

Water salinity and productivity recorded by ostracod assemblages and their carbon isotopes since the early Holocene at Lake Qinghai on the northeastern Qinghai–Tibet Plateau, China



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ABSTRACT

Lake Qinghai, the largest saline lake in China, is a closed-basin lake with a salinity of 16 g/L and is situated in the sensitive semi-arid zone between the Asian monsoon-controlled area and the westerly jet stream-influenced area. With the support of the International Continental Drilling Program (ICDP), Lake Qinghai was drilled in 2005 using the ICDP GLAD800 drilling system. Two ostracod species, i.e., *Limnocythere inopinata* and *Eucypris mareotica*, were found only in the upper 5.15 m of the drilled core 1F, covering 12 ka, where the depths of 5.15 to 3.15 m (12.0–7.4 ka) are dominated by *E. mareotica* and the depths of 3.15 to 0 m (7.4 ka–present) are dominated by *L. inopinata*.

The presence of the ostracod *Eucypris mareotica* was related to the high salinity of the water (exceeding 30 g/L), and the dominant species of ostracod (*Limnocythere inopinata*) was related to the brackish water (3–16 g/L) in the Lake Qinghai area (Li et al., 2010). The changes in the carbon isotope in the modern ostracod shells were related to the water salinity and productivity on the lake bottom in Lake Qinghai (Li et al., 2012). On this basis, this study evaluated the changes in lake salinity and productivity and their relation to climatic change using changes in the relative abundances of ostracod fossil species assemblages and the stable carbon isotope in ostracod shells from core 1F and other published data (e.g., total organic carbon content, $\delta^{13}\text{C}_{\text{TOC}}$ and ice core $\delta^{18}\text{O}$).

The single occurrence of ostracod *Eucypris mareotica* and the highest average $\delta^{13}\text{C}$ values (-0.2‰) in their shells indicated that the lake salinity and productivity were very high, a phenomenon that was related to the high temperature and low lake level (caused by intense evaporation even though the precipitation increased sharply) in the early Holocene. The decreased abundance of ostracod *E. mareotica* and the lowest average $\delta^{13}\text{C}$ values (-2.0‰) in ostracod shells showed that the lake salinity and productivity decreased because of the increased lake level and decreased temperatures in the middle Holocene. Finally, the lake level decreased, but the water salinity and the lake productivity gradually increased because of the high E/P ratio related to the increased temperature in the late Holocene.

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1. Introduction

Ostracods, which are microcrustaceans with calcite valves (exuviate eight times during their life), are widely distributed in lakes, and the valves of different instars and adults are present in lake sediments. In recent decades, ostracod shell geochemistry and isotope chemistry have increasingly been applied to reconstruct past variations in the changes in the evaporation and precipitation (Holmes, 2001; Schwalb, 2003; Dettman et al., 2005; Holmes et al., 2007; Liu et al., 2007; Mischke et al., 2010; Escobar et al., 2012), salinity (Chivas et al., 1986; Holmes, 1996; De Deckker et al., 1999), and temperature (Zhang et al.,

1989, 1994; Xia et al., 1997; Hammarlund, 1999) of lake waters that are associated with changes in regional environments.

The $\delta^{18}\text{O}$ of ostracod shells depends primarily on both the $\delta^{18}\text{O}$ and the temperature of the host water. Oxygen isotope values in ostracod shells are also affected by salinity changes (Liu et al., 2009) and 'vital offsets' (von Grafenstein et al., 1999; Keatings et al., 2002; Decrouy et al., 2011). The $\delta^{18}\text{O}$ in ostracod shells has been explained by the variation in temperature or the evaporation/precipitation (E/P) ratio related to climatic change in different regions. Typically, the $\delta^{18}\text{O}$ of lake water is closely related to the E/P ratio in arid/semi-arid regions (Lister et al., 1991; Xia et al., 1997; Holmes et al., 2007), although the $\delta^{18}\text{O}$ of lake water can be altered by various factors such as source water, temperature, and humidity in the lake area (Ricketts et al., 2001). Therefore, the $\delta^{18}\text{O}$ in ostracod shells is influenced by changes in the E/P ratio in closed basin lakes and is related to the paleoclimatic changes in arid/semi-arid regions

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(Henderson et al., 2003; Holmes et al., 2007). The $\delta^{13}\text{C}$ of ostracod shells is controlled primarily by dissolved inorganic carbon (DIC) in the ambient water (von Grafenstein et al., 1999). Generally, the carbon isotopic composition of lake DIC is controlled by three predominant factors: the isotopic composition of inflowing waters, the CO_2 exchange between the atmosphere, and the lake water and the photosynthesis/respiration of aquatic plants within the lake (Oana and Deevey, 1960; Quay et al., 1986; Hollander and McKenzie, 1991; Zhang et al., 1995; Miyajima et al., 1997; Wang and Veizer, 2000; Schwalb, 2003). The carbon isotopic composition of ostracod shells has been used as a proxy for groundwater input, changes in the vegetative cover of the watershed, and changes in limnological conditions, including biological productivity (Fritz et al., 1975; Talbot, 1990; Schwalb et al., 1999; Mayer and Schwark, 1999; Valero-Garcés et al., 1995), atmospheric CO_2 exchange (Schwalb et al., 1999; Leng and Marshall, 2004; Sklyarov et al., 2010; Decrouy et al., 2011), and salinity (Sampei et al., 2005) in different areas. Carbon isotope concentrations in ostracod shells have rarely been fully exploited as proxies because their interpretation is considered difficult to assess, and only a few coupled oxygen and carbon isotope records span the entire postglacial evolution of the studied lake (Mischke et al., 2010; Escobar et al., 2012; Schwalb et al., 2013).

Lake Qinghai, the largest saline lake in China, is a closed-basin lake with a salinity of approximately 16 g/L that is situated in the sensitive semi-arid zone between the Asian monsoon-controlled area and the westerly jet stream-influenced area (Shen et al., 2005; Henderson et al., 2010). This region is highly sensitive to global climate change. The oxygen isotopic composition of ostracods has been used to indicate changes in the paleotemperature, effective humidity, water level, effective precipitation, and monsoon pattern (Zhang et al., 1989; Lister et al., 1991; Zhang et al., 1994; Henderson et al., 2003; Liu et al., 2007). The oxygen isotopic composition of ostracods from a 12 ka core has been used to indicate relative changes in paleotemperature (Zhang et al., 1989). Based on that same core, Lister et al. (1991) suggested that effective humidity (evaporation/input water ratio) controls the $\delta^{18}\text{O}$ values of lake water and its corresponding ostracods. A study of a short core covering approximately 300 years showed that the oxygen isotopic composition of

ostracods can be used to evaluate the changes in water level and effective precipitation (Henderson et al., 2003). Recently, new data from two studies showed that the oxygen isotopic composition of ostracods can be used as a proxy for the strength of the Asian monsoon (Liu et al., 2007; An et al., 2012). In addition, the geochemical processes that influenced the recent environment of Lake Qinghai and the significance of the ostracod $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ have been studied using the ostracods collected from the surface sediment (Liu et al., 2009; Li et al., 2012). The results from the previous studies showed that changes in the ostracod $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ values have the potential to provide an indirect indication of changes in water salinity (Liu et al., 2009; Li et al., 2012).

