Carbon and oxygen isotopic records from Lake Tuosu over the last 120 years in the Qaidam Basin,
northwestern China: the implications for paleoenvironmental reconstruction

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Abstract: Isotopic compositions of total organic carbon (TOC) and authigenic carbonate in lakes have been widely used to reconstruct paleoclimatic changes and the depositional environments of lake sediments. However, since these proxies are often controlled by multiple environmental factors, detailed examinations of modern environmental processes is necessary before further applying them into paleoclimatic studies, especially in arid/semi-arid northwestern China. Here we generate High-resolution multi-proxy sedimentary records from Lake Tuosu, a hydrologically closed, saline and alkaline lake located at the north margin of the Qaidam Basin, through analysis of carbon isotope of TOC, and $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ values of ostracods over the last 120 years. Together with the meteorological data (precipitation and temperature), lake area record, and other tree-ring evidence, we examine how these sedimentary indices respond to changes in hydrologic balance and climate at interannual to decadal timescales. We found that sedimentary $\delta^{13}\text{C}_{\text{org}}$ values resemble the variation of lake areas of Lake Tuosu over the last 40 years, suggesting that $\delta^{13}\text{C}_{\text{org}}$ values would be an ideal indicator of lake area/level fluctuations and thus effective moisture variations (precipitation vs. evaporation). However, ostracod $\delta^{18}\text{O}$, which was previously used as proxies of effective precipitation, is not well correlated with $\delta^{13}\text{C}_{\text{org}}$ values in Lake Tuosu. Therefore, the changes of ostracod $\delta^{18}\text{O}$ values cannot be straightforwardly explained as the effective precipitation. Instead, the isotopic composition of carbonate would be additionally controlled by other factors including isotopic compositions of input water and drainage pattern.

Key words: $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$, Ostracoda, Total organic carbon, Paleoenvironment, Qaidam Basin

1. Introduction

The northeastern Tibetan Plateau, located at a triple junction of influences of the Asian summer monsoon, westerly jet stream and Siberian high, is of considerable significance with regard to regional responses to global climate change. Due to the lack of relatively long instrumental records, past climatic changes in this region have been reconstructed mainly by natural archives instead, including tree rings, ice core and lake sediments (e.g., Kelts et al., 1989; Zhang et al., 1989a, b; Sun et al., 1991; Thompson, 1995; Yao et al., 1996; Yu and Kelts, 2002; Shao et al., 2005; Liu et al., 2006; Zhao et al., 2010, 2013; Fan et al., 2012; Liu et al., 2015a). Therefore, reasonably interpreted records of past climatic variability are vital to our understanding of the sensitivity of climatic change to different forcings and to better prediction on its future behavior.

Lakes, especially hydrologically closed lakes, are natural integrators of surficial processes and are important information sources for paleoclimatic reconstruction in the northeast Tibetan Plateau (Lister et al., 1991; Zhang et al., 2003, 2009; Ji et al., 2005; Shen et al., 2005; Liu et al., 2007; Henderson et al., 2010; He et al., 2013; Chen et al., 2015). Changes in volume, chemistry, and isotopic compositions of lake sediments and organisms commonly are influenced by variations in effective moisture and temperature (Holmes et al., 2007; Li et al., 2012a, b; Liu et al., 2013; Li and Liu, 2014). As an indicator of environmental change in lakes, the isotopic compositions of carbonates and total organic matters (TOM) have been used in lake studies to decipher paleoenvironmental conditions on the north Tibetan Plateau (Henderson et al., 2003; Xu et al., 2006; Colman et al., 2007; Aichner et al., 2010a; Mischke et al., 2010; Wang et al., 2013a; Thomas et al., 2014; Liu et al., 2015b).

In general, $\delta^{18}\text{O}$ values of lacustrine authigenic carbonates are mainly controlled by the isotopic composition of the water at the time when carbonates precipitated in lakes, with secondary modification by temperature (0.24‰ decrease in the $\delta^{18}\text{O}$ value of carbonate for every 1°C increase in water temperature, O'Neil et al., 1969). Therefore, records of $\delta^{18}\text{O}$ values of carbonate in lake sediments have been widely used to indicate changes in the lake's Evaporation/Precipitation ratio (P/E), salinity (Liu et al., 2009a) and hydrological balance (Lister et al., 1991; Henderson et al., 2003; Leng and Marshall, 2004; Qiang et al., 2005; Yuan et al. 2006), although the $\delta^{18}\text{O}$ of lake carbonates has also been occasionally used as an indicator of temperature (e.g., Xu et al., 2006, 2014). In the case of northeastern Tibetan Plateau, a study from the Qaidam Basin showed that variations in carbonate $\delta^{18}\text{O}$ values could not have been the result of varying effective precipitation but were due to changes in water temperature and $\delta^{18}\text{O}$ of the source water (Holmes et al., 2007). However, another study indicated that the oxygen isotopic compositions of ostracod shells can be used to indicate changes in precipitation over a short time scale in Qaidam Basin (Li et al., 2012b). A recent study also suggested that variation in carbonate $\delta^{18}\text{O}$ values from lake sediments cannot be explained as changes in effective moisture in arid area (Liu et al., 2014a).

