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Seasonal/Interannual Variation and Controlling Factors for Oxygen and Carbon Isotopes of Ostracod Shells Collected From a Time-Series Sediment Trap in Lake Qinghai

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Because the shell substance of an ostracod is derived entirely from the water body where it lives, its chemical compositions are sensitive to aquatic environment and thus have been used to reconstruct past climatic and environmental changes. However, there is controversy about the controlling factors for the different compositions of ostracod shells from various water bodies. In this study, seasonal and interannual variations in daily flux and stable oxygen-carbon isotopic compositions ($\delta^{18}O$, $\delta^{13}C$) for two species of ostracod shells (*Limnocythere inopinata* and *Eucypris mareotica*) and their controlling factors are discussed, based on ostracod shell samples collected from a time-series sediment trap from July 2010 through September 2012 and from surface sediments in Lake Qinghai, which were correlated with the state-of-the-art sensing data of the lake water. The results show that the daily flux of *L. inopinata* shells is an order of magnitude higher than that of *E. mareotica*. The $\delta^{18}O$ and $\delta^{13}C$ of both *L. inopinata* and *E. mareotica* shells have distinctly interannual and seasonal variations, with species differences. Interannual differences of $\delta^{18}O$ for the two species of ostracod shells directly reflect the systematic differences of the summer water temperature between 2010 and 2012. We propose that seasonal variations of both $\delta^{18}O$ and $\delta^{13}C$ for the two species are affected by the precipitation of authigenic carbonates in microenvironment induced by high water temperature in summers, highlighting their environmental implications in Lake Qinghai.

Keywords: ostracod shell, abundance, stable O-C isotopes, seasonal variation, controlling factor, Lake Qinghai

INTRODUCTION

As small, bivalved crustaceans in various water bodies, ostracod shells consist of low magnesium (Mg) calcite, which is derived almost entirely from the water body where they live, and are often well preserved in sediments. The chemical compositions of ostracod shells are, therefore, ideally used to trace limnological conditions and to reconstruct (paleo)environment, because they are sensitive to water chemistry (e.g., Chivas et al., 1985; Chivas et al., 1986; Holmes, 1996; Holmes et al., 1998; Boomer et al., 2003). In most cases, the stable oxygen and carbon isotopic compositions ($\delta^{18}O$, $\delta^{13}C$)

of lacustrine ostracod shells are generally considered to reflect those of the lake water (Stuiver, 1970; Holmes, 1996; von Grafenstein et al., 1999; Jin et al., 2009; Caporaletti, 2011). However, in addition to the water chemistry, there are other factors controlling the variations in both $\delta^{18}O$ and $\delta^{13}C$ of lacustrine ostracod shells, such as water temperature, authigenic carbonate precipitation, and/or isotopic fractionation between the shell and water, particularly for $\delta^{13}C$ (e.g., Mckenzie, 1985; Herczeg and Fairbanks, 1987; Heaton et al., 1995; von Grafenstein et al., 1999; Keatings et al., 2002; Decrouy et al., 2011; Devriendt et al., 2017). These factors make the current explanations about the controlling factors for the isotopic compositions of ostracod shells controversial and uncertain.

For Lake Qinghai, the largest lake located on the northeastern Tibetan Plateau, ostracod shells in its sediments have been used to reflect lake water conditions and, thus, Asian summer monsoon change. For example, Zhang et al. (1994) analyzed $\delta^{18}O$ and Sr/Ca ratios of ostracod shells from Lake Qinghai and discussed changes in salinity, lake water level, and temperature for the past 12000 years. The following ostracod studies of Lake Qinghai showed that the $\delta^{18}O$ ratios can reflect lake water level and, thus, the precipitation/evaporation (P/E) budget associated with the Asian summer monsoon system (Lister et al., 1991; Liu et al., 2007; An et al., 2012). Meanwhile, other studies have shown that the isotopic composition of ostracod shells in Lake Qinghai reflects summer bottom-water conditions, with species difference (Henderson et al., 2003; Liu et al., 2009), whereas their $\delta^{13}C$ is affected by the $\delta^{13}C$ of dissolved inorganic carbon (DIC) and can reflect lake water salinity change (Li et al., 2012; Li and Liu, 2014). Additionally, these isotopic analyses used samples of several ostracod valves from sediments, which might be comprised of shells moulting at different seasons and years, since sedimentation rate is averaged at 1.0 mm/yr in Lake Qinghai (Henderson et al., 2003). Being considered dramatic seasonal to interannual limnological change, it is essential for the understanding of seasonal variations within and between populations of ostracods and association with limnological processes (Decrouy et al., 2011). There is currently little information on the seasonal variations in $\delta^{18}O$ and $\delta^{13}C$ of lacustrine ostracod shells in Lake Qinghai.

In this study, we report the seasonal $\delta^{18}O$ and $\delta^{13}C$ of modern ostracod shells collected from a time-series sediment trap from July 2010 through September 2012 in Lake Qinghai. The limnological conditions controlling both seasonal $\delta^{18}O$ and $\delta^{13}C$ of modern ostracod shells are discussed, through correlation with the state-of-the-art sensing data of lake water.

MATERIALS AND METHODS

As the largest lake with brackish water on the northeastern Tibetan Plateau (**Figure 1A**), Lake Qinghai (36°32′–37°15′N, 99°36′–100°47′E) is located within an intermontane depression at the tectonically active margin of the plateau. Today, Lake Qinghai, at an altitude of 3,194 m above sea level (a.s.l.), has a water volume of 71.6 km^3 and a catchment area of about 29,660 km^2. As a hydrologically closed lake, it is of particular interest due to its unique geographical/geological settings and dramatic seasonal to interannual limnological change. The lake lies in a transitional zone where climate is sensitive to the East Asian and Indian monsoons and the Westerly Jet Stream. Mean annual precipitation (1951–2000) is 357 mm, but evaporation is 3–4 times higher than precipitation (Li et al., 2007). Average annual air temperature (1951–2007) is ~1.2°C.

From July 13, 2010, to September 25, 2012, a McLane Mark 8–13 time-series sediment trap was deployed about 10 m under the lake water surface (**Figure 1C**) in the southern depocenter of Lake Qinghai (36°48′39.1″N, 100°8′12.0″E; **Figure 1B**). The Mark 8–13 sediment trap is a time-series instrument that uses 13 cup sample bottles to collect settling particles *in situ*. Due to the low sedimentation rate (~1 mm/yr) and ice cover during winters, the sediment trap was recovered and deployed every 6 months, such that the collection time for each sample was 10–14 days. Meanwhile, an OS305 CTD (Conductance, Temperature, Depth) sensor was bound to the sediment trap to monitor lake water parameters every 30 min. These state-of-the-art sensing data recorded the limnological conditions. Owing to running out of battery, there lack sensing data between February 18 and June 10, 2011. In addition, 17 samples of the topmost 2 cm of sediment were collected from extensive sites within the lake.

