerly jet stream and the Siberian high, is of considerable significance with regard to regional responses to global climate change. The Qaidam Basin is a large intermontane endorheic basin at the NE TP and is enclosed by three large mountain belts, the Altun Mountains, the Qilian Mountains in the northeast. The Qaidam Basin covers an area of 120,000 km², has an elevation of 2800 m a.s.l. and has a catchment of approximately 250,000 km² (Chen and Bowler, 1986). The northeastern Tibetan Plateau (NE TP) is a large intermontane endorheic basin at the NE TP and is enclosed by three large mountain belts, the Altun Mountains in the northwest, the eastern Kunlun Mountains in the south and the Qilian Mountains in the northeast. The Qaidam Basin covers an area of 120,000 km², has an elevation of 2800 m a.s.l. and has a catchment of approximately 250,000 km² (Chen and Bowler, 1986).

Qarhan Salt Lake is the largest playa located in the central eastern Qaidam Basin, NE TP (Fig. 1A), an area characterized by a very thick sequence of Quaternary sediments that exceed 3000 m in places (Liu et al., 1998). Continuous lacustrine sediments may provide excellent archives of detailed paleo-environmental data during climatic change in the NE TP. Over the past three decades, significant research efforts have been directed toward investigating halite mineral, paleo-climate and the evolutionary history of salt lakes in the Qaidam Basin (Chen and Bowler, 1986; Zhang, 1987; Chen et al., 1990; Huang and Chen, 1990; Zhang et al., 1993, 2007; Zhao et al., 2007; Liu et al., 2008; Fan et al., 2010); however, the Late Pleistocene paleoclimatic variation in the eastern Qaidam Basin is still largely unclear, in part, to limited numbers of long-sequenced paleoclimatic records. Most previous records extend only as far back as the last glacial or early Holocene Epoch (Zha et al., 2007, 2008; Liu et al., 2008), although there are a few low resolution paleoclimatic records extending back to the last glacial or the Late Pleistocene (Chen and Bowler, 1986; Chen et al., 1990; Huang and Chen, 1990; 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 the Qarhan Salt Lake, has been regarded as better geomorphic evidence to reflect the evolutionary history of the Qarhan paleolake (Chen et al., 1990). Zhang et al. (2007) reconstructed the lake level history and climatic change of the Qarhan paleolake based on dating results and multi-proxies analysis of the Shell Bar and revealed that there were relatively humid climatic conditions during marine isotope stage 3 (MIS3), which corresponded to a mega-paleolake preserved in Qaidam Basin. However, new studies of the Shell Bar dating to MIS 5 (Lai et al., 2014) indicate that, regardless of its age, the Shell Bar is not related to a lake but rather to a stream.

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These low resolution paleoclimate records of lacustrine deposits, together with various geomorphic and sedimentological explanations for the Shell Bar, still cannot explain how the Qarhan mega-paleolake formed and evolved during the Late Pleistocene. Furthermore, there are no high resolution pollen records covering the glacial/interglacial cycles from lacustrine deposits in the Qarhan Salt Lake. Thus, the history of vegetation and climate change during the Late Pleistocene in the central eastern Qaidam Basin is poorly understood. This study, which was compiled from the core 102 m in length, provides the first high resolution pollen record covering the entire late part of the last interglacial period and last glaciation period in central eastern Qaidam Basin. Our objectives were to reconstruct the regional vegetation change and climatic variability during the Late Pleistocene and to provide insights regarding the evolution of the Qarhan Salt Lake during the Late Pleistocene.

2. Physical setting

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 distance from west to east is approximately 168 km and the distance from north to south ranges between 20 and 40 km, thus, covering an area of approximately 5856 km² (Chen and Bowler, 1985, 1986). The Qarhan Salt Lake was a depositional center of Qaidam Basin during the Quaternary, with lacustrine deposits reaching ~3000 m in thickness (Liu et al., 1998). The lake has an elevation of 2675 m a.s.l. at the lowest point in the depression (Chen and Bowler, 1985). From west to east in this playa, the Qarhan Salt Lake is divided into four sections Bieletan, Dabuxun, Qarhan and Huobuxun (Fig. 1B). The Qarhan Salt Lake distributes to 10 brine lakes around the playa, and the field investigation indicates that there are 18 rivers originating from the Kunlun Mountain to feed into the Qarhan Salt Lake (Yu et al., 2009). The landforms are composed of wind-erosion yardangs, salt lake playas, aeolian deposits, and Gobi from west to east.