Thus, it is often difficult to interpret the carbonates $\delta^{18}\text{O}$ data unambiguously unless detailed observations of modern environmental processes are available because the $\delta^{18}\text{O}$ of lake carbonates are often controlled by multiple environmental factors (Leng and Marshall, 2004; Liu et al., 2007; Holmes et al., 2007; Liu et al., 2009a). In addition, another isotopic proxy, the $\delta^{13}\text{C}$ values from lake carbonates, has rarely been fully exploited as proxies because their interpretation is thought to be difficult to assess and only a few coupled oxygen and carbon isotope records

spanning the entire postglacial evolution of the studied lake was reported (Mischke et al., 2010; Schwalb et al., 2013).

$\delta^{13}\text{C}$ values of sedimentary TOM ($\delta^{13}\text{C}_{\text{org}}$) are also an important proxy for tracking variation in the water depth, temperature, aquatic biomass, and the relative contribution of terrestrial sources in lakes (Meyers, 1994, 1997; Shen et al., 2005; Xu et al., 2006; Mackay et al., 2012), which are all directly or indirectly linked to changes in the climate of the lake catchments (Leng and Marshall, 2004). Basically, lacustrine sedimentary TOM consists of a mixture of organic materials from sources within the lake including aquatic plants and microorganisms, and external sources like vegetation and soils and aeolian dust around the catchment. Since these sources have distinguishable isotopic signatures, information on changes in proportion of different TOM sources would be well preserved in the stable isotope composition of sedimentary TOM (Meyers, 1994; Lücke and Brauer, 2004). Studies in Lake Qinghai on the northeastern Tibetan Plateau have shown that the TOM is mainly from water-depth related aquatic plants with distinctive $\delta^{13}\text{C}$ values, thus $\delta^{13}\text{C}$ values of sedimentary TOM mainly reflect changes in water depth (Wang et al., 2013b; Liu et al., 2013, 2015b). However, whether this method can be used in other lakes with similar environmental setting, need further investigation.

In this paper, we evaluate controls on the lake-sediment carbon and oxygen isotopic compositions of carbonates and total organic matters from Lake Tuosu, located at the northeastern edge of the Qaidam Basin on the northern Tibetan Plateau. On this base, the environmental implications of these proxies would help us understand paleoclimatic and paleoenvironmental changes using the materials from lakes.

2. Study site

Lake Tuosu (37°04' N, 96°50' E) is located at the northeastern edge of the Qaidam Basin on the NE Tibetan Plateau (Fig. 1). The Qaidam Basin, with an area of 120,000 km², is surrounded by the Kunlun Mountains to the south, the Altun Mountains to the west and the Qilian Mountains to the north and east. The surrounding mountains rise to an elevation of >5000 m above sea level, while the average elevation of the basin is 2800 m. The surface area of Lake Tuosu is approximately 145 km² with a maximum water depth of 25 m. The water of Lake Tuosu was mainly obtained from Lake Hurleg through a ~ 3 km long river northwest of the lake besides, some ground water and intermittent river water from around mountains. Lake Hurleg (37°17' N, 96°54' E) is a freshwater lake, which is mainly fed by the Bayin River, the Balegen River and groundwater from the mountains north of the basin (Fig. 1).

The region is in an extremely arid desert climate. The annual precipitation is about 180 mm and annual mean temperature is 4°C, based on recent 50 yr climate data from the nearby Delingha meteorological station. Most precipitation falls as rain during the summer months. The potential evapotranspiration is about 2000 mm. Modern vegetation of this region is dominated by desert plant communities, mainly consisting of Chenopodiaceae (including *Salsola abrotanoides*, *Kalidium gracile*, *Ceratoides aritim*, *Haloxylon ammodendron* and *Sympegma regelii*), Ephedra, Nitraria and Asteraceae (Zhao et al., 2008).

3. Materials and methods

A 33-cm sediment core (TSLC14-1) was taken from Lake Tuosu in April 2014 at approximately 12 m water depth (37°10'36" N, 96°57'12" E) using the UWITEC corer 60. The sediment core was sub-sampled at continuous 0.5 cm intervals shortly after core collection. The core was mainly consist of grey clay, and did not show finely laminated sediments. The presence

of green living algae (*Cladophora*) on the top core and its homogeneous lithology suggested that the core was successive. Because of bad age control on ^{210}Pb data of core TSLC14-1 (Fig. 2), another 30-cm sediment core (TSLC14-2) was collected to check the age model of TSLC14-1 in December 2014 at approximately 18 m water depth ($37^{\circ}10'12''\text{N}$, $96^{\circ}57'54''\text{E}$) in Lake Tuosu. Core TSLC14-2 was also sub-sampled at continuous 0.5 cm intervals shortly after core collection. The core was successive with homogeneous lithology, and sediments of the core mainly consist of grey clay and some algae residue. The chronology of core TSLC14-2 is based on both ^{137}Cs and ^{210}Pb data for the past 50 years using a linear sedimentation model.

