Aquatic Species Dominate Organic Matter in Qinghai Lake during the Holocene: Evidence from Eolian Deposits around the Lake

Fangming Zeng*1, Xiangjun Liu1, Xiangzhong Li2, Chongyi Li3

ABSTRACT: Total organic carbon (TOC) in lake sediments and its stable carbon isotope (δ13Corg) are widely applied to investigate paleoenvironmental changes even though their implications are complicated and multi-explanatory. Organic geochemistry studies of lake sediments from Qinghai Lake have been investigated, but some interpretations are controversial. In this study, TOC of one Holocene eolian section and δ13Corg of three eolian sections were studied around Qinghai Lake. Results indicate that the TOC content in eolian deposits was low during the Early Holocene, and gradually increased to high values during the Middle and Late Holocene. The variation in TOC content of eolian deposits is different from that in the lacustrine sequence from Qinghai Lake during the Holocene. The δ13Corg values in the eolian sections were relatively stable, with oscillation amplitudes of -4‰ (ranging from -25.8‰ to -22.1‰), in contrast to ~10‰ variations in δ13Corg values (varying from -30‰ to -20‰) in lacustrine sediments. Through comparison of TOC and δ13Corg values between eolian deposits and lacustrine sediments, we can confirm indications that the organic matter in Qinghai Lake sediments during the Holocene was primarily a contribution of the aquatic species in the lake. This is significant for understanding the origin of organic matter in lake sediments on the northeastern Qinghai-Tibetan Plateau and for paleoenvironmental inferences using such proxies.

KEY WORDS: Qinghai Lake, total organic carbon (TOC), organic carbon isotope (δ13Corg), Qinghai-Tibetan Plateau.

0 INTRODUCTION

Total organic carbon (TOC) and its stable carbon isotope (δ13Corg) are common paleoenvironmental proxies, since TOC is thought to reflect primary productivity within a drainage basin, and δ13Corg can indicate past vegetation types (C3 or C4 plants). These proxies can reveal the source(s) of the organic matter in sediments (Liu et al., 2013; Zhang et al., 2013; Meyers, 2003, 1994). However, both proxies are also influenced by source variations, transportational and depositional processes, diagenesis, and preservations conditions, offering different multiple solutions and making their interpretation difficult (Pearson and Coplen, 1978). In the arid regions of northwestern China, TOC and δ13Corg in lakes are considered to be affected by local precipitation (Yang et al., 2015; Liu et al., 2013; Xu et al., 2006), groundwater and riverine water discharge (Hou et al., 2014) in drainage basin.

Qinghai Lake (36°54′N, 100°12′E) lies on the northeastern Qinghai-Tibetan Plateau (QTP) (Fig. 1). Its size and proximity to three climate systems (South Asian Monsoon, East Asian Monsoon and the Westerlies) make it sensitive to global climate change (An et al., 2012; Madsen et al., 2008). Thus, a series of research projects at the lake has been carried out to reconstruct palaeoclimates. Organic geochemistry proxies have often been used to reconstruct paleoenvironmental change in the Qinghai Lake area (Liu X J et al., 2014; Thomas et al., 2014; Liu W G et al., 2013; An et al., 2012; Xu et al., 2006; Shen et al., 2005; Zhang et al., 2002). While TOC and δ13Corg measurements on lacustrine sediments taken from Qinghai Lake drill cores have been done, interpretations are debatable. Some studies suggest TOC and δ13Corg primarily indicate the quantity of terrigenous organic materials in the lake sediments (Liu et al., 2014; Thomas et al., 2014; Xu et al., 2006; Zhang et al., 2002), while others suggest they mainly reflect

variation in aquatic plant productivity compared to small terrestri al contribution (Liu et al., 2013; Shen et al., 2005). In addition, some researchers contend that the $\delta^{13}$C of terrestri al organic matter in lacustrine sediments is related either to temper ature change (Zhang et al., 2002) or to precipitation variations (Xu et al., 2006), while those who contend the organic matter of lacustrine sediments is primarily from aquatic plants have suggested either that $\delta^{13}$C is likely an indicator for lake primary productivity (Shen et al., 2005), or that it is a result of shifts in aquatic plant types related to variations in lake levels (Liu et al., 2013).

