Glacier fluctuations of Muztag Ata and temperature changes during the Late Holocene in westernmost Tibetan Plateau, based on glaciolacustrine sediment records

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Abstract Late Holocene glacial variations of Muztag Ata in Pamir Mountains (westernmost Tibetan Plateau) were studied based on the analysis of grainsize, magnetic susceptibility, elements (Zr, Zr/Rb, Rb/Sr) from an 8.3-m long distal glaciolacustrine sediment core of Kalakuli Lake. High silt and Zr content, Zr/Rb ratio and magnetic susceptibility values, and low clay content and Rb/Sr ratio are used to indicate the glacier advance, while low silt and Zr content, Zr/Rb ratio and magnetic susceptibility values, and high clay content and Rb/Sr ratio are used to reflect the glacier retreat. Our results show that there are four glacier expansion episodes occurring in 4200-3800 cal yr BP, 2950-2300 cal yr BP, 1700-1070 cal yr BP, and 570-100 cal yr BP, and four glacial retreat periods of 3800-2950 cal yr BP, 2300-1700 cal yr BP, 1150-570 cal yr BP, and 100 cal yr BP-present. The four glacier expansion episodes are generally in agreement with the glacial activities indicted by ^{10}Be terrestrial cosmogenic nuclide surface-exposure dating of boulders on the moraines at nearby Muztag Ata and Kongur Shan, as well as temporally coincident with the Late Holocene ice-rafting events in the North Atlantic (i.e. Bond events 0 to 3). Over the last 2000 years, our reconstructed glacial variations are in temporal agreement with reconstructed temperature from China and the Northern Hemisphere, i.e., glacial advance responding to low temperature and glacial retreat to high temperature, indicating that glacial variations at centennial time scales in western Tibetan Plateau are very sensitive to temperature.

Keywords Glaciolacustrine sediment, Westernmost Tibetan Plateau, Glacier variation, Kalakuli Lake, Late Holocene, temperature

1. Introduction

The Tibetan Plateau is assumed to sensitively respond to regional and global climate change [*Prell and Kutzbach*, 1992; *Zhisheng et al.*, 2001], accordingly the on-going glaciers retreats on the Tibetan Plateau were explained by global warming [*Gardelle et al.*, 2013; *Kääb et al.*, 2012; *Khromova et al.*, 2006; *Mölg et al.*, 2013; *Yao et al.*, 2012]. Therefore, studying the past glacier variations on the Tibetan Plateau is very important to understand the responses to regional and global climate change. In particular, the westernmost Tibetan Plateau is influenced by Asian monsoons in the east, the Westerlies in the west, and the natural orographic barrier by the Pamir-Karakoam-Himalaya mountain ranges [*Bookhagen and Burbank*, 2010]. Conventionally, the reconstructions of the past glacier variations have been based mostly on the dating of moraine-ridge sequences and on moraine-stratigraphic studies [*Grove*, 1988; *Patzelt*, 1974]. This approach was widely used in many studies in the monsoon-influenced regions of Tibetan Plateau [*Lehmkuhl et al.*, 1998; *Owen et al.*, 1997; *Owen et al.*, 1998; *Owen et al.*, 2003a; *Owen et al.*, 2003b; *Owen et al.*, 2005; *Owen*, 2009; *Sharma and Owen*, 1996]. Recently, the well-preserved moraine successions have also been reconstructed in Muztag Ata and Kongur Shan, and in Central Karakoram which receive their most precipitation from westerly air masses [*Derbyshire and Owen*, 1997; *Seong et al.*, 2007; *Seong et al.*, 2009]. However, the moraine-stratigraphic approach is impossible to obtain continuous and high-resolution glacier records. In the late 1970s and 1980s sediments in lakes located downstream from glaciers was used to obtain not only continuous, but also high-resolution glacial records of the Holocene [*Karlén*, 1976; 1981; 1988; *Leonard*, 1986a; b]. Thus, the Holocene glacial variations recorded from distal (downstream) glaciolacustrine sediment cores in both Europe and North America have been well obtained [*Dahl et al.*, 2002; *Dahl et al.*, 2003; *Leonard and Reasoner*, 1999; *Lie et al.*, 2003a; b; *Lie et al.*, 2004; *Matthews*, 2005; *Matthews et al.*, 2005; *Matthews and Dresser*, 2008; *Nesje*, 1992; *Nesje et al.*, 2000; *Nesje et al.*, 2001], but this approach is rarely used to reconstruct the Holocene variations in the Tibetan Plateau. Therefore, the main objectives of this paper are (1) to set up a continuous record of late Holocene glacial variations in Muztag Ata of westernmost Tibet based on distal glaciolacustrine sediments in Kalakuli lake; (2) to compare our results with other records to obtain an supra-regional view on late Holocene glacier development; and (3) to discuss the relationship between the temperature variations and glacial activities at centennial time scales in the westernmost Tibetan Plateau during late Holocene.

