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Developing inorganic carbon-based radiocarbon chronologies for Holocene lake sediments in arid NW China

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ABSTRACT

Inorganic carbonates are often used to establish radiocarbon (^{14}C) chronologies for lake sediments when terrestrial plant remains (TPR) are rare or when bulk organic matter is insufficient for dating, a problem that is common for many lakes in arid regions. However, the reservoir effect (RE), as well as old carbon contributed from the lakes catchment make it difficult to establish reliable chronologies. Here we present a systematic study of inorganic ^{14}C ages of two lake-sediment sequences, one from a small-enclosed saline lake – Lake Gahai in Qaidam Basin, and the other from a large freshwater lake – Lake Bosten in Xinjiang. Modern dissolved inorganic carbon (DIC) of the lakes, paleo-lake sediments exposed in the catchment, and mollusk shells in core sediments from Lake Gahai were dated to assess the RE and the contribution of pre-aged carbon to the old ages in the cores. We propose a statistical regression to assess more than one RE for the ^{14}C carbonate ages within our sedimentary sequences. Old radiocarbon ages contributed by detrital carbonates were assessed by comparing the ages of mollusk shells with those of carbonates at the same sediment depths. We established the RE of the authigenic component and assessed detrital old carbon contributions to our two sites, and this was used to correct the ^{14}C ages. Based on this approach, we developed age models for both cores, and tested them using ^{210}Pb ages in both cores and TPR-based ^{14}C-ages recovered from Lake Bosten. We further tested our age models by comparing carbonate-based oxygen isotope ($\delta^{18}O$) records from both lakes to an independently-dated regional speleothem $\delta^{18}O$ record. Our results suggest if sedimentary sequences are densely dated and the RE and the contribution of old carbon from detrital carbonates can be ascertained, robust chronological frameworks based on carbonate-based ^{14}C determinations can be established.

1. Introduction

Lacustrine sediments record valuable information about regional environmental changes and human impact during the late Quaternary, provided they are well dated (Yang et al., 2015). Radiocarbon (^{14}C) dating has long been one of the most frequently used dating techniques in establishing a reliable chronology for lake sediments spanning the ~50,000 years (Geyh et al., 1999). Terrestrial plant remains (TPR) are often the best material for ^{14}C dating in lake sediments because they use atmospheric carbon, and therefore contain no old carbon, provided they have not been reworked (Abbott and Stafford, 1996; Geyh et al., 1998; Oswald et al., 2005; Colman et al., 2009; Bertrand et al., 2012; Hou et al., 2012). Bulk or aquatic organic matter is often used for ^{14}C dating in the absence of suitable TPRs, although these can only be reliable if the 'reservoir effect' (RE) is properly assessed (Shen et al., 2005; Henderson et al., 2010; Mischke et al., 2010; Watanabe et al., 2010; Bertrand et al., 2012). Inorganic (calcium carbonate) carbon, including authigenic and biogenic carbonates have been used to date sediments that lack organic carbon, especially for lakes in arid regions, where the vegetation in the catchment is sparse or the aquatic productivity is limited due to high lake water salinity. The

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use of carbonate for ^{14}C dating materials often generates dates that are far older than the true ages (Fontes et al., 1996; Wu et al., 2010; Yang et al., 2010), because of the incorporation of old carbon into the samples from either the dissolved inorganic carbon (DIC) pool of the lake water (the RE for the authigenic component of the carbonate) or from catchment-derived carbonate (the detrital component of the carbonates). Accurate determination of the RE and the old detrital carbonate contribution is therefore essential to establishing an accurate and precise chronology using carbonate-based radiocarbon ages.

A number of studies have examined the RE on ^{14}C ages on bulk, aquatic organic matter and biological remains of aquatic organisms that feed on aquatic material, based on general comparative estimates (Hendy and Hall, 2006; Shishlina et al., 2007, 2012; Zhou et al., 2009; Olsen et al., 2010; Ascough et al., 2010, 2011; Wood et al., 2013; Zhao et al., 2013), calculations based on carbon (C) and nitrogen (N) isotopes (Lanting and van der Plicht, 1998; Cook et al., 2001; Watanabe et al., 2010; Bronk Ramsey et al., 2014), N/C ratios (Bertrand et al., 2012) or models (Soulet et al., 2011; Watanabe et al., 2013; Yu et al., 2007, 2014; Groot et al., 2014; Hart, 2014). However, as inorganic carbon is less frequently dated for radiocarbon estimates, the RE of inorganic carbon dates in lake sediments is not fully understood.

In previous studies of inorganic carbon-based dating, the RE has either not been corrected (Gasse et al., 1991) or been assumed to be constant and estimated either by regression of the dated ages versus the depth of sedimentary cores and then using the intercept on the age axis to represent the RE (Fontes et al., 1996), or by using the age of modern DIC samples (Hou et al., 2012). A chronology is then established by subtracting the intercept of the regression or the modern DIC ages from the radiocarbon age determinations. However, recent researches suggest that the RE may not be constant through time (e.g. Lake Sugan, Zhou et al., 2009; Lake Qinghai, Hou et al., 2012; An et al., 2012; Zhou et al., 2014; Lake Kusai, Liu et al., 2014; Lake Xingyun, Zhou et al., 2015). Thus, the RE of each dated sample remains an unresolved problem for dating both of organic and inorganic carbon, although several approaches to assessing RE have been developed (see Hou et al., 2012). We present a statistical regression method for assessing more than one RE for inorganic ^{14}C ages in one sedimentary sequence by using sediment cores from a saline lake, Lake Gahai in the Qaidam Basin, NE Tibetan Plateau and a freshwater lake, Lake Bosten in Xinjiang, NW China. We aim to use the ^{14}C ages from inorganic carbon to establish chronologies acceptable with this method for continuous Holocene lacustrine sedimentary sequences in arid NW China.

