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A 700-year macrophyte productivity record inferred from isotopes of macrophyte remains and bulk carbonates in Lake Koucha, northeast Qinghai–Tibetan Plateau

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ABSTRACT

The isotopic composition of total organic carbon (TOC) in lakes has been widely used to interpret paleoclimatic changes and the depositional environments of lake sediments. However, the main factors that affect the carbon isotopes of TOC may vary in different lake sediment records, limiting the ability of organic carbon isotopes to explain biogeochemical and environmental changes, especially in lakes with a large number of aquatic plants. In this study, the $\delta^{13}C$ values of macrophyte remains and bulk carbonate in a sedimentary core from Lake Koucha were investigated to evaluate their paleoenvironmental implications. We found that the bulk carbonate was dominated by authigenic carbonates formed in the lake and that their $\delta^{18}O$ and $\delta^{13}C$ values can be used to reconstruct environmental changes in the Lake Koucha area. The macrophyte productivity derived from the carbon isotopic offset between the macrophyte remains and the bulk carbonate ($\varepsilon_{remains-BC}$) in the Lake Koucha area agree well with total solar irradiance (TSI) records inferred from $\Delta^{10}Be$ and temperature records based on tree rings from the Qinghai–Tibetan Plateau. Although the distribution of macrophytes is related to water depth according past studies and our observations in the field, our findings suggest that changes in macrophyte productivity may be primarily driven by temperature changes in the Lake Koucha area.

1. Introduction

The Tibetan Plateau (TP) is one of the most sensitive regions to global climate change, and it involves complex interactions between the mid-latitude westerly circulation and the subtropical Asia monsoon circulation, acting as a bridge between high- and low-latitude climatic processes. In recent decades, the paleoenvironmental/paleoclimatic changes on the TP across different time scales have been widely studied using various natural archives, such as ice cores (Yao et al., 1996; Thompson et al., 1997, 2003), tree rings (Shao et al., 2005; Liu et al., 2009a,b; Yang et al., 2014) and lake sediments (Lister et al., 1991; Shen et al., 2005; Liu et al., 2006; Colman et al., 2007; An et al., 2012; Zhao et al., 2013; Woszczyk et al., 2014). Among these, lake sediment sequences have been the most frequently used because of the large number of lakes on the TP that provide potential records for paleoclimatic reconstructions, especially for late Holocene (Xu et al., 2006a, 2014; Zhao et al., 2010; Wang et al., 2013; He et al., 2013a,b; Chen et al., 2015).

The use of stable C isotopes to investigate past lake levels, temperatures, primary productivity, nutrient dynamics and moisture availability is well documented in lakes in this area (Qiang et al., 2005; Xu et al., 2006a, 2014; Mischke et al., 2008; Herzschuh et al., 2010a,b; Liu et al., 2013; Li and Liu, 2014; Woszczyk et al., 2014). Bulk organic matter in lake sediment is derived from plants and organisms with different $\delta^{13}C$ values that live in the lake and its watershed. Consequently, the bulk organic matter contains an integrated isotopic signal that reflects the collective paleoclimate and paleoenvironmental variations (Meyers and Teranes, 2001). The carbon isotope ratios ($\delta^{13}C$) of lacustrine carbonates are primarily a function of the $\delta^{13}C$ values of the dissolved inorganic carbon (DIC) in the lake and the isotopic fractionation between DIC and precipitated carbonate (Deines et al., 1974; Buchardt and Fritz, 1980). In general, three predominant

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factors control the carbon isotopic composition of lake DIC: the isotopic composition of inflowing waters, CO_2 exchange between the atmosphere and the lake water, and the photosynthesis/respiration of aquatic plants within the lake (Herczeg, 1987; Hollander and Mckenzie, 1991; Zhang et al., 1995; Miyajima et al., 1997; Wang and Veizer, 2000). Therefore, paleoclimatic or paleoenvironmental interpretations of the carbon isotopic composition of authigenic carbonate and sedimentary TOC may be different because the isotopic signals in authigenic carbonate and TOC may be affected by multiple factors, such as the carbon isotopic signals from different sources, such as atmosphere CO_2, the input of terrestrial plants, the decomposition of aquatic plants, etc., in lakes on the TP or in other regions (Talbot and Livingstone, 1989; Leng and Marshall, 2004; Piovano et al., 2004; Qiang et al., 2005; Xu et al., 2006a, 2014; Mischke et al., 2008; Lei et al., 2010; Herzschuh et al., 2010a,b; Liu et al., 2013; Li and Liu, 2014; Woszczyk et al., 2014).

Recent studies have shown that the TOC content is primarily controlled by aquatic plants, and aquatic plant macrofossils can be well preserved in lake sediments because of the low temperatures in many lakes on the eastern TP (Lin et al., 2002; Aichner et al., 2010a,b; Herzschuh et al., 2010b; Liu et al., 2013; Qiang et al., 2013). $\delta^{13}C_{TOC}$ and carbonate $\delta^{13}C$ values were used to reconstruct variations in primary productivity and lake nutrients, respectively, since the early Holocene in Lake Koucha (Mischke et al., 2008; Herzschuh et al., 2010a,b). Isotopic analyses ($\delta^{13}C$ and $\delta^{15}N$) of fossil aquatic plants (*Potamogeton pectinatus*) have been used to study lake nutrient variability in Lake Koucha and Lake Luanhaizi on the northeast TP (Herzschuh et al., 2010a,b). In addition, a recent study has shown that the $\delta^{13}C$ values of *Potamogeton pectinatus* may have the potential to indicate variations in water depth (Qiang et al., 2013). However, the climatic and environmental significance of the $\delta^{13}C_{TOC}$ and carbonate $\delta^{13}C$ values from these lakes have not been well evaluated until now.

