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Reevaluation of carbonate concentration and oxygen isotope records from Lake Qinghai, the northeastern Tibetan Plateau

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ABSTRACT

Lake Qinghai is the largest lake on the Tibetan Plateau, and it is also one of the important sites for studying global environmental changes. Over the past 30 years, many studies have used oxygen isotope of authigenic carbonates from the lake as the proxy to infer past environmental and climate changes on the Plateau. However, debate on interpretations of isotopic data and their environmental implications still exist, largely due to the complex arid environment settings and multiple sources/species for carbonate minerals within the lake. In this study, we systematically analyze $\delta^{18}O$ values in different-type carbonates collected [i.e. bulk carbonates, ostracode shells, *Chara* encrustations, and fine-grain (< 63 μm) carbonate minerals] from modern lake sediments and surrounding soils, as well as the down-core $\delta^{18}O$ values of bulk/fine-grain carbonates since the Last Glacial Maximum. Together with previously published $\delta^{18}O$ records from ostracode shells, we try to re-evaluate the controlling factors of variations in lacustrine carbonate $\delta^{18}O$ data and to infer environmental changes on the northeastern Tibetan Plateau since the Last Glacial Maximum. Our results show that the lake depth, or the size of the water body, is an important factor to influence the lake water and carbonate $\delta^{18}O$ values. A shallow and small lake would be more easily influenced by precipitation $\delta^{18}O$ which is characterized by negative values at Lake Qinghai region, while a deep and large lake would be better to reflect environmental changes such as the precipitation-evaporation balance. The "lake volume" effect might be an explanation for the negative carbonate $\delta^{18}O$ values during the early Holocene, which was likely caused by an increased influence of negative $\delta^{18}O$ values in precipitation and glacial melt water under a small and shallow water body. The $\delta^{18}O$ values of ostracode shells and bulk carbonates show similar variations since both of them are dominated by lake water oxygen isotopic composition, but they still have distinct geochemical information. The isotopic differences between ostracode and bulk carbonates probably reflect the temperature differences between the surface and the bottom of lake water. In addition, the $\delta^{18}O$ values of evaporative induced carbonates may correlate with carbonate contents, while those of *Chara* encrustations do not show any correlation with carbonate contents. Our results suggest that special caution would be necessary when using lacustrine $\delta^{18}O$ values of authigenic carbonates to infer past hydrological and climate changes in an arid environment.

1. Introduction

The Tibetan Plateau is the home of many lakes, and the sediment of these lakes contains rich information for paleoclimatic, paleoenvironmental, and paleolimnologicial studies. Numerous investigations have been performed on these lakes to better understand past regional and global climatic and environmental changes in this geographical important region (e.g. Mischke et al., 2010; Aichner et al., 2012; An et al., 2012; He et al., 2013; Zhao et al., 2013; Chen et al., 2016; Hou et al., 2017). Among these lakes, Lake Qinghai is the largest one, located on the northeastern corner of the Tibetan Plateau (Fig. 1), also the intersection of several major global atmosphere circulations, including East Asian summer monsoon, Indian summer monsoon, and the westerly. Because of these important characteristics and its sensitivity to global climate changes, Lake Qinghai has been constantly chosen by many researchers as the study site to infer past climatic and environmental changes on the Tibetan Plateau (e.g., Huang, 1988; Zhang et al., 1989; Kelts et al., 1989; Lister et al., 1991; Henderson et al., 2003; Liu et al., 2007, 2013; 2015a; Colman et al., 2007; An et al., 2012; Chen et al., 2016).

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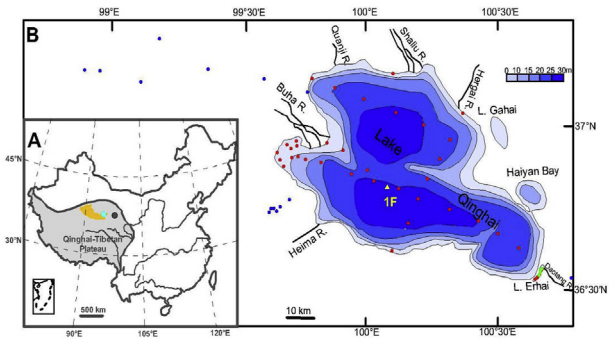

Fig. 1. Location and settings. (A) Map showing study site of Lake Qinghai (black dot) and Hurleg Lake (blue dot). The grey and yellow shaded areas indicate the Tibetan Plateau and the Qiadam Basin, respectively. (B) Hydrologic setting and bathymetry map of Lake Qinghai. The coring location of core IF is indicated by the yellow triangle. Modern samples for surface sediments (red), soils (blue), and live *Chara* (green) are indicated by dots. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Oxygen isotope of lacustrine carbonates is a powerful tool to infer past hydrological and climatic changes (Talbot, 1990; Gat, 1995; Leng and Marshall, 2004; Steinman and Abbott, 2013), which has been widely used for terrestrial paleoclimatic and paleoenrironmental studies (e.g. Phillips et al., 1994; Vassiljev, 1998; Hu et al., 1999; Filippi et al., 1999; Rowe and Dunbar, 2004; Morrill et al., 2006; Jones and Roberts, 2008; Bluszcz et al., 2009; Jones and Imbers, 2010; Thevenon et al., 2012; Stansell et al., 2012; Zanchetta et al., 2012; Li and Morrill, 2013; Dean et al., 2015; Steinman et al., 2016). Since the pioneer studies in 1980s (Zhang et al., 1989), $\delta^{18}O$ of ostracode shells from Lake Qinghai has been repeatedly used as the proxy to study climatic and environmental changes, and numerous $\delta^{18}O$ records from ostracode shells have been reported over the past 30 years (Lister et al., 1991; Shen et al., 2005; Liu et al., 2007; An et al., 2012; Chen et al., 2016; Li and Liu, 2017). Until now, however, the interpretation of these records is still controversial. In the first study, ostracode $\delta^{18}O$ values were used to reconstruct temperature variations in Lake Qinghai area (Zhang et al., 1989). Shortly after, another study explained that ostracode $\delta^{18}O$ values were controlled by the isotopic composition of lake water, which was influenced by the lake water balance and in turn the East Asian monsoon precipitation (Lister et al., 1991). Later on, this interpretation has been widely followed, and many records have been reported for studying variations of East Asian summer monsoon at various time scales (Shen et al., 2005; Liu et al., 2007; An et al., 2012; Chen et al., 2016; Li and Liu, 2017).