It is estimated that the modern organic carbon burial rate in Qinghai Lake is about 7.23 g·m$^{-2}$·a$^{-1}$, and that the organic matter in lake sediments is primarily derived from particulate organic carbon in lake water, of which ~80% is of terrestri al origin (Xu et al., 2013). $\delta^{13}$C$_{org}$ values of modern terrestrial plants and in situ surface deposits, aquatic plants and surface lacustrine sediments in Qinghai Lake show that the $\delta^{13}$C$_{org}$ values of terrestrial plants varied from -27.7‰ to -24.5‰ with an average value of -25.8‰, and that the $\delta^{13}$C$_{org}$ values of modern surface soils varied from -26.9‰ to -24.8‰ with an average value of -25.4‰ (Liu et al., 2013). At present the algae genus Cladophora grows well in Qinghai Lake from depths of several meters to more than 22 m, and has a high productivity (more than 50 g·m$^{-2}$ in wet weight), while submerged plants (mainly Potamogeton and Ruppia) are only found in shallow water (LZGI, 1979). The Cladophora in Qinghai Lake has low $\delta^{13}$C$_{org}$ values (-33.6‰ to -28.6‰) and the values become more negative with increasing water depth (Liu et al., 2013). However, submerged plants have enriched $\delta^{13}$C$_{org}$ values (-17.8‰ to -15.9‰), and the values do not change with depth. The $\delta^{13}$C$_{org}$ of surface lacustrine sediments varies from -28.6‰ to -21.2‰, with an average value of -24.6‰ (Liu et al., 2013). Based on these $\delta^{13}$C$_{org}$ values of different materials, they suggest that the total organic material of lacustrine sediments is mainly generated from internal carbon sources (Liu et al., 2013). In short, the sources of organic materials in modern lacustrine sediments remain controversal, and, by extension, debates about the origins of organic materials preserved in ancient lacustrine sediments remain unresolved.

To better understand the sources of organic matter in lake sediments from Qinghai Lake during the Holocene, we analyzed the TOC of a Holocene loess section and the $\delta^{13}$C$_{org}$ of three loess sections around Qinghai Lake, and then compared those results with other studies from lake sediments and Alpine wetlands. The aim of this study was to further investigate the source of TOC in Qinghai Lake using both the lake and terrestrial proxies in the Qinghai Lake area.

1 MATERIALS AND METHODS

1.1 Section Description and Sampling

Qinghai Lake is ~4 400 km$^2$ in area and with a present lake level of ~3 194 m a.s.l. (above sea level) and has a maximum lake depth of ~30 m (Xu et al., 2013; Liu et al., 2011). Its catchment is 29 660 km$^2$, with a prismatic shape (LZGI, 1979). The mean annual temperature and mean annual precipitation in this drainage basin are ~ -0.1 °C and ~373 mm, respectively (An et al., 2012). Mean air temperature varies between -14.7 and -10.4 °C in January and -10.4 to -14.7 °C in July (Xu et al., 2013). More than 65% of the annual precipitation falls in the summer (June, July and August) (An et al., 2012). The Buha River, on the west side of the lake, contributes more than 60% of the total runoff. Other rivers that supply the lake are the Shaliu, Haergai, Quanji and Heima rivers. At present, the Asian Summer Monsoon (ASM) influences the Qinghai Lake area in summer, while the Westerlies dominate in winter (An et al., 2012).

The Zhongyangchang (ZYC) eolian section (36°38’N, 100°52’E) lies at the southeastern margin of Qinghai Lake (Fig. 1b). The exposed ZYC Section is ~1.5 m thick, and can be divided stratigraphically from top to bottom into a modern soil, loess containing a paleosol, and eolian sand. The top 0.3 m is a loose modern soil, with sediments coarser than the underlying loess and paleosol. The loess and paleosol occur from a depth of 0.3 to 1.0 m. The transition between the paleosol and lower loess is gradual (Fig. 2). The loess and paleosol are hard and
1.2 Dating Methods

Because the loess sediments of the ZYC Section contained no visible in situ buried organic remains or plant seeds, bulk organic sediments were used for radiocarbon dating. Accelerated mass spectrometry (AMS) radiocarbon dating of these bulk organic samples was conducted at the Center for Applied Isotope Studies, University of Georgia, USA.

The equivalent doses \( (D_e) \) of the OSL samples were measured in the Luminescence Dating Laboratory of China University of Geosciences (Wuhan). The pretreatment methods and \( D_e \) measure protocol of the OSL samples are described in Liu et al. (2012). Radionuclide activity concentrations were determined from measurements of U, Th and K concentrations using neutron activation analysis (NAA) of dried and ground bulk samples. The U, Th and K concentrations were measured in China Institute of Atomic Energy in Beijing.