Although the paleoclimatic implications of the oxygen isotope in ostracod shells during the Holocene in Lake Qinghai have been discussed in many previous studies (Zhang et al., 1989; Lister et al., 1991; Henderson et al., 2003; Liu et al., 2007; An et al., 2012), the carbon isotopes in ostracod shells have rarely been used as proxies for paleoenvironmental change in the past studies. Therefore, we particularly emphasize the factors controlling the occurrence of ostracods and the carbon isotopic compositions of their shells in this study. The carbon isotopic differences between two ostracod species (*Eucypris mareotica* and *Limnocythere inopinata*) are then presented for Lake Qinghai. Based on our findings and previous work, the hydrochemical and hydrographic implications of ostracod assemblage and the ostracod carbon isotopes from a 12 ka core are described compared with the ostracod oxygen isotopic data in Lake Qinghai.

2. Study region

Lake Qinghai ($36^\circ 32' - 37^\circ 15' \text{N}$, $99^\circ 36' - 100^\circ 47' \text{E}$) lies in a closed intermontane basin on the Qinghai Tibet Plateau and has an area of $\sim 4260 \text{ km}^2$, a maximum water depth of 27 m, and an average water depth of 21 m (Fig. 1). The mean annual precipitation, annual temperature, and annual evaporation are 400 mm, -0.1°C , and 800–1000 mm, respectively (Henderson et al., 2003; Liu et al., 2008). Rivers draining the surrounding area provide a major water source for Lake Qinghai. Meltwater from the surrounding mountain glaciers accounts for only

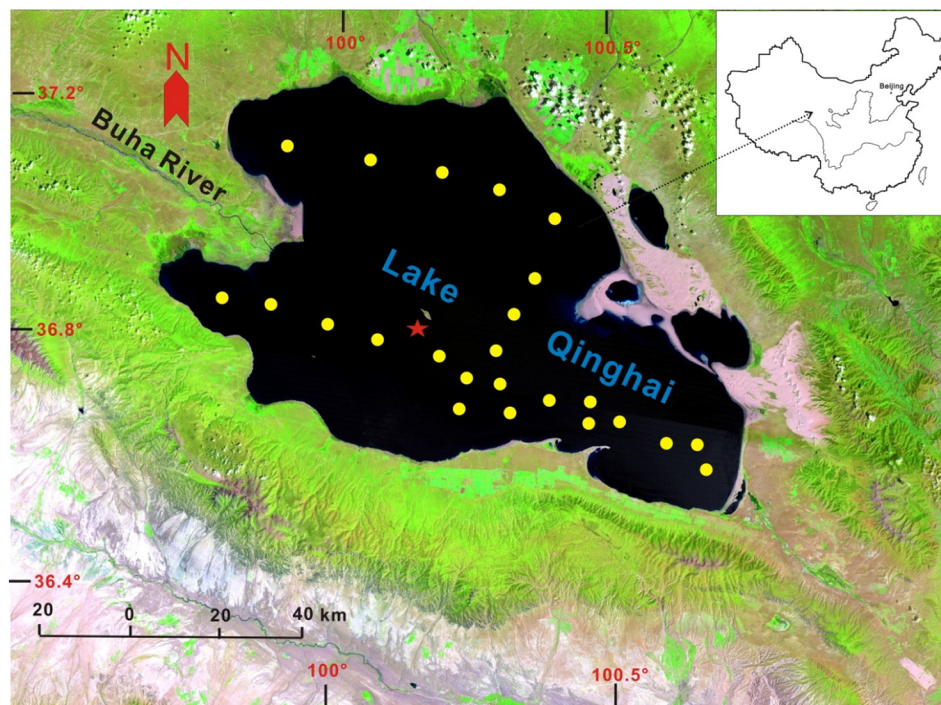


Fig. 1. Map of Lake Qinghai and its surroundings. The red five-pointed stars show the 1F and 1A core sites, and the yellow solid circles represent the sites where surface sediments were collected to study the distribution of ostracod in the lake, as reported by Li et al. (2010, 2012). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

0.3% of the total runoff and does not appear to have made a significant contribution since the early Holocene (Lister et al., 1991; Henderson et al., 2010). These source waters together with evaporation represent the dominant control of lake salinity in Lake Qinghai, and an excess of evaporation over precipitation has produced a brackish/saline alkaline lake with a salinity of 16.0 g/L and pH of 9.2 (Liu et al., 2009). The surface water temperature during the summer is usually higher (approximately 13–16 °C) than the temperature of the bottom water (4–6 °C) because of temperature stratification during the summer (Lister et al., 1991).

Two ostracod species, i.e., *Limnocythere inopinata* and *Eucypris mareotica*, are found only in modern Lake Qinghai (Li et al., 2010; Li and Jin, 2013). *Limnocythere inopinata* can crawl only on the surface sediments, but *E. mareotica* can swim up to the surface sediment, according to our observations and published data (Yin et al., 1999; Meisch, 2000). The ostracods *E. mareotica* and *L. inopinata* tend to be present during the late spring to early autumn on the lake bottom (Henderson et al., 2003), and *E. mareotica* was hatched later than *L. inopinata*, according to our observations and reported data (Li and Jin, 2013). The two species can live from late spring to late autumn, with a life cycle of approximately 30 days for *L. inopinata* and 45 days for *E. mareotica* (Li and Liu, 2010a,b; Li and Jin, 2013).

At present, the biomass content in the water of Lake Qinghai is much lower than it is in the bottom sediment (Yang and Wang, 1997). Biological investigations have identified approximately 45 genera of algae and eight species of vascular plants from the bottom sediment in Lake Qinghai (Yang and Wang, 1997). *Cladophora*, the dominant genus of algae, is distributed on the lake bottom in deep water; broken *Cladophora* usually float on the surface (Yang and Wang, 1997). However, submerged plants are distributed only in estuaries and in shallow water along the shores. Moreover, the biomass of these species is difficult to quantify (Yang and Wang, 1997). The vegetation surrounding Lake Qinghai is specific to semi-arid to arid climates and high altitudes, consisting primarily of alpine meadows and steppe grasses. The terrestrial vegetation species (grasses) in the Lake Qinghai area are dominated by *Oxytropis ochrocephala*, *Agropyron* sp., *Kobresia* sp., *Poa* sp., *Achnatherum* sp., and *Stipa* sp. (Duan and Xu, 2012; Liu et al., 2013). In general, the $\delta^{13}\text{C}_{\text{org}}$ values of the terrestrial vegetation indicate that terrestrial plants are dominated by C_3 plants in the Lake Qinghai area (Liu et al., 2013).