Nevertheless, the monsoon interpretation has been questioned by recent studies based on compound-specific hydrogen isotope from the same lake, in which the stable isotopes of Lake Qinghai have been proposed as an indicator for interactive influences of moistures from East Asian summer monsoon and the westerly circulations (Thomas et al., 2016; Chen et al., 2016; Li and Liu, 2017). Nevertheless, modern precipitation isotopic data from the westerly region seem to show more complex features and may not be able to support this interpretation (Cheng et al., 2012). Collectively, the current main question is what is the dominant control of the lake water isotopic composition at Lake Qinghai, East Asian summer monsoon, the westerly, or other factors? The answer for this question will help not only to infer past climate changes on the Tibetan Plateau, but also to better understand the carbonate isotopic geochemistry in other plateau lakes under unstable environments.

In this study, we first systematically investigate the contents and isotopic compositions of different types of carbonate (Ostracode shells, *Chara* encrustations, total carbonates, and fine-grain carbonates) of modern lake sediments and soils samples collected from Lake Qinghai and several lakes around Lake Qinghai and the nearby Qaidam Basin. Then we analyze variations in contents and oxygen isotope compositions of total carbonates and fine carbonates from a sediment core. Together with previously published ostracode oxygen isotope data, we aim to (1) understand the modern processes of carbonate isotopic geochemistry at Lake Qinghai; (2) infer environmental changes at Lake Qinghai since the last glacial maximum; and (3) provide a new mechanism for the application of carbonate isotope data in paleoclimate reconstructions in unstable arid environments like Lake Qinghai.

2. Materials and methods

Lake Qinghai (36°15′–38°20′ N, 97°50′–101°20′ E, ~3200 m a.s.l.) is located in the northeastern Tibetan Plateau (Fig. 1A). The lake is a closed-basin saline lake surrounded by mountains. The maximum water depth of the lake is 27 m, and the surface area is ~4400 km^2. Lake Qinghai is located in a large catchment basin, with the total catchment area of ~29,660 km^2. The lake is mainly recharged by six large rivers and many small creeks, with the Buha River contributing ~50% of inflow water (Li and Liu, 2017). There are no visible outflow rivers or creeks. There are also many other lakes and ponds with different sizes in the catchment basin, including Gahai Lake, Haiyan Bay, and Earhai Lake etc.

The catchment area of Lake Qinghai is the conjuncture place of the East Asian summer monsoon, Indian summer monsoon, and the westerly circulations (An et al., 2012). Therefore, this region is under typical semi-arid inland temperate continental climate with strong seasonality. Instrumental data shows the mean annual temperature is about 1 °C, and the mean annual precipitation is about 400 mm with 65% of it falling in the summer. The catchment basin is covered by alpine grasslands and alpine shrubs. Bedrock and surrounding deposits include Early Paleozoic sandstone, phyllite, schist, gneiss and volcanic rocks with crystalline, with very limited limestone.

A total of 16 surface sediment samples were collected from Lake Qinghai and nearby Erhai, and Hurleg Lake in the nearby Qaidam Basin (Table 1), and 17 soil samples from surrounding areas of Lake Qinghai (Table 2, Fig. 1B). The 32 m-long core IF was collected in the summer of 2005 by Sino-US cooperation project, at the lake center with a water depth of ~27 m (Fig. 1B). Detailed chronology of this core has been published and described previously (An et al., 2012; Zhou et al., 2014), which shows that the core spans the past 18 ka. The core was subsampled at continuously 1-cm intervals, and we used 370 subsamples from the top 8 m for analyses in this study.

For fine-grained carbonate (< 63 μm), about 5 g sediment samples were soaked in deionized water for about 2 h, and then wet sieved with a 250-mesh sieve (63-μm mesh). Well-dispersed sediment samples were poured into 63 μm standard stainless steel sieve, and then rinsed with deionized water to isolate sediment particles less than 63 μm. Smaller than 63 μm particles (considered fine-grained carbonate) were centrifuged and oven dried at 40 °C for oxygen isotope analysis.

For all the carbonate samples, about 1 g of each bulk sediment sample was leached with deionized water in order to isolate the isotopic signals of the calcium carbonate from those of the pore water and water-soluble carbonate. These samples were then oven dried at 40 °C for isotopic analyses.

For surface soil samples, each sample was dried and sieved through 100 mesh followed by grinding for the determination of mineral composition and carbonate oxygen isotope.

For modern *Chara* encrustations, the sludge of aquatic plants from Qinghai Lake and Qaidam Basin lakes was washed with lake water in the field and then cleaned with deionized water in the laboratory. Samples were ground to 100 mesh after freeze-drying for the determination of mineral composition and carbonate oxygen isotope.

For carbonate mineral analyses, the X-ray diffraction technique was used with X'Pert Pro MPD, using copper target, Ni filter and a super-array detector (40 kV and 40 mA). *Chara* encrustations, surface

Table 1
Mineral contents and stable isotopes of *Chara* encrustations and bulk sediments from lakes in Qinghai area. The percentages of aragonite and calcite are relative to the total carbonate.

Samples	Lake	Type	Latitude (N)	Longitude (E)	Altitude (m)	Carbonate (%)	Aragonite (%)	Calcite (%)	$\delta^{13}C$ (‰)	$\delta^{18}O$ (‰)
Bio-1	Lake Erhai	*Chara*	36°34′16″	100°44′04″	3203	32.5	100	0	2.2	−1.7
Bio-2	Lake Erhai	*Chara*	36°34′13″	100°43′57″	3203	38.2	100	0	2.8	−0.7
Bio-3	Lake Erhai	*Chara*	36°34′00′	100°43′52″	3203	36.0	100	0	3.8	−0.5
Bio-4	Lake Erhai	*Chara*	36°33′44″	100°43′45″	3203	37.5	100	0	4.2	0.2
Bio-5	Lake Keluke	*Chara*	37°17′13.20″	96°53′30.37″	2815	41.6	71	29	4.0	−6.5
Bio-6	Lake Keluke	*Chara*	37°17′18.25″	96°53′29.78″	2815	39.1	52	48	3.2	−6.6
Bio-7	Lake Keluke	*Chara*	37°17′41.42″	96°53′39.50″	2815	37.8	62	38	4.1	−6.4
Bio-8	Lake Keluke	*Chara*	37°17′56.50″	96°53′47.21″	2815	35.7	59	41	4.2	−6.9
EHLS15-2	Lake Erhai	sediment	36°34′13″	100°43′57″	3203	38.8	83	18	1.8	−1.1
EHLS15-4	Lake Erhai	sediment	36°33′44″	100°43′45″	3203	40.4	84	16	4.4	0.1
EHLS15-5	Lake Erhai	sediment	36°33′21″	100°43′31″	3203	43.4	87	13	4.9	1.2
QHS16-21	Lake Erhai	sediment	36°32′51.9″	100°43′12.0″	3198	21.8	85	15	2.3	−0.8
QHS15-1	Lake Qinghai	sediment	36°56′27″	99°58′07″	3200	33.0	78	22	2.4	0.9
QHS15-2	Lake Qinghai	sediment	36°56′27″	99°58′07″	3200	33.0	78	22	2.1	1.0
QHS15-3	Lake Qinghai	sediment	36°56′27″	99°58′07″	3200	31.7	78	22	3.3	2.9
QHS15-4	Lake Qinghai	sediment	36°56′27″	99°58′07″	3200	29.6	74	26	2.1	1.0