In this study, a total of 45 trap sediment samples collected during July 2010 and September 2012 in Lake Qinghai were used to pick up ostracod shells. After removed lake water from the bottle, each sample was sieved using deionized water; >63 μm fraction was then dried on a petri dish; adult ostracod shells of both species (*Limnocythere inopinata* and *Eucypris mareotica*) were picked out from each sample using a fine paint-brush. The abundance of each species (valves/m^2/d) was obtained using the number of adult ostracod shells, sediment weight, collection days, and surface area of the sediment trap (0.25 m^2). Following the same procedure, adult ostracod shells of both species were picked out from 17 surface sediment samples.

Well-preserved adult ostracod shells were selected from the trap and surface sediment samples for stable isotopic analyses. Twenty to twenty five valves of *L. inopinata* and four to five valves of *E. mareotica*, respectively, were used for analyses of $\delta^{18}O$ and $\delta^{13}C$. All specimens were then removed adhering detrital particles using a fine paint-brush, and allowed them to dry. Oxygen and carbon isotope analyses of ostracod shells were conducted using a Finigan MAT252 mass spectrometer with carbonate device (Kiel II). Meanwhile, carbonates in fine-grained fractions (<63 μm) of both trap and surface sediment samples were also analyzed for oxygen and carbon isotopic compositions. The <63 μm fraction was pretreated overnight with a 5% H_2O_2 solution to remove organic matter, and then reacted with anhydrous H_3PO_4 in vacuo overnight at a constant temperature of 25°C. The liberated CO_2 was separated from water vapor and its stable isotope content measured also on a Finigan MAT252 mass spectrometer. All isotope results are reported in $\delta^{18}O$ and $\delta^{13}C$ notation per mil (‰) versus VPDB, based on calibration of the laboratory standards against NSB-19. Analytical reproducibility was better than ±0.10‰ (2σ) for $\delta^{18}O$ and $\delta^{13}C$ using both systems. All pretreatment and analyses were carried out at the State Key laboratory of Loess and Quaternary Geology (SKLLQG), Institute of Earth Environment, Chinese Academy of Sciences (IEECAS).

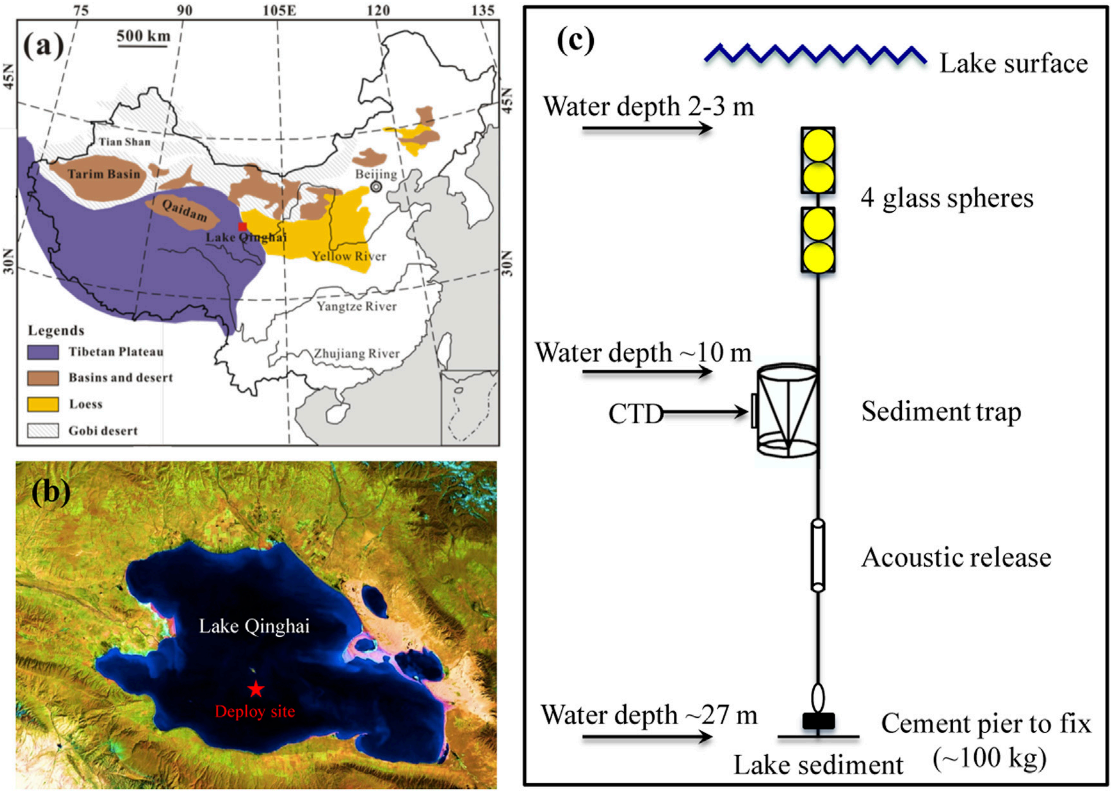

FIGURE 1 | (A) Sketch map showing the location of Lake Qinghai (red square) and the surrounding region, including the Tibetan Plateau, the Chinese Loess Plateau, the Qaidam and Tarim Basins, and the Gobi desert. **(B)** The deployed (red solid star) site of the Mark 8–13 time-series sediment trap in Lake Qinghai. **(C)** Underwater mooring design of Mark 8–13 sediment trap in Lake Qinghai.

Meanwhile, the oxygen isotopic compositions of 13 lake water samples collected by the sediment trap during October 12 and September were analyzed using a Delta V IRMS mass spectrometer with Gas Bench II. For each analysis, 0.2 ml water samples were equilibrated for 18 h with instrument grade CO_2 at 25°C. The equilibrated CO_2 was measured for the oxygen isotopic compositions. The oxygen isotopic results are reported in $\delta^{18}O$ notation permil (‰) deviations relative to the SMOW standard (**Table 1**). The analytical accuracy is better than 0.2‰. The oxygen isotopic analysis of water was carried out at the Institute of Tibetan Plateau Research, CAS.

RESULTS

Limnological Conditions During 2010 and 2012

During the period of the sediment trap deployment (July 13, 2010, to September 25, 2012), Lake Qinghai experienced two entire limnological cycles as shown by lake water temperature, salinity, and level (**Figures 2–4**). The lake water temperature and salinity varied from −0.7°C to 15.4°C and from 12.08 to 13.16 PSU (Practical Salinity Units), respectively. Relative to the dry seasons, both parameters fluctuated largely during the summers, associated with monsoonal rainfall. For example, salinity had a 0.2 to 0.4 PSU change within one day. For the same period, water level in Lake Qinghai varied between 3,193.40 m and 3,194.53 m, with the highest water level occurring in summer 2012 (**Figure 2**). In general, salinity in the dry seasons was higher than that of the monsoonal seasons. As the lake water level increased during the monsoonal seasons, salinity tended to decrease. However, there was a negative relation between salinity and temperature (**Figure 3**), meaning that there was low salinity when temperature was high, even when the water level was low (**Figure 2**). The decreased salinity can be attributed to the removal of Mg^{2+} and Ca^{2+} by the precipitation of authigenic carbonates from the water column due to high temperature, because the Lake Qinghai water was supersaturated with respect to both calcite and dolomite (Jin et al., 2010; Jin et al., 2013a).