2. Study area

Kalakuli Lake (N38°25.83′-38°27.57′, E 75°02.27′-75°04.17′, 3645 m a.s.l.) is located in the Pamir Mountains, which connects the Tibetan Plateau with further Central Asian Mountain ranges (Fig.1). Its area is about 10 km^2. It has a shallow lake basin with an average water depth of 15 m and a maximum depth of 20 m. Kalakuli Lake lies 20 km downstream from the glaciers on the southern flank of the Muztag Ata massif (7546 m a.s.l.). The lake receives glacial meltwater from Muztag Ata massif, and has a small outflow, at its northern margin, to Kangxiwa River (Fig.1).

The 49-year (1961-2009) meteorological data from Tashikuergan (37.77° N, 75.23° E;

3100 m a.s.l), about 75 km to the south from Kalakuli Lake, west of Kusai Lake from Lake, indicate the mean annual temperature is 0.7 °C and the mean annual precipitation is 127 mm. The highest precipitation occurs in spring (March to May) as a result of the penetration of the midlatitude westerlies into the region (Miehe et al., 2001). Summer precipitation, which could be associated with the south Asian monsoon, accounts for <30% of the annual total [*Barry and Chorley*, 2003].

3. Materials and methods

During October 2008, we collected two long sediment cores from the central part of Kalakuli Lake at a water depth of 16.0 m using UWITEC coring equipment (Fig. 1; N38°26.381′, E75°03.435′). Magnetic susceptibility (MS) of two long cores was scanned with 2-cm resolution at Nanjing Institute of Geography and limnology, Chinese Academy of Sciences (NIGLAS-CAS), using a Bartington MS2C loop sensor with a loop diameter of 10 cm. MS results in standard units, SI, are given in 10^{-6}. An 8.30 m long composite sediment core was constructed by MS correlations of the two long cores, in order to ensure that the core is continuous and no overlap exists.

Radiocarbon dates were obtained on organic matter from seventeen samples using accelerated mass spectroscopy (AMS). Eight measurements were carried out at National Isotope Centre, Institute of Geological and Nuclear Sciences Ltd (GNS Science), New Zealand, and nine at Beta Analytic Inc..

Non-destructive X-ray fluorescence (XRF) measurements on split core surfaces at 1 cm resolution were performed with an Avaatech XRF Core Scanner [*Richter et al.*, 2006] at Alfred Wegener Institute for Polar and Marine Research in Bremerhaven, Germany. The elements Al, Si, P, S, Cl, K, Ca, Ti, Cr, Fe, Mn, Co, and Rh were measured at an X-ray voltage of 10kV, while the elements Zn, Ga, Br, Rb, Sr, Y, Zr, Au, Pb, and Bi at an X-ray voltage of 30kV. All results are reported in counts per second (cps). As XRF core scanning data is considered to be semi-quantitative, elemental ratios have been used rather than direct counts [*Richter et al.*, 2006; *Weltje and Tjallingii*, 2008].

For grainsize determinations the samples were pretreated with 10-20 ml of 10% H_2O_2 to remove organic matter, washed with 10% HCl to remove carbonates, rinsed with deionized water, and then treated with 10 ml of 0.05 M $(NaPO_3)_6$ on an ultrasonic vibrator for 10 min to facilitate dispersion. Grainsize distributions between 0.02 μm and 2000 μm were determined using a Malvern Mastersizer 2000 analyzer.

Samples for magnetic susceptibility measurement taken from 2 cm intervals were oven-dried below 40 °C to prevent possible alteration of the magnetic properties of the sediment, and packed into 10 cm^3 plastic boxes, then determined in volume specific SI units normalized for sample mass using a Bartington MS2 susceptibility meter. Measurements were repeated at least 3 times in order to test their reproducibility.