sediment and soil samples were packed into a rectangle cavity and scanned in a step-scan mode (0.0167°/step) over the angular range of 5–70° (2θ). Scattered X-ray intensities were collected for 29.8 s at each step. The relative contents of aragonite and calcite were obtained by semi-quantitative analysis using the Highscore software.

All carbonate samples (bulk carbonate and fine-grained carbonate) were analyzed for $^{18}O/^{16}O$ at IEECAS using an isotope ratio mass spectrometer (MAT-252) with an automated Carbonate Preparation Device (Kiel II). Results are expressed in delta (δ) notation relative to the V-PDB standard. Repeated analyses of lab standard carbonates with known $\delta^{18}O$ values were carried out daily to ensure instrumental accuracy. The analytical error of the laboratory standard is approximately ± 0.2‰ for $\delta^{18}O$.

3. Results

3.1. Modern lacustrine carbonates and their oxygen isotope

The oxygen isotopic values of bulk carbonate of surface sediments collected from Lake Qinghai and surrounding small ponds range from −10‰ to 4.2‰ (Fig. 2, this result includes previous data from Liu et al., 2009), with lower values in shallow part of the lake and surrounding ponds but higher values in lake center. The 4 modern sediment samples from Lake Qinghai and 4 samples from nearby Erhai Lake show high carbonate content in bulk sediment samples, with 29.6–33% at Lake Qinghai and 21.8–43.4% at Erhai Lake, respectively. These carbonates are dominated by aragonite, about 74–78% at Lake Qinghai and 83–87% at Erhai Lake (Table 1). The oxygen isotope values of these bulk carbonates range from 0.9 to 2.9‰ at Lake Qinghai, and −1.1–1.2‰ at Erhai Lake.

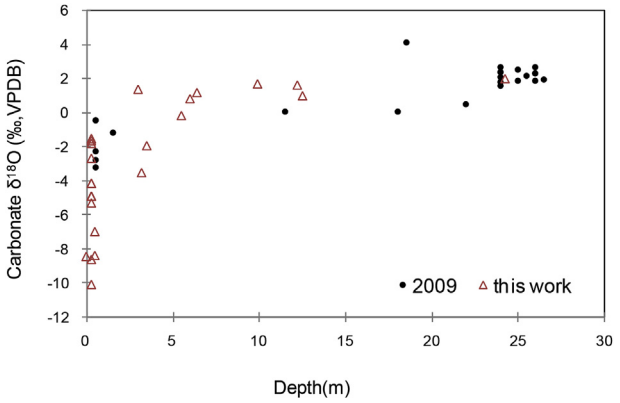

Fig. 2. Relation between $\delta^{18}O$ values of modern bulk carbonates and lake depth. Red triangles represent results from this work, and black dots indicate results from our previous work (Liu et al., 2009). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Live *Charas* from freshwater Erhai Lake and Hurleg Lake from the

Table 2
Mineral contents and stable isotopes of surface soil samples from Lake Qinghai area. The percentages of aragonite and calcite are relative to the total carbonate.

No	Latitude (N)	Longitude (E)	Altitude(m)	Carbonate, TIC (%)	Aragonite (%)	Calcite (%)	$\delta^{18}O$, TIC (‰)	Carbonate, fine (%)	$\delta^{18}O$, fine (‰)
1	36°47′12.6′	99°40′51.4′	3359	0.2	0	100	−8.9	0.4	−9.1
2	37°08′00.9′	99°30′42.6′	3245	15.9	0	100	−9.3	19.4	−9.4
3	37°12′41.8′	99°10′25.5′	3334	15.9	0	100	−9.7	19.5	−8.2
4	37°21′12.0′	98°54′20.4′	3450	13.9	0	100	−8.7	9.4	−9.0
5	37°08′41.5′	98°24′48.7′	3566	19.9	0	100	−9.1	17.1	−8.1
6	37°08′08.3′	98°31′02.8′	3246	16.4	0	100	−11.1	14.7	−7.9
7	37°02′24.0′	98°47′02.9′	3207	8.4	0	100	−8.2	8.0	−8.4
8	37°05′43.8′	99°46′01.3′	3207	11.3	0	100	−6.3	7.9	−7.4
9	37°05′43.8′	99°46′01.3′	3207	10.8	0	100	−6.9	6.1	−7.3
10	36°45′03.9″	99°36′31.5″	3826	7.4	0	100	−8.1	6.7	−9.4
11	36°45′47.5″	99°37′11.3″	3640	3.6	0	100	−8.3	9.7	−9.1
12	36.763	99.613	3720	9.3	0	100	−7.8	6.3	−9.3
13	36.764	99.635	3572	8.3	0	100	−8.5	8.6	−8.7
14	36.764	99.635	3572	9.0	0	100	−8.0	9.2	−8.7
15	36.772	99.648	3464	8.5	0	100	−8.3	7.3	−9.3
16	36.772	99.648	3464	11.4	0	100	−8.4	5.9	−8.6
17	36.447	101.119	3328	14.2	0	100	−8.0	13.7	−8.2

Qaidam Basin, coated with calcified encrustations, have high carbonate contents ranging from 32 to 42% (Table 1). These carbonates are dominated by aragonite rather than calcite, with 100% of aragonite at Lake Erhai and 59–71% of aragonite at Hurleg Lake. In comparison, other aquatic plants are coated with very limited carbonates (not listed). The oxygen isotope values of these *Chara* encrustations are about −1.7–0.2‰ at Erhai Lake and −6.4 to −6.9‰ at Hurleg Lake (Table 1). Results between bulk carbonate and *Chara* encrustations at Erhai Lake are quite close.