3. Materials and methods

3.1. Materials

With the support of the International Continental Drilling Program (ICDP), Lake Qinghai was drilled in 2005 using the ICDP GLAD800 drilling system. The longest and highest quality parallel drilling cores (1F and 1A), which covered the climatic change history since the last glacial maximum, were obtained from the center of the southwestern sub-basin with a depth of approximately 27 m, shown as the red five-pointed star in Fig. 1 (An et al., 2012). In this study, the subsamples from the upper 5.15 m of the 1F core were used for ostracod collection at 5-cm intervals. The TOC content data and the organic carbon isotopes of the 1F core are from the published data of An et al. (2012) and Liu et al. (2013). In addition, the water salinity that was inferred using the ostracod Sr/Ca data from the QH85-A core (covering approximately 12 ka) was used to support our interpretation of varied salinity levels in Lake Qinghai (Zhang et al., 1989, 1994).

3.2. Methods

3.2.1. Sediment dating

A total of 65 samples were used for ^{14}C dating of the 1F and 1A cores (1Fs) (An et al., 2012). Among these samples, 52 samples were of total organic content (TOC) from bulk sediments from 1Fs, 6 Ruppiaceae seeds (from 4.16 to 4.97 m of the 1F core), and 7 plant remains (from 6.70 to 8.38 m of the 1F core) (An et al., 2012). Except for anomalous

data, 57 dates were used to establish the age model for 1Fs after calibration using CALIB 51038 and CALPAL2007 (Weninger et al., 2007). The radiocarbon dating of the sediment samples from 57 stratigraphic levels of 1Fs reveals that the 1Fs' core covered approximately 32 ka (An et al., 2012). More detailed information can be found in An et al. (2012). Using the age model reported by An et al. (2012), the calculated age of the upper 5.15 m of the 1F core covered approximately 12 ka in this study.

3.2.2. Ostracod analysis

The wet sediment samples were soaked in deionized water for approximately 24 h and then wet-sieved with a 250-mesh sieve. Material remaining on the sieve was dried at room temperature for the collection of ostracods. Empty ostracod shells were then picked using a fine brush and deionized water; the adult ostracods cleaned with deionized water according to the reported method (Li et al., 2007) were used for isotope analysis in this study.

All ostracod samples (approximately 4 to 6 shells of *Eucypris mareotica* and 10 to 14 shells of *Limnocythere inopinata* per sample) were analyzed for $^{13}\text{C}/^{12}\text{C}$ and $^{18}\text{O}/^{16}\text{O}$ at the Institute of Earth Environment CAS using an isotope ratio mass spectrometer (MAT-252) with an automated carbonate preparation device (Kiel II). The results are expressed in delta (δ) notation relative to the V-PDB standard. Repeated analyses of laboratory standard carbonates (TTB1) with known $\delta^{13}\text{C}$ values were carried out daily to ensure instrumental accuracy. The analytical error of the laboratory standard was approximately $\pm 0.20\%$ for $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$.

4. Results

Two ostracod species, i.e., *Limnocythere inopinata* and *Eucypris mareotica*, are found only in the upper 5.15 m of 1F, covering 12 ka, where depths of 5.15 to 3.15 m (12.0–7.4 ka) are dominated by *E. mareotica* and depths of 3.15 to 0 m (7.4 ka–present) are dominated by *L. inopinata* (as shown in Fig. 2). For some depths, *L. inopinata* and *E. mareotica* are present together in the 1F core (Fig. 2). From 12 ka to 7.4 ka, *E. mareotica* is the predominant species in the 1F core (Fig. 2). However, the percentage of *E. mareotica* decreased sharply at 7.4 ka, and *L. inopinata* was first present and gradually became the dominant species in the core at this time stage (Fig. 2). From 7.4 ka to 3.5 ka, *E. mareotica* and *L. inopinata* coexisted during some periods in the core. However, *E. mareotica* was the dominant species between 6.7 ka and 5.8 ka in the 1F core (Fig. 2). In addition, *E. mareotica* was almost absent after approximately 5.5 ka, but they were abruptly absent at approximately 3.5 ka in the 1F core (Fig. 2). From 3.5 ka to the present, *L. inopinata* was the dominant species; limited occurrences of *E. mareotica* were found. Moreover, the abundance of *E. mareotica* increased sharply at 3.0 ka, 1.0 ka, and 0.1 ka in the core (Fig. 2).

From 12 ka to 7.4 ka, the $\delta^{13}\text{C}$ values of *Eucypris mareotica* varied from -2.01% to 2.43% , and the average $\delta^{13}\text{C}$ value was approximately -0.2% in the 1F core (Fig. 2). In this period, the $\delta^{13}\text{C}$ values of *E. mareotica* first became low and then increased after approximately 9.2 ka (Fig. 2). From 7.4 ka to 3.5 ka, the $\delta^{13}\text{C}$ values of *Limnocythere inopinata* varied from -3.66% to 0.02% with large fluctuation, and the $\delta^{13}\text{C}$ values of *E. mareotica* were 0.29% and 1.49% at 6.7 ka and 5.8 ka, respectively (Fig. 2). The average $\delta^{13}\text{C}$ value was approximately -2.00% in the middle Holocene (Fig. 2). From 3.5 ka to the present, the $\delta^{13}\text{C}_{\text{ostracod}}$ values gradually increased from -1.94% to 0.14% , and the average $\delta^{13}\text{C}$ value was approximately -0.97% (Fig. 2). Table 1 shows that the $\delta^{13}\text{C}$ of the benthic *E. mareotica*, which can swim up to the surface sediments, was consistently higher than the $\delta^{13}\text{C}$ of the benthic *L. inopinata* (the average $\delta^{13}\text{C}$ difference between these two species was approximately 2.17%) when these two species were present together in core 1F. This difference is similar to the results of the past studies on the carbon isotopic differences between *E. mareotica* and *L. inopinata* from modern surface sediments and other cores (QH-85A) in Lake Qinghai (Li et al., 2007, 2012).