4. Results

4.1. Chronology

The seventeen radiocarbon ages show a general linear correlation, confirming a continuous sediment record. Previous studies have shown that the dissolved inorganic carbon (DIC) in melt water from glaciers could easily lead to older radiocarbon dates in lake sediments, which is so-called the “Reservoir Effect” [*Doran et al.*, 1994; *Doran et al.*, 1999; *Squyres et al.*, 1991]. Based on the ^{210}Pb/^{137}Cs dating results [*Yao*, 2011], the 0 a BP (1950 A.D.) appears at ca. 10.5 cm, where 1880 a BP was inferred from the extrapolation of the upper two radiocarbon dates. Here, we assume a constant “Reservoir Effect” as 1880 years and corrected all the radiocarbon dates before calibration (Table. 1, Fig. 2A). The calibration and age-depth model were constructed using the recently developed Bayesian method [*Blaauw and Christen*, 2011], which taking the accumulation rates into account. The model was carried out the default settings for lake sediments with 5-cm resolution, and calibrated using IntCal09 dataset [*Reimer et al.*, 2009] (Fig. 2B).

4.2. Grainsize

Almost no changes of grain-size variations are visible from visual inspection of the core. The sediment consists of clayey silt with silt varying from 48% to 90% with an average of 78%. The variation of clay percentage is opposite to that of silt throughout the core (Fig.3A, B). Sand fraction only accounts for 2.5%, but can reach 20-30% in some levels.

4.3. Magnetic susceptibility

Values for MS vary between 22.9 and 38.7× 10-6 SI (Fig.3C). MS starts to decrease and reaches its minimum values at depth of ca. 4.8 m. Maxima values in MS occur at 2.8 m. Then the MS shows a decreasing trend between 2.8 and 0 m. The variation of MS is in parallel with that of silt, i.e., high values of MS corresponds to high content of silt (Fig.3B and C).

4.4. Zr, Zr/Rb, and Rb/Sr

The variations of Zr content and Zr/Rb ratio are in parallel with these of silt content and MS values (Fig.3B, C, D, and E), but show an opposite trend to variations of clay content (Fig. 3A, D, and E). Conversely, high Rb/Sr ratio corresponds to low MS values and low silt content, but to high clay content (Fig.3 A, B, C, and E).

5. Discussion

5.1. Proxy interpretation for glacier activity

Grain-size variations are indicators of glacier activity, because glacially eroded and downstream transported particles produce characteristic signatures in glaciolacustrine sediments [*Boulton*, 1978; *Matthews et al.*, 2000; *Matthews et al.*, 2005; *Nesje et al.*, 2001]. In particular, abrasion by wet-based glaciers can produce abundant silt-sized particles in times of glacier advances [*Boulton*, 1978; *Drewry and Drewry*, 1986; *Haldorsen*, 1981; *Matthews et al.*, 2000; *Matthews et al.*, 2005].Although mean or median grain size variations of glaciolacustrine sediments were also used as indicator for glacier activity [*Leemann and Niessen*, 1994a; b; *Souch*, 1994], taking the silt fractions as proxy for glacier activity is more reasonable as it is of direct glacigenic origin [*Matthews et al.*, 2000; *Matthews et al.*, 2005; *Nesje et al.*, 2001]. Accordingly, we use high content of silt fractions in sediments of Kalakuli Lake to reflect the glacial advance of Muztag Ata, and low content of silt fractions to indicate the glacier retreat.

Magnetic susceptibility of lake sediments is usually used to indicate the erosion and transport of clastic sediments in lake catchments [*Snowball and Thompson*, 1990; *Snowball et al.*, 1999]. In lakes without non-glacial inputs, increased surface runoff caused by rainfall at warm and humid conditions will lead to more clastic materials, and thus result in high magnetic susceptibility values[*Karlén and Matthews*, 1992]. If the minerogenic component is of glacigenic origin, magnetic susceptibility should therefore prove a useful index of glacier activity [*Karlén and Matthews*, 1992]. A study of sediment from nine Norwegian glaciers shows a strong positive correlation between glacier size and calculated sediment transport in proglacial rivers [*Roland and Haakensen*, 1985]. Therefore, relatively high magnetic susceptibility values should correspond with relatively large glaciers [*Matthews et al.*, 2000; *Matthews et al.*, 2005; *Nesje et al.*, 2001].

