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Lake Qinghai sediment geochemistry linked to hydroclimate variability since the last glacial

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ABSTRACT

Geochemistry of basin sediments from semi-arid regions is valuable to understand past hydroclimatic changes. Here, we investigate the links of sedimentary geochemistry (Rb, Sr, Ca/Zr, TOC, and $\%CaCO_3$), carbonate mineralogy and ostracod shell $\delta^{18}O$ of Lake Qinghai, a basin proximal to major dust production centers at mid-latitudes of the Northern Hemisphere, to changes in depositional conditions and hydroclimate during the past 32 ka. Surface lacustrine sediments are characterized by low-Rb, high-Sr, low-Rb/Sr, high-$\%CaCO_3$ and high-Ca/Zr values, in contrast to the chemical compositions of eolian loess (high-Rb, low-Sr, high-Rb/Sr, low-$\%CaCO_3$, and low-Ca/Zr). A direct comparison of soluble Ca and Sr in two short cores with instrumental water discharge data suggests that lacustrine precipitates in Lake Qinghai are dominated by authigenic aragonite formed under Ca^{2+}-limited water conditions, and that the accumulation rate of aragonite dominantly depends on solute fluxes into the lake during the rainy seasons (late May to September). Our high-resolution down-core records show that sediments during the last glacial (~32–19.8 ka) had high-Rb, low-Sr, low-$\%CaCO_3$, and low-Ca/Zr, indicating eolian dust (loess) accumulation in a desiccated basin under dry glacial conditions, further supported by grain size and pollen results. This type of sedimentation was maintained during the last deglacial (~19.8–11.5 ka), but interrupted by episodic lacustrine precipitates with high-Sr, high-$\%CaCO_3$, high-Ca/Zr, and low-Rb. At ~11.5 ka, sedimentary Rb/Sr, Ca/Zr, $\%CaCO_3$ and TOC show dramatic and permanent changes, implying an abrupt shift in the atmospheric circulation at the onset of the Holocene in the Lake Qinghai region. Lacustrine precipitates have persisted throughout the Holocene with a maximum during the early to mid-Holocene (~10.5–8.0 ka). Since ~8.0 ka, the gradual and significant decreases in aragonite and Sr accumulations in tandem with increasing dust deposit and more positive ostracod $\delta^{18}O$ may be linked to a weakening of Asian summer monsoons during the mid-to-late Holocene. Overall, our records appear to show a high sensitivity of sediment development and geochemistry in Lake Qinghai to the regional hydroclimate changes since the last glacial.

1. Introduction

Dust deposition plays a significant role in transporting exogenous materials to lacustrine sediments, in particular to lake systems located at mid-latitudes of the northern hemisphere (e.g. Andreae, 1996; Dean, 1997; Lawrence and Neff, 2009; Wan et al., 2012). When dust compositions remain stable and are different from those of the catchment, changes in dust fluxes of various provenances should affect lake sediment chemistry (e.g. Guerzoni et al., 1999; Ganor et al., 2003; Jin et al., 2009; Mulitza et al., 2010). Determining compositions of dust and temporary changes in the dust fluxes to the basin of interest is essential (1) to understand sediment chemistry, (2) to extract information contained in the sediments, and (3) to reconstruct the paleoenvironment from various proxies of sediments. Therefore, down-core lacustrine sediment geochemistry may be used to infer variations of dust budget in the past, which could be potentially linked to the regional environmental history. This study aims to investigate a suite of

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sedimentary geochemistry tracers in Lake Qinghai and their responses to hydroclimate changes during the last 32 ka.

Owing to its unique geological and climatic settings (Fig. 1a), Lake Qinghai has attracted many studies for paleoclimatic and ecosystem reconstructions (e.g. Lister et al., 1991; Shen et al., 2005; Ji et al., 2005; An et al., 2012; Fu et al., 2013; Liu et al., 2014; Thomas et al., 2014), and is one of most intensively investigated lake systems (see the reviews by Colman et al. (2007) and Henderson and Holmes (2009)). Previous studies have provided valuable information about climate changes and their responses to the interplay between the northern Westerlies and Eastern Asian or Indian summer monsoons during the last 16 ka. For example, measurements of pollen, total organic carbon (TOC), grain size, carbonate content (%$CaCO_3$) and ostracod shell stable isotopes for sediment cores QH85-14 (e.g. Kelts et al., 1989; Lister et al., 1991) and QH2000 (Liu et al., 2003; Shen et al., 2005) suggested a warming in Lake Qinghai starting around 14.5 ka (corresponding to Bølling warming in Greenland), followed by a brief cold reversal. These studies showed that the maximum warming occurred at ~10.0 ka, and remained warmer than the present until ~4.0 ka. Based on grain size, TOC and %$CaCO_3$ proxies from core 1Fs, An et al. (2012) suggested a dry condition predominantly controlled by the northern Westerlies during the Last Glacial Maximum (LGM) with greater westerly influence, and much wetter conditions during the early Holocene which was attributed to a greater influence of the Indian and Eastern Asian summer monsoons. Despite these efforts invested so far, past hydrological and depositional conditions of Lake Qinghai remain poorly constrained, limiting our understanding of sediment proxies and their hydroclimatic implications.