Seasonal Variation in the Daily Flux of Ostracod Shells in Lake Qinghai

There were two species of ostracods in the trap sediments collected during July 2010 and September 2012 in Lake Qinghai, i.e., *L. inopinata* and *E. mareotica*, both of which have been dominant in its lake sediments since the last glacial period (Lister et al., 1991; Zhang et al., 1994; Liu et al., 2007; An et al., 2012). In general, the daily flux of *L. inopinata* shell was an order of magnitude higher than that of *E. mareotica*, as listed in

TABLE 1 | Oxygen and carbon isotopic compositions for two species of adult ostracod shells (*L. inopinata* and *E. mareotica*) and carbonates of the <63 μm sediment fraction, and $\delta^{18}O$ of lake water collected by a time-series sediment trap during July 2010 through September 2012 in Lake Qinghai.

Trap series	Sampling date	*Limnocythere inopinata*			*Eucypris mareotica*			<63 μm carbonates		Lake water
		Daily flux	$\delta^{13}C$	$\delta^{18}O$	Daily flux	$\delta^{13}C$	$\delta^{18}O$	$\delta^{13}C$	$\delta^{18}O$	$\delta^{18}O_{SMOW}$
		Valves/m^2/d	‰	‰	Valves/m^2/d	‰	‰	‰	‰	‰
ST-1-1	2010/7/13–2010/7/23	—	−1.14	4.91	—	—	—	0.52	4.38	—
ST-1-2	2010/7/23–2010/8/1	—	−0.64	4.61	—	0.12	4.51	1.24	3.32	—
ST-1-3	2010/8/1–2010/8/11	250	−0.90	4.65	36	0.01	4.34	0.60	3.98	—
ST-1-4	2010/8/11–2010/8/21	182	−1.02	4.78	7	−0.78	4.24	0.75	4.12	—
ST-1-5	2010/8/21–2010/8/30	294	−0.98	4.80	20	−0.29	4.47	0.75	3.88	—
ST-1-6	2010/8/30–2010/9/9	256	—	—	17	−1.00	4.16	0.82	3.77	—
ST-1-7	2010/9/9–2010/9/19	316	—	—	22	−0.34	4.10	0.72	3.78	—
ST-1-8	2010/9/19–2010/9/28	1,113	−0.11	5.63	185	−0.25	5.90	0.83	3.57	—
ST-1-9	2010/9/28–2010/10/8	2,406	—	—	101	−0.40	4.61	0.50	3.48	—
ST-1-10	2010/10/8–2010/10/15	37	−0.57	4.44	5	−0.83	5.05	0.96	3.58	—
ST-2-1	2010/10/16–2010/11/3	190	−0.71	4.37	36	−0.41	4.16	2.96	3.01	—
ST-2-2	2010/11/4–2010/11/20	6	−0.82	4.37	3	−0.81	4.09	3.17	2.87	—
ST-2-3	2010/11/20–2010/12/8	1	—	—	1	—	—	2.31	2.84	—
ST-2-4	2010/12/9–2010/12/25	2	—	—	1	—	—	2.35	2.82	—
ST-2-5	2010/12/25–2011/1/12	0	—	—	1	—	—	—	—	—
ST-2-6	2011/1/13–2011/1/29	0	—	—	0	—	—	—	—	—
ST-2-7	2011/1/29–2011/2/16	0	—	—	0	—	—	—	—	—
ST-2-8	2011/2/17–2011/3/5	0	—	—	0	—	—	—	—	—
ST-2-9	2011/3/5–2011/3/23	0	—	—	0	—	—	—	—	—
ST-2-10	2011/3/24–2011/4/9	0	—	—	0	—	—	—	—	—
ST-2-11	2011/4/9–2011/4/27	0	—	—	0	—	—	—	—	—
ST-2-12	2011/4/28–2011/5/14	0	—	—	0	—	—	—	—	—
ST-2-13	2011/5/14–2011/6/1	0	—	—	0	—	—	2.71	1.37	—
ST-3-1	2011/6/10–2011/6/23	451	−0.63	4.87	3	—	—	2.74	2.39	—
ST-3-2	2011/6/23–2011/7/7	3	—	—	0	—	—	2.24	1.08	—
ST-3-3	2011/7/7–2011/7/20	123	−1.09	5.74	1	—	—	2.22	1.73	—
ST-3-4	2011/7/20–2011/8/2	5	—	—	2	—	—	—	—	—
ST-3-5	2011/8/2–2011/8/15	108	−1.36	4.72	18	—	—	1.02	1.73	—
ST-3-6	2011/8/15–2011/8/29	516	−1.07	5.67	51	−0.17	4.11	1.22	2.68	—
ST-3-7	2011/8/29–2011/9/11	146	−1.09	5.00	15	−0.14	4.49	1.46	2.34	—
ST-3-8	2011/9/11–2011/9/24	185	−1.13	5.33	6	−0.10	4.14	1.30	2.77	—
ST-3-9	2011/9/24–2011/10/7	156	−1.01	4.92	312	−0.16	4.85	2.35	2.29	—
ST-4-1	2011/10/8–2011/11/5	87	−0.81	5.00	10	−0.45	5.22	1.72	3.48	1.95
ST-4-2	2011/11/5–2011/12/3	208	−1.05	6.16	6	—	—	2.87	3.19	1.85
ST-4-3	2011/12/3–2012/1/1	9	−0.95	6.39	2	−0.15	6.13	3.34	3.46	2.10
ST-4-4	2012/1/1–2012/1/29	4	—	—	1	−0.86	5.87	3.11	2.92	2.16
ST-4-5	2012/1/29–2012/2/26	0	—	—	0	—	—	3.08	3.33	2.09
ST-4-6	2012/2/26–2012/3/25	0	—	—	0	—	—	3.19	3.58	1.79
ST-4-7	2012/3/25–2012/4/22	0	—	—	0	—	—	—	—	1.89
ST-4-8	2012/4/22–2012/5/20	5	−0.25	5.72	1	—	—	2.63	2.22	2.23
ST-4-9	2012/5/20–2012/6/17	17	−0.37	5.65	2	−0.30	5.06	2.93	3.11	2.07
ST-4-10	2012/6/17–2012/7/16	57	−1.02	6.47	1	−0.25	5.92	2.54	3.38	2.07
ST-4-11	2012/7/16–2012/8/13	57	−1.52	7.08	1	−1.02	4.21	2.88	3.15	1.94
ST-4-12	2012/8/13–2012/9/10	606	−1.19	5.27	23	−0.59	4.48	2.46	3.30	2.14
ST-4-13	2012/9/10–2012/9/25	237	−1.25	5.89	6	−0.50	4.40	2.54	3.28	1.89

Table 1. There were dramatic seasonal variations in daily fluxes for both ostracods. High fluxes for both ostracods appeared during the monsoonal seasons, i.e., June through October (**Figure 2**). There were no or little shells found during winter and spring for both species. Flux peaks were 2,406 valves/m^2/d for *L. inopinata* shells in late August 2010 and 312 valves/m^2/d for *E. mareotica* in early September 2011 (**Table 1**).