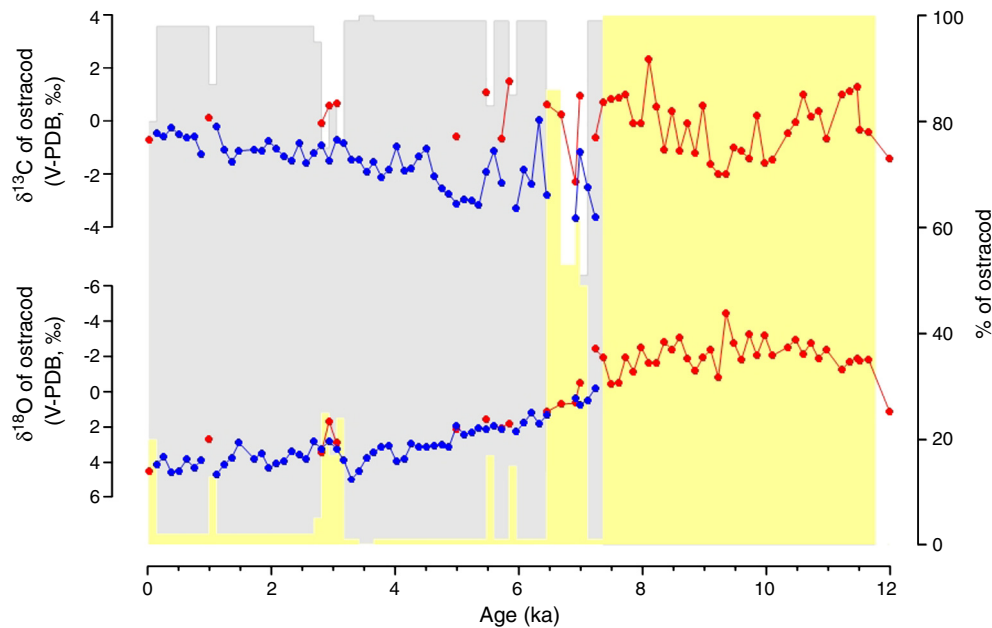


Fig. 2. Ostracod relative abundance percentages (the yellow area represents *E. mareotica*, and the gray area represents *L. inopinata*) and the $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ variations of ostracod shells that were recorded by the 1F core since 12.0 ka in Lake Qinghai (the blue solid circles represent isotopic data of *L. inopinata*, and the red solid circles represent isotopic of *E. mareotica*). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

The $\delta^{18}\text{O}$ values of *Eucypris mareotica* varied from -4.47% to 1.13% , and the average $\delta^{18}\text{O}$ value was approximately -2.00% in the 1F core in the early Holocene (Fig. 2). In addition, the $\delta^{18}\text{O}$ values of *E. mareotica* also first became low and then increased after approximately 9.2 ka (Fig. 2). From 7.4 ka to 3.5 ka, the $\delta^{18}\text{O}$ values of *Limnocythere inopinata* gradually varied from -0.21% to 3.94% , and the $\delta^{18}\text{O}$ values of *E. mareotica* were 0.70% and 1.77% at 6.7 ka and 5.8 ka, respectively (Fig. 2). The average $\delta^{18}\text{O}$ value was approximately 2.28% from 7.4 ka to 3.5 ka in the 1F core (Fig. 2). From 3.5 ka to the present, the $\delta^{18}\text{O}_{\text{ostracod}}$ values gradually increased from 2.69% to 4.96% , and the average $\delta^{18}\text{O}$ value was approximately 3.84% (Fig. 2).

5. Discussion

5.1. $\delta^{13}\text{C}_{\text{ostracod}}$ as a proxy of changes of productivity

As shown in the results, the ostracod $\delta^{13}\text{C}$ values in *Eucypris mareotica* were consistently higher than the $\delta^{13}\text{C}$ values of *Limnocythere inopinata* when these species were present together in core 1F. The $\delta^{13}\text{C}$ of ostracods is usually thought to be mainly controlled by the $\delta^{13}\text{C}$ of the dissolved inorganic carbonate (DIC) in ambient lake water (von Grafenstein et al., 1999), although the $\delta^{13}\text{C}$ of ostracod valves may be

related to the pH of the surrounding water (Keatings et al., 2002; Li and Liu, 2010a). Our previous studies have shown that carbon isotopic compositions of ostracod shells (*E. mareotica*) may not be in isotopic equilibrium with the water DIC under culture conditions (Li and Liu, 2010a), and *L. inopinata* can form their shells under non-equilibrium carbon isotopic conditions (approximately 2–3‰ lower than the equilibrium values caused by incomplete valve calcification, micro-habitat effects and ‘vital offsets’) (von Grafenstein et al., 1999; Decrouy et al., 2011). Moreover, lower $\delta^{13}\text{C}_{\text{ostracod}}$ values have been interpreted as ‘vital offsets’ related to the biomineralization processes (Decrouy et al., 2011).

Pérez et al. (2013) suggested that the oxygen and carbon isotopes in ostracod shells were also influenced by their living styles (benthic, nektobenthic, or swimmers). *Eucypris mareotica* can swim up to the surface sediment, but *Limnocythere inopinata* commonly crawls on the surface sediments. The $\delta^{13}\text{C}_{\text{DIC}}$ values of water in the sediment may frequently be affected by CO_2 fluxes from aerobic respiration and the anaerobic degradation of organic matter and may thus have more negative values. Therefore, the negative $\delta^{13}\text{C}_{\text{DIC}}$ values of water on the sediments may result in the low $\delta^{13}\text{C}$ values of the *L. inopinata* living on the lake bottom. However, *E. mareotica* can swim up to the surface sediment, so the carbon isotope in their shells was infrequently affected by the CO_2 fluxes deleted in ^{13}C from aerobic respiration and the anaerobic degradation of organic matter and may thus have more enriched values. Thus, the carbon isotopic differences between these two species may be affected by different carbon fractionation, ascribed to ‘vital offsets’, and their different habitats (living styles).

The carbon isotopic difference between *Eucypris mareotica* and *Limnocythere inopinata* may also be affected by the carbon isotopic variation of DIC related to the time of ostracod occurrence and the composition of their microhabitats in Lake Qinghai. As previously established, the species distribution of these ostracods is related to variations in water salinity in the Lake Qinghai area (Li et al., 2010), but the occurrence of ostracods may be related to the water temperature, according to previous reports and our observations (Santamaria et al., 1992; Yin et al., 1999). Generally, *L. inopinata* tends to be present during the late spring to early autumn (Henderson et al., 2003). The results of a new study show that the maximum abundance of *L. inopinata* was present in mid-June, when the water temperature was higher than $4\text{ }^\circ\text{C}$.

Table 1

The carbon isotopic composition of ostracods *L. inopinata* and *E. mareotica* coexisting at different depths and ages in the 1F core.

Depth (m)	Age (ka)	<i>Limnocythere inopinata</i>	<i>Eucypris mareotica</i>
		$\delta^{13}\text{C}$ (V-PDB, ‰)	$\delta^{13}\text{C}$ (V-PDB, ‰)
1.20	2.81	−0.90	−0.07
1.26	2.93	−1.49	0.57
1.31	3.05	−0.70	0.67
2.14	4.99	−3.13	−0.35
2.35	5.48	−1.90	1.09
2.45	5.72	−2.34	−0.69
2.76	6.45	−2.80	0.64
2.96	6.91	−3.66	−2.29
2.99	6.98	−2.29	0.97
3.10	7.23	−3.62	−0.62

However, the maximum abundance of *E. mareotica* was present in early August, when the water temperature was higher than 6 °C in Lake Qinghai (Li and Jin, 2013). In addition, the abundance of ostracod shells (2500 shells/m²·day) in 2010 was higher than the abundance (500 shells/m²·day) in 2011, and the mean annual water temperature in 2010 was higher than that in 2011 in Lake Qinghai (Li and Jin, 2013). Therefore, we speculate that *L. inopinata* may have hatched on the lake bottom at low temperatures before June but that the hatching of *E. mareotica* may require higher temperatures than the hatching of *L. inopinata*. Therefore, the hatching of *E. mareotica* may be later than the hatching of *L. inopinata* because the water temperature is lower than the water temperature at which *L. inopinata* hatches.