1.3 TOC and \( \delta^{13}C_{org} \) Measurements

The bulk samples were dried at room temperature, gently crushed to pass through a 75 μm sieve, oven dried at 50 °C for 24 h, and treated with 10% HCl for 48 h to remove carbonate in the sediments. The samples were then washed 10 times with distilled water and oven dried at 40 °C for 24 h. TOC and \( \delta^{13}C_{org} \) were analyzed on a Vario Pyro Cube Elemental Analyzer, coupled with a continuous flow IsoPrime 100 Isotope Ratio Mass Spectrometry C/N module. TOC concentrations (written as %) were calculated by known values of sulphanalimide and GBW07454 (Luochuan Loess from the Chinese Loess Plateau). The \( \delta^{13}C_{org} \) values were corrected to a VPDB scale with a notation of \( \delta \) using the two-point correction method (Coplen et al., 2006), with international standards of IAEA-CH3 (-24.72‰) and IAEA-601 (-28.74‰). Standard samples for carbon concentrations and isotopic ratio were analyzed at the beginning of each sample batch and between each 10 to 20 samples in order to monitor machine drift and to obtain the necessary precision. TOC precision and \( \delta^{13}C_{org} \) precision are about 0.5% and <0.15‰, respectively.

2 RESULTS AND DISCUSSION

2.1 Age Model of ZYC Section

Radiocarbon dating and OSL dating results for the ZYC Section are listed in Tables 1 and 2, respectively, and shown on Fig. 2. The radiocarbon ages were calibrated to calendar years using CALIB 7.0 with IntCal13 (Reimer et al., 2013). The OSL and radiocarbon ages are all in stratigraphic order, but are not all consistent with each other (Fig. 3). There are four radiocarbon ages younger than the corresponding OSL ages. Radiocarbon ages of bulk organic matter should be treated as minimal ages since small unidentified plant roots can intrude into older sediments or mobile organic compounds can be translocated into deeper layers (Feng et al., 2013; Orlova and Panychev, 1993; Head et al., 1989). The remaining two radiocarbon ages at the depth of 0.30 and 0.68 m are within or close to the 2σ ranges of their corresponding OSL ages. A large number of grass roots intrude into the depth of ~50 cm in the ZYC Section (Fig. 2). The accuracy of the bulk organic radiocarbon ages in the ZYC Section are difficult to estimate. However, OSL ages are demonstrated to have advantages for dating eolian sediments.

Figure 2. Stratigraphic profile of the ZYC Section showing age estimates. White squares represent OSL dating samples; white circles represent radiocarbon dating samples.

compact, containing numerous pores, and fibrous plant roots. Loose eolian sand occurs below the loess and continues downwards to an unknown depth (Fig. 2). The top 1.2 m of the section was cleaned for sample collection. Six samples for optically stimulated luminescence (OSL) dating and six bulk sediment samples for radiocarbon dating were collected from the section (Fig. 2). Sixty samples for proxy analyses were taken at 2 cm intervals from the section.

The Jiangxigou (JXG) Section (36°35’0.05”N, 100°18’0.49”E) is composed of eolian deposits. The lithology of the section from surface to bottom is: 0–30 cm, loose modern sandy soil, containing a large number of plant roots; 30–105 cm, paleosol layer, presenting gray-black color; 105–175 cm, loess layer, showing yellow color; 175–200 cm is yellow eolian sand. Previous OSL ages indicate that the age is 12.9 ka at the depth of 140 cm (Liu et al., 2012). Fifteen samples for \( \delta^{13}C_{org} \) determination were obtained at about 10 cm intervals from depths of 0–140 cm.

The Heimahe 1 (HMH1) Section (36°44’20.48”N, 99°45’34.07”E) is composed of eolian deposits (above the depth of 240 cm) and gravels (below the depth of 240 cm). The lithology of the section from top to bottom is: 0–30 cm, coarse and loose modern sandy soil, containing abundant plant roots; 30–160 cm, compact paleosol layer; 160–240 cm, moderately consolidated loess layer. Previous studies show that the age in the lower part of the nearby Heimahe Section is about 13 ka (Zhao et al., 2009; Madsen et al., 2006). Twenty-four samples for \( \delta^{13}C_{org} \) analyses were collected at about 10 cm intervals from the depth of 0–245 cm.
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<table>
<thead>
<tr>
<th>Table 1</th>
<th>Radiocarbon dating results for the ZYC Section</th>
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<td>Loess</td>
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<td>ZYC107</td>
<td>Eolian sands</td>
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*ZYC49 has been reported in Liu et al. (2012) as ZYC-A.