Carbonate contents of bulk soil samples around Lake Qinghai vary from 0.2 to 19.9%, which are quite similar with carbonate contents from fine-grained minerals (< 63 μm) ranging from 0.4 to 19.5%. These soil carbonates are all calcite, rather than aragonite which is dominant in lacustrine sediments. The oxygen isotope values of bulk carbonate of these soil samples changes from −11.1 to −6.3‰, while their oxygen isotope values of fine-grained carbonates vary in a smaller range between −9.4 and −7.3‰ (Table 2).

3.2. Downcore carbonate isotopes from core IF

The $\delta^{18}O$ data of bulk carbonate and fine-grained carbonate show overall very similar variations. From the last glacial maximum to the end of deglaciation, both $\delta^{18}O$ records show pronounced centennial-scale variations ranging between −11 and 5‰ (Fig. 3). Since the Holocene starting around 11 ka, both records show relatively stable changes with subtle centennial variations. The oxygen isotope values are relatively low (about −1‰) between 11 and 7 ka, slightly change to higher values of about 1‰ from 7 to 6 ka, and then become stable until present.

4. Discussion

4.1. Origin and isotope composition of carbonate in modern environment of Qinghai Lake

Bulk carbonate at these lakes has complex sources, mainly contributed by *Chara* encrustations, ostracode shells, evaporate carbonates, and terrigenous detrital carbonates. Different sourced carbonates could have quite different $\delta^{18}O$ values, and therefore, $\delta^{18}O$ values of bulk carbonate could be influenced by those multiple sourced carbonates and reflect a combined effect (i.e. Filippi et al, 1999; Hu et al., 1999; Xu et al., 2006; Liu et al., 2009; Thevenon et al, 2012; Zanchetta et al., 2012; Horton et al., 2016). Our previous study shows that $\delta^{18}O$ values of modern bulk carbonate at Qinghai Lake are quite close to that of the ostracode shells and fine-grained carbonates (< 63 μm) (Liu et al., 2009), with very similar changing tendency from lake shore to the center. This indicates that bulk carbonates at Lake Qinghai are dominated by authigenic carbonates. Authigenic carbonate is an evaporite, which reflects the immediate isotopic signal of lake water. The studies of modern process also showed that the oxygen isotope values of carbonate can record the oxygen isotope changes of lake water (Anderson et al., 2001; Jahren et al., 2001; Kirby et al., 2001).

Previous studies paid little attention to the potential influence of *Chara* encrustations on the bulk carbonate at Lake Qinghai, as there is no live *Chara* presented because of the high salinity. At nearby Erhai Lake and Hurleg Lake, we captured and analyzed live *Chara* coated with calcified encrustations. The results show unexpected high aragonite contents, with 100% at Erhai Lake and 59–71% at Hurleg Lake (Table 1). However, we notice a large difference exists between the two lakes, and this should be an interesting question for our future work. Carbonates in the sediment of Lake Qinghai, especially those from the deeper part of the lake, are mainly authigenic carbonates. Analyses of the carbonates from Lake Qinghai and nearby Lake Erhai show that these authigenic carbonates are dominated by aragonites (~80%) rather than calcites (Table 1).

Comparing to the aragonite dominated bulk carbonates in lake surface samples, carbonate minerals from soil samples around Lake Qinghai are pure calcite without any aragonite (Table 2). The $\delta^{18}O$ values of soil carbonates are quite close to that of freshwater body around Lake Qinghai (Liu et al., 2009), as soil carbonates mainly come from pedogenic carbonates (Liu et al., 2009). Therefore, they can reflect the oxygen isotope composition of modern precipitation.

Comparison of the results of these three different types of carbonates further supports that carbonates in modern sediment of Lake Qinghai are dominated by authigenic carbonates, with high aragonite contents. In addition, the downcore $\delta^{18}O$ values of bulk carbonates, fine-grained carbonates, and previously published ostracode shells (Li and Liu, 2017) show very similar variations since the last glacial maximum (Fig. 3). These lines of evidence indicate that the bulk carbonate at Lake Qinghai are dominated by authigenic rather than allothogenic carbonates.

4.2. Factors affecting variations in oxygen isotope compositions of lake water at Qinghai Lake

Oxygen isotope of authigenic carbonate in lake sediment is controlled by isotope compositions of lake water, which in turn responses to hydrological changes driven by climate change. At Lake Qinghai, the key question is what is the dominant control of the lake water isotope composition?

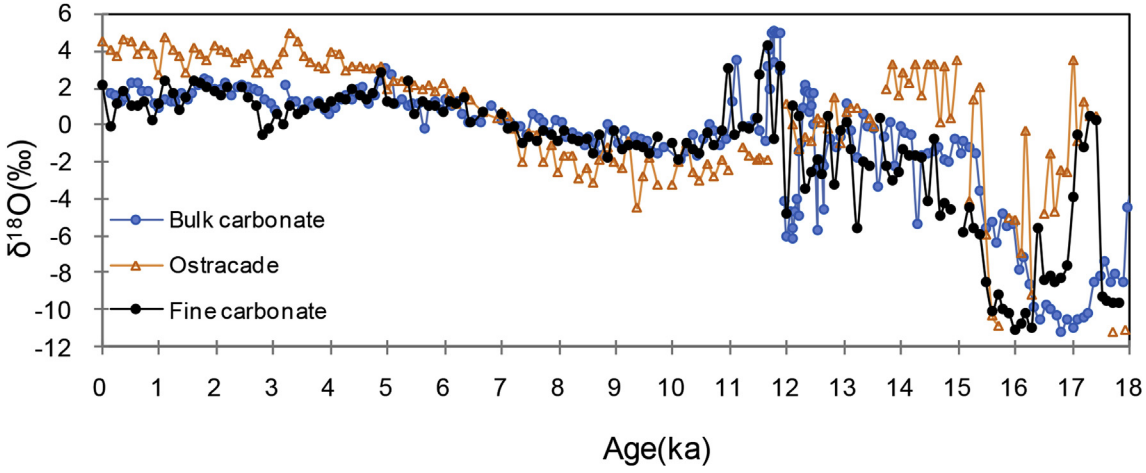

Fig. 3. Carbonate $\delta^{18}O$ records of bulk carbonates (blue dots), ostracode shells (red triangles), and fine carbonates (< 63 μm) from core IF at Lake Qinghai. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Currently, lake water isotopes could be influenced by isotopic compositions of inflowing rivers, precipitations on the lake and catchment basin, and then modified by the evaporation effect on the lake surface (Gat, 1995; Shapley et al., 2008; Jones and Imbers, 2010; Steinman et al., 2010; Steinman and Abbott, 2013). At long decadal- or centennial-scales, inflowing rivers ultimately come from regional precipitation in the catchment basin. As a result, lake water isotopes are controlled by the isotopic balance of average precipitation in the catchment basin and evaporation effect on the lake surface. Therefore, most previous studies have interpreted carbonate $\delta^{18}O$ at Lake Qinghai as the proxy of lake water balance and then regional hydroclimate changes (Lister et al., 1991; Shen et al., 2005; An et al., 2012; Chen et al., 2016). However, some recent studies have suggested that low ostracode $\delta^{18}O$ values during the last glacial maximum at Lake Qinghai could be influence by the moisture transported by the westerly which may have depleted $\delta^{18}O$ (e.g. Li and Liu, 2017).