The bulk carbonate content was determined by using the neutralization-titration method (Hesse, 1971). Approximately 0.3 g sediment sample was reacted with 30 ml HCl (0.2 mol L^{-1}) for 24 hours and then centrifuged. Ten milliliters of supernatant with 2 drops phenolphthalein solution was titrated by NaOH (0.1 mol L^{-1}), with an analytical precision better than 0.5%.

The wet sediment samples were soaked in deionized water for approximately 2 h, and then wet sieved with a 250-mesh sieve. The sieved materials were dried at room temperature for the collection of ostracods. Empty ostracod shells were then picked using a fine brush and deionized water, and the adult ostracods that were cleaned with deionized water were used for isotope analysis.

About 3 g of each wet sediment sample was freeze-dried. The dried samples were then ground in an agate mortar, sieved through a 200 mesh screen and homogenized for isotopic measurement. The sieved sediment samples were treated with 2M HCl for 24 h at room temperature to remove carbonates. Subsequently, the samples were rinsed to a pH of approximately 7 with deionized water and dried at 40°C for $\delta^{13}\text{C}_{\text{org}}$ measurement.

Ostracod samples (4~6 valves per sample for ostracod *E. mareotica*) were analyzed for $^{13}\text{C}/^{12}\text{C}$ and $^{18}\text{O}/^{16}\text{O}$ at the Institute of Earth Environmental, Chinese Academy of Sciences (IEECAS), 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 with known isotopic values were performed daily to ensure instrumental accuracy. The analytical error of the laboratory standard was both approximately $\pm 0.1\text{‰}$ for $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$.

The acid and dried samples were combusted for 4 h at 850 °C in evacuated sealed quartz tubes in the presence of 1 g of CuO, 1 g of Cu and Pt foil. The carbon dioxide was then cryogenically purified. The isotopic ratios of the purified CO_2 were measured using a Finnigan MAT 251 gas source mass spectrometer at IEECAS. Isotopic ratios are reported using δ -notation as per mil (‰) differences relative the V-PDB standard for C. The overall precision of the $\delta^{13}\text{C}$ analyses was less than 0.2‰.

4. Results

4.1 Chronology

As showed in Figure 2, the excess ^{210}Pb activity of core TSLC14-1 is very scattered, and has no any relationship with depth (Fig. 2a). The age of the ^{137}Cs peak at 20 cm could be determined to be 1963 AD in core TSLC14-1 (Fig. 2a). The average sedimentation rate was calculated to be 0.4 cm/yr for core TSLC14-1. The chronology of the up 20 cm of core TSLC14-2 was determined by the ^{210}Pb - ^{137}Cs dating method (Fig. 2b), using a Constant Initial Concentration (CIC) computer model (Appleby, 2001). The excess ^{210}Pb activity showed a simple exponential relationship with depth (Fig. 2b). From the ^{210}Pb profile, the age of the ^{137}Cs peak at 8.5 cm was determined to be

1959 AD, very close to the presumed ^{137}Cs peak age of 1963 AD in core TSLC14-2 (Fig. 2b). This correspondence validates the accuracy of the ^{210}Pb dating. For this reason we use ^{210}Pb as the primary age control on core TSLC14-2. From ^{210}Pb data the average sedimentation rate was then calculated to be 0.13 cm/yr, which is much lower than the sedimentary rate of core TSLC14-1.

In general, the bulk carbonate content of core TSLC14-1 and TSLC14-2 showed very similar varied trends (Fig. 3a, 3b). The highest bulk carbonate content in core TSLC14-1 at 9.5 cm corresponds with the peak value in core TSLC14-2 at 4 cm, and the ages of these two point are very similar (about 1989 AD at 9.5 cm and 1992 AD at 4 cm) according to the age model based ^{137}Cs data of core TSLC14-1 and ^{210}Pb data of TSLC14-2, respectively (Fig. 3c). The next peak value of bulk carbonate content in core TSLC14-1 at 23.5 cm generally corresponds to the value in core TSLC 14-2 at 11.5 cm, but the ages of these two points are very different (about 1954 AD at 23.5 cm and 1927 AD at 11.5cm). So, the calculated age of TSLC14-1 at 23.5 cm or other ages before 1963 AD may be unreasonable only using the ^{137}Cs data (Fig 3c). Therefore, the age model of core TSLC14-1 was established using the ^{137}Cs after 1963 AD and the ^{210}Pb data of core TSLC14-2 before 1963 AD according to the comparison of bulk carbonate content in these two cores (Fig. 3a, 3b). In general, the age of core TSLC14-1 covers about past 120 yrs in this study (Fig. 3c).

