Quaternary Research 84 (2015) 415–422

Contents lists available at ScienceDirect

Quaternary Research

journal homepage: www.elsevier.com/locate/yqres

Late Quaternary carbon cycling responses to environmental change revealed by multi-proxy analyses of a sediment core from an upland lake in southwest China

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ARTICLE INFO

Article history:
Received 19 April 2015
Available online 21 October 2015

Editor: Derek Booth

Keywords:
Carbon isotopes
Carbon cycling
Asian summer monsoon
Last glacial maximum
Lake

ABSTRACT

Stable carbon isotope ($\delta^{13}C$) values of organic matter in lacustrine sediments are commonly used to trace past changes in terrestrial and aquatic carbon cycles. Here we use a high-resolution, well-dated $\delta^{13}C$ record from Lake Tengchongqinghai (TCQH) in southwestern China, together with other proxy indices, to reconstruct the paleolimnological history over the past 18.5 ka. Organic matter in the sediments of Lake TCQH is derived predominately from aquatic macrophytes. The lacustrine primary productivity is closely linked with lake-level changes affected by variations in the strength of the Asian summer monsoon and modified by evapotranspiration. Similar to lake sediments world-wide, a ca. −3‰ shift occurred in the $\delta^{13}C$ values of Lake TCQH in response to the significant increase in atmospheric CO_2 concentration during the last deglaciation. In the Holocene, the availability of dissolved CO_2 in the lake water of Lake TCQH was determined by variations in hydraulic energy: low water turbulence creates a thick, stagnant boundary layer around aquatic plants, which will restrict the rate of CO_2 diffusion and result in more positive $\delta^{13}C$ values of aquatic plants. In contrast, significant water turbulence dramatically reduces the boundary layer thickness leading to more negative $\delta^{13}C$ values of aquatic plants.

Introduction

Despite the small fraction of the Earth's surface occupied by inland waters, they play an important role in the global carbon cycle (Cole et al., 2007; Battin et al., 2009; Tranvik et al., 2009; Dong et al., 2012). In aquatic ecosystems, primary producers generally have a much higher affinity for dissolved CO_2 than for bicarbonate (Rost et al., 2003). Moreover, primary producers differ in their ability to take up dissolved CO_2 or bicarbonate, and these physiological differences may affect their species assemblages and successions given changes in aquatic carbon chemistry (Rost et al., 2003, 2008). The partial pressure of atmospheric carbon dioxide (pCO_2) has increased significantly over the last centuries, from about 280 parts per million by volume (ppmv) in pre-industrial times to the present level of 385 ppmv, as a result of the accelerating combustion of fossil fuels; and it is predicted to double in the coming century (Solomon et al., 2007). Rising pCO_2 has altered both the carbon chemistry and pH of fresh water and is of profound significance for photosynthesis by primary producers. Laboratory studies have revealed that increased pCO_2 will affect the elemental stoichiometry of primary producers, increase primary productivity, and alter the community composition of freshwater ecosystems in the future (Schippers et al., 2004; Verschoor et al., 2013; Verspagen et al., 2014). Therefore, variations in pCO_2 may have played an important role in the evolution of freshwater ecosystems. In addition, the freshwater carbon chemistry is sensitive to climate change (Battarbee et al., 2002). Understanding of the natural long-term changes in the carbon cycle and its impact on ecosystems, however, is hindered by lack of relevant paleoenvironmental records (Meyers and Horie, 1993; Street-Perrott et al., 1997, 2004; Prokopenko et al., 1999).

The transition from the last glacial maximum to the Holocene is a key interval for paleoenvironmental study, including research on the changes of temperature and CO_2 (Prokopenko et al., 1999). The high-resolution CO_2 record from the EPICA Dome C ice core indicates that pCO_2 began to rise from 18 ka, and pCO_2 had increased to 265 ppmv by the beginning of the Holocene and was relatively stable before the industrial revolution (Monnin, 2001; Monnin et al., 2004). Thus, the period from the last glacial maximum onwards is ideal for studying the response of lake carbon cycles and ecosystems to climate change. Stable carbon isotope ($\delta^{13}C$) values contain important information on major biogeochemical processes in lacustrine systems. This information has been used to reconstruct changes in temperature, precipitation, pCO_2, and lacustrine primary productivity, all of which are indirectly linked to the lake carbon cycle (Meyers, 1997; Leng and Marshall, 2004). However, the bulk organic matter content of lake sediments consists of a mixture of organic materials from allochthonous and