In fact, many other factors could influence lake water isotopic compositions. For example, lake residence time and inflowing water versus lake volume ratio could also have affected the $\delta^{18}O$ of lake water (Pearson and Coplen, 1978). Our previous study at Lake Qinghai showed that modern $\delta^{18}O$ values of lake water, ostracode shells, and authigenic carbonates from shallow lake and surrounding small ponds were close to the isotopic composition of regional precipitations, while $\delta^{18}O$ values were gradually enriched with increased water depth from lake shore to lake center (Fig. 2, Liu et al., 2009). Similarly, $\delta^{18}O$ values are getting enriched with increasing water salinity from shallow to deeper parts of the lake, with a more distinct relation at shallow lake (Fig. 4). This relation is possibly due to differences in relative contributions between residue lake water and inflowing rivers at different locations of the lake, as lake water in large lakes like Lake Qinghai can not be quickly mixed. In this semi-arid region, evaporation effect strongly enriches the $\delta^{18}O$ of lake water. At shallow part of the lake, low-$\delta^{18}O$ inflowing rivers will effectively deplete lake water $\delta^{18}O$ values. From shallow to deep lake, the decreasing contribution of inflowing rivers and increasing contribution of evaporate residue water will induce enriched lake water $\delta^{18}O$ values. Therefore, over long timescales, the dynamic equilibrium caused by changing lake size and volume could be an important factor to influence lake water and precipitated carbonate $\delta^{18}O$ values (Fig. 5).

4.3. Variations in carbonate $\delta^{18}O$ values at Qinghai Lake since the last glacial maximum

Although there are differences in the details, the general consistent $\delta^{18}O$ variations in bulk carbonates (fine-grained carbonates as well) and ostracode shells indicate that both records have recorded variations in

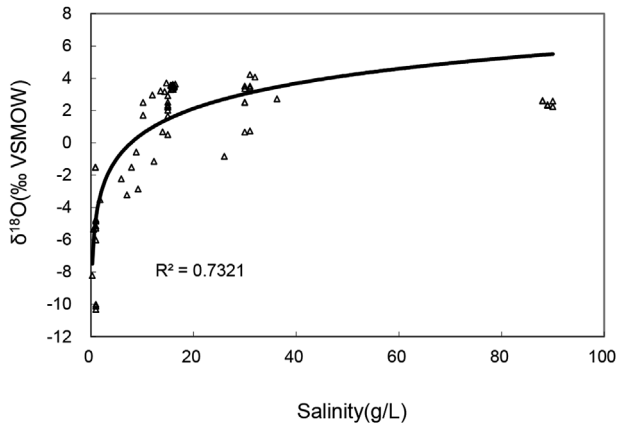

Fig. 4. Relation between lake water $\delta^{18}O$ values and salinity at Lake Qinghai catchment. The data include new results from this work and results from our previous work (Liu et al., 2009).

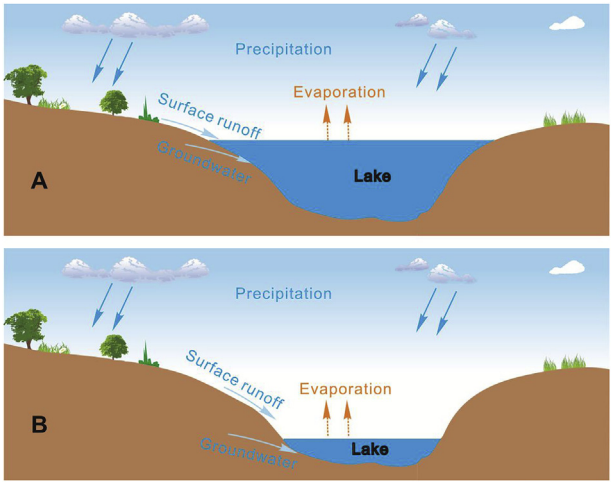

Fig. 5. Cartoon showing the "lake volume" effect on water isotopes, under similar climate and hydrological conditions including precipitation, evaporation, and inflowing rivers. (A) For a large and deep lake, lake water isotopes are less likely influenced by inflowing water but controlled by isotopic water balance between inflowing and evaporation water balance. (B) For a small and shallow lake, lake water isotopes tend to be easily influenced by inflowing water.

isotopic composition of lake water since the last glacial maximum (Fig. 3), which in turn have been driven by climate changes. Also, the detailed differences of both records would help to better understand the published ostracode $\delta^{18}O$ variations, which have been interpreted in different ways.

4.3.1. Relationship between carbonate formation and carbonate $\delta^{18}O$ values at Lake Qinghai

Based on the above comparison of oxygen isotope compositions between bulk carbonates and ostracode shells, we find quite similar changes. It helps to confirm that carbonates formed in Lake Qinghai since the last glacial maximum are dominated by authigenic carbonates, and oxygen isotopes of these authigenic carbonates have been mainly controlled by the lake water isotopes. However, in addition to ostracode shells and *Chara* encrustations, authigenic carbonates formed in lakes also include evaporation induced carbonates, which is hard to isolate. We also investigate the relation between carbonate contents and bulk carbonate $\delta^{18}O$ values (Fig. 6), which would help to better understand the source of these authigenic carbonates and their isotopic interpretations. During the last glacial maximum, there is no clear relation between carbonate contents and bulk carbonate $\delta^{18}O$ values. In this period, the lake was very shallow and small (Li and Liu, 2017), and carbonate contents was low. The bulk carbonates contains authigenic carbonates and probably more detrital soil carbonates. Therefore, the evaporation had limited effect on lake water isotope composition. During the last deglaciation, carbonate contents and bulk carbonate $\delta^{18}O$ values show a clear linear relation (Fig. 6A), with more carbonate contents corresponding with higher bulk carbonate $\delta^{18}O$ values, which was probably caused by the increasing evaporation effect when climate getting warmer.