4.2 The isotopes of ostracod and total organic matter

Only the ostracod *Eucypris mareotica* was found in the surface sediment and other layers in core TSLC14-1 at Lake Tuosu. The ostracod *E. mareotica* was very scarce from early 1990s to the early 2000s (about 2006 AD). Measured ostracod $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ values exhibit relatively large variations with the average values of 2.26‰ and 6.65‰ over the last 120 yrs (Fig. 4c). Beginning

at the bottom of the core, ostracod $\delta^{18}\text{O}$ values increase with some fluctuation until late 1980s, but ostracod $\delta^{13}\text{C}$ values were almost constant with little variation at first and sharply increased at late 1980s (Fig. 4c). Then ostracod $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ values both decreased with large fluctuation, but most of ostracod $\delta^{13}\text{C}$ values were at high level from early 1990s to now (Fig. 4c). The ostracod $\delta^{13}\text{C}$ data is positively correlated with the $^{13}\text{C}_{\text{org}}$ data in core TSLC14-1 ($r = 0.65$, $p < 0.01$, $n = 66$), but is not correlated with ostracod $\delta^{18}\text{O}$ data.

The $\delta^{13}\text{C}_{\text{org}}$ values vary largely between -26.03‰ and -17.81‰ , with an average of -21.80‰ in core TSLC14-1 over the last 120 yrs (Fig. 4d). The $\delta^{13}\text{C}_{\text{org}}$ values show constant increasing trend with large fluctuation until the early 1990s, and then the value kept in high level from the early 1990s to about 2005 AD. The $\delta^{13}\text{C}_{\text{org}}$ values sharply decrease from 2005 AD to now (Fig. 4d).

5. Discussions

5.1. Sedimentary $\delta^{13}\text{C}_{\text{org}}$ as a proxy of lake level/area variation

Usually, changes in $\delta^{13}\text{C}_{\text{org}}$ values from lakes were explained as variation in types of terrestrial plants (C_3/C_4 ratio) related to climatic changes based on assumption that sedimentary TOM were mainly contributed by terrestrial plants (Talbot and Johannessen, 1992). Many environmental conditions, including temperature, precipitation, relative air humidity, soil moisture, irradiance and the concentration of atmospheric CO_2 , influence the rate of photosynthesis or stomata conductance and can also affect the carbon isotopic compositions of terrestrial plants (Ehleringer and Cooper, 1988).

As showed in Figure 5, atmospheric CO_2 increased by ~ 100 ppm over the last ~ 120 yrs due to the increasing anthropogenic input (Fig. 5a, Friedli et al., 1986; Schubert and Jahren, 2012).

The $\delta^{13}\text{C}$ values of plant leaves can decrease by 2.0‰ for a 100 ppm increase in atmospheric CO_2 concentration (Feng and Epstein, 1995). Moreover, the $\delta^{13}\text{C}$ value of the atmospheric CO_2 decreased by 1~2‰ in the past 100 years (Fig. 5a, Friedli et al., 1986; Schubert and Jahren, 2012), leading to more negative $\delta^{13}\text{C}$ values of terrestrial plants. In addition, numerous studies have shown that the relative humidity, as well as the amount of precipitation, is generally negatively related to the $\delta^{13}\text{C}$ of terrestrial plants (Farquhar et al., 1982; Ning et al., 2008). A shortage of water causes plants to close their stoma, reducing the intercellular partial pressures of CO_2 in the plants, which leads to higher $\delta^{13}\text{C}$ values of plants living in drier conditions, but increasing precipitation may cause low terrestrial plant $\delta^{13}\text{C}$ values. For instance, the mean $\delta^{13}\text{C}$ values in the Chinese Loess Plateau decrease 0.49 ~1.1‰ when the annual precipitation increased by 100 mm (Wang et al., 2003; Liu et al., 2005). The tree-ring data showed that the precipitation have increased in Lake Tuosu area over the last 100 years (Fig. 4b), leading to a decrease in $\delta^{13}\text{C}$ values of terrestrial plants. Further, increase in temperature would increase the $\delta^{13}\text{C}$ values of terrestrial plants (Wang et al., 2013c) and counteract the decreasing effect of both atmospheric CO_2 and precipitation. However, based on a comprehensive investigation of a large number of species across a temperature gradient along the 400 mm mean annual precipitation isoline in northern China (Wang et al., 2013c), the temperature effect in this area would be approximately 0.1‰/°C, only account for minor modification on $\delta^{13}\text{C}$ values of terrestrial plants. Therefore, all these factors mentioned here would result in decreased $\delta^{13}\text{C}$ values of terrestrial plants in Lake Tuosu area. Considering the fact that the sedimentary $\delta^{13}\text{C}_{\text{org}}$ values of Lake Tuosu increased by ~7‰ in the core over the past 120 years (Fig. 5), terrestrial plants in the catchment might hardly be the main contributor of sedimentary TOM.