The Qarhan Salt Lake area is one of the driest places in the world with a mean annual temperature of 5.33 °C, a mean annual precipitation level of approximately 24 mm and an annual potential evaporation level of approximately 3564 mm, according to climate averages at reported at the Qarhan meteorologic station (Fan et al., 2014a). However, the mean annual precipitation on the northern slopes of the Kunlun Mountain is slightly greater than that of the Qarhan Salt Lake. Additionally, the average wind speed is 4.3 m/s and relative moisture is 27.7% (Yu et al., 2009). The vegetation types surrounding Qarhan Salt Lake vary with altitude. Between 2700 and 3700 m, the vegetation is characterized by typical desert vegetation and halophilous species, mainly Salsola abrotanoides, Kalidium gracile, Halostachys caspica, Ephedra przewalskii, Nitraria tangutorum, Calligonum mongolicunl and Tamarix chinesis.
Poaceae and Cyperaceae-dominated meadow are scattered on the southern side of the Qarhan Salt Lake Playa where groundwater seeps out. Aquatic plant taxa along the river bank are mainly Phragmites communities, Typha spp., Ruppia spp. and Potamogeton spp. With increasing distance from the Qarhan Playa south to the Kunlun Mountain, at 3600 to 4100 m, the alpine steppe is composed of Stipa purpurea, Asteraceae (including Artemisia spp., Ajania fruticulosa and Asterothamnus centralasiaticus), Oxytropis ochrocephala, Potentilla fruticosa, Clematis florida, and Brachanthemum gobicum. Alpine desert with scattered Ceratoides compacta, tibet ajania Alchemilla and Saussurea medusa is restricted to the Kunlun Mountains at an elevation between 4100 and 4700 m (Hou, 2001).

3. Materials and methods

3.1. Sediment core and dating

The ISL1A core (37°3′50″N, 94°43′41″E) was obtained from west of the Qarhan Salt Lake (Fig. 1B). The lithostratigraphy of the core alternates primarily between evaporite layers and silt–clay sediment layers from 0 to 51.1 m, and between fresh-water silt and organic-rich clay sediments from 51.1 to 102 m (Fig. 2).

Twelve clay samples containing dark organic matter were collected from the upper 54.5 m of the core for accelerator mass spectrometry (AMS) 14C dating, and eight halite samples were collected from the upper 46.0 m of the core for 230Th dating. An assessment and comparison of these 230Th and AMS 14C ages have been discussed in detail in another paper (Fan et al., 2014b). In addition, three carbonate samples were collected from 64.5 to 98.9 m of the core for isochron 230Th dating. The impure carbonate samples were dissolved with 0.1 M HCl, 1 M HCl, and HF–HClO4, respectively, to obtain isochron 230Th ages. Chemical procedures followed those described by Ma et al. (2004, 2010a,b).

230Th ages of carbonate deposits were determined using an Octète® plus alpha spectrometer, with a vacuum of 20 mT and an energy resolution (FWHM) of approximately 25 keV at 5.15 MeV. Analyses were conducted at the U-series Dating Laboratory of The Institute of Geology and Geophysics, Chinese Academy of Sciences.

3.2. Laboratory work and pollen analysis

Approximately 10 g of sediment from each of the 143 subsamples was used for pollen analysis. Pollen subsamples were sieved and then subject to flotation in a heavy liquid solution (KI + HI + Zn) with a specific gravity of approximately 2.0 g/ml to extract pollen from sediments, followed by acetolysis treatment as described in Moore et al. (1991). Pollen concentration values were calculated by adding Lycopodium tablets to weighed sediment samples. Pollen taxa were identified under an optical microscope at ×400 magnification and ×1000 magnification was used for critical identifications. Pollen sums were usually N 300 terrestrial pollen grains. Identifications followed Wang et al. (1995) and were aided by modern reference collections. Pollen percentages were calculated based on the total terrestrial pollen sum, while percentages of Pediastrum colonies were calculated based on the pollen sum plus Pediastrum counts. Pollen diagrams were plotted using Tilia 2.0.

4. Result

4.1. Chronology

Twelve AMS 14C ages of total organic carbon (TOC) and eight 230Th ages of halite in the upper 54.5 m of the sediment core of ISL1A were compared and discussed (Fan et al., 2014b). Three isochron 230Th 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 leachates (L),
residuals (R) and whole-samples (W). We employed 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 presented in Supplementary Table 1.

In this study, we first selected those ages in stratigraphic order to establish the age–depth framework in ISL1A (Fig. 2). By comparing $^{230}$Th ages of halite with AMS $^{14}$C ages of TOC in ISL1A, we found that the upper four AMS $^{14}$C ages from 4.65 to 30.29 m are in good agreement with the upper six $^{230}$Th ages from 0.35 to 32.29 m in this core. As presented in Fig. 2, the AMS $^{14}$C age (8661 ± 45 cal BP) of TOC at a depth of 4.65 m is close to $^{230}$Th ages (8.2 ± 0.3 ka) of halite at a depth of 0.35 m. Thus, we chose the $^{230}$Th ages (8.2 ± 0.3 ka) of halite at a depth of 0.35 m to establish the age of the top of the ISL1A core. Similarly, as the AMS $^{14}$C age 19.087 ± 65 cal BP at the depth of 13.01 m were in agreement with $^{230}$Th age 19.4 ± 0.8 ka of halite at a depth of 12.01 m, we chose the AMS $^{14}$C age for the ISL1A chronology framework. However, the AMS $^{14}$C age of TOC from 22.18 m and $^{230}$Th age of halite from 37.21 m in this core was obviously older than other from other ages between 20.22 and 46.00 m. Thus, we rejected those two ages. AMS $^{14}$C ages at 30.29 and 54.50 m were constant or younger with increasing depth. Therefore, we argue that AMS $^{14}$C ages of TOC and $^{230}$Th ages of halite in the upper 30 m of lacustrine sediments are reliable, while other AMS $^{14}$C ages of TOC between 30.29 and 54.50 m of lacustrine sediments are underestimated due, in part, to the contamination by underground water (Fan et al., 2014b). Due to the U content of TOC fraction in a sample from 85.78 m, which was found to be the lowest, and as such, the age of this sample was different from that of the other two samples obtained from 64.54 m and 98.90 m. Therefore, we selected two isochron $^{230}$Th ages of lake carbonates at 64.54 and 98.90 m to establish the age model (Fig. 2). In general, the age model in ISL1A is more reasonable.

