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Glacial activity reflected in a continuous lacustrine record since the early Holocene from the proglacial Laigu Lake on the southeastern Tibetan Plateau

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ABSTRACT

The southeastern Tibetan Plateau is an important area of monsoonal maritime glaciation, and it serves as a watershed for several major Asian rivers, including the Brahmaputra River and the Lantsang River. Glacial activity is sensitive to climate change in this area. However, due to high annual ablation and accumulation in this region, ice cores over long time scales are difficult to retrieve. In addition, reconstructed glacial activity from moraine dates is usually discontinuous. Here, we use a sediment core retrieved from Laigu Lake, which is a proglacial lake located in the headwaters of the Parlung Zangbo River, the largest tributary of the Brahmaputra River, to reflect glacial activities over the last ~8000 years in this area. Samples of the sediment core were analyzed for magnetic susceptibility, XRF (X-ray florescence) scanned elemental concentration and grain size. The results indicated that the magnetic susceptibility and CPS (peak area counts per second) of strontium (Sr) could be used as proxies for glacial activity. The CPS of Sr and the magnetic susceptibility were lower and the glacial activity was weak before 4.3 cal ka BP. Expansion of the glaciers in this area began from 4.3 cal ka BP and continued to develop after ~3.3 cal ka BP. From 2.2 cal ka BP to 1.6 cal ka BP, the glaciers retreated substantially, followed by another development period until the onset of modern global warming. Based on our findings and other climate records, we concluded that glacial activity in the southeastern Tibetan Plateau areas was mainly influenced by Northern Hemisphere temperatures and summer insolation over a sub-orbital time scale, but did not respond to the Indian monsoon.

1. Introduction

Glaciers are important components of the cryosphere and provide substantial feedback regarding climate variability by changing the surface energy balance and serving as sensors of climate change (Lemke et al., 2007). Among many factors, summer temperatures and insolation are believed to be the two most important factors affecting glacial activity at a hemispheric scale, which is supported by the good agreement between glacial expansion trends and declines of summer temperature and insolation in the Northern Hemisphere since the middle Holocene (Masson-Delmotte et al., 2013). However, spatial differences exist in glacial history records, especially over shorter time scales, which cannot be explained by summer temperatures and insolation alone (Jansen et al., 2007 and Masson-Delmotte et al., 2013).

The Tibetan Plateau (TP) and its surrounding mountains comprise the largest area covered by glaciers other than the polar region (Yao et al., 2012). Complicated atmospheric circulation patterns result in different responses of glaciers to climate change across this area. In recent decades, most glaciers on the plateau are shrinking because of climatic warming, whereas some glaciers in Karakorum and eastern Pamir are stable or expanding, which is believed to be a result of enhanced winter precipitation recharge from the westerlies (Yao et al., 2012). In the mid-late Holocene, the glaciers on the TP generally expanded, coinciding with a decline of summer temperatures and solar radiation (Yi et al., 2008). However, studies on the southern slope of Himalaya show that glaciers advanced during early and middle Holocene and responded to monsoonal precipitation (e.g., Phillips et al., 2000, Gayer et al., 2006 and Finkel et al., 2003). Owen (2009) also argues that glacial activities in the Tibet monsoonal area were controlled by the Indian monsoon.

Previously, Holocene glacier histories on the TP have often been reconstructed using moraine dates, which reflect the direct changes of glacier area and intensity (Owen, 2009 and Yi et al., 2008). However, these reconstructions are always discontinuous because moraines

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represent the maximum extent of the glacial advance. Discontinuous records limit the understanding of the relationship between glacial activities and climate change. Therefore, combining this approach with other methods of reconstructing continuous glacier records is indispensable (Jansen et al., 2007). At high latitudes or altitude zones, glaciers erode land surfaces as they advance and leave proglacial lakes due to their retreat. Because proglacial lakes are directly recharged by meltwater from glaciers, the sediments of these types of lakes are widely used for qualitative and even semi-quantitative glacier change research by using proxies such as grain size and magnetic susceptibility. These proxies are effective for indicating upstream glacier activity and have greatly improved continuous studies of glacial activities during the Holocene (e.g., Matthews et al., 2000 and Stansell et al., 2014).

The Indian monsoon has a profound influence on the regional climate of the southeastern TP because it brings substantial precipitation. More than 6000 temperate maritime glaciers are present in this area, covering a total area of approximately 9500 km^2 (Shi et al., 2008). Many of these glaciers are distributed in the Parlung Zangbo River catchment, which is the largest tributary of the Brahmaputra River. The glaciers in this area are characterized by intense annual ablation and accumulation, which makes it difficult to elucidate the relationship between precipitation/temperature and glacier mass balance compared to other regions (Shi et al., 2008 and Yang et al., 2013). These glaciers are quickly retreating due to global warming. For example, the annual mass balance of the Parlung No. 94 glacier experienced approximately −0.9 m water equivalent from 2005 to 2010 (Yang et al., 2013). Consequently, proglacial lakes increase in amount and area because of extensive amounts of glacial meltwater (Xin et al., 2009). Because of difficulties to obtain a long-term ice core record and the absence of moraine dates between the last deglaciation and neoglaciation, knowledge of Holocene glacier activity in this region is sparse. However, research on proglacial lake sediments makes it possible to reconstruct a continuous and long-term record of glacial activity through the Holocene. In this study, based on an investigation of a lake sediment core from Laigu Lake, we try to reconstruct a continuous record reflecting glacial activity in this catchment. Further, we compare it to other glacial activity records in the southeastern Tibetan Plateau areas to discuss responses of glacial activities to climate change in this area.