Although we suggest that climatic induced factors on terrestrial plants might not be the main reason of the increase in the sedimentary $\delta^{13}\text{C}_{\text{org}}$ values of Lake Tuosu, changes in vegetation type of the terrestrial plants can not be neglected. The pollen data in the Lake Tuosu area showed that the terrestrial vegetation changed from *Artemisia* to *Chenopodiaceae* after 1960 AD (Zhao et al., 2010). Since most *Chenopodiaceae* species are C_4 plants with high $\delta^{13}\text{C}_{\text{org}}$ values in the range of $-16.3\text{‰} \sim -11.2\text{‰}$ in the northeastern Qinghai-Tibet Plateau (Li et al., 2005), the increased TOM $\delta^{13}\text{C}_{\text{org}}$ values in core TSLC14-1 might also have been affected by the contribution of terrestrial *Chenopodiaceae* with high $\delta^{13}\text{C}_{\text{org}}$ values more or less after 1960 AD in Lake Tuosu.

In fact, lacustrine sedimentary TOM consists of a mixture of organic materials from sources within the lake (e.g., aquatic plants and microorganisms) and external sources (e.g., different vegetation, soils and aeolian dust in the catchment). Since these sources may have distinguishable isotopic signatures, changes in the sources of TOM may likewise be reflected in the stable isotope composition of sedimentary TOM (Meyers, 1994; Lücke and Brauer, 2004). Recently, many studies showed that the sedimentary TOM are mainly contributed by aquatic plants in some lakes on the northeastern Tibetan Plateau (Mischke et al., 2008; Aichner et al., 2010a, 2010b; Herzsuh et al., 2010a, 2010b; Tuo et al., 2011; Liu et al., 2013; Qiang et al., 2013). In addition, some studies also suggested that the distribution of aquatic plants is more sensitive to water depth for different species in lakes on the northeastern Tibetan Plateau (Liu et al., 2013; Qiang et al., 2013). Hence sedimentary $\delta^{13}\text{C}_{\text{org}}$ was successfully used as a potential proxy of lake level in lakes on the northeastern Tibetan Plateau (Liu et al., 2013; Qiang et al., 2013).

In Lake Tuosu, *Cladophora* gradually presents at the sites with water depth of about 5~6 m, and takes dominated at depth exceeding ~10.5 m. Instead as submerged phanerogamic plants,

Potamogeton was dominated at the shallow water area, and was almost absent at lake level deeper than about 11.5 m in Lake Tuosu. This distribution of aquatic plants in Lake Tuosu is very similar with the distribution of aquatic plants in Lake Qinghai (Liu et al., 2013). In Lake Qinghai, *Cladophora* shows negative $\delta^{13}\text{C}_{\text{org}}$ values (-33.6‰ to -28.6‰) in the deep water areas (> 10 m), but submerged phanerogamic plants (*Potamogeton* and *Ruppia L.*) were enriched in $\delta^{13}\text{C}_{\text{org}}$ values (-17.8‰ to -15.4‰) in shallow water (Liu et al., 2013). Therefore, we suggest that the $\delta^{13}\text{C}_{\text{org}}$ values may be also used to indicate change of lake level or lake volumes related to the balance between water input from precipitation and water loss through evaporation in Lake Tuosu. Basically, the $\delta^{13}\text{C}_{\text{org}}$ values of sediments from Lake Tuosu may decrease with increasing lake level or lake volume because only *Cladophora* with low $\delta^{13}\text{C}$ values is living in the lake bottom.

Unfortunately, no data of lake level changes but lake area derived from remote sensing image can be used for recent 40 years (Liu et al., 2014b) are available in Lake Tuosu. According to the positive relation of observed lake level and lake area in Lake Qinghai which is ca. 250 km² northeast of Lake Tuosu over the past 20 years ($r=0.95$, $p<0.01$, $n=20$, Feng and Li, 2006; Cui and Li, 2015) and the factor that both Lake Qinghai and Lake Tuosu are tectonic lakes, we assume that the variation in lake area may be equal with lake level changes in Lake Tuosu like that in Lake Qinghai. Based on this assumption, the relationship between lake area/level and TOC $\delta^{13}\text{C}$ values from core TSLC14-1 covering approximately the last 40 years was studied. In general, the lake area/level sharply decreased from early 1970s to early 2000s, and the minimal lake area reached about 132.6 km² around 2001 in the Lake Tuosu (Fig.5b), and the $\delta^{13}\text{C}_{\text{org}}$ values from core TSLC14-1 constantly increased with the shrinking lake area during this period (Fig. 5b). Since the early 2000s, the $\delta^{13}\text{C}_{\text{org}}$ values from core TSLC14-1 generally decreased with enlarging lake area

in Lake Tuosu again (Fig.5b). In general, the $\delta^{13}\text{C}_{\text{org}}$ values from core TSLC14-1 are negatively correlated with lake area in Lake Tuosu over the past 40 years ($r = -0.73$, $p < 0.01$, $n = 13$). Simply put, the $\delta^{13}\text{C}_{\text{org}}$ values from core TSLC14-1 almost linearly correlate with changes in lake area (increasing $\delta^{13}\text{C}_{\text{org}}$ value corresponds to shrinking lake area) in Lake Tuosu, supporting the idea that the $\delta^{13}\text{C}_{\text{org}}$ values may be used to indicate lake level changes in Lake Tuosu.