Furthermore, *L. inopinata* appeared during late May and early June, earlier than *E. mareotica*, which secreted shells during late July, indicating that *E. mareotica* grew one and half months later than *L. inopinata*. Meanwhile, there was distinct interannual variation in both species. Daily fluxes of both ostracods in 2010 were higher than those in 2012, though the highest flux of *E. mareotica* appeared in early September 2011.

Ostracod $\delta^{18}O$ and $\delta^{13}C$ in Lake Qinghai

The values of $\delta^{18}O$ and $\delta^{13}C$ for both species of ostracod shells collected from Lake Qinghai during July 2010 through September 2012 are listed in **Table 1**. There were no data for some samples due to no or limited shells, mainly for those collected during winters and springs. The $\delta^{18}O$ values varied from 4.37‰ to 7.08‰ (averaging 5.30‰) for the adult *L. inopinata* shells and from 4.09‰ to 6.13‰ (averaging 4.72‰) for the adult *E. mareotica* (**Table 1**). It is obvious that *L. inopinata* shells had higher $\delta^{18}O$ values than those of *E. mareotica*. There was a systematic difference for $\delta^{18}O$ of 0.56‰ between the two species, with similar seasonal and interannual variations (**Figure 4**). In general, the $\delta^{18}O$ values of both ostracod shells in 2010 were lower than those in 2011 and 2102, with high $\delta^{18}O$ values occurring during the middle summers.

Contrary to the $\delta^{18}O$ values, the $\delta^{13}C$ values of *L. inopinata* shells were generally 0.53‰ lower than those of *E. mareotica* (**Figure 5**). The $\delta^{13}C$ values varied from −1.52‰ to −0.11‰ (averaging −0.91‰) for the adult *L. inopinata* shells and from −1.02‰ to 0.12‰ (averaging −0.42‰) for the adult *E. mareotica* (**Table 1**). Another interesting observation was that the $\delta^{13}C$ values of *E. mareotica* shells showed a general decreasing trend for each year, so do that of *L. inopinata* shells in 2012 (**Figure 5**). There were little interannual $\delta^{13}C$ variations for both ostracods between 2010 and 2012.

Relative to seasonal ostracod shells from the sediment trap, the ostracod $\delta^{18}O$ and $\delta^{13}C$ of both species from the surface sediment varied little, ranging from 3.64‰ to 4.79‰ for $\delta^{18}O$ and −1.30‰ to −0.27‰ for $\delta^{13}C$ of *L. inopinata* shells (**Figure 6**); corresponding values for *E. mareotica* shells were from 3.28‰ to 4.89‰ for $\delta^{18}O$ and from −0.78 to 0.42‰ for $\delta^{13}C$, respectively (**Table 2**). Meanwhile, $\delta^{18}O$ values of *L. inopinata* shells were slightly higher than those of *E. mareotica*, and the opposite was true for $\delta^{13}C$ (**Figure 6**).

The $\delta^{18}O$ and $\delta^{13}C$ of Fine-Grained Carbonates

The fine-grained carbonates in modern Lake Qinghai were essentially dominated by authigenic aragonite and low-Mg calcite (Henderson et al., 2003; Jin et al., 2013a). The $\delta^{18}O$ values of authigenic carbonates in the <63 μm fractions of the seasonal trap sediments had a large range, varying from 1.08‰ to 4.12‰ with an average of 3.03‰ (**Table 1**). Meanwhile, the $\delta^{18}O$ values of authigenic carbonates were all lower than those of both ostracod shells for the same seasons (**Figure 3**). Similar to the seasonal and interannual variation in the ostracod $\delta^{18}O$, the $\delta^{18}O$ values of authigenic carbonates varied little and decreased from summer to winter in 2010, whereas in both 2011 and 2012 the carbonate $\delta^{18}O$ varied largely but increased from spring to summer and then remained at high values (**Figure 3**).

The $\delta^{13}C$ of fine-grained carbonates varied from 0.50‰ to 3.34‰, averaging 1.97‰, with higher values in the dry seasons than in the monsoon seasons. Contrary to the $\delta^{18}O$ values, the carbonate $\delta^{13}C$ values were nearly all higher than those of both ostracod shells (**Figure 4**).

Relative to those of the trap sediments, $\delta^{18}O$ and $\delta^{13}C$ of fine-grained carbonates of the surface sediments varied little, ranging from −0.48‰ to 2.52‰ (1.43 ± 0.86‰) for $\delta^{18}O$ and from 1.60‰ to 2.79‰ (2.33 ± 0.36‰) for $\delta^{13}C$, respectively (**Table 2**). Similar to the trap sediments, the $\delta^{18}O$ values of authigenic carbonates were lower, but the $\delta^{13}C$ values were higher than those of both ostracod shells.

DISCUSSION

The Relation Between Ostracod Flux and Limnological Conditions

The occurrence and abundance of ostracod species are affected by various limnological conditions, including the water body nature (such as its size, shape, turbidity, and substrate), water temperature, salinity, ionic composition, food supply, and predation (Holmes, 1996). For a given water body, the distribution and flux of an individual ostracod species are closely related to the seasonal changes of water temperature and salinity, so that the flux of ostracod shells is used to reflect the variation in water temperature and/or salinity (De Deckker and Forester, 1988; Holmes et al., 1998; Lu and An, 2010). In Lake Qinghai, when the water temperature reached 4°C in spring, the first flux peak of *L. inopinata* shells occurred, whereas the peak of *E. mareotica* shells occurred when the water temperature reached 6°C (**Figure 2**). Based on the growth periods before reaching maturity of the two species (1 month for *L. inopinata* and one and half months for *E. mareotica*), both ostracods began to reproduce during the dry seasons when the temperature was higher than 2°C; there was no ostracod shell growth below 2°C. This indicates that water temperature was the key controlling factor for ostracod growth, though there was a negative correlation between temperature and salinity (**Figure 3**). Indeed, both ostracod species lived in a wide range of salinity. *L. inopinata* can live in fresh water to the Baltic Sea, but it becomes a dominant species in water bodies with low to middle salinity (0.5–20.0‰) (Meisch, 2000; Wang et al., 2021). *E. mareotica* also has a wide tolerance limit to salinity, living in fresh to saline water bodies with salinity up to 325‰ (Li et al., 2010); it becomes a dominant species in water bodies with high salinity (18–40‰) and ultra-high salinity (>50 g/L) (Huang, 1984). Similarly, Zhang et al. (2006) investigated the distribution of ostracod species within the Lake Qinghai area and demonstrated that *L. inopinata* dominated in low salinity waters but *E. mareotica* in relatively high salinity waters. In fact, the salinity of modern Lake Qinghai varied between 12.6 and 13.1 PSU during the trap deployment period (**Figure 2**) and was suitable for both ostracods living. As a result, salinity is not the controlling factor for ostracod habitat in Lake Qinghai, even though its limnic salinity is more suitable for *L. inopinata*, which is the reason why the daily flux of *L. inopinata* shells is an order of magnitude higher than that of *E. mareotica*.