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http://dx.doi.org/10.1016/j.yqres.2015.09.004
0033-5894/

autochthonous sources. These diverse sources of organic matter can have different isotopic values and contribute varying and possibly unknown amounts of carbon thereby resulting in misleading bulk organic carbon isotopic signatures. Therefore it may be difficult to evaluate directly the varying environmental influences on the isotopic signature of sedimentary organic matter, and thus other indicators need to be used to identify the organic matter sources and the environmental implications of their $\delta^{13}C$ values.

The Yunnan–Guizhou Plateau, located in southwestern China, is predominantly influenced by the Indian summer monsoon, which can trigger serious floods and droughts. The numerous lakes present across this region are often tectonically derived fault lakes that were formed in the Late Pliocene and the early Quaternary (Shen, 2013). Hence, a comprehensive study of their sedimentary records can provide information regarding climatic and environmental changes from at last the last glacial maximum onwards. Here we present a new, well-dated, high-resolution multi-proxy paleolimnological record from Lake Tengchongqinghai (TCQH) in southwestern China. The record comprises total organic carbon (TOC), total nitrogen (TN), C/N ratio, $\delta^{13}C$ of bulk organic matter, median grain size (Md), dry bulk density and chlorophyll *a*, which together provide new insights into changes in the Indian summer monsoon and its impacts on the regional carbon cycle over the last 18.5 ka.

Regional setting

Lake TCQH (25°07′48″–25°08′6″ N, 98°34′11″–98°34′16″ E; elevation ca. 1885 m) is located in Tengchong County, western Yunnan Province, southwestern China (Fig. 1a). It is a crater lake with an area of 0.25 km^2 and a catchment area of 1.5 km^2. The maximum water depth is 8.1 m and the mean water depth is about 5.2 m. Since Lake TCQH is a hydrologically closed lake, the water balance is controlled primary by precipitation, groundwater and surface runoff from the surrounding catchment. Geologically, the catchment is composed of andesite and basalt. Lake TCQH and the adjacent region experience a subtropical monsoon climate. The mean annual air temperature is ~14.7°C; the mean annual precipitation is ~1425 mm; the rainy season between May and October accounts for 84% of the total mean annual precipitation, and the average annual evaporation is ~1575 mm. The dense terrestrial vegetation in the catchment consists mainly of evergreen *Quercus*, *Castanopsis*, *Lithocarpus* and *Pinus*. Certain basins and slopes in the surrounding area have been used for cultivation. The lake is currently eutrophic and the shallow areas are covered by submerged macrophytes including *Phragmites communis*, *Myriophyllum spicatum* and *Trapaincisa* sp.

Material and methods

Sediment cores and chronology

In July 2010 we recovered an 830-cm-long sediment core (TCQH10-1) from the center of the lake in a water depth of 6.3 m, using an UWITEC platform with a percussion corer (Fig. 1b). The sediment cores were split longitudinally and photographed, and were then subsampled continuously at 1-cm intervals and stored at 4°C prior to analysis. The sediment chronology was established using accelerator mass spectrometry (AMS) ^{14}C dating on 10 terrestrial plant fragments (Zhang et al., 2015). The analyses were performed by the National Isotope Centre, Institute of Geological and Nuclear Sciences Ltd, New Zealand, and by the Beta Analytic Radiocarbon Dating Laboratory. The resulting AMS ^{14}C dates were calibrated using the IntCal13 dataset implemented in R 3.1.0 with default settings for lake sediments at 10-cm intervals (R Development Core Team, 2013; Reimer et al., 2013). The results were then interpolated using a Bayesian model, taking sediment accumulation rates into account, in order to construct the final age-depth model (Blaauw and Andres Christen, 2011). These results indicate that the age of the base of the core is 18.5 cal ka BP (Fig. 2a). The sediment accumulation rate displays a prominent change at ca. 1000 cal yr BP, yielding an average sedimentation rate of 38.5 cm/ka for the period before this and 173.5 cm/ka for the last millennium (Fig. 2b).