In Lake Qinghai, *Cladophora* with low $\delta^{13}\text{C}$ values (about –34.1‰ to –32.1‰) are present in the bottom sediment (Liu et al., 2013). When *Cladophora* flourish, the $\delta^{13}\text{C}$ values of the bottom water DIC may increase because *Cladophora* prefer using ¹²C for photosynthesis. However, the $\delta^{13}\text{C}$ values of the bottom water DIC should decrease due to the CO₂ with low $\delta^{13}\text{C}$ values released when dead *Cladophora* decompose on the lake bottom in Lake Qinghai. The bottom water $\delta^{13}\text{C}_{\text{DIC}}$ may also be affected by the CO₂ with low $\delta^{13}\text{C}$ values that is released when dead *Cladophora* decompose in winter and early spring. However, the bottom water $\delta^{13}\text{C}_{\text{DIC}}$ may rise because of the strong photosynthesis of the *Cladophora* in late spring and summer in Lake Qinghai. As noted above, *Eucypris mareotica* may be hatched at high temperatures in the early summer. If *Cladophora* also flourish at that time, the strong photosynthesis of *Cladophora* may cause the enriched $\delta^{13}\text{C}$ values of the water DIC. In this case, the enriched $\delta^{13}\text{C}$ values of the water DIC result in the high $\delta^{13}\text{C}$ values of *E. mareotica* in Lake Qinghai. Therefore, we posit that the carbon isotopic variation in DIC relative to the flourishing of *Cladophora* may be an important reason for the carbon isotopic differences between *E. mareotica* and *Limnocythere inopinata* in Lake Qinghai.

We suggest that the carbon isotopic differences between *Eucypris mareotica* and *Limnocythere inopinata* may be affected primarily by the variation of $\delta^{13}\text{C}_{\text{DIC}}$ at different ostracod hatching times, living styles, and 'vital offsets'. In addition, flourishing of *Cladophora* evidently influences the carbon isotopic composition in ostracod shells, so the variation in $\delta^{13}\text{C}_{\text{ostracod}}$ can be used as a proxy for changes of productivity.

5.2. $\delta^{13}\text{C}$ in fossil ostracod species

The results from previous studies have shown that *Eucypris mareotica* can tolerate very high salinity, and the presence of this species indicates high salinity (exceeding 30 g/L) in lakes distributed in the Qaidam Basin and Lake Qinghai area (Sun et al., 1993; Li et al., 2010). The maximum abundance of *Limnocythere inopinata* was found in sample sites with salinities ranging from 4.6 g/L to 14.7 g/L (Li et al., 2010). Therefore, the presence of *E. mareotica* and *L. inopinata* may indicate high salinity (exceeding 30 g/L) and low salinity (4.6 g/L to 14.7 g/L), respectively. Although there were only two species of ostracods, the variation in ostracod assemblages may be used in this study to indicate salinity changes for the last 12 ka.

To further investigate the significance of carbon isotopes of modern lake carbonates, the carbon isotope of the ostracods, bulk carbonate, fine-grained carbonates, and dissolved inorganic carbon (DIC) of associated water have been evaluated in the Lake Qinghai area (Li et al., 2012). In modern Lake Qinghai, the $\delta^{13}\text{C}_{\text{DIC}}$ of surface lake water is generally controlled by the gas exchange between lake water and the atmosphere relative to strong evaporation (Li et al., 2012). For example, strong evaporation related to high temperatures can raise the *p*CO₂ of a lake, resulting in enriched $\delta^{13}\text{C}_{\text{DIC}}$ through the loss of ¹²C-enriched CO₂ to the atmosphere in arid areas and closed lakes. In addition, the ostracods *Limnocythere inopinata* and *Eucypris mareotica* both live on the lake bottom, and the $\delta^{13}\text{C}_{\text{DIC}}$ values where the ostracod shells were precipitated may be affected by the photosynthesis of the *Cladophora* on the lake bottom. The lake productivity (much more *Cladophora* flourish at high temperature) increases with temperature and results in enriched

$\delta^{13}\text{C}_{\text{DIC}}$ values. Additionally, the water salinity may increase through strong evaporation that is related to high temperatures. Because the variations in the $\delta^{13}\text{C}$ values of carbonates are controlled primarily by the carbon-isotope ratios of the lake water DIC, they in turn are indirectly related to water salinity (Li et al., 2012) and productivity.

However, a single species was not always present in the lake sediment through the entire long core. Therefore, it is important to consider whether the carbon isotopic bias among multiple ostracod species affected the explanation of the varied salinity and productivity using the $\delta^{13}\text{C}_{\text{ostracod}}$ values during the Holocene. It is very difficult to quantify the differences between *Eucypris mareotica* and *Limnocythere inopinata* because we have never collected two living species at the same site. Moreover, the carbon isotopic difference between *E. mareotica* and *L. inopinata* caused by the ostracod hatching time is difficult to evaluate because the ostracod hatching time cannot be determined accurately. Therefore, the ostracod $\delta^{13}\text{C}$ changes are discussed without carbon isotopic equalization for these two species though neither species covers the entire period covered in the 1F core (Fig. 2).