Because of the amplification effect at high elevations (Liu et al., 2009; Diffenbaugh et al., 2012), Lake Qinghai, located at ~3200 m above sea level (m a.s.l.), is particularly sensitive to hydroclimate changes. Today, hydroclimate at Lake Qinghai is mainly affected by the convergence of the northern Westerlies and monsoonal-dominated climate regimes (Fig. 1a). Another advantage is that the hydrologically-closed drainage is minimally disturbed by anthropogenic activities, making the sediments in this lake ideal to investigate geochemistry changes in response to natural processes including moisture sources to the lake and hydroclimate changes affecting the region (Fig. 1b).

As a huge water body located at the midpoint of the modern "airborne dust corridor" (Fig. 1a) (Liu et al., 2008), Lake Qinghai receives materials from catchment weathering and airborne dust inputs, both of which are closely linked to hydroclimatic conditions. A significant contribution of dust to modern Lake Qinghai is strongly supported by modeling (Jin et al., 2009) and field measurements of seasonal river water chemistry (Jin et al., 2011) and eolian dust (Wan et al., 2012). Furthermore, yellow–brown sediments at some periods in core 14B in Lake Qinghai have been described as underwater loess deposition (Lister et al., 1991). Sediments of eolian origin have also been supported by more recent works on color, grain size and morphology of sediments (An et al., 2012; Fu et al., 2013). Detailed knowledge of relative contributions of dust to Lake Qinghai is crucial for understanding (1) impacts of mineral aerosols on sediment properties, (2) proxy implications for hydroclimatic conditions, and (3) interactions between the Indian and East Asian summer monsoons and the Westerlies in the past. However, we have limited information about the flux and geochemistry of dust into Lake Qinghai, limiting our understanding of the relationship between dust deposition and hydroclimate changes in the past. We fill in this critical gap in this study.

An 18.3 m long high-resolution sediment core (1Fs) provides a unique opportunity to gain insight into dust contributions to Lake Qinghai during last glacial-interglacial cycle. This work builds on previous work by An et al. (2012) who developed an age model (cf. Zhou et al., 2014) and initial climatic reconstruction from the 1Fs. In order to identify relative contributions of eolian dust versus lacustrine precipitates to Lake Qinghai sediments under different depositional and hydroclimatic conditions, we have focused on a few geochemical tracers including Rb, Sr, and Ca/Zr for recent lake and river sediments and catchment loess, and for sediments from the core 1Fs. In the context of existing sedimentological and biological records, we then discuss changes of dust input and lacustrine precipitates in relation to the regional hydroclimate dynamics since the last glacial.

2. Hydrological and geological settings of the Lake Qinghai catchment

Lake Qinghai has been a hydrologically closed drainage system since ~36 ka (Chen et al., 1990). During the last century, the surface area of the lake shrank from 4980 km^2 to ~4260 km^2 in 2006 (Li et al., 2007). The modern lake is located at an altitude of 3194 m a.s.l., with a water volume of 71.6 km^3 and a catchment area of about 29,660 km^2. Today's lake water has an average salinity of 15.5 g/L and pH of 9.06. Currently, the lake is Ca^{2+}-limited and is saturated with respect to carbonates. Lake sediment is dominated by silty clays and authigenic carbonates (aragonite and calcite).

The lake is currently fed by five major rivers including Buha, Shaliu, Hargai, Quanji, and Heima Rivers (Fig. 1b), with a total annul water discharge of ~1.56×10^9 m^3 (Li et al., 2007). The main runoff supply today is from the Buha River from the west, which feeds annually ~50% of the total runoff and ~70% of the total sand loading to the lake. The average annual water discharge was ~0.94×10^9 m^3 in 1959–2013 at the Buha Hydrology Station, with ~85% occurring during monsoon season (late May to September). By comparison, the annual water discharge of the Shaliu River at Gangcha County is about one third of discharge from the Buha River.

Within the Lake Qinghai catchment, the average annual air temperature was ~1.2 °C from 1951 to 2005. The annual mean precipitation was 383 mm, about 1/4–1/3 of the evaporation, during 1959–2011 (Jin et al., 2011). The lake develops a thermal stratification (hypolimnion <6 °C, epilimnion 12–15 °C) during summer, and is frozen from late October to April (Yan et al., 2002).

The Lake Qinghai catchment comprises of hummocky terrains of predominantly late Paleozoic marine limestone and sandstones, Triassic granites, Mesozoic diorite and granodiorite with minor late Cambrian phyllite and gneiss (LIGCAS, 1979). About one fifth of the catchment is overlain by Quaternary to recent loess and alluvial/lacustrine sediments surrounding the lake and its contributing rivers.

3. Samples and analyses

3.1. Surface sediment and loess samples

We collected 17 surface lake sediments, 24 local loess, and 25 suspended sediment samples from five largest rivers within the Lake Qinghai catchment. Suspended sediments were sampled by passing water during monsoon seasons through 0.2 μm nylon filters. Samples of fresh loess and lake surface sediment were collected from extensive sites within the catchment (Fig. 1b).

3.2. Core sediments and age models

The 18.3-m-long 1Fs core was composited the cores 1F with 1A based on the correlations of lithological and proxy data (An et al., 2012). Both 1F and 1A were retrieved from the same site at the deposition-center (36°48′40.7″N, 100°08′13.5″E, 3194 m a.s.l.) of the southwestern sub-basin in Lake Qinghai in 2005 using the ICDP