Analytical methods

Samples were collected at 2-cm intervals for analysis of dry bulk density, grain size, TOC, TN, C/N ratio, bulk organic matter $\delta^{13}C$, and chlorophyll *a*. The samples were freeze-dried and dry bulk density was measured as dry mass per unit wet volume (Liu et al., 2000).

Grain size analysis was performed using a Malvern MS 2000 laser grain-size analyzer at 2-cm intervals. The subsamples were pretreated with 30% H_2O_2 to remove organic matter and then with 10% HCl to remove carbonates. Subsequently, the samples were rinsed to a pH of

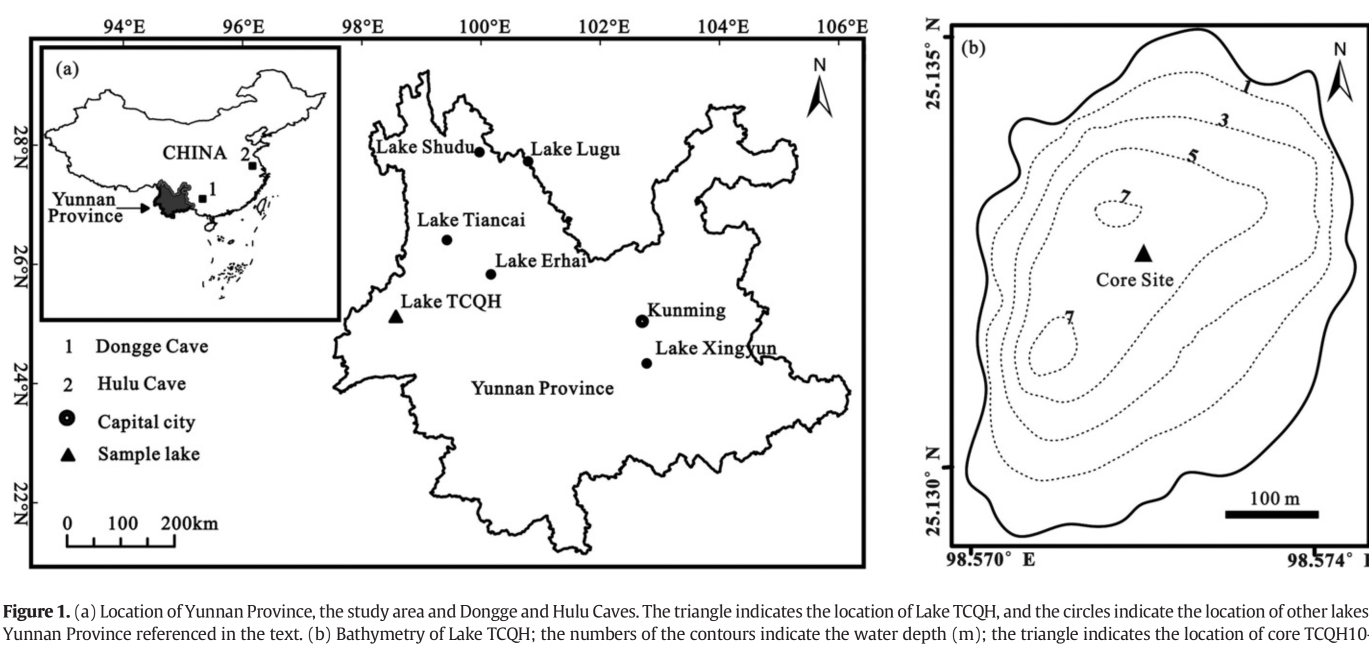

Figure 1. (a) Location of Yunnan Province, the study area and Dongge and Hulu Caves. The triangle indicates the location of Lake TCQH, and the circles indicate the location of other lakes in Yunnan Province referenced in the text. (b) Bathymetry of Lake TCQH; the numbers of the contours indicate the water depth (m); the triangle indicates the location of core TCQH10-1. Scale bar = 100 m.