Based on the results of previous work and the above results, we investigated the variation in salinity and productivity using the variation in ostracod assemblages and $\delta^{13}\text{C}_{\text{ostracod}}$ recorded in core 1F. From 12 ka to 7.4 ka, *Eucypris mareotica* was nearly the only species in the 1F core. The dominance of *E. mareotica* and the highest average $\delta^{13}\text{C}_{\text{ostracod}}$ values indicate that the water salinity and productivity were at a very high level during this time stage (Fig. 2). In addition, the lake level was very low in the early Holocene (Lister et al., 1991; Liu et al., 2013). The ostracod was almost absent before 11.6 ka, corresponding to the cold and dry Younger Dryas (YD) event. In general, the high salinity and productivity showed that the climate was warm after 11.6 ka, but the large fluctuation of salinity and productivity indicated that the climate was unstable during this time period. The variation in $\delta^{13}\text{C}_{\text{ostracod}}$ values showed that the water salinity and productivity first decreased from 11.6 ka to 9.2 ka, and the salinity and productivity then gradually increased from 9.2 ka to 7.4 ka (Fig. 2) and further increased from 9 ka until 7.4 ka. The salinity inferred from the Sa/Ca ratio of the ostracod shells (Zhang et al., 1989, 1994) and the TOC content (An et al., 2012) also showed similar changes in the $\delta^{13}\text{C}_{\text{ostracod}}$ values in the early Holocene. The results of a recent study showed that the strengthening of the Asian monsoon abruptly increased at approximately 11.5 ka, and the front of the intensified Asian monsoon penetrated to Lake Qinghai (An et al., 2012). The Asian monsoon became weak after approximately 9.0 ka (An et al., 2012). Therefore, the variation in water salinity and productivity may be affected by the changes in the effective moisture and temperature relative to the strengthening of the Asian monsoon. From 7.4 ka, *E. mareotica* decreased sharply, and *Limnocythere inopinata* became the dominant species in the core (Fig. 2). The decreased abundance of *E. mareotica* and the lowest average $\delta^{13}\text{C}_{\text{ostracod}}$ values indicate that the water salinity and productivity decreased after 7.4 ka in Lake Qinghai (Fig. 2). The reported TOC content also decreased with fluctuations after 7.4 ka (An et al., 2012). The lake level had been rising in the middle Holocene (Lister et al., 1991; Liu et al., 2013). Thus, the water salinity may be reduced with increasing lake level, and the productivity on the lake bottom may also be reduced and caused by lower temperatures with increasing water depth. However, the frequent presence of $\delta^{13}\text{C}_{\text{ostracod}}$ peaks indicated that the water salinity and productivity were still high at approximately 6.7 ka and 5.6 ka. In addition, the large fluctuation in the $\delta^{13}\text{C}_{\text{ostracod}}$ values showed that the water salinity and productivity frequently varied during the middle Holocene. The sudden changes in ostracod species and frequent variation of $\delta^{13}\text{C}_{\text{ostracod}}$ values may indicate an unstable state in the lacustrine environment and the climate from 7.4 ka to 5.0 ka. The more negative $\delta^{13}\text{C}_{\text{ostracod}}$ values indicate that the salinity and productivity were generally very low during the 5.0 ka to 3.5 ka. From 3.5 ka to the present, *L. inopinata* was the dominant species, and the $\delta^{13}\text{C}_{\text{ostracod}}$ values gradually increased with small fluctuations (Fig. 2). In addition, *E. mareotica* gradually recurred from 3.5 ka to the

present in Lake Qinghai. The variation in ostracod assemblages and the increased $\delta^{13}\text{C}_{\text{Ostracod}}$ values indicate that the water salinity and productivity gradually increased after 3.5 ka. Moreover, the sharply increased abundance of *E. mareotica* may indicate a sudden increased salinity at 3.0 ka, 1.0 ka, and 0.1 ka. Previous studies have shown that the lake level was reduced by decreasing monsoon precipitation and that the temperature may have increased in the late Holocene (Lister et al., 1991; Thompson et al., 1997; Liu et al., 2013). Therefore, the increased water salinity and productivity may be caused by the reduced lake level and increased temperature in the late Holocene.

5.3. Factors affecting $\delta^{13}\text{C}$ values in ostracod shells

Zhang et al. (1989, 1994) used Sr/Ca data from ostracods to determine the salinity change in Lake Qinghai. The inferred salinity using Sr/Ca data for the ostracods demonstrated that the salinity was very high before 7.5 ka and that it subsequently fluctuated and decreased from 7.5 ka to 3.5 ka. Then, the salinity gradually increased from 3.5 ka to the present in Lake Qinghai (Fig. 3a). The salinity changes inferred from the ostracod assemblages and their carbon isotopes in our study show similar trends as the results deduced from the ostracod