Figure 3. OSL and ¹⁴C ages plotted against depth for the ZYC Section. The OSL ages are plotted with 2σ standard deviations. The calibrated ¹⁴C ages are plotted after converting the 2σ radiocarbon ages to calendar years using CALIB 7.0 with IntCal13 (Reimer et al., 2013).

The TOC values of the ZYC Section and the KTN Section (Lu et al., 2015) were low during the Early Holocene, but gradually increased through the Middle and Late Holocene, with the exception of one reversal during 1–0.6 ka (Fig. 4a). OSL ages indicate that sedimentation rate of the KTN Section is generally greater than that of the ZYC Section in this study, so the TOC values for the KTN Section are lower than TOC values for the ZYC Section. In contrast, the
Figure 4. Comparison of organic matter related proxy records. (a) TOC; (b) $\delta^{13}$C$_{org}$ (the light-gray band represents range of variation of $\delta^{13}$C$_{org}$ in the ZYC, JXG and HMH1 sections); (c) C/N ratio. Data source: 1 cited from Shen et al. (2005); 2 is the ZYC Section from this study; 3 cited from Lu et al. (2015); 4 cited from Liu et al. (2013); 5 cited from Liu et al. (2014). Note that 1, 4, and 5 are lacustrine records, while 2 and 3 are eolian records.

Figure 5. $\delta^{13}$C$_{org}$ values in the HMH1 and JXG sections around Qinghai Lake.

TOC values of lacustrine sediments in Qinghai Lake have high values from 10.5–4 ka, then decrease after 4 ka (Shen et al., 2005) (Fig. 4a). In addition, the TOC contents in the lake sediments (QH-2000 core) are obviously higher than those in the surrounding eolian deposits (Fig. 4a). These differences in TOC variation trends and concentration between terrestrial eolian deposits and the lacustrine sediments during the Holocene suggest that organic materials preserved in Qinghai Lake sediments did not originate primarily from terrestrial ecosystems.

The $\delta^{13}$C$_{org}$ values from the ZYC Section are quite stable, fluctuating between -24.8‰ and -25.8‰ (with an oscillation amplitude of 1.0‰) (Fig. 4b). In addition, the $\delta^{13}$C$_{org}$ values from the JXG section fluctuate between -24.7‰ and -23.2‰ (with an oscillation amplitude of 1.5‰). The $\delta^{13}$C$_{org}$ values from the HMH1 Section range from -24.1‰ to -22.1‰ (with an oscillation amplitude of 2.0‰) (Fig. 5). In all, the $\delta^{13}$C$_{org}$ values from the ZYC, JXG and HMH1 sections vary between -25.8‰ and -22.1‰ (with an oscillation amplitude of 3.7‰). However, the $\delta^{13}$C$_{org}$ values of the lacustrine sediments in the Qinghai Lake have much larger amplitudes of ~10‰ (Fig. 4b). $\delta^{13}$C$_{org}$ values of terrestrial wetland to the north of Qinghai Lake range from -28.0‰ to -22.1‰ over the past 8 ka, with a slight amplitude variation of ~6‰ (Liu, 2013). If terrestrial ecosystems supplied large amounts of organic matter to the lake sediments in the Qinghai Lake during the Holocene, it is difficult to explain how the limited range of $\delta^{13}$C$_{org}$ variation for terrestrial ecosystems (either -25.8‰– -22.1‰ or -28.0‰– -22.1‰) could cause the $\delta^{13}$C$_{org}$ values of lacustrine sediments to fluctuate from -30‰ to -20‰ (10‰ in amplitude) (Liu et al., 2013; Shen et al., 2005). The submerged plant $\delta^{13}$C$_{org}$ values in Qinghai Lake vary from -17.8‰ to -15.9‰, while Cladophora $\delta^{13}$C$_{org}$ values vary from -33.6‰ to -28.6‰ (Liu et al., 2013).
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*Cladophora* can live in water more than 22 m deep and have a high biomass in Qinghai Lake (LZGI, 1979). Therefore, it may be that changes in the dominant aquatic species (submerged plants or *Cladophora*) in the lake, responding to Holocene climate changes and corresponding lake level fluctuations, caused the \[\delta^{13}C_{\text{org}}\] values to oscillate between -30‰ and -20‰.