In hydrologically closed lakes, changes in water volume (and lake level/area) commonly result from variations in effective moisture: the balance of precipitation inflow over evaporation (i.e., P/E; Leng and Marshall, 2004). In addition, the instrumented annual evaporation data for the last 50 years from the Delingha meteorological station which is ca. 50 km northeast of Lake Tuosu is well correlated with average annual temperature, and the evaporation co-varied with temperature for the last 50 years in the Lake Tuosu area (Fig. 6). Therefore, the annual precipitation and temperature data from this station is also used to test which is the main factor controlling lake level changes over the last 40 yrs in Lake Tuosu.

Generally, the precipitation amount and temperature both started to increase from early 1970s in the Lake Tuosu area, although the temperature slightly decreased after the mid 2000s (Fig. 7). The variation in lake area/level showed the opposite trends with the changes of precipitation over the last 40 years in Lake Tuosu area (Fig. 7). This suggests that increased precipitation would not be the major contributor of effective moisture in this region, since higher precipitation is normally expected to accompany a shift to enlarged water area or deep water in lakes. Based on the correlated analysis, the lake area was negatively correlated with temperature over the past 40 years in Lake Tuosu area ($r = -0.81$, $p < 0.01$, $n = 12$). Therefore, we suspect that the lake area/level change may be mainly controlled by temperature-induced evaporation in Lake Tuosu.

Evidence for precipitation and temperature changes (Shao et al., 2005; Liu et al., 2009b), and the variation in lake level indicated by $\delta^{13}\text{C}_{\text{org}}$ values (this study) in Lake Tuosu area over the past ~120 years was compared to further test the above assumption (Fig. 4). Fluctuations in temperature from the 1880s to the 1970s could potentially explain changes in lake level recorded by TSLC14-1 $\delta^{13}\text{C}_{\text{org}}$ values during that period (Fig. 4). Although the precipitation showed increasing trend, the lake level still decreased with increased temperature during this period in Lake Tuosu. Overall, the changes of temperature resulted in evaporation changes had a strong effect on the lake level variations of Lake Tuosu.

5.2 The environmental implication of ostracod $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ values, and their relation with $\delta^{13}\text{C}_{\text{org}}$ values

In this study, only single ostracod species (*E. mareotica*) was collected in the surface lake sediment and the 120-year sedimentary core in Lake Tuosu. The presence of ostracod shells including early instars and adult in samples of core TSLC14-1 indicates that the ostracod *E. mareotica* might be autochthonous around the coring site. *E. mareotica* is good swimmer living the lake bottom, which can not only crawl on the surface sediments but also can swim up to the surface sediment. According to our field observation, the ostracod *E. mareotica* can form its shells in early April when the water temperature reaches to about 7~9°C, and the adult specimens have been collected at late April or early May. Living animal is still collected in late September in Lake Tuosu. The ostracod *E. mareotica* can tolerate wide salinity ranges and was usually found in salt lakes in the Qaidam Basin (Sun et al., 1993; Li et al., 2010), but the monospecific presence of this single species usually indicates high water salinity in lakes (Li et al., 2010; Li and Liu, 2014). Therefore, the appearance of only *E. mareotica* in core TSLC14-1 through the past 120 years may

indicate that the lake salinity was constant high during the time in Lake Tuosu. Meanwhile, the advantage of the same species being present throughout the core is that isotope analyses can be undertaken on one species and therefore the vital offset will remain the same for each analysis.

In hydrologically-closed and arid lakes, changes in lake water $\delta^{18}\text{O}$ also commonly result from variations in effective moisture (i.e., P/E, Leng and Marshall, 2004). When P/E decreases, the lake water becomes enriched with ^{18}O because of the preferential evaporative loss of water with ^{16}O , whereas the opposite occurs in periods of increased effective moisture. In general, the lake level or lake volume also should be increased due to increased P/E, whereas the opposite occurs when the effective precipitation decreased in closed lakes. Therefore, the ostracod $\delta^{18}\text{O}$ values should co-vary with $\delta^{13}\text{C}_{\text{org}}$ values because it can record variation in lake level for Lake Tuosu.

According to Figure 4, both ostracod $\delta^{18}\text{O}$ and TOM $\delta^{13}\text{C}_{\text{org}}$ values increased from 1880s to early 1980s respectively corresponding with decreased effective precipitation and lake level in Lake Tuosu area. The relatively stable high ostracod $\delta^{18}\text{O}$ values showed that effective precipitation was very low during the period of 1970s to 1980s, but the low TOM $\delta^{13}\text{C}_{\text{org}}$ values showed that the lake level suddenly increased and then decreased at around 1975 AD in Lake Tuosu. Very high TOM $\delta^{13}\text{C}_{\text{org}}$ values showed that the lake level was very low but the effective precipitation was high indicated by low ostracod $\delta^{18}\text{O}$ values after early 1990s in the Lake Tuosu region. In addition, the result of correlated analysis showed that the ostracod $\delta^{18}\text{O}$ values are positively correlated with lake area in Lake Tusuo over the past 40 years ($r= 0.63$, $p<0.01$, $n=12$). This result is contrary with the knowledge that the ostracod $\delta^{18}\text{O}$ values should decrease with increased lake area/level caused by increasing effective precipitation. Consequently, the variation

in ostracod $\delta^{18}\text{O}$ values could not be directly explained as the changes of lake level/area and thus effective precipitation/moisture in Lake Tuosu.