4.2. Lithology

We describe the core sediment starting from the sediment surface using a centimeter scale. The top 17.73 m (22 ka) of the core sediments consist primarily of halite and halite with silt. The sediment between 17.73 and 21.73 m (22 to 25.3 ka) is marked by interbedded halite with a silt layer and silt. Between 21.73 and 31.57 m (25.3 to 32.5 ka) the sediments mainly consist of laminated gray silt-clay with two intercalated halite silt layers. The sediments consist of silt-rich halite and interbedded layers of halite silt between 31.57 and 47.36 m (32.5 to 50.2 ka). Between 47.36 and 74.29 m (50.2 to 71.6 ka), the sediments consist of laminated gray/green silty clay. A halite–gypsum silt layer is embedded in this silt-clay section between 49.59 and 51.59 m (52.1 to 53.2 ka). The lowermost section, from 74.29 to 102.03 m (71.6 to 94.6 ka) consists primarily of dark organic-rich clay.

4.3. Fossil pollen spectra

A total of 67 pollen types are identified from the core ISL1A at Qarhan Salt Lake. A summary percentage pollen diagram with 33 selected taxa is presented in Fig. 3. Herbs and shrubs pollen taxa are dominant in the majority of the samples, ranging from 72.7% to 99.1%, with an average of 93.3%. They are characterized by a high level of Artemisia (7.0 to 63.2%, average 31.5%), Chenopodiaceae (4.3 to 53.4%, average 23.9%) and Ephedra (0 to 26.6%, average 7.2%). However, Poaceae, Cyperaceae, Asteraceae, Nitraria are also important components, while Ranunculaceae, Fabaceae, Brassicaceae, Elaeagnaceae, Thalictrum and Polygonaceae are frequently present. Arboreal pollen is less dominant, with a mean of 3.0%. Artemisia dominates the pollen frequency, ranging from 0 to 13.4% (average 3.2%). In subzone B1, the amount of Artemisia decreases slightly and the amount of Chenopodiaceae increases moderately. The amount of Ephedra decreases moderately with a mean of 2.2%, and the amount of Nitraria rises slightly and exceeds 5% in the middle of subzone B2, with a mean of 3.0%. Ephedra decreases dramatically in this zone with a mean of 0.7% and the amount of Nitraria increases moderately and exceeds 5% in the middle of subzone B2, with a mean of 3.0%. Ephedra decreases dramatically in subzone B2, and appears in only few samples, that is, less than 1%.

4.3.2. Pollen zone B (72.6–61.7 ka; 76.34–63.49 m)

In zone B, the pollen spectrum is still dominated by herb polls Ar- temisia and Chenopodiaceae. Pollen zone B can be divided into two subzones B1 (72.6 to 66.3 ka; 76.34 to 69.02 m) and B2 (66.3 to 61.7 ka; 69.02 to 63.49 m).

In subzone B1, the amount of Artemisia and Chenopodiaceae are similar to those of subzone A1. Poaceae and Cyperaceae increase moderately in this zone, the former ranging from 4.6 to 15.7% (average 8.5%) and the latter from 0.5 to 19% (average 7.3%). The amount of Picea increases to 22.6% in the middle part of the zone with a mean of 5.4%. The amount of Pediastrum is still high and fluctuates between 2.0 and 81.3% (average 16.7%). The amount of Artemisia slightly decreases in subzone B2, while the amount of Chenopodiaceae increases moderately. The amount of Ephedra decreases moderately with a mean of 2.2%, and the amount of Nitraria rises slightly and exceeds 5% in the middle of subzone B2, with a mean of 3.0%. Pediastrum decreases dramatically in subzone B2.

4.3.3. Pollen zone C (61.7–51.2 ka; 63.49–48.70 m)

Zone C can be divided into two subzones C1 (61.7 to 55.8 ka; 63.49 to 55.14 m) and C2 (55.8 to 51.2 ka; 55.14 to 48.70 m). The pollen distribution changes in zone C are the most dramatic of the sequence.