We reinterpret positive \[\delta^{13}C_{\text{org}}\] values during the Early Holocene to have been caused by an increase in submerged plant productivity and halophilic plants around the lake as the lake level was relatively shallow during Early Holocene (Liu et al., 2013). Although lake levels were low during the Early Holocene (Liu et al., 2013; Yu, 2005), summer insolation was high and the summer monsoon intensified (Liu et al., 2014; An et al., 2012). These enhanced climatic conditions, coupled with the additional oxygen associated with shallow lake levels and sun light, resulted in increased submerged plant growth. During the Middle and Late Holocene, the water level was several meters higher than at present (Liu et al., 2015), and algae (mainly *Cladophora*) became the dominant contributor to lacustrine organic matter, causing the \[\delta^{13}C_{\text{org}}\] values to become more negative (Liu et al., 2013).

The C/N ratio of organic matter is often used to distinguish the proportions of aquatic and terrestrial material contributed to lacustrine sediments (Meyers, 1994). Aquatic plants and lacustrine plankton have low C/N ratios, typically in the range of 4 and 10, whereas terrestrial plants usually have C/N ratios of 20 or greater (Meyers and Lallier-Vergès, 1999). The C/N ratios of lacustrine sediments in the Qinghai Lake are relatively stable, varying slightly around 10 (Liu et al., 2014; Shen et al., 2005), with the only exception being a disturbance during 1.3–2.8 ka; there are only two C/N ratios are greater than 20 at 1.9 ka (with value of 29.43) and at 2.7 ka (with value of 25.91) (Fig. 4c) (Shen et al., 2005). These results suggest that the organic matter in the lake sediments from the Qinghai Lake during the Holocene comes mainly from aquatic organisms.

### 2.3 Pollen Records in Qinghai Lake Area and Their Implication for Vegetation Changes

Based on the above analysis, the \[\delta^{13}C_{\text{org}}\] values and the C/N ratios of the organic materials preserved in lacustrine sediments in Qinghai Lake during the Holocene were dominantly derived from organisms within the lake itself. These aquatic plants were likely to have been predominantly algae, since pollen records from the lacustrine sediments show little abundance of submerged plants during the Holocene (Figs. 6a, 6b).

Pollen records from lacustrine sediments suggest an extensive forest expansion occurred in the Qinghai Lake drainage basin during the Holocene optimum period (Liu et al., 2002; Du and Kong, 1989). However, pollen records from loess sections near the lake indicate that local vegetation was dominated by shrub and herb plants during the Holocene, and that the local terrestrial ecosystem did not change significantly (Fig. 6) (Hou et al., 2013; Chen et al., 1991). The limited variance of \[\delta^{13}C_{\text{org}}\] values in ZYC, JXG and HMH1 sections also indicate that the terrestrial ecosystem was relatively stable during the Holocene. Therefore, we suggest that there were only small patches of forest in the immediate vicinity of Qinghai Lake and that most of the tree pollen in the lake sediments was probably

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**Figure 6.** Pollen records in Qinghai Lake and on the adjacent landscape. (a) From the QH85-14 drill core (Du and Kong, 1989); (b) from the QH-2000 drill core (Liu et al., 2002); (c) from the JXG-2 Section at Jiangxigou site (Hou et al., 2013); (d) from the Halali Section (Chen et al., 1991).
supplied by long-distance transport of pollen from higher elevations via both wind and water.

3 CONCLUSIONS

In this study, three eolian sections at the margin of the Qinghai Lake were investigated. We found that: (1) interpretation of radiocarbon ages for bulk organic matter from the ZYC Section is complex, but the OSL ages in this section seem more reasonable; (2) the TOC variations trend of the eolian deposits are different from those of lacustrine sediments in the Qinghai Lake, and the δ13C of the eolian deposits has a limited range of variation when compared with lacustrine sediments; (3) our results, in combination with organic geochemistry proxies previously reported for lacustrine and eolian deposits, indicate that the organic matter preserved in lacustrine sediments in Qinghai Lake during the Holocene was predominantly derived from aquatic species; (4) the local terrestrial ecosystem in the Qinghai Lake vicinity during the Holocene was relatively stable, and it was dominated by shrub and herb plants, with forest cover limited to a few local places.

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