During the early to middle Holocene, carbonate contents increased to the highest values over the entire core and varied from ~40% to 65%, while bulk carbonate $\delta^{18}O$ values remained at relatively low values around −3 − −1‰ (Fig. 6). Therefore, unlike the evaporation induced higher $\delta^{18}O$ values with more carbonates, there is no relation between carbonate contents and carbonate $\delta^{18}O$ values. A previous study at Lake Qinghai showed that changes in carbonate contents at Lake Qinghai were mainly caused by changes in aragonite, with quite consistent calcite contents throughout the sediment core (Fig. 7, Liu et al., 2009). The significantly increased carbonate contents during the early to middle Holocene were caused by increased aragonite as well

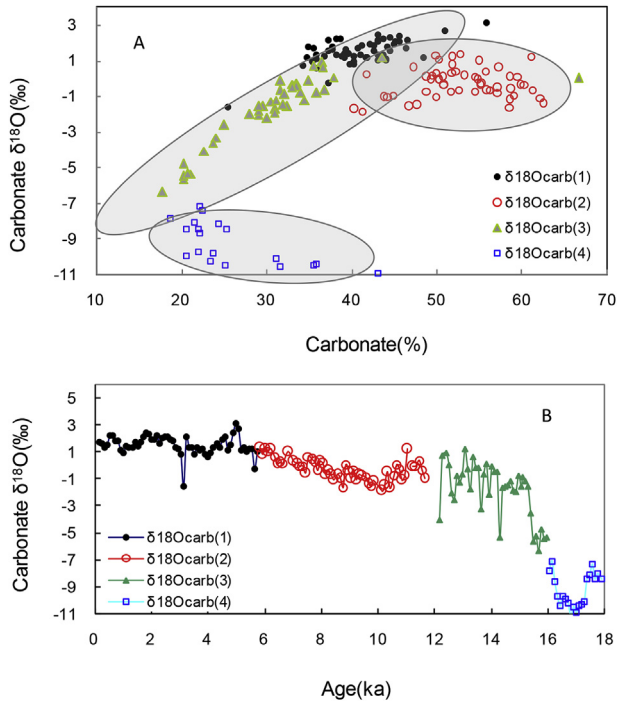

Fig. 6. (A) Relation between bulk carbonate $\delta^{18}O$ values and carbonate contents from core IF, divided with four time intervals. (B) Bulk carbonate $\delta^{18}O$ record from core IF at Lake Qinghai, divided with four time intervals. The 4 time intervals include16-18 ka (blue squares), 11.7–16 ka (green triangles), 5.7–11.7 ka (red circles), and 0–5.7 ka (black dots). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

(Fig. 7), due to low lake levels (< 8 m) at that time. According to our results from modern samples around Lake Qinghai region, the increased aragonite likely came from *Chara* encrustations which are precipitated because of the photosynthesis of *Chara* and then the removal of CO_2 from lake water. During the late Holocene, the positive correlation between carbonate contents and carbonate $\delta^{18}O$ values probably indicate evaporation became the main influence for carbonate precipitation.

Overall, changes in carbonate $\delta^{18}O$ values at Lake Qinghai since the last glacial maximum cannot be simply interpreted as the balance of average precipitation in the catchment basin and evaporate effect on the lake surface. The formation of different types of carbonates should be carefully considered.

4.3.2. Influence of water depth on carbonate $\delta^{18}O$ values during the Holocene

For closed lakes, carbonate $\delta^{18}O$ has been usually used to track the water balance between precipitation and evaporation (Leng and Marshall, 2004; Chen et al., 2016; Li and Liu, 2017). Therefore, carbonate $\delta^{18}O$ at Lake Qinghai has been widely interpreted as East Asian summer monsoon induced precipitation/evaporation water balance (or effective humidity). For example, the low $\delta^{18}O$ values during the early Holocene (Fig. 3) has been interpreted as the results of high lake levels under increased monsoon precipitation or high temperatures (Lister et al., 1991; Liu et al., 2007; An et al., 2012). However, as described in a recent review paper (Chen et al., 2016), this interpretation will not work for the early Holocene climate optimum, when monsoon precipitation increased but lake level was low (Fig. 8) (Zhang et al., 1989; Yu and Kelts, 2002; Liu et al., 2013, 2015a; b; 2017; Wang et al., 2014). Therefore, how to explain the low carbonate $\delta^{18}O$ values under low lake levels during the early Holocene remains a puzzle but important question. According to the concept of equilibrium between precipitation and evaporation in a lake, low carbonate $\delta^{18}O$ values should indicate a positive water balance (more precipitation than evaporation) and increased lake levels, rather than decreased lake levels.

Based on our result of modern lake sediment and soil samples, we propose that "volume effect" would be the most likely explanation for the low carbonate $\delta^{18}O$ values and low lake levels during the early Holocene. At that time, although East Asian summer monsoon strengthened and monsoon precipitation increased, temperature increased as well, and higher temperature would induce higher evaporation effect. Also, increased overall temperature would reduce the freezing days, which would in turn further increase the evaporation effect. If the temperature increased by 2–3° during the early Holocene, the freezing days of the lake would decrease for several months, and the evaporation would significantly increase in this arid region. Therefore, the accumulation of lake water from the nearly dry condition at the last glacial would be slow, and thus the lake is still small and shallow during the early Holocene.

Low carbonate $\delta^{18}O$ values during the early Holocene likely reflect low lake water $\delta^{18}O$ values, which is more influenced by direct precipitations with low $\delta^{18}O$ values in the entire Lake Qinghai catchment basin rather than evaporation on the lake surface. In a small and shallow lake at arid region, strong evaporation effect on the lake surface would reduce the lake volume and increase lake water $\delta^{18}O$ values, while the small lake would be more easily influenced by precipitation and snow melt water with low $\delta^{18}O$ values accumulated in the large catchment basin. The water source of the lake is supplied by surrounding rivers, while the river water is a mixture of precipitation, groundwater, snow melt water and glacial melting water. The $\delta^{18}O$ values of river water from Lake Qinghai area ranged from −9.8‰ to −6.2‰ (Liu et al., 2009; Cui and Li, 2015). In other words, the isotopic water balance of precipitation and evaporation was easily broken by the precipitation and snow melt water supply for a small and shallow lake. Therefore, lake water $\delta^{18}O$ values would decrease and induce low carbonate $\delta^{18}O$ values, just like the current condition of Lake Erhai. After 6 ka, with temperature and evaporation effect decreased, the lake became larger and deeper. The increased residence time of lake water would effectively increase lake water $\delta^{18}O$ values, which would induce higher carbonate $\delta^{18}O$ values. Thus, variations in lake water $\delta^{18}O$ are not only the result of the balance between precipitation and evaporation, but also influenced by other environmental factors closely related with changes in lake volume through time. That is why we can observe the more negative carbonate $\delta^{18}O$ values during the last glacial maximum and the early Holocene climate optimum.