In the subzone C1, Artemisia increases (average 35.2%) and Chenopodiaceae decreases moderately (average 18.1%). Poaceae decreases in this zone, ranging from 1 to 10.8% (average 5.6%), while the amount of conifer pollen Picea increases slightly, fluctuating from 0 to 16.7% (average 4.4%). Pediastrum also appears in this subzone, ranging from 0 to 13.4% (average 3.2%). The pollen subzone C2 is still dominated by Artemisia and Chenopodiaceae, the former fluctuating between 21.1 and 50% (average 31.8%) and the latter from 9.5 to 39.3% (average 21%). The amount of Poaceae ranges from 0 to 15.8% (average 6.1%), and Cyperaceae ranges from 1.5 to 10.6% (average 5.1%). Astereae increases in this zone and varies from 1.6 to 7.1% (average 4.5%). The abundance of Pediastrum increases dramatically in this zone as it does not appear in the lower part of subzone C2, swiftly rising to 90.5% in the upper part of subzone C2.

4.3.4. Pollen zone D (51.2–25.3 ka; 48.70–22.46 m)

Pollen zone D can be divided into two subzones D1 (51.2 to 43 ka; 48.70 to 40.77 m) and D2 (43 to 25.3 ka; 40.77 to 22.46 m).
Pollen zone D1 is dominated by *Artemisia* and Halophytic *Ephedra*. The former varies from 30.7 to 54.7% (average 44.3%) and the latter from 5.5 to 26.6% (average 16.2%). The amount of Chenopodiaceae decreases in this pollen zone, ranging from 4.3 to 18.8% (average 11.2%). The abundance of Cyperaceae decreases markedly in this zone, ranging from 1.2 to 7.4% (average 3.4%), as does Asteraceae, with a mean of 1.7%. Tree taxa are dominated by *Betula* (0.6 to 7.6%; average 2.8%), *Picea* (0 to 4.4%; average 1.7%) and Cupressaceae (0.4 to 4.4%; average 1.3%). *Pediastrum*, however, has disappeared from this zone. Pollen zone D2 is dominated by Chenopodiaceae and *Artemisia*, the former fluctuating from 18.3 to 53.4% (average 32.5%) and the latter from 7.0 to 44.1% (average 22.1%). The abundance of *Ephedra* has also declined in this zone, fluctuating between 0 and 11.3% (average 4.2%). In contrast, Poaceae and Cyperaceae increase in this zone, the former varying from 3.8 to 13.4% (average 8.3%) and the latter from 1.3 to 21.4% (average 6.0%). Arboreal pollen was sporadically present in this zone, including *Picea*, *Pinus*, *Betula* and Cupressaceae, with a mean value less than 1%.

4.3.5. Pollen zone E (25.3–11.3 ka; 22.46–4.32 m)

Pollen distribution and concentration are unstable in this zone with the amount of *Artemisia* varying from 7.1 to 58.5% (average 33.2%) and the amount of Chenopodiaceae varying from 7.0 to 41.5% (average

![Fig. 3. Pollen percentage diagram from core ISL1A, at Qarhan Lake, Qaidam Basin, NE TP.](image)
15.5%). The abundance of *Ephedra* is increases moderately, fluctuating between 1.6 and 16.1% (average 8.5%), Poaceae and Asteraceae exhibited regular presence with an average of 9.3% and 2.3%, respectively. The abundance of Cyperaceae decreases in this zone, varying from 0 to 4.7% (average 3.0%), while Ranunculaceae reaches its highest value, fluctuating between 0 and 17.4% (average 4.5%). Other sporadically present shrubs and herbs include *Nitraria*, Tamaricaceae, Ranunculaceae, Fabaceae, Elaeagnaceae, Caryophyllaceae and Brassicaceae. The abundance of arboreal pollen increases slightly in this zone with *Picea* ranging from 0 to 7.1 (average 1.8%), *Pinus* ranging from 0 to 5.2% (average 1.1%) and *Betula* ranging from 0 to 5.2% (average 1.3%).

5. Discussion

5.1. Proxy interpretation

The *Artemisia*/Chenopodiaceae (A/C) ratio has been commonly used as an indicator of effective moisture in arid and semi-arid regions where *Artemisia* and Chenopodiaceae are the dominant plants (El-Moslimmy, 1990; Liu et al., 1999; Tarasov et al., 1999; Zheng et al., 2008; Zhao et al., 2012b), as *Artemisia* requires more water than Chenopodiaceae during the growing season. Previous studies suggest that the A/C ratio can be used to distinguish the vegetation types in the regions of steppes, steppe deserts and deserts (Liu et al., 1999; Herzschuh et al., 2003; Luo et al., 2010; Zhao et al., 2012a). Our previous studies with respect to the northern TP have further demonstrated a positive relationship between the A/C ratio and mean annual precipitation (Zhao et al., 2008; Wei et al., 2011). However, soil salinity, pollen productivity and transportation, vegetation community composition and sample provenance (e.g. soil and lake sediments) affect the values of the A/C ratio in different vegetation zones (Zhao et al., 2012b). Thus, these factors may affect the reliability of the application of the A/C ratio in reconstructing vegetation and climate from lake cores. The Qarhan Salt Lake is a large enclosed lake, with many inflow rivers originating from the surrounding high mountains pouring into the lake. These inflow rivers carry many pollen grains from surrounding mountains and intrazonal plant communities into the lake. Therefore, the A/C ratio from lake cores may underestimate the degree of desertification because of the amount of *Artemisia* pollen from intrazonal plant communities being transported by water to the lake, which further complicates the understanding of the A/C ratio. Accordingly, attention should be paid to those situations when reconstructing the paleo-vegetation change of the Qaidam Basin.