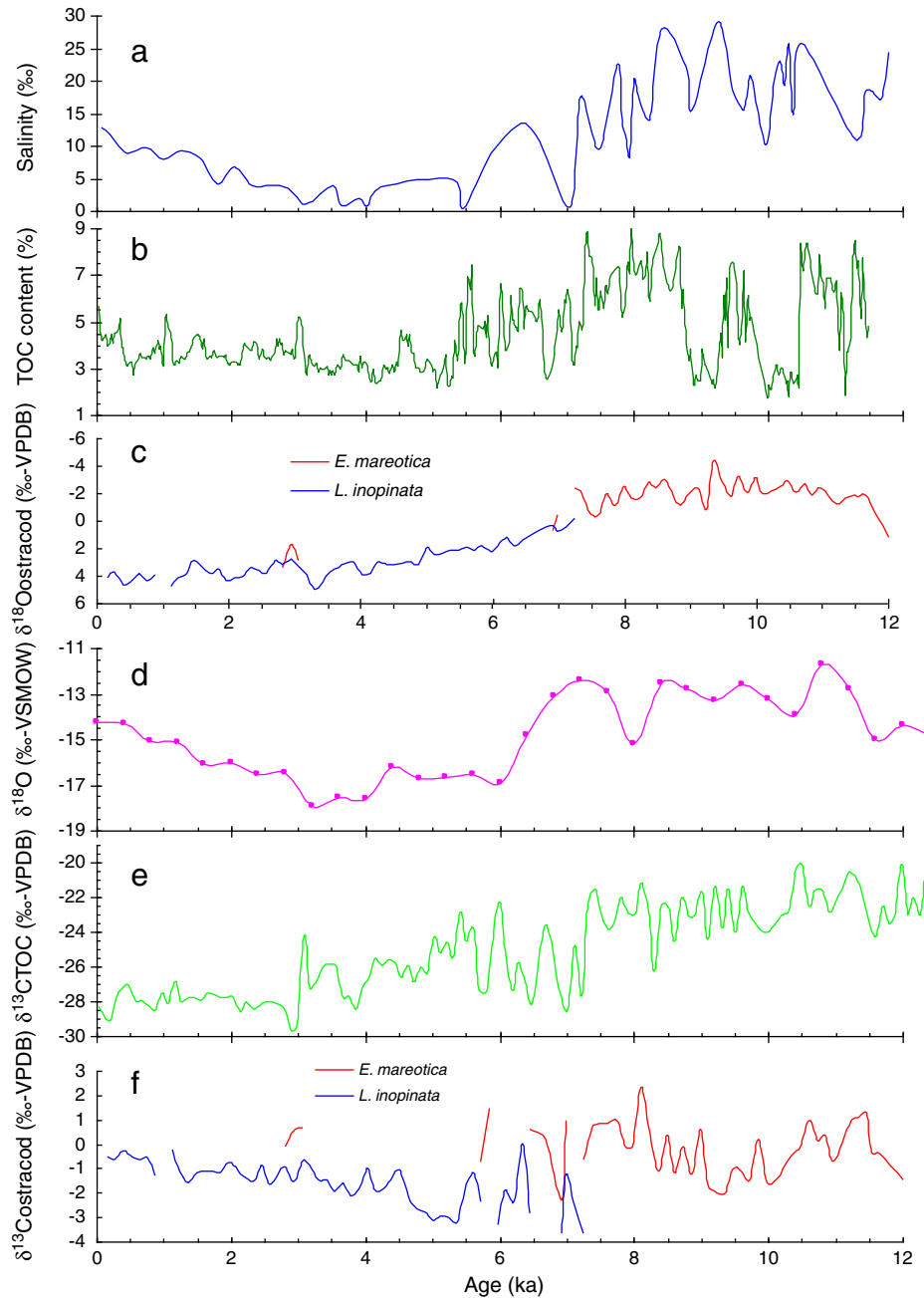


Fig. 3. The $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ variations of ostracod shells that were recorded by the 1F core covering approximately 12 ka was compared with other records since the early Holocene in Lake Qinghai and Qinghai–Tibet Plateau. a) The inferred water salinity using the ostracod Sr/Ca data from the QH85-A core (Zhang et al., 1989, 1994); b) the TOC content recorded by the 1F core (An et al., 2012); c) the $\delta^{18}\text{O}$ variation of ostracod shells recorded by the 1F core in this study (the blue line represents the $\delta^{18}\text{O}$ values of *L. inopinata*, and the red line represents the $\delta^{18}\text{O}$ values of *E. mareotica*); d) the $\delta^{18}\text{O}$ variation from the Guliya ice core from the Qinghai–Tibet Plateau (Thompson et al., 1997); e) the $\delta^{13}\text{C}_{\text{org}}$ variation of sedimentary total organic matter recorded by the 1F core (Liu et al., 2013); and f) the $\delta^{13}\text{C}$ variation of ostracod shells recorded by the 1F core in this study (the blue line represents $\delta^{13}\text{C}$ values of *L. inopinata*, and the red line represents $\delta^{13}\text{C}$ values of *E. mareotica*). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Sr/Ca data in Lake Qinghai (Zhang et al., 1989, 1994). The consistent results suggest that the salinity variation deduced from the ostracod assemblages and their carbon isotopes is logical and reliable in Lake Qinghai. However, the $\delta^{13}\text{C}$ values in ostracod shells were also affected by the variation in lake productivity.

Fig. 3 shows that the variation of $\delta^{13}\text{C}_{\text{ostracod}}$ was also similar to the change in TOC content in the 1F core. From 12 ka to 7.5 ka, the TOC content was the highest (indicated high productivity), corresponding well with the highest abundances of *Eucypris mareotica* and the high $\delta^{13}\text{C}_{\text{ostracod}}$ values. Moreover, a sharp decrease in TOC content (decreased productivity) was coupled with the negative $\delta^{13}\text{C}_{\text{ostracod}}$ values during the early Holocene (Fig. 3). From 7.5 ka to 3.5 ka, the TOC content decreased with large fluctuations. The decreased TOC content was followed by more negative $\delta^{13}\text{C}_{\text{ostracod}}$ values in Lake Qinghai (Fig. 3). The TOC content generally increased from 3.5 ka to the present in Lake Qinghai with small fluctuations (Fig. 3b) (An et al., 2012). Similarly, the $\delta^{13}\text{C}_{\text{ostracod}}$ values become enriched from 3.5 ka to the present in Lake Qinghai (Fig. 3).

In modern Lake Qinghai, the variation in the $\delta^{13}\text{C}_{\text{DIC}}$ values of surface lake water may be controlled primarily by the CO_2 exchange between the atmosphere and the lake waters because of the small change in primary productivity (Li et al., 2012). However, the carbon isotope content of bottom-water DIC may also be affected by the primary productivity and the decomposition of organic matter in Lake Qinghai because there are large amounts of *Cladophora* on the lake bottom (Liu et al., 2013). Most non-marine ostracods are benthic animals, and some species live in the lake sediment-water interface. Therefore, the carbon isotopic compositions of ostracod shells should be controlled primarily by the carbon isotope of the bottom-water DIC in lakes. The $\delta^{13}\text{C}_{\text{DIC}}$ values of the bottom water may frequently be affected by the photosynthesis of aquatic plants and CO_2 fluxes from aerobic respiration and the anaerobic degradation of organic matter in Lake Qinghai (Li et al., 2012). Moreover, adult ostracod shells are usually formed in late spring to summer, with the flourishing of aquatic plants (Li and Jin, 2013). Therefore, the ostracod carbon isotope is related to the TOC content, primarily from the aquatic plants in Lake Qinghai. The increased primary productivity may cause the enriched $\delta^{13}\text{C}_{\text{DIC}}$ values of the lake water and ultimately result in the enriched $\delta^{13}\text{C}_{\text{ostracod}}$ values in lakes. Moreover, the water salinity may increase via strong evaporation related to high lake temperatures in summer. Therefore, the water salinity and productivity evaluated using the $\delta^{13}\text{C}_{\text{ostracod}}$ values showed a variation similar to that of the TOC content in the 1F core from Lake Qinghai (Fig. 3).

5.4. Interpretation of $\delta^{13}\text{C}$ values in ostracod shells

The single presence of *Eucypris mareotica* and the high average $\delta^{13}\text{C}_{\text{ostracod}}$ values indicated that the water salinity and productivity were high in the early Holocene. The results of a new study showed that the enriched $\delta^{13}\text{C}$ values of total organic matter indicated a very low lake level during the early Holocene in Lake Qinghai (Liu et al., 2013). However, the depleted $\delta^{18}\text{O}$ of *E. mareotica* from the 1F core indicated increases in effective humidity, implying strengthened Asian monsoon intensity in the early Holocene (Lister et al., 1991; An et al., 2012) (Fig. 3c). We must therefore ask why the salinity and productivity are so high with a low lake level, with the high effective humidity indicated by negative $\delta^{18}\text{O}$ values in ostracod shells in the early Holocene.

As we know, the $\delta^{18}\text{O}$ of ostracod shells depends mainly on both the $\delta^{18}\text{O}$ and the temperature of the host water. The mean annual precipitation in the arid, high-altitude Lake Qinghai area varies widely: it is approximately 200 mm around the lake but increases to over 400 mm in the surrounding mountains, according to previous reports and the meteorological data of recent decades (Liu et al., 2009). However, the annual evaporation can be as high as 1400 mm, according to the reported meteorological data of recent decades in the lake area. Therefore, rivers draining the surrounding area provide a major water source for Lake Qinghai. These source waters together with evaporation represent the

dominant control of water isotopes (Liu et al., 2009). Mixing the two end members of resident lake water and river water may also be an important factor in water isotopes. Most of the precipitation occurred mainly in the summer and autumn, and *Eucypris mareotica* was also present in these seasons. Therefore, the negative $\delta^{18}\text{O}$ values in ostracod shells may be caused by the frequent dilution of river water with depleted $\delta^{18}\text{O}$ values in summer. In addition, the $\delta^{18}\text{O}$ data from the Guliya ice core show that the temperature was high during the early Holocene on the Qinghai–Tibet Plateau (Fig. 3d). The negative $\delta^{18}\text{O}$ values in ostracod shells may also be affected by the high temperatures in this period.