4.3.3. Comparison of the oxygen isotope of total carbonate and ostracods in Qinghai Lake

Although the $\delta^{18}O$ records of bulk carbonates and ostracode shells share the same general pattern since the Holocene, we can still observe some detailed differences between both records (Fig. 3). Comparing with ostracode $\delta^{18}O$ values, bulk carbonate (or fine-grained carbonate) $\delta^{18}O$ values were higher during the early Holocene, but lower during the past 6 ka. Stable isotopes of these authigenic carbonates can reflect lake water isotopic composition and different components of carbonates form in different environments within the lake water. Modern lake water isotope analyses show that lake surface and bottom water $\delta^{18}O$ values have no significant difference from lakeside to lake center (27 m depth) in Qinghai Lake (Liu et al., 2009). Alternatively, water-depth depended water temperature could cause the difference, as ostracodes live in the lake bottom while other authigenic carbonates are formed at the lake surface (Liu et al., 2009). Higher water temperature would induce low carbonate $\delta^{18}O$ values, and vice versa. In a shallow lake, the temperature difference between the lake surface and lake bottom would be quite small. However, in a deep lake, the temperature difference would be increased.

During the last glacial maximum and deglaciation, the lake is

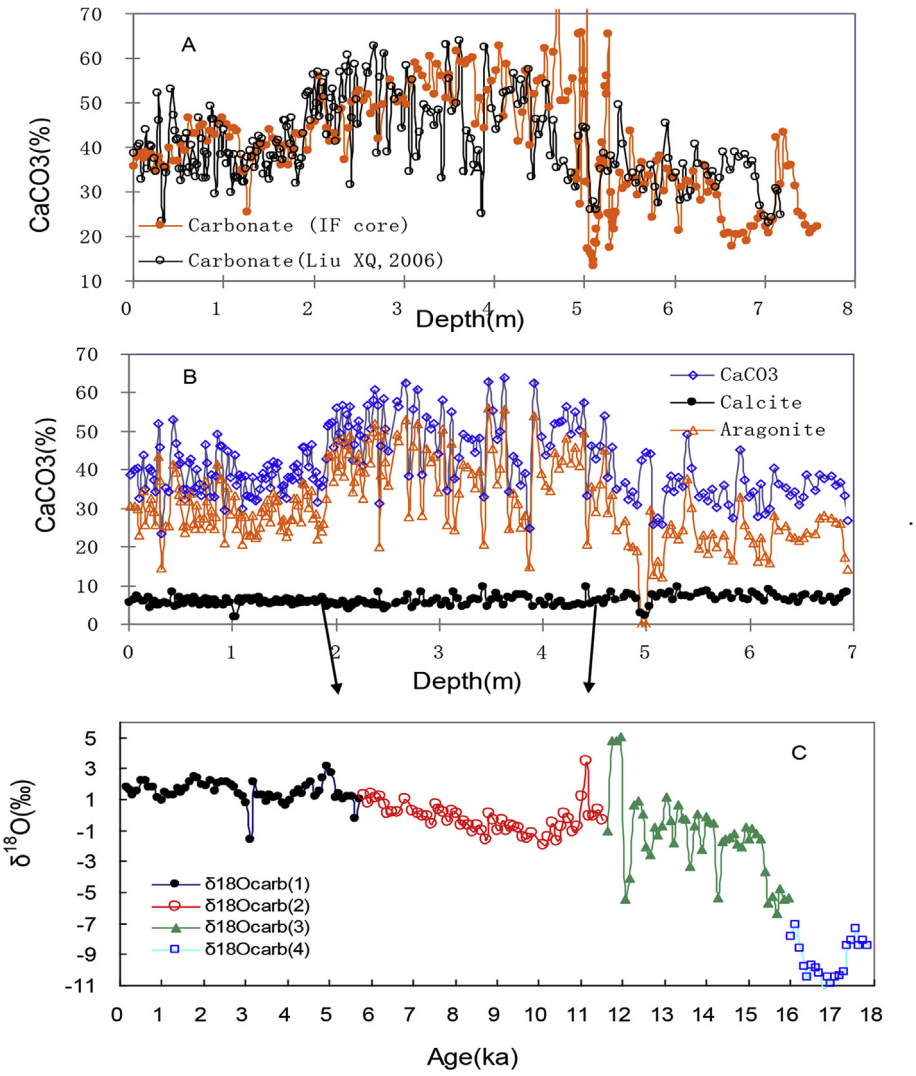

Fig. 7. (A) Comparison of bulk carbonate contents between core IF (this study) and core QH-2000 (Liu et al., 2006). (B) Records of bulk carbonates, aragonite contents, and calcite contents from core IF. (C) Bulk carbonate $\delta^{18}O$ record from core IF at Lake Qinghai, divided with four time intervals. The 4 time intervals include16-18 ka (blue squares), 11.7–16 ka (green trangles), 5.7–11.7 ka (red circles), and 0–5.7 ka (black dots). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

overall small and shallow (Li and Liu, 2017), and carbonate $\delta^{18}O$ values show relatively large fluctuations. Between 15.6 and 13.5 ka, $\delta^{18}O$ values of ostracode shells were clearly higher than that of bulk carbonates, probably indicating rapid increase in lake levels due to glacial melting during the Bølling-Allerød warm period. During the early Holocene around 12–8 ka, ostracode $\delta^{18}O$ values were lower than that of bulk carbonates and fine-grained carbonates. This phenomenon is possibly related with the dominance of precipitated *Chara* encrustations during this interval, which could have different isotopic fractionation factors during their formation. This issue should be carefully investigated in the future.

During the middle to late Holocene after 8 ka, $\delta^{18}O$ values of ostracode shells have gradually become higher than that of bulk carbonates. The significant isotopic differences of these two groups likely have been caused by the increase in lake depth and temperature stratification in water column. Carbonate formed by evaporation is in the lake surface where temperature would be higher than that of the lake bottom during the growing season. Therefore, $\delta^{18}O$ values of ostracode shells formed in the lake bottom were lower than that of bulk carbonates and fine-grained carbonates formed in the lake surface. After 3 ka, the isotopic differences of these two groups have been stabilized, and the $\delta^{18}O$ values of bulk carbonates, fine-grained carbonates and ostracods are consistent with those of modern surface sediments in Qinghai Lake (Liu et al., 2009), indicating a relatively stable lake water depth.