In seasonal variations, the daily fluxes of both species of ostracod shells co-varied with lake water temperature (**Figure 2**), indicating the direct control of water temperature on ostracod reproducibility in Lake Qinghai (Chivas et al., 1985; Holmes, 1996). Thus, high temperature favors ostracod reproducibility. Along with the decrease of summer water temperature from 2010 to 2012, daily fluxes of ostracod shells of both species also decreased (**Figure 2**). Interannual variation in

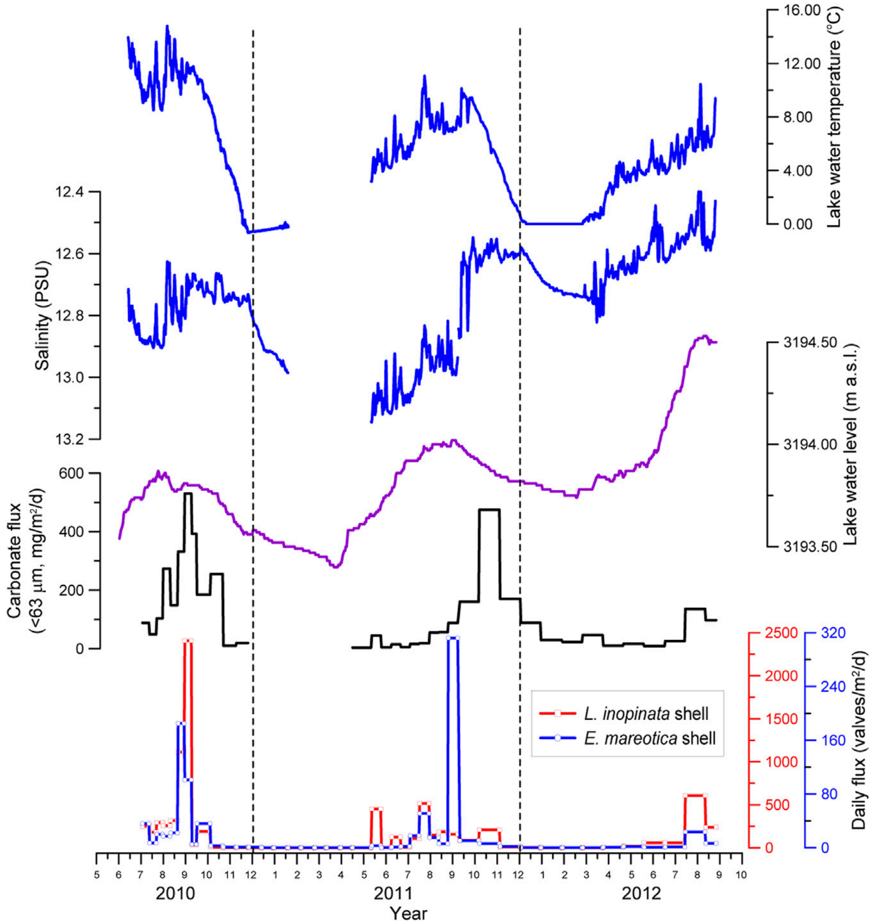

FIGURE 2 | Variations in abundance for two species of adult ostracod shells (*L. inopinata* and *E. mareotica*) and carbonate flux from July 2010 to September 2012, along with water temperature, salinity, and water level of Lake Qinghai.

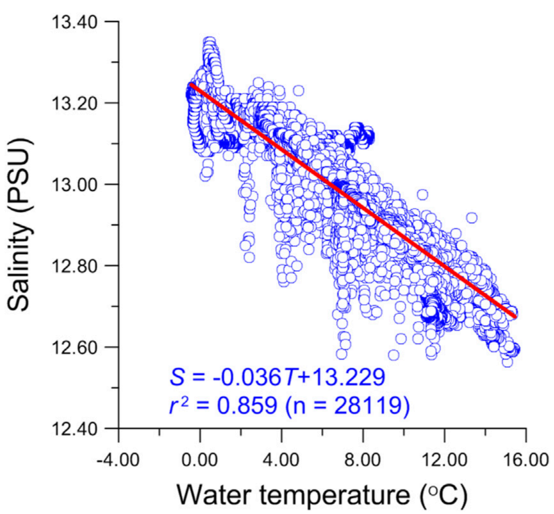

FIGURE 3 | Linear relationship between water temperature and salinity in Lake Qinghai during July 2010 through September 2012.

daily fluxes of ostracod shells further confirms the control of water temperature on ostracod reproducibility in Lake Qinghai.

The Control of Seasonal Ostracod $\delta^{18}O$ in Lake Qinghai

The $\delta^{18}O$ of lacustrine ostracod shells is controlled by water temperature and, more importantly in closed lakes, the isotope composition of the water at the time of carbonate precipitation. When lake water temperature increased, the $\delta^{18}O$ of ostracod shells decreased, with a positive correlation with lake water $\delta^{18}O$ (e.g., Heaton et al., 1995; Xia, 1996; Xia et al., 1997). The 2–3°C difference of summer water temperature between 2010 and 2011 resulted in the observed ostracod $\delta^{18}O$ difference (0.45‰) exactly (**Figure 4**), assuming that temperature was the a single controlling factor alone, following a gradient change of 0.24‰ per 1°C for ostracod $\delta^{18}O$ (O'Neil et al., 1969). Consequently, the interannual variation in ostracod $\delta^{18}O$ in Lake Qinghai can be regarded as the direct response to lake water temperature, i.e., lower ostracod $\delta^{18}O$ values for the two species during the