*Pediastrum*, which belongs to the Chlorophyceae green algae, has been associated with the different latitudes of lake sediments throughout the world. Paleoenvironmental interpretations from records of *Pediastrum* in lake sediments are not straightforward as previous studies are interpreted as reflecting changes in temperatures and the nutritional status of the fresh water lakes (Rull et al., 2008; Mackay et al., 2013), fluctuations in water levels (Sylvestre, 2002; Chestprow-Lusty et al., 2005; Jiang et al., 2006; Sarmaja-Korjonen et al., 2006; Zhao et al., 2007; Gosling et al., 2008; Whitney and Mayle, 2012), as well as links to levels of pH and DOC (Weckström et al., 2010). As the *Pediastrum* genus contains many species of diverse ecological affiliations, its abundance in sediments reflects a variety of aquatic conditions (Whitney and Mayle, 2012). However, it has been confirmed that *Pediastrum* currently prefers fresh or brackish water, and it has not adapted to hyper-saline water conditions. Furthermore, it has been demonstrated that *Pediastrum* colonies increase with water depth in lakes of the northeastern Qaidam Basin (Zhao et al., 2007), and the survival depth of *Pediastrum* is considered to be no more than 15 m (Zheng et al., 2003; Zhang et al., 2004). Given that *Pediastrum* communities are found to vary among different lake habitats (Danielsen, 2010; Kaufman et al., 2010), we speculate that an increase in the salinity of the lake indicates a shrinking of the lake water body and a low lake level. In contrast, a decrease in salinity indicates a relatively high lake level. Thus, the salinity associated with lake level change of the Qarhan paleolake during the Late Pleistocene may be qualitatively inferred from the varying concentrations of *Pediastrum*. The alterations in lithostratigraphy provide a robust signal regarding the core that indicates a consistent whole-basin response to climate change. Halite was deposited during lake lowstands (i.e., dry climate), whereas clay-rich sediments were deposited during lake highstands (i.e., wet climate) when runoff and detrital input to the lake were relatively high. The increase of the clay content in the core sediment indicates an increase in precipitation and runoff, while, in contrast, the halite deposition layers indicate an arid climate. Thus, alternations between halite and clay deposition reflect dry–wet climate change cycles in the Basin.

5.2. Lithology-inferred climate

In the interval from 94 to 53.2 ka (102 to 51.59 m), the core sediment consisted of organic-rich silty clay. This suggests that conditions were relatively moist during the late MIS 5, 4, and early MIS 3. The first layer of gypsum and halite occurred at 53.2 to 52.1 ka (51.59 to 49.93 m) and may have been deposited at the same time as the Heinrich event 5 (Broecker et al., 1992; Guo et al., 1996), although the resolution of the IS1A chronology model is low and there is high dating uncertainty in this interval. The onset of evaporation during this period signifies lowstand of the lake and relatively dry conditions in the basin. The Qaidam Basin experienced rapid climate changes between 50.2 and 32.5 ka (47.36 to 31.57 m) as marked by the millennial-scale oscillations in halite and clay deposition. Clay-rich sediments deposited between 32.5 and 25.3 ka (31.57 to 22.46 m) suggests an increase in runoff of the lake under relatively wet climatic conditions. The amount of halite deposited in the core sediment since 25.3 ka indicates that the lake level decreased significantly in volume and saline compared to previous periods of the Late Pleistocene. And very arid conditions occurred in Qarhan Salt Lake during MIS2. However, Lithological sequences from Chaka Salt Lake of eastern edge of Qaidam Basin indicate that a clastic-dominated, freshwater lake was developed between 17.2 and 11.4 cal ka BP (Liu et al., 2008). A possible interpretation for this discrepancy is that evaporation caused by warmer temperature in Qarhan Salt Lake may have been sufficient to balance the quantity of melting glacial water and the precipitation, but it may not have been sufficient in Chaka Salt Lake.