In this study, we present isotopic analyses of aquatic macrophyte remains, bulk carbonate and total organic matter from Lake Koucha on the northeast TP. The aims of this study were to evaluate $\varepsilon_{remains-BC}$ ($\delta^{13}C_{macrophyte\ remains} - \delta^{13}C_{bulk\ carbonate}$) as a potential proxy for macrophyte productivity and its relationship with hydrological and climatic changes in Lake Koucha.

2. Studied sites

Lake Koucha (34.0°N; 97.2°E), situated on the northeastern Tibetan Plateau, is a freshwater lake with a maximum depth of 7.0 m. The lake lies at an elevation of 4530 m on the southern flank of the Bayan Har Mountains, an eastern range of the Tangulashan (Fig. 1). The lake occupies a glacially eroded, wide depression in the southern foreland of the Bayan Har Mountains. The region was entirely covered by a local ice cap during the penultimate glaciation, according to the published data (Zhou and Li, 1998; Heyman et al., 2011). Therefore, glacial drift sediments are widespread around the lake and mainly comprise locally derived erosion products of Triassic black quartz arenites. Large erratic boulders of granite are exposed in places and were likely transported over ~40 km from the central Bayan Har Mountains to the lake site. Several small streams feed the lake. The catchment area of the open-basin lake is approximately 88 km^2, which is only five times the size of the lake itself (18 km^2). A single outflowing stream is one of the upper tributaries of the Yellow River.

The climate is dominated by the Asian monsoon system. Regional instrumental data collected by a weather station over the last 50 years reveal cool temperatures during summer and precipitation mainly occurring between June and September (Maduo weather station at 98.22°E, 34.91°N, 4273 m asl; T_{July} = 7.8 °C, T_{ann} = −4.0 °C, P_{ann} = 321 mm). The mean annual precipitation at a weather station 20 km to the south of the lake (Qingshuihe, 4415 m asl) is 511 mm, and the mean annual temperature is −4.8 °C, according to the published data of Fan et al. (2004). The annual potential evapotranspiration is relatively low, with a value of approximately 700 mm (Ling, 1999).

The lake itself is densely populated by aquatic macrophytes, primarily *Potamogeton pectinatus*, to a depth of 4 m, according to published data (Herzschuh et al., 2009). No submerged macrophytes were observed in water depths exceeding 4 m. In shallower areas with a water depth less than 0.8 m, mats were intermixed with *Batrachium bungei* (a water crowfoot species). The marginal lake vegetation is dominated by emergent Cyperaceae species (Mischke et al., 2008; Herzschuh et al., 2010a,b). The vegetation around Lake Koucha is dominated by dense *Kobresia* meadows. At higher elevations in the nearby Bayan Har Mountains, vegetation grades into sparse alpine vegetation. Areas above ~5000 m are free of vegetation (Herzschuh et al., 2009).

3. Materials and methods

A 41-cm-long core (KCC14-3) was drilled in the northern part of the lake (34.0108°N and 97.2422°E, water depth 2.5 m) in late April 2014 using Livingstone coring equipment. This coring site is near the position of another core (34.0122°N and 97.2404°E) described by Mischke et al. (2008) (Fig. 1). The new core consists of sandy marl with quantities of fossil aquatic plants. The entire core was sub-sampled at continuous 0.5 cm intervals for use in this study.

According to the ^{137}Cs data, the top of core KCC14-3 may have been disturbed when the core was collected because of the large number of aquatic plants living on the lake bottom (Table 1). The total organic carbon of two macrophyte remains (Potamogeton) was measured for radiocarbon dating via acceleration mass spectrometry (AMS) at the Xi'an AMS Center, China (Table 1). The two radiocarbon dating samples were chemically treated according to the standard acid–alkali–acid procedure based on the laboratory's analytic standard pretreatment protocols. The reservoir effect (1812 ± 22 years) due to old carbon was determined from the ^{14}C age of the surface macrophyte remains. The radiocarbon ages of other ^{14}C measurements were then corrected using the corresponding reservoir ages (Table 1). The reservoir-corrected radiocarbon ages of the samples were converted to calendar ages (Table 1) using the software Calib601 (Reimer et al., 2009). The age–depth relationship was established using a linear interpolation between calibrated calendar ages between the depth of 36 cm and the assumed 'zero' age (AD 2013) at the top of the core. Each 1-cm-thick sample represents approximately 16 years of sedimentation, and this sedimentation rate is similar to the sedimentation rate of another 180-cm core (14 years/cm) (Mischke et al., 2008), which was collected near position of the core KCC14-3.

The wet sediments were all freeze-dried. The macrophyte remains were separated from the sedimentary samples for the carbon isotope measurements. The dried sediment without aquatic plants was ground in an agate mortar, sieved through a 200-mesh screen and homogenized. Then, the selected plant samples and portions of the ground sediment were treated with 2 M 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. The dried samples (including plants and sediments) 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 the Institute of Earth Environmental, Chinese Academy of Sciences (IEECAS). The isotopic ratios are reported

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