In fact, past studies showed that variations in carbonate $\delta^{18}\text{O}$ values could not have been the result of varying effective precipitation but were due to changes in water temperature and $\delta^{18}\text{O}$ of the source water in lakes in or around Qaidam Basin (Holmes et al., 2007; Liu et al., 2009a). The low and decreased ostracod $\delta^{18}\text{O}$ values may be caused by increased temperature and changes in $\delta^{18}\text{O}$ values of source water when the lake level was low after 1990s in Lake Tuosu. Although there was unavailable water temperature data, result of a past study showed that the lake water temperature would vary with air temperature in the Qinghai-Tibet Plateau (Ke and Song, 2014). So, the varied ostracod $\delta^{18}\text{O}$ values in core TSLC14-1 are compared with changes of annual temperature in Lake Tuosu area over the past 50 years (Fig. 4).

In general, the ostracod $\delta^{18}\text{O}$ values in core TSLC14-1 are negatively correlated with annual temperature ($r = -0.62$, $p < 0.01$, $n = 40$) and annual precipitation ($r = -0.39$, $p < 0.05$, $n = 40$) over the past 50 years in the Lake Tuosu area. This result suggested that the ostracod $\delta^{18}\text{O}$ values may be evidently affected by temperature and amount of precipitation in Lake Tuosu. Some studies showed that annual change of $\delta^{18}\text{O}$ in precipitation was affected by ‘temperature effect’, and the precipitation $\delta^{18}\text{O}$ value became higher with increased temperature in the Delinghai area (Li et al., 2006; Yu et al., 2006; Liu et al., 2014b). The precipitation $\delta^{18}\text{O}$ values may be enriched with increased temperature over the past 50 yrs in Lake Tuosu area, and the enriched $\delta^{18}\text{O}$ precipitation resulted in the high $\delta^{18}\text{O}$ value of source water into the lake based on the constant conditions of catchment of Lake Tuosu. The $\delta^{18}\text{O}$ records of ice core and stalagmite also showed that precipitation $\delta^{18}\text{O}$ value has been become high during recent 50 years in the Qinghai-Tibet Plateau

(Thompson et al., 2003; Yang et al., 2007). Therefore, the high ostracod $\delta^{18}\text{O}$ values in core TSLC14-1 might be also caused by increased source water $\delta^{18}\text{O}$ values in period of the 1960s to 1990s.

The result of this study further supports the past knowledge that the changes in carbonate $\delta^{18}\text{O}$ values cannot be simply explained as the effective precipitation/moisture but other factors such as changes in isotopic compositions of source water and lake level, and drainage pattern may affect the carbonate $\delta^{18}\text{O}$ values from lakes in arid areas (Mischke and Wünnemann, 2006; Holmes et al., 2007; Liu et al., 2009a; Henderson et al., 2010).

The carbonate $\delta^{13}\text{C}$ is controlled primarily by dissolved inorganic carbon (DIC) in the ambient water which is controlled generally by three predominant factors: the isotopic composition of inflowing waters, the CO_2 exchange between atmosphere and lake water and the photosynthesis/respiration of aquatic plants within the lake (von Grafenstein et al., 1999; Schwalb, 2003). The carbon isotopic composition of carbonate 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 (Schwalb et al., 1999; Mischke et al., 2010; Li and Liu, 2014) and atmospheric CO_2 exchange related to temperature (Qiang et al., 2005; Lei et al., 2010; Xu et al., 2006, 2014) in lakes on the Tibetan Plateau.

In this study the ostracod $\delta^{13}\text{C}$ value is positively correlated with $\delta^{13}\text{C}_{\text{org}}$ value ($r=0.65$, $p<0.01$, $n=66$) in core TSLC14-1 over the past 120 years in Lake Tuosu. Most of non-marine ostracods are benthic animals, and ostracod *E. mareotica* is good swimmer living in the sediment-water interface according to our laboratory observation. As mentioned above, the atmosphere CO_2 concentration has increased and its carbon isotope values have decreased in

recent 120 years. However, the ostracod $\delta^{13}\text{C}$ values increased after the 1980s in core TSLC14-1 (Fig. 4), tentatively suggesting that the variation in $\delta^{13}\text{C}$ values of water DIC and ostracod may be not mainly controlled by atmosphere CO_2 and its carbon isotopes in Lake Tuosu area. Others, the carbon isotope content of bottom-water DIC may be affected by the primary productivity and the decomposition of organic matter because there are large amounts of aquatic plants on the lake bottom in Lake Tuosu. 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 Tuosu. Therefore, the carbon isotopic compositions of ostracod shells should be controlled primarily by the carbon isotope of the bottom-water DIC related to biological activity and changes of aquatic plant species in Lake Tuosu. This can explain the good dependency between ostracod $\delta^{13}\text{C}$ values and $\delta^{13}\text{C}_{\text{org}}$ values from core TSLC14-1. In addition, the relatively high primary productivity in warm conditions would result in the high $\delta^{13}\text{C}_{\text{DIC}}$ values and ostracod $\delta^{13}\text{C}$ values. However, the variation in ostracod $\delta^{13}\text{C}$ values was not well consistent with temperature change over the last 120 years considering the uncertainty in the age profiles in Lake Tuosu. In general, ostracod $\delta^{13}\text{C}$ values were still low when the temperature increased from 1880s to early 1990s, and then the ostracod $\delta^{13}\text{C}$ values suddenly increased and kept at high level after early 1990s at high temperature in Lake Tuosu (Fig. 4).