5.3. Pollen inferred vegetation history and evolution of Qarhan paleolake

We use the pollen distributions in the IS1A core to infer the vegetation, environment and paleolake level changes of the Qarhan Salt Lake during the Late Pleistocene. In the pollen record, *Artemisia* and Chenopodiaceae were the most abundant taxa, though *Ephedra*, Poaceae, Cyperaceae, Asteraceae, *Nitraria*, Polygonaceae, Ranunculaceae and Fabaceae were also important components. The main problem in the use of the pollen data in paleo-vegetation and paleo-climate studies is defining the pollen representation and its provenance. Previous studies indicate that pollen grains of lake sediment are originated from whole drainage basin vegetation and that the local vegetation around the lake can, to a certain extent, influence the distribution of pollen in the lake (Xu et al., 2005; Shang et al., 2009). The Qarhan Salt Lake is a large enclosed lake that has many inflowing rivers, which combined with high winds common to the area, further complicates the interpretation of the fossil pollen of the core sediments. Previous studies (Herzschuh et al., 2010; Wei et al., 2011) of the northeastern TP show that in the temperate steppe zone, pollen spectra are dominated by *Artemisia* and Chenopodiaceae along with an abundance of Poaceae, Fabaceae and Asteraceae. In the desert zone, Chenopodiaceae and *Ephedra* dominate the pollen spectra, while there are relatively low percentages of *Artemisia*. However, *Nitraria* and *Calilgonum* are also frequently present in the pollen spectra. Cyperaceae and Poaceae are typically found in moister environments or around lakes (Sun et al., 2003; Shang et al., 2009). *Artemisia*, Chenopodiaceae and *Ephedra* have a high representation value, are strong pollen producers and have

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effective dispersal mechanisms, while Cyperaceae exhibits moderate relative representation ratios compared with Poaceae (Wei et al., 2011). Most previous studies indicate that percentages of Poaceae in arid and semi-arid China are normally <10% and are under-represented (Liu et al., 1999; Li et al., 2005). Other pollen taxa, including Asteraceae, Polygonaceae, Ranunculaceae, Fabaceae and Rosaceae, occurring in alpine meadows and temperate steppes, are also under-represented. Accordingly, it is concluded that the representativeness and provenance of the pollen taxa should be carefully considered.

5.3.1. 94 to 51.2 ka (late MIS 5, 4, and early MIS 3)

During the late MIS 5 (94 to 72.6 ka), the steppe vegetation dominated by Artemisia, Poaceae and Chenopodiaceae developed around the lake, and Ephedra shrub probably occurred in the foothills of the south-central Kunlun Mountain. Pediastrum was frequently present during this period, indicating relatively high lake levels and low values of salinity with respect to the lake in a relatively warm and wet climate. Interestingly, Chenopodiaceae, usually found in arid or salty-rich environments, shows a remarkable increase in abundance between 84.2 and 80.6 ka, suggesting that a Chenopodiaceae dominated steppe-desert developed around the lake, which coincided with a dry climate in the Qaidam Basin.

During early MIS 4 (72.6 to 66.3 ka), the vegetation consisted of Artemisia dominated steppe. The amount of Poaceae and Cyperaceae increased moderately, and Pediastrum proliferated during this period, suggesting lower levels of salinity and relatively higher lake levels. Meanwhile, Picea, which typically found in wet and cool climate, commonly occurring at the elevations from 2500 to 4000 m a.s.l., mean annual temperature (MAT) from −1 to 10 °C and MAP from 450 to 850 mm, reached its highest values (22.5%) (Lu et al., 2004, 2008). The conditions further indicate that the sparse forest likely occurred in the nearby mountains. Accordingly, the pollen composition during this period was slightly different from that of the late MIS 5, thus suggesting slight differences in climatic conditions between these two periods, with a cooler, wetter climatic condition dominating during this period.

Vegetation and climate changed dramatically between 66.3 and 61.7 ka as the steppe desert vegetation dominated by Chenopodiaceae and Artemisia developed in the central eastern Qaidam Basin, while Pediastrum disappeared during this period. These events suggest a relatively high level of salinity in the lake and low lake levels due to a relatively cold, dry climate. Steppe vegetation dominated by Artemisia, Chenopodiaceae and Poaceae occurred again during the late MIS 4 and early MIS 3 (61.7 to 51.2 ka). Patches of deciduous forest dominated by Betula and Populus probably occurred in the mountain valleys of the basin during this period, while Pediastrum was also continuously present during this time, thus indicating a relatively low level of salinity and higher lake levels.