Lister et al. (1991) suggest that the lake level was very low, even close to being dry at 11.6 ka, and that the enriched ostracod $\delta^{18}\text{O}$ indicated very dry conditions in the Lake Qinghai area (Fig. 3c). Then, the lake level slowly increased, caused by increasing precipitation that was related to strengthening of the Asian monsoon and stress evaporation after 11.6 ka. Therefore, we inferred that the salinity may have been very high with a very low lake level before 11.6 ka in Lake Qinghai. Although the Asian monsoon (AM) has been intensified (Dykoski et al., 2005), which may result in the increasing precipitation and more river-supplied water in early Holocene (Shang, 2009), the lake level was still low, as indicated by the $\delta^{13}\text{C}$ of total organic matter in Lake Qinghai (Fig. 3e). Herzsuh (2006) reconstructed the moisture conditions in Central Asia during the last 50,000 years using 75 paleoclimate records. Of the 75 records, most were from the southeastern Tibetan Plateau and show that the warmest, wettest Holocene climate conditions occurred during the early Holocene (Herzsuh, 2006). Other records in northwest and north central China and in Mongolia, however, show a temperature maximum in the middle Holocene, rather than the early Holocene. The majority of these paleoclimate records suggest reduced moisture since the middle Holocene (Herzsuh, 2006). In addition, the $\delta^{18}\text{O}$ data from the Guliya ice core show that the temperature was high during the early Holocene on the Qinghai–Tibet Plateau (Fig. 3d) (Thompson et al., 1997). Although the increasing precipitation coupled with the intensification of the AM should cause more input water to the lake, high temperatures may have caused strong evaporation and resulted in the large losses of lake water. The lake volume may have been enlarged very little in the early Holocene. The variation in salinity may be controlled mainly by the mixing of the two end members of resident lake water with very high salinity and limited fresh source water relative to the increased precipitation and strong loss through evaporation after 11.6 ka. Therefore, the salinity might be still high because of the limited increase in lake volume during the early Holocene. As shown in Fig. 3, the ostracod $\delta^{18}\text{O}$ values and $\delta^{13}\text{C}$ values both decreased from 12.0 ka to approximately 9.2 ka; the values became enriched from 9.2 ka to approximately 7.4 ka. The similar varied trend of the ostracod isotope indicated that the variation in ostracod isotopes may be caused by the common factors suggested above. In addition, the more enriched ostracod $\delta^{13}\text{C}$ values suggest that the ostracod carbon isotope may be affected by the high primary productivity (indicated as the high TOC content) related to high temperatures during the early Holocene in Lake Qinghai.

The enriched ostracod $\delta^{18}\text{O}$ values showed that the effective humidity decreased from 7.4 ka to 3.5 ka in Lake Qinghai area. However, the negative $\delta^{13}\text{C}$ of total organic matter indicated that the lake level increased from 7.4 ka to 3.5 ka in Lake Qinghai (Liu et al., 2013). These results showed that the lake volume was enlarged, with a limited increase in effective humidity indicated by the enriched ostracod $\delta^{18}\text{O}$ values in Lake Qinghai from 7.4 ka to 3.5 ka (Liu et al., 2013). However, the variation in lake volume/level shows large fluctuations with an increasing trend from 7.4 ka to 3.5 ka in Lake Qinghai. The increased lake volume/level may result in the decreased water salinity from 7.4 ka to 3.5 ka in Lake Qinghai. The pollen and carbon isotope black carbon data from other studies show that the climate was very warm and humid during this time period in the north of China (Shang, 2009; Wang et al., 2013). The evaporation may have sharply decreased because of the decreased temperatures compared with the early Holocene

recorded in ice cores (Fig. 3d), and this decreased evaporation may have resulted in a lower E/P ratio in the Lake Qinghai area during the middle Holocene. In addition, previous studies have shown that the climate was humid because of the increased precipitation during the middle Holocene in north China (Wang et al., 2013). The increased precipitation may have resulted in the lower E/P ratio in Lake Qinghai. Although recent studies have suggested that the middle Holocene is marked by a reduced monsoon precipitation compared with the early Holocene (An et al., 2012; Liu et al., 2014), the precipitation may still be high. Therefore, the lower loss of water caused by a low E/P ratio and high precipitation may have resulted in the increased lake level and decreased water salinity during the middle Holocene. The decreased productivity may be caused by a decreased bottom temperature because of the increased water depth.

The decreased ostracod $\delta^{18}\text{O}$ values showed that the effective humidity suddenly increased at approximately 3.5 ka, and the gradually decreased $\delta^{18}\text{O}$ values showed a decreased effective humidity after 3.0 ka in Lake Qinghai. In addition, the most negative $\delta^{13}\text{C}$ of total organic matter showed that the lake volume/level reached maximum, and the slightly enriched $\delta^{13}\text{C}$ of total organic matter showed the decreased lake level after 3.0 ka in Lake Qinghai (Liu et al., 2013). Similarly, the increased ostracod $\delta^{13}\text{C}$ values at a small range suggested that the water salinity and productivity increased little after 3.0 ka in Lake Qinghai. Although the results of previous studies showed that the precipitation increased relative to the intensified Asian monsoon during the late Holocene in Lake Qinghai (Liu et al., 2007; An et al., 2012), the $\delta^{18}\text{O}$ data of the ice core show that the temperature increased rapidly from 3.0 ka to the present (Fig. 3d). Therefore, the E/P ratio might increase because of the strong evaporation related to the increased temperature and decreased effective humidity related to a slight enhancement in the Asian monsoon in Lake Qinghai. As a result, the water salinity increased slightly, and the lake level decreased slightly during the late Holocene in Lake Qinghai.

Climatic conditions and lake environment may be summarized as follows: 1) low lake level, high water salinity and productivity under the warmest and wetter climate during the early Holocene, 2) fluctuating lake level, decreasing water salinity and productivity under the warm and wet climate during the middle Holocene, and 3) increasing lake level, increasing water salinity and productivity under the warm and dry climate in the late Holocene.

6. Conclusions

The variations in the $\delta^{13}\text{C}_{\text{Ostracod}}$ values and ostracod species demonstrate that the water salinity and productivity may have been very high because of intense evaporation and high temperatures, though the precipitation increased sharply in response to the intensification of the Asian monsoon during the early Holocene. Thereafter, the salinity and productivity decreased because of a low E/P ratio during the middle Holocene. Finally, the salinity gradually increased because of a high E/P ratio that was related to the increased temperature and the slight enhancement of the Asian monsoon in the late Holocene. The results of this study suggest that the carbon isotopic compositions of ostracod shells associated with the changes in ostracod assemblages can be used to assess the variation in water salinity and productivity in some lakes located on the Qinghai–Tibet Plateau.

In addition, the results of our study and other studies suggest that we cannot evaluate dry–wet fluctuations using single proxies from lakes located in arid areas. Moisture and temperature conditions must be inferred independently from appropriate proxies, and the environmental variations can be then evaluated synthetically in arid regions.

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