2. Study area

The study area is situated at the southeastern margin of the TP (Fig. 1a). Laigu Lake is located in the source area of the Parlung Zangbo River, on the northern slope of Kangri Gampo, which is in the eastern Nyainqentanglha ranges. This lake consists of two individual proglacial sub-lakes, which are separated by moraines (Fig. 1b). The eastern lake is at 3978 m asl and is approximately 60 m higher than the other lake, with a total area of 2.67 × 10^6 m^2 based on LandSat ETM images. Based on our field investigation, the maximum depth of the lake is 33.5 m and the lake water pH is approximately 8.6, with specific conductivity of 130 μS/cm (Fig. 1c). Meltwater runoff is derived from the Zuoqiupu glacier and Xirinongpu glacier, the latter flowing first through Cuocha Lake and Xuena Lake, then flowing into and recharging the lake from the southeast where an alluvial fan exists at the lake inlet. There is a distance of 7 km between the lake and the Zuoqiupu glacier terminal, and meltwater runoff is the only inflow supply. An outflow also exists on the northwestern part of the east lake, where it is dammed by glacial moraines. The outflowing water enters the Parlung Zangbo River through Ranwu Lake. The lake is frozen during winter. In summer, the lake water is turbid with a strong outflow, whereas it is clear and the outflow is weak in the fall.

Observation data from a meteorological station (28°39′N, 97°28′E; 2327 m asl) in Zayu County from 1991 to 2000 indicated that most precipitation fell between March and October every year (Yang et al., 2013). An automatic weather station at 4600 m asl in the study area recorded a multi-year average temperature of −1.7 °C. The highest daily mean temperature was approximately 9 °C in August, and the lowest was −14 °C in January. The annual average precipitation was 552 mm (340–660 mm), and the monthly precipitation exhibited a double-peak pattern, most of which fell in the spring and summer (Ju et al., 2015).

Alpine middle lobe rhododendron shrubs are distributed in the catchment between 3900 m and 4100 m asl, and alpine bush and meadow grow above 4100 m asl, including *Rhododendron nivale*, *Salix faxionianoides* and other high-altitude plants (Zhang et al., 1988). Although calcareous slate is widely spread in the catchment, biotite monzonite granite exists as the main bedrock along the front edge of the glaciers, with primary minerals of plagioclase, potash feldspar and biotite and accessory minerals of titanite, magnetite and zircon (Chen et al., 1994) (Fig. 1b).

3. Materials and methods

In February 2012, a 3.82-m sediment core (LGLC12-1) was retrieved in the east lake on the frozen surface by using a piston corer. The water depth at the core site (29°18.5′N, 96°50′E) is 33.5 m (Fig. 1c). The core was cut lengthwise and one half was sampled in 1-cm intervals in the lab. This core is dense with low water content. The top 10-cm section of the core is dominated by sandy silt, and most parts of the core consist of silt. AMS ^{14}C dating of bulk organic carbon was performed on 11 samples at Beta Analytic Inc. (Miami, FL, US). The variation of the LGLC12-1 core's sediment rate with depth was modeled by Bacon software (version 2.2) using a Bayesian age-depth model (Blaauw and Christen, 2011 and R Core Team, 2014). The modeling was based on 11 radiocarbon ages (conventional age) of bulk organic matter that were calibrated using the IntCal 13 Database (Reimer et al., 2013). An age-depth relationship was then estimated (Fig. 2).

The total inorganic carbon (TIC) was analyzed every 2 cm on a Shimadzu TOC-V$_{CPH}$ carbon analyzer, and the results were presented as a mass percentage. After removing organic carbon and carbonate by H_2O_2 and HCl, the grain size was determined at 2-cm intervals using a Mastersizer 2000 laser particle sizer (detection size range: 0.02–2000 μm), at the Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences. The grain size data were processed using GRADISTAT-Version 8.0 software (Blott and Pye, 2001).

The other half of the core was scanned on an Itrax core scanner at the Key Laboratory of Tibetan Environmental Changes and Land Surface Processes, Institute of Tibetan Plateau Research, Chinese Academy of Sciences. Nondestructive X-ray fluorescence (XRF) was measured using a molybdenum tube under a voltage of 30 kV and a current of 30 mA. The scanning step was 0.3 mm with a dwell time of 12 s. Detailed descriptions of the elements that can be detected and the detection limit for each element have been presented elsewhere (e.g., Croudace et al., 2006). The elemental concentrations from the XRF scanner are presented as CPS (peak area counts per second). The principle component analysis (PCA) was performed on the element CPS by using C2 software (Juggins, 2007).

Magnetic measurements were performed on a Bartington MS3 susceptibility meter attached to the Itrax core scanner at an interval of 4 mm. Magnetic susceptibility was represented as volume-specific SI units.

4. Results

4.1. Chronology

All radiocarbon ages are listed in Table 1. The oldest conventional age is 8500 ± 30 years BP (at 340 cm depth). Based on the Bacon model results, the estimated age of the surface layer is 2792 years BP. Taking the retrieval time of the core into account (2012), there is a difference of 2852 years between the Bacon model age and actual age of the surface layer. We assume that the carbon reservoir age of