Therefore, we suggest that the ostracod $\delta^{13}\text{C}$ values may be mainly controlled by $\delta^{13}\text{C}_{\text{DIC}}$ values which may be mainly contributed by the carbon isotope of aquatic plants species related to lake level changes and primary productivity in Lake Tuosu. In a word, the ostracod $\delta^{13}\text{C}$ can be used to indicate changes of primary productivity based on considering the possible changes of aquatic plants species related to lake level variations in Lake Tuosu or similar lakes.

6. Conclusions

This study presents high-resolution multi-proxy records from Lake Tuosu spanning the last 120 years in the Qaidam Basin. Comparison with the instrumental record and records derived from tree-rings back to the 1880s allows us to examine changes in carbon isotope of TOM, $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ of ostracod in response to changes in temperature, precipitation and lake level. The results of this study suggest that the proxy of $\delta^{13}\text{C}_{\text{org}}$ are either directly or indirectly associated with changes in lake level in this closed-basin lake as evidenced by the result that the $\delta^{13}\text{C}_{\text{org}}$ record from Lake Tuosu well parallels the record of lake area which is mainly controlled by evaporation related to temperature back to early 1970s. This correlation is apparently due to the fact that $\delta^{13}\text{C}_{\text{org}}$ values were mainly contributed by the aquatic plants which species would sensitively change with the lake's hydrologic balance (lake level changes). The ostracod $\delta^{13}\text{C}$ can be used to indicate variation in primary productivity based on evaluating the possible changes of aquatic plants species related to lake level changes in Lake Tuosu or similar lakes. In addition, the $\delta^{18}\text{O}$ values of ostracods did not well co-varied with lake level (effective precipitation) changes indicated by $\delta^{13}\text{C}_{\text{org}}$ values from TSLC14-1 for the last 120 yrs in Lake Tuosu. This result suggests that the changes in ostracod $\delta^{18}\text{O}$ values cannot be straightforwardly explained as the effective precipitation but other factors like isotopic compositions of input water, drainage pattern and the lake volume may affect the ostracods $\delta^{18}\text{O}$ values from lakes in arid area. In the future, much more works should be carried out to clear the climatic significance of isotopic compositions of total organic matters and carbonate from modern lakes in arid area.

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Captions

Figure 1. Map of Lake Gahai, Lake Tuosu, Lake Hurleg and their surrounding environment.

Figure 2. ^{210}Pb and ^{137}Cs data of cores TSLC14-1 (a) and TSLC14-2 (b) at Lake Tuosu in the Qaidam Basin

Figure 3. Age model of core TSLC14-1 used in this study. a) Changes of bulk carbonate content in core TSLC14-1 with depth; b) changes of bulk carbonate content in core TSLC14-2 with depth; c) created age model of core TSLC14-1 using ^{137}Cs data (red), age model of core TSLC14-2 using ^{210}Pb data (blue), used age model of core TSLC14-1 (green).

Figure 4. Ostracod $\delta^{18}\text{O}$ values (red), ostracod $\delta^{13}\text{C}$ values (black) (3c) and sedimentary $\delta^{13}\text{C}_{\text{org}}$ values (blue) from core TSLC14-1 over the last 120 years (3d), and their correlation with temperature (3a, yellow represents data from tree-ring and green represents instrumental data) and precipitation (3b, grey represents data from tree-ring and light blue represents instrumental data) recorded by instruments in Delingha weather station and derived from tree-ring for the last 120 yrs (Shao et al., 2005; Liu et al., 2009b).

Figure 5. Correlation of sedimentary $\delta^{13}\text{C}_{\text{org}}$ values from core TSLC14-1 with atmosphere CO_2

concentration (green) and its carbon isotope (yellow) since the 1880s (Friedli et al., 1986; Schubert and Jahren, 2012), and lake area changes from remote sensing data (red dots, Liu et al., 2014b) since the 1970s in Lake Tuosu.

Figure 6. Correlation of monthly evaporation with average month temperature from the Delingha weather station for the last 50 years.

Figure 7. Correlation of lake area from remote sensing data (blue dots, Liu et al., 2014b) with precipitation (yellow line) and temperature (purple line) from Delingha weather station for the recent 40 years.

Figure 1

Figure 2

Figure 3

Figure 4

Figure 5

Figure 6

Figure 7