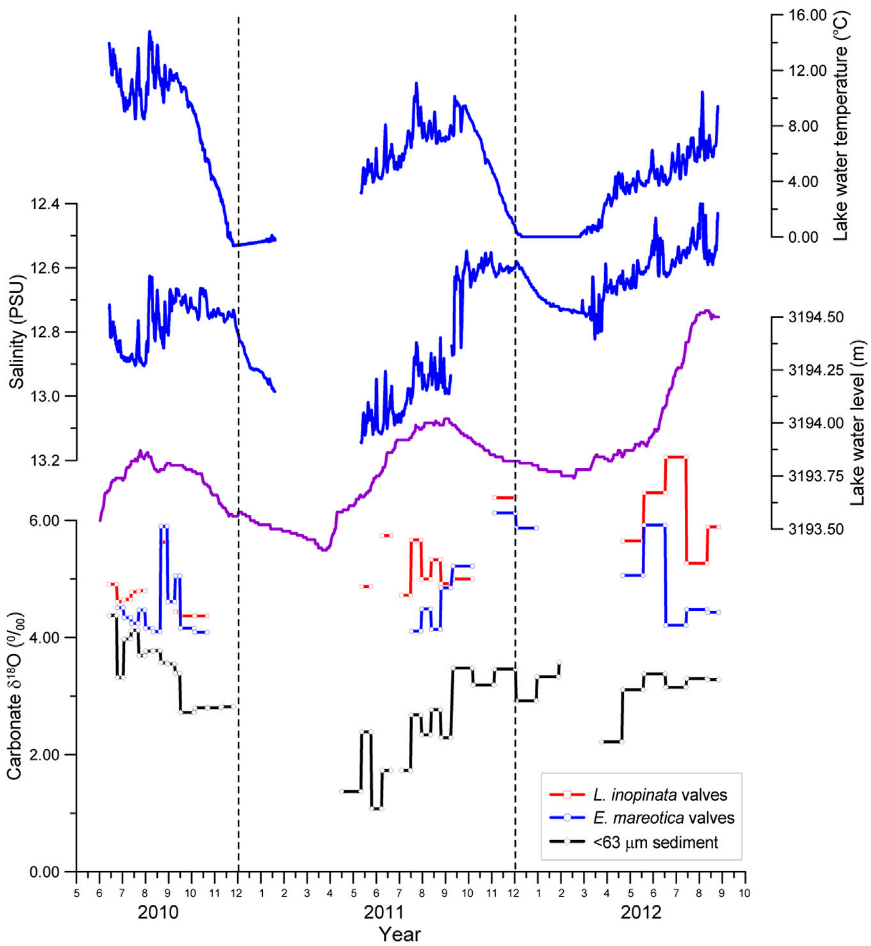

FIGURE 4 | Seasonal and interannual variations in $\delta^{18}O$ ratios for two species of adult ostracod shells (*L. inopinata* and *E. mareotica*) and carbonates of the <63 μm fraction in sediment from July 2010 to September 2012, along with water temperature, salinity, and water level of Lake Qinghai.

warmer summer in 2010 than those in 2011 and 2012. There was a synchronous seasonal variation between ostracod $\delta^{18}O$ and water temperature (**Figure 4**). In particular in 2010 and 2012, the highest ostracod $\delta^{18}O$ values of both species appeared during the periods with high temperature. As a result, the seasonal variation of ostracod shells in Lake Qinghai was not a function of water temperature, rather than of the isotope composition of lake water.

The isotopic composition of lake water is controlled by the P/E ratio and, to a lesser extent, by the $\delta^{18}O$ and the amount of rain, and local hydrological conditions (Lister et al., 1991; von Grafenstein et al., 1999; Leng and Marshall, 2004). Then, which factor dominates seasonal variation in the water $\delta^{18}O$ of Lake Qinghai? First, there was a large range of rain $\delta^{18}O$, ranging between −18.6‰ and +0.6‰ in 2008, for example (Jin et al., 2013b). These values were lower than the $\delta^{18}O_{SMOW}$ of modern lake water. As a result, increasing water level in the past decade decreased the $\delta^{18}O$ of lake water from 3.42 ± 0.25‰ in 2006 (Liu et al., 2009) to 2.01 ± 0.14‰ in 2012 (**Table 1**) in Lake Qinghai. The increased lake level in Lake Qinghai since 2005 was considered to be a result of increasing annual rainfall and/or changing rainfall pattern, rather than temperature and evaporation (Jin et al., 2013b; Fan et al., 2021). However, the lake water $\delta^{18}O_{SMOW}$ vary seasonally little (**Table 1**), so that the impact of annual rainfall (~1.25 km^3/yr) is minor for this huge lake with a water volume of 71.6 km^3. Second, the $\delta^{18}O$ values of river water fluctuated around −7.0‰ in the Buha River, the largest river within the Lake Qinghai catchment, with more than half of the annual runoff into the lake (Jin et al., 2013b), which excludes the impact of other water sources, such as glacial melt water (Zhang et al., 1988). On the contrary, the water loss due to strong evaporation under high temperature can lead to enriched-^{18}O in lake water in summer. Therefore, the $\delta^{18}O$ of lake water is controlled mainly by evaporation, i.e., the parameter E in the P/E ratio over annual and decadal timescales.

Usually, the $\delta^{18}O$ of carbonate is mainly controlled by the $\delta^{18}O$ and temperature of water body where and when the carbonate is precipitated. For a hydrological-closed system, low P/E ratios (high E) in summer would make $\delta^{18}O$ positive for both lake water and ostracod shells in Lake Qinghai. However, the ostracod $\delta^{18}O$ of both species tended to decrease during the peak summers, though there were some high ostracod $\delta^{18}O$ values (**Figure 4**). In Lake Qinghai, the seasonal variation in ostraocd $\delta^{18}O$ was approximately over 2.5‰ (**Table 1**), much