5.3.2. 51.2–25.3 ka

The middle MIS 3 is marked by the expansion of Artemisia and Ephedra dominated vegetation and the disappearance of Pediastrum in the core sediment. This coincides with a salt-bearing deposit in the core, which suggests lowstand of the lake and relatively dry climate conditions in the core since 51.2 ka. A pollen assemblage of Artemisia and Ephedra is rarely found in modern samples of TP because the ecological habitats of Artemisia and Ephedra are different. Artemisia is dominant in temperate steppe zones in northern China, while Ephedra frequently appears in arid and semiarid areas of northwestern China and the Qaidam Basin (Li et al., 2005; Zhao and Herzschuh, 2009; Wei et al., 2011). In this stage, high values of Artemisia pollen probably ascribed to dry climatic conditions led to lower lake levels and riverbed exposure, which are suitable habitats for the colonization of an Artemisia dominated community. The rivers then transported the Artemisia pollen to the lake. The expansion of an Ephedra shrub-steppe during the glacial stage was also recorded in Lake Urmia, NW Iran, and the analog of Ephedra and Artemisia dominated vegetation type in the present was reported from the foothills of Iran in an arid area (Djamali et al., 2008). Thus, herein we infer that the relatively dry climate at that time led to increased evaporation and a drop in effective humidity, thus promoting the development of Ephedra because the drop in the lake level led to a low water table in the basin. Ephedra dominated shrub-desert vegetation developed in the foothills around the lake during the middle MIS 3 (51.2 to 43 ka), while Chenopodiaceae dominated desert vegetation began to appear around the lake as early as 43 ka. The increase in Chenopodiaceae may, therefore, reflect lower lake levels and the resultant extension of suitable habitats for the colonization of halophilous Chenopodiaceae. Nevertheless, the climate improved between 32.5 and 25.3 ka, and Artemisia was the dominant desert steppe vegetation growing in the vicinity of the lake. The deposition of an organic-rich silty clay corresponded with the higher A/C ratio in the core sediments, thus suggesting higher lake levels, which then diluted the water body from a hyper-saline concentration to a brackish concentration. However, it is further noted that the range of lake expansion was limited during this stage.

5.3.3. 25.3–11.3 ka (Late-glacial)

A detailed picture of late glacial vegetation dynamics cannot be given herein because of the low resolution of this stage. However, a decline in pollen concentration is likely a signal of a cold, dry climatic condition during this stage. Desert vegetation dominated by Chenopodiaceae and Ephedra probably developed in the basin, and relatively high percentages of Artemisia, likely due to seasonal river flows, transported the Artemisia pollen from the riverbeds to the lake. This corresponded with the deposition of the amount of halite in the core sediment. At the same time, a lower input of terrigenous siliciclastic sediments was the result of the drying up of the streams, and accordingly, the Qarhan Salt Lake finally evolved into a dry playa by the end of MIS 2.

5.4. Regional correlation and possible mechanism

In order to better understand Qarhan Salt Lake evolution and its response to regional and global climatic changes, we made a comparison between the pollen record of Qarhan Salt Lake and other palaeoclimatic proxy records in the TP, as well as regional and global climate changes (Fig. 4). During the interglacial MIS 5 and inter-stadials MIS3c and MIS3a, Artemisia dominated steppe vegetation developed in the central eastern basin. Meanwhile, Pediasrum also appeared continually during the late MIS 5 and MIS3c in the core sediment, indicating a relatively wetter climate and high lake level. Clay-rich sediments were deposited during MIS 5, MIS3c and MIS3a in the core sediment, which also reflected an increase in precipitation and runoff in the Basin. This conclusion has been verified by geomorphic and chronometric evidence at Galhai, Tonson and Qinghai Lakes on the NE TP. Geomorphic and optically stimulated luminescence (OSL) ages demonstrate that higher lake level periods of the Galai Lake occurred at 85 to 72 and 63 to 55 ka, which correspond to late MIS 5 and early MIS 3 (Fan et al., 2010, 2012). Meanwhile, a high lake level of Tonson Lake during MIS 3 was recorded at 31 ka (Fan et al., 2012). Furthermore, a large number of high paleo-shorelines have been identified along the southern margin of Qinghai Lake, and OSL dating results suggest that high lake levels that are ~20 to 66 m above that of the modern lake occurred at ~110–75 ka (Madsen et al., 2008; Liu et al., 2010; Rhode et al., 2010). Pollen record from Zoige Basin of eastern Tibetan Plateau indicate that coniferous forest expanded in the catchment of the Zoige Basin during last interglacial and some periods of last glacial (Chen et al., 1999). Palaeoclimatic proxy records from ice-cores, stalagmites and Chinese loess during the late Pleistocene also allow us to speculate on the causes and teleconnections of global climate changes (Fig. 4). The δ18O curve of the Guliya ice-core (Thompson et al., 1997) from the west Kunlun Mountains on the northern margin of the TP indicates that higher regional temperatures were recorded during MIS5, MIS3c and MIS3a. These climate changes are consistent with
Glacial cycles recorded in Northern Hemisphere ice-cores (Stuiver and Grootes, 2000). In addition, loess archives provided similar evidence, such as fine grain sizes accumulated during MIS5, MIS3c and MIS3a (Ding et al., 1999), thus, implying a strengthening in intensity of the Asian summer monsoon (ASM) and a declining winter monsoon circulation. It was also confirmed by δ¹⁸O of stalagmites recorded in the East Asian area (Wang et al., 2001, 2008). The Qarhan Salt Lake is located in the eastern Qaidam Basin of the NE TP, just beyond the northern limit of the modern ASM influence (Winkler and Wang, 1993). In this study, while we cannot confirm that the front of intensified ASM westward penetration brought some precipitation to the southeastern edge of lake catchments of Qarhan paleolake during the last interglacial, reconstructed climate record indicate that there was high humidity in central eastern Qaidam Basin during these stages. These same conditions were also present in Qinghai Lake, which is near Qaidam Basin. Accordingly, more climate records are needed to identify the causes of the climate changes during the last interglacial in the basin.