2. Study sites

We investigated two lakes that are located beyond the modern summer monsoon limit in arid NW China (Fig. 1a). One is Lake Gahai, a small-enclosed saline lake (surface area of the lake is ~35 km^2) located in the eastern corner of Qaidam Basin on the northern Tibetan Plateau (Fig. 1b) with no perennial rivers flowing into the lake. Groundwater appears as springs on the northwestern and eastern shores (Fig. 1b). The regional climate is arid with a mean annual precipitation of *c.* 160 mm and a potential evaporation of *c.* 2000 $mm \cdot a^{-1}$ (Zhao et al., 2008). Evaporation is the main mechanism of water loss from the lake resulting in high salinity of the lake water (ca. 91 $g\ L^{-1}$). The pH of the lake water is 8.28 (Chen et al., 2007), with major cations and anions of $Na^+ > K^+ > Mg^{2+} > Ca^{2+}$ and $Cl^- > SO_4^{2-} > CO_3^{2-} > HCO_3^-$. There is a small area of wetland with grass and shrubs to the east of the lake, but vegetation around the lake is sparse and of desertic type (Zhao et al., 2008).

The lake productivity is low, organic matter content in the sediments is less than 3%, and plant remains in the sediments are rare. ^{210}Pb and ^{137}Cs-dated short cores from Lake Gahai suggest a high sedimentation rate (the top 22 cm sediments covers the last 50 years at water depth of 6.4 m in northwest part of the lake, Zhao et al., 2008) and carbonate content, pollen and oxygen and carbon isotopes of ostracod shells suggest the lake is very sensitive to regional paleoclimate change over the late Holocene (Zhao et al., 2008; Li et al., 2012). Lake Gahai has long been a target for drilling with two long cores (DG02: 35 m; DG03: 37 m) drilled on the northern shore of Lake Gahai in 2003 proved to be of Holocene age, but the age control was poor due to lack of organic matter coupled with age reversals (Chen et al., 2007; Cao et al., 2009; Pan and Chen, 2010; He et al., 2014), indicating the difficulty of obtaining a chronology in such lakes in arid NW China.

The other lake is Lake Bosten, a large freshwater lake located in the southeastern part of Yanqi Basin on the south slope of Tianshan Moutains in Xinjiang, NW China (Fig. 1c). It is the largest inland freshwater lake (*c.* 1000 km^2) in China. The lake is in an extremely arid region with mean annual precipitation of 70 mm and annual potential evaporation of *c.* 2000 mm (Huang et al., 2009). The Kaidu River is the major river that recharges the lake in the west, accounting for more than 80% of the total water input. The lake water flows out of the lake through Peacock River (Fig. 1c). The current salinity of the lake water is 1.8 $g\ L^{-1}$ and the pH of the lake water is 8.5. Similar to Lake Gahai, the organic matter content in the sediments is low (1–4%, Wünnemann et al., 2003; Zhang et al., 2010) and terrestrial plant remains are rarely found in the cores. Previous research on sediment cores from this lake has generally employed dating using bulk organic matter or more rarely plant remains (Wünnemann et al., 2003, 2006; Mischke and Wünnemann, 2006; Huang et al., 2009), leading to uncertainties in the resulting age models.

3. Materials and methods

3.1. Lake Gahai (core GHB)

A 14-m long core (GHB) was recovered in May 2008 using a UWITEC drilling platform at a water depth of 11.4 m in Lake Gahai (Fig. 1b). A sand layer at 14 m sediment depth terminated the drilling hole. The sediments above the sand layer are continuous and are greyish clay, with some silt to silty clay (Fig. 2a). The total organic carbon (TOC) in the sediment is lower than 3%, therefore only 1 sample at 55.08 cm contained sufficient plant remains for ^{14}C dating. As a result, we selected 28 carbonates samples at approximately 50 cm intervals to ^{14}C date the inorganic carbon (Fig. 2a). The selected samples were wet-sieved with deionized water through a 360-mesh sieve (44 μm) and the fine fraction was used for AMS ^{14}C dating. 17 fine-grained samples were measured in the AMS ^{14}C lab of Peking University, China and the other 11 samples, together with one sample of plant remains, were dated at Beta Analytic Inc., USA. Mollusk shells found in four of the samples (Fig. 2a) were also dated at Beta Analytic Inc. Both laboratories use the standard AMS ^{14}C dating procedures for dating of carbonate sediments. The conventional half-life of 5568-year is used when calculating ^{14}C ages with the measured percent modern carbon (pMC) value of each sample (Table 1).

Samples of the total dissolved inorganic carbon (DIC) of the lake water were collected from Lake Gahai and two other lakes (Toson and Hurleg) in the catchment (Table 2 and Fig. 3). DIC was precipitated on site as $BaCO_3$ by adding 15 ml of saturated $Ba(OH)_2$ solution to 85 ml of surface water following the method of Kusakabe (2001). Precipitated $BaCO_3$ from the water samples was filtered using cellulose nitrate filter papers, washed several times with deionized water and then transferred into glass vials and