5. Conclusions and implications

Our results indicate that carbonates in modern sediments of Lake Qinghai are dominated by authigenic carbonates, with high aragonite contents. Comparison of downcore $\delta^{18}O$ values of bulk carbonates, fine-grained carbonates, and previously published ostracode shells show very similar variations since the last glacial maximum, indicating that the bulk carbonate at Lake Qinghai are dominated by authigenic carbonates.

Currently, Lake Qinghai is a large lake which cannot be quickly mixed. At shallow part of the lake, inflowing rivers with low-$\delta^{18}O$ values will effectively deplete lake water $\delta^{18}O$ values. From shallow to deep lake, the decreasing contribution of inflowing rivers and increasing contribution of evaporated residue water will induce enriched lake water $\delta^{18}O$ values (Liu et al., 2009). Over long timescales, the similar explanation could still work for changing lake volume and size, as a shallow and small lake would be more easily influenced by precipitation carrying negative $\delta^{18}O$ values at Lake Qinghai region. This

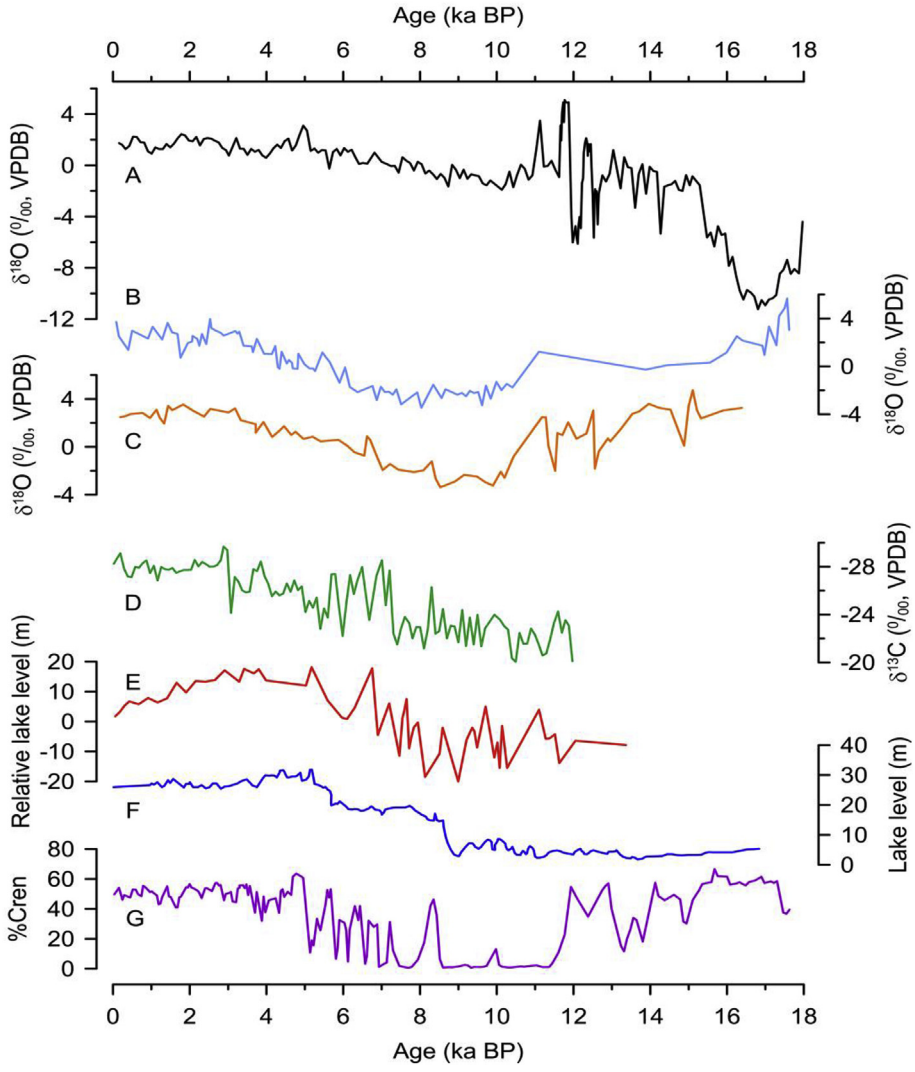

Fig. 8. Comparison between $\delta^{18}O$ variation and proxy-reconstructed lake-level variation of Lake Qinghai during the past 18 ka. (A) Bulk carbonate $\delta^{18}O$ of core IF. (B) Ostracode $\delta^{18}O$ of core QH-2000 (Liu et al., 2007). (C) Ostracode $\delta^{18}O$ of core 14B (Lister et al., 1991). (D) The $\delta^{13}C$ of total organic matter of core IF, with more negative values indicating higher lake level (Liu et al., 2013). (E) Water level variations based on ostracode Sr/Ca value of core QH-16A (Zhang et al., 1994). (F) Reconstructed water depth variation from core Q14B (Yu, 2005). (G) The %Cren record of core QH-2011, with higher values indicating higher lake level (Wang et al., 2015).

"lake volume" effect can be used to explain the negative carbonate $\delta^{18}O$ values during the early Holocene, which were likely caused by an increased influence of precipitation and glacial melt water with negative $\delta^{18}O$ values under a small and shallow water body.

In other stages, during the last glacial period, the dry climate would induce a shallow and small lake. Bulk carbonate $\delta^{18}O$ values reflected contribution of authigenic carbonate and terrestrial soil carbonates, while ostracode $\delta^{18}O$ values showed large-magnitude fluctuations probably due to frequent changes in lake volume. During the mid-Holocene, increase in water depth and lake volume caused negative $\delta^{18}O$ values in ostracodes, *Chara* encrustations, as well as evaporative induced carbonates. During the late Holocene, decreased temperature and weakened evaporation effect further increased the water depth, and this would decrease the precipitations of *Chara* encrustations and increase the lake water $\delta^{18}O$ values.

Down core $\delta^{18}O$ values of ostracode shells and bulk carbonates show similar variations since the last glacial period, but have distinct geochemical information. The ostracode $\delta^{18}O$ are mainly controlled by the water temperature at the bottom of the lake, while $\delta^{18}O$ values in other carbonates are mainly controlled by lake surface temperature. Isotopic differences between these two groups of carbonates may thus reflect the temperature differences between the surface and bottom water, which is related with lake water depth.

Overall, our results suggest that special caution would be necessary when using lacustrine $\delta^{18}O$ values of authigenic carbonates to infer past hydrological and climate changes in an arid environment.

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