Climate and lake level during early MIS4 differ little from other records, as a relatively high percentage of Artemisia, Picea and Pediastrum suggest cool and relatively wet climatic conditions and high lake levels. This may be related to the relatively high precipitation and low evaporation rates during this period. During late MIS4, Pediastrum disappeared and the A/C ratio decreased in the core sediment, indicating a colder, dryer climate in the central eastern Qaidam Basin. Chenopodiaceae dominated the desert steppe developed around the lake during this stage. The GISP2 δ¹⁸O value decreased with small

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**Fig. 4.** Comparison of late Pleistocene pollen records from core ISL1A with other proxy records. (A), Insolation at 35°N averaged over the months of June, July and August. (B, C, D, E), Pollen records of core ISL1A in the dashed blue box. (F), Mean grain size of Chinese Loess Plateau (Ding et al., 1999). (G), δ¹⁸O of Hulu cave stalagmites (Wang et al., 2008). (H), δ¹⁸O of Guliya ice-core (Thompson et al., 1997). (I), δ¹⁸O of Greenland ice-core (Stuiver and Grootes, 2000).
fluctuations during late MIS4, implying decreasing temperatures (Stuiver and Grootes, 2000). A cold, dry climate is also suggested by a loess deposition in Chinese loess sections during this period (Guo et al., 1996). The extinction of Pediastrum and expansion of Ephedra-shrub desert occurred simultaneously with halite bearing deposits in the core sediments during MIS3b, indicating a dry climatic condition. This result was confirmed by the ostracode assemblages of a Luanhaizi Lake core from the Qilian Mountains, which indicated cold and dry conditions prevailed and a high sequence of playa deposits accumulated after 45 ka (Mischke et al., 2005). The pollen record from Lanzhou also indicates that arboreal pollen decreased significantly in abundance at 46.0–39.0 ka (Jiang et al., 2011). A cold, dry climate was also recorded during MIS2 based on the decline of pollen concentration and the deposition of halite in the core sediment. Previous studies on Pleistocene glaci- bers demonstrated that a Late Pleistocene glacier in northeastern TP advanced during MIS3b and MIS2 (Owen et al., 2003; Owen et al., 2006; Ou et al., 2014). Meanwhile, the mean moisture values decrease noticeably in central Asia after 2.7 ka BP (Herzschuh, 2006). From MIS 3 to MIS 2, a climate decline can be observed with the gradual coarsening of eolian grain size (Chen et al., 1997). The δ18O value of Hulu stalagmites also indicate a decreasing moisture trend during MIS3b and MIS2 under lower NHSI (Wang et al., 2008). The pollen record from the East China Sea show that subtropical trees were notably fewer during the Late Glacial Maximum (LGM) and the terminal period of MIS 3, suggesting a colder, dryer climate (Zheng et al., 2011). During the last glacial, the ASM was weak and Westerlies were dominant on the Tibetan Plateau (Fan et al., 2012). Thus, the weak NHSI account for cold and dry climatic conditions in the study area during glacial stages.

6. Conclusions
The pollen diagrams from Qarhan Salt Lake are the longest record of past vegetation from the central eastern Qaidam Basin in NE TP. During the late MIS5, early MIS4 and early MIS3, organic-rich clay lacustrine deposits and the frequently presence of Pediastrum reveal that the Qarhan paleolake had a relatively high lake level and oligohaline water conditions. Artemisia and Chenopodiaceae dominated steppe vegetation developed around the lake, thus indicating a warmer and wetter climate. During late MIS4, Chenopodiaceae dominated the desert steppe developed around the lake, and Pediastrum disappeared in the core sediment, reflecting dryer climatic conditions and a low lake level. Ephedra-shrub desert developed during middle MIS3, which coincided with the disappearance of Pediastrum and the salt-bearing deposit in the core sediment, reflecting dryer climatic conditions. The predominance of Chenopodiaceae in the halophytic communities occurred around the lake since 43 ka. However, the climate was much less severe between 32.5 and 25.3 ka, as inferred from the clay-rich sediment deposition in the core sediment while Pediastrum disappeared around the lake. Pollen concentrations obviously declined since 25.3 ka, based on the amount of halite deposited in the core sediment, thus suggesting cold and dry climatic conditions in the Qaidam Basin. A regional correlation between the pollen record of the core ISL1A and other climate records suggest that runoff and effective humidity increased under higher NHSI during the late MIS5, MIS3c and MIS3a, while weak NHSI accounts for cold and dry climatic conditions during the glacial stages in the study area.

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Appendix A. Supplementary data
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References