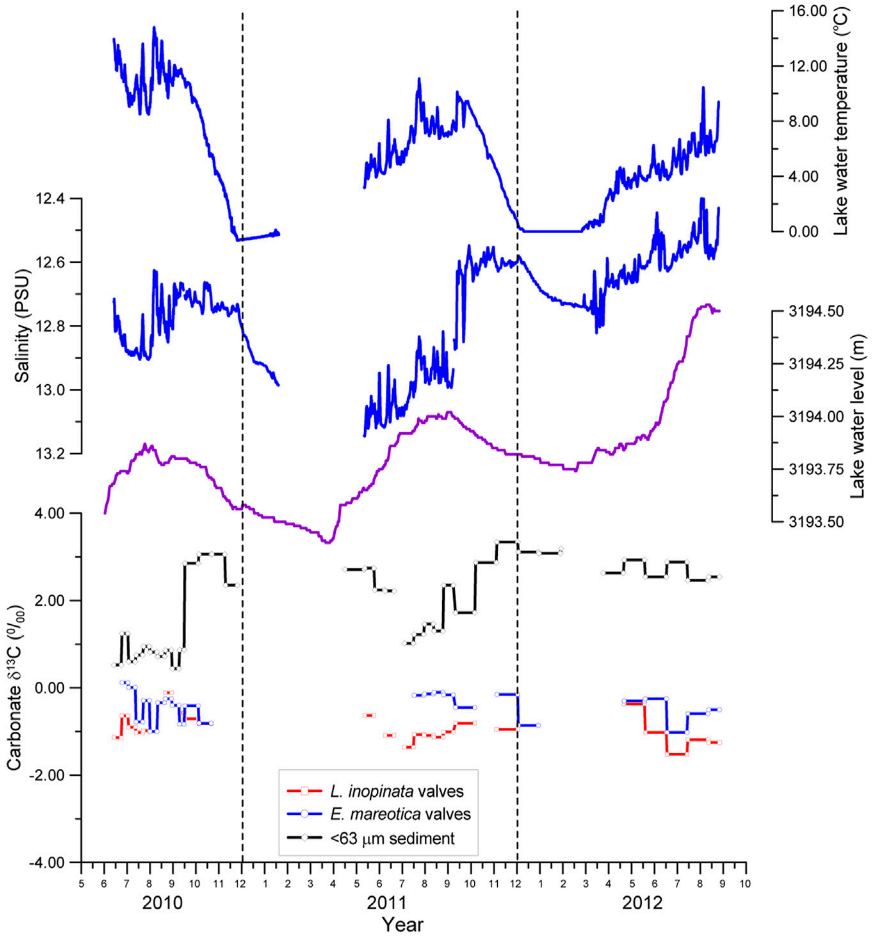

FIGURE 5 | Seasonal and interannual variations in $\delta^{13}C$ ratios for two species of adult ostracod shells (*L. inopinata* and *E. mareotica*) and carbonates of the <63 µm fraction in sediment from July 2010 to September 2012, along with water temperature, salinity, and water level of Lake Qinghai.

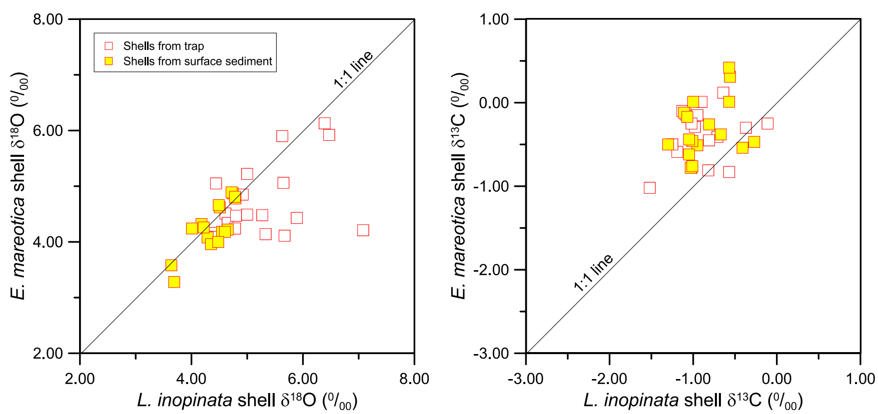

FIGURE 6 | The correlations of **(A)** $\delta^{18}O$ and **(B)** $\delta^{13}C$ between two species of adult ostracod shells (*L. inopinata* and *E. mareotica*) from the sediment trap and surface sediment in Lake Qinghai.

larger than that of the lake water $\delta^{18}O$ based on our monitoring water $\delta^{18}O$ data from April to September in 2012 (**Table 1**). It indicates that variation in lake water $\delta^{18}O$ is not the main factor for seasonal change of ostracod $\delta^{18}O$ in Lake Qinghai. In fact, the ostraocd $\delta^{18}O$ value should decrease with increasing water temperature when its host water $\delta^{18}O$ is stable. Thus, the

TABLE 2 | Oxygen and carbon isotopic compositions of ostracod shells (*L. inopinata* and *E. mareotica*) and carbonate fraction (<63 μm) of surface sediments in Lake Qinghai.

Sample No.	*L. inopinata*		*E. mareotica*		<63 μm carbonates	
	$\delta^{13}C$	$\delta^{18}O$	$\delta^{13}C$	$\delta^{18}O$	$\delta^{13}C$	$\delta^{18}O$
	‰	‰	‰	‰	‰	‰
QH-S1	−0.95	4.29	−0.51	4.08	2.79	1.82
QH-S2	−1.30	4.55	−0.50	4.18	2.38	1.24
QH-S3	−0.41	4.18	−0.54	4.32	2.68	2.29
QH-S4	−1.01	4.01	−0.46	4.24	2.51	2.14
QH-S5	−0.27	4.65	−0.47	4.22	2.18	1.14
QH-S6	−0.56	4.74	0.31	4.87	2.38	1.65
QH-S7	−0.81	4.79	−0.26	4.78	2.48	1.52
QH-S8	−0.57	4.72	0.01	4.89	2.79	2.52
QH-S9	−1.00	4.78	0.01	4.81	2.29	1.56
QH-S10	−0.67	4.60	−0.38	4.18	2.28	1.28
QH-S11	−1.11	3.64	−0.12	3.58	1.60	−0.30
QH-S12	−1.03	3.69	−0.78	3.28	1.73	−0.48
QH-S13	−1.05	4.22	−0.62	4.26	2.31	1.61
QH-S14	−0.57	4.51	0.42	4.62	2.32	1.50
QH-S15	−1.07	4.49	−0.17	4.66	2.48	1.93
QH-S16	−1.05	4.35	−0.44	3.96	1.67	0.48
QH-S17	−1.01	4.48	−0.76	4.00	2.66	2.47
Average	−0.85	4.39	−0.31	4.29	2.33	1.43
std	0.29	0.35	0.34	0.45	0.36	0.86

water temperature does also not control seasonal ostracod $\delta^{18}O$ changes in Lake Qinghai.

Considering that the fine particles collected by the sediment traps were dominated by authigenic aragonite, we compared the $\delta^{18}O$ values of ostracod shells with those of carbonates in the <63 μm fraction from the same traps. The results showed that they had a similar variation pattern, but the $\delta^{18}O$ values of the carbonates (3.03 ± 0.77‰) were higher than that of the lake water (2.01 ± 0.14‰). The precipitation of authigenic and biogenic carbonates, both with high $\delta^{18}O$, would result in low $\delta^{18}O$ lake water, as demonstrated by the $\delta^{18}O$–$\delta^{13}C$ relationship between ostracod shells and carbonates (**Figure 7**). Indeed, the salinity also tended to decrease during the peak summers, as a direct result of the removal of Mg^{2+} and Ca^{2+} from the lake water column due to the precipitation of authigenic carbonates (Jin et al., 2013a). We therefore propose that the seasonal variation in ostracod $\delta^{18}O$ was a result of decreasing lake water $\delta^{18}O$ in microenvironment induced by the precipitation of authigenic carbonates. A similar $\delta^{18}O$ variation of ostracod shells and carbonates was also observed in recent sediments (Henderson et al., 2003). These results showed a synchronous $\delta^{18}O$ change between the ostracod shells and authigenic carbonates (<80 μm fraction of lake sediments), though carbonate $\delta^{18}O$ values were always lower than those of ostracod shells for the same samples (Henderson et al., 2003). These observations further indicate the control of the precipitation of authigenic carbonates on $\delta^{18}O$ of lake water and ostracod shells.

The Control of Seasonal Ostracod $\delta^{13}C$ in Lake Qinghai

The carbon of lacustrine carbonates (including ostracod shells) mainly comes from DIC in the host water, which in turn is controlled by the catchment and within-lake processes. The sources of DIC are complex and affect its $\delta^{13}C$, including bedrock and soil carbon as catchment sources, the long-term balance of photosynthesis and organic decay within the lake (Mckenzie, 1985; Herczeg and Fairbanks, 1987; Kelts and Talbot, 1990; Cole et al., 1994). As a result, there were complex relationships between ostracod $\delta^{13}C$ and water conditions. The variation ranges in $\delta^{13}C$ of both ostracod shells and authigenic carbonates were smaller than those of $\delta^{18}O$, without obvious correlations with either water temperature or salinity (**Figure 5**). Previous study showed that the temperature effect of $\delta^{13}C$ is weak for carbonates (Li et al, 2010), further supporting the complex relationships between water temperature and $\delta^{13}C$ of both ostracod species in Lake Qinghai. Indeed, the seasonal $\delta^{13}C$ change in authigenic carbonates was much larger than those of the ostracod shells.

In addition, opposite of $\delta^{18}O$, the ostracod $\delta^{13}C$ values varied little, with slightly lighter $\delta^{13}C$ of *L. inopinata* shells than those of *E. mareotica* (**Figure 6**). We propose that the systematic vital effects of $\delta^{18}O$ and $\delta^{13}C$ between ostracod species at the same seasons can be attributed to their living habitats. For example, photosynthesis of algae would result in different micro-environmental $\delta^{18}O$ and $\delta^{13}C$ values (Holmes, 1996; Li and Yu, 2001). *L. inopinata* prefers to creep on the benthos of the lake, while *E. mareotica* likes to swim and cling to algae (Lu and An, 2010; Li and Liu, 2014), which may result in slight differences of $\delta^{18}O$ and $\delta^{13}C$ values for the two ostracod species.

On the other hand, the precipitation of authigenic carbonates would control the $\delta^{13}C$ of DIC and then of the ostracod shells as well, as demonstrated by the $\delta^{18}O$–$\delta^{13}C$ relationship between ostracod shells and carbonates (**Figure 7**). It is also supported by the mirror variation in contemporaneous $\delta^{13}C$ values for the <63 μm carbonates and ostracod shells from the traps (**Figure 5**). A similar variation was also observed in much higher $\delta^{13}C$ values of

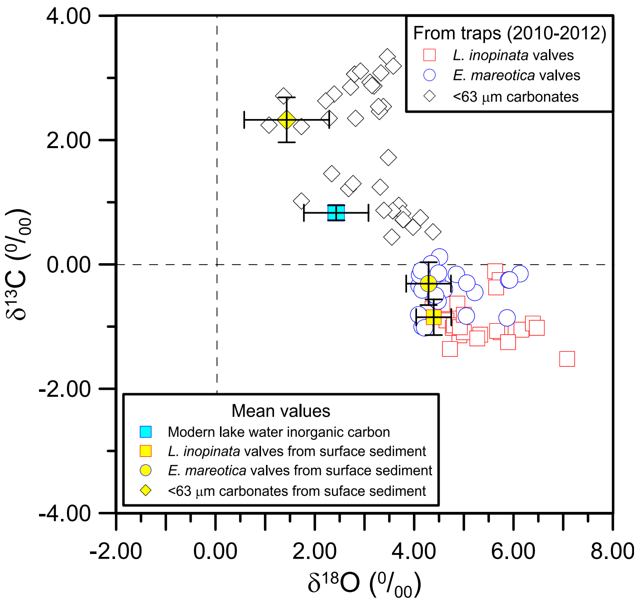

FIGURE 7 | The relationship of $\delta^{18}O$ and $\delta^{13}C$ among total inorganic carbon in lake water, adult ostracod shells (*L. inopinata* and *E. mareotica*), and <63 μm carbonates from the sediment trap and surface sediment in Lake Qinghai. The data of the core QING 6 are cited from Henderson et al. (2003).

the <80 μm carbonates than those of the ostracod shells in the past 300 years (Henderson et al., 2003). Therefore, we confirm that the seasonal variations in ostracod $\delta^{18}O$ and $\delta^{13}C$ is a result of decreasing $\delta^{18}O$ but increasing $\delta^{13}C$ in the lake water induced by the precipitation of authigenic carbonates. If so, chemical variations of ostracod shells in Lake Qinghai, particularly for $\delta^{18}O$, may provide an indication of water discharge and thus effective rainfall during monsoonal seasons (late May to September), because authigenic carbonate in Lake Qinghai sediments was largely controlled by solute fluxes into the lake by runoff within the catchment (Jin et al., 2010; Jin et al., 2015). Lake Qinghai water is supersaturated with respect to aragonite and calcite, where any available Ca^{2+} from rivers would be rapidly removed by the precipitation of authigenic carbonates, mainly during the summer months (Jin et al., 2010).

CONCLUSION

The seasonal samples collected by a time-series sediment trap provided insight into the controlling factors of interannual/seasonal variations in the flux and the chemical compositions of ostracod shells in Lake Qinghai on the northeastern corner of the Tibetan Plateau. Based on the daily flux, $\delta^{18}O$ and $\delta^{13}C$ of ostracod shell samples collected by a time-series sediment trap from southern basin of Lake Qinghai during July 2010 and September 2012, we found that both of *L. inopinata* and *E. mareotica* flourished during summer and early autumn, with a slight difference with growth periods and reproducibility between species. One of most important observations was that growth and flux of the two ostracod species were controlled directly by lake water temperature, which was correlated with the state-of-the-art sensing data of lake water. The interannual variation in ostracod $\delta^{18}O$ mainly reflected the difference of lake water temperature, whereas their seasonal variation was controlled chiefly by the precipitation of authigenic carbonates induced by high water temperature, especially during the summer months. The precipitation of authigenic carbonates with higher $\delta^{18}O$ than lake water resulted in low ostracod $\delta^{18}O$ for both species. The factors affecting ostracod $\delta^{13}C$ were complex, with a vital effect. Further information on the modern isotope systematics of the lake is needed to better understand the role of precipitation of authigenic carbonates on ostracod $\delta^{13}C$ for different seasons.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article, further inquiries can be directed to the corresponding author.

AUTHOR CONTRIBUTIONS

ZJ and FZ designed and managed the project and measured isotopes. ZJ, FZ, and XL developed interpretations and wrote the manuscript with help from all authors. JW and CJ picked the shells and helped to measure isotopes and data interpretation. All authors commented on the manuscript.

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