Zirconium is enriched in medium to coarse silts and is associated with heavy minerals like zircon [*Dypvik and Harris*, 2001; *Fralick and Kronberg*, 1997]. Accordingly, it traces the abundance of relatively coarse, sandy siliciclastic materials consisting of clay minerals and micas [*Dypvik and Harris*, 2001; *Heymann et al.*, 2013; *Kylander et al.*, 2011]. Rb, in contrast, is abundant in clay minerals that dominate the fine grained, siliciclastic material. Accordingly, the Zr/Rb-ratio traces grainsize changes with Zr/Rb-ratios indicating coarse-grained material and low Zr/Rb ratios indicating fine-grained material [*Dypvik and Harris*, 2001; *Heymann et al.*, 2013; *Kylander et al.*, 2011]. On average the sand fraction in Kalakuli Lake sediment core sums up to only 2.5%. Accordingly, the Zr/Rb-ratio may reflect relative changes in the silt vs. the clay fraction and thus glacier activity with high ratios tracing glacier advance. Due to the substitution of Sr for Ca in the carbonate lattice, Sr is normally associated with in-lake precipitation of carbonates such as calcite and aragonite [*Dean and Arthur*, 1998; *Hammer et al.*, 1990]. The carbonate precipitation is mainly controlled by evaporation and temperature. High evaporation or warmer temperature may lead to high carbonate content. However, in the glaciolacustrine context, glacier retreat caused by high temperature will result in fresh glacial meltwater which is unfavorable to carbonate precipitation. Low temperature during a glacier advance, on the other hand, also lead to reduced carbonate precipitation. Therefore, the Rb/Sr-ratio depends on the amount of Rb which is strongly linked to the clay mineral assemblage. Accordingly, low Rb/Sr ratios are related to a strong input of silt indicating glacier advance.

5.2. The late Holocene glacier variations

Based on the variations of grainsize, MS, Zr content, Zr/Rb ratios, and Rb/Sr ratios in the sediment core of Kalakuli Lake, we can reconstruct the Late Holocene glacier fluctuations of Muztag Ata (Fig.3). Four periods, 4200-3800 cal yr BP, 2950-2300 cal yr BP, 1700-1070 cal yr BP, and 570-100 cal yr BP, are characterized by low content of clay fractions, high content of Zr and silt fractions, high magnetic susceptibility values, high Zr/Rb ratio, and low Rb/Sr ratio, which reveals that the glacier advanced during these four periods. These four glacial advances, within dating errors, are generally in agreement with the glacial activities indicted by ^{10}Be terrestrial cosmogenic nuclide surface-exposure dating of boulders on the moraines in Muztag Ata and Kongur Shan of western Tibetan Plateau [*Seong et al.*, 2009]. Their results show that the glaciers advanced at ca. 4.2 ± 0.3 ka, 3.3 ± 0.6 ka, 1.4 ± 0.1ka, and a few hundred years ago during the late Holocene [*Seong et al.*, 2009]. Furthermore, the four glacier expansion episodes revealed both by glaciolacustrine sediment (this study) and by moraine successions, temporally coincide with the Late Holocene ice-rafting events in the North Atlantic (i.e. Bond events 0 to 3) [*Bond et al.*, 2001]. The content of clay fractions and Rb/Sr ratio are high and content of Zr and silt fractions, magnetic susceptibility values, and ZR/Rb ratio are low during four periods of 3800-2950 cal yr BP, 2300-1700 cal yr BP, 1070-570 cal yr BP, and 100 cal yr BP-present, which indicates that glacier retreated in these four periods (Fig.3 and Fig.4).

5.3. The glacier variations and their linkage to temperature changes over the last 2000 years

Decadal-scale glacier variations and their response to global warming, based on satellite and meteorological data, have been widely studied in Pamir-Karakoam-Himalaya mountain ranges [*Gardelle et al.*, 2013; *Kääb et al.*, 2012; *Khromova et al.*, 2006; *Mölg et al.*, 2013; *Yao et al.*, 2012]. Here, we compare centennial- scale glacier variations of Muztag Ata to the temperature regional and global changes reconstructed using compilations of proxies records over the last 2000 years [*Christiansen and Charpentier Ljungqvist*, 2012; *Ljungqvist*, 2010; *Mann and Jones*, 2003; *Yang et al.*, 2002]. Three distinct glacial retreat episodes occurring in

0-240 A.D., 880-1380 A.D., 1900 A.D.-present, correlate well with Roman warm period (RWP), Medieval Warm Period (MWP), and Current Warm Period (CWP), respectively. Between these three glacial retreat episodes, there are two glacial expansion periods occurring in 240-880 A.D. and 1380-1900 A.D., which correspond to Dark Age Cold Period (DACP) and Little Ice Age (LIA), respectively. Accordingly, the history of glacier activity at centennial time scale in westernmost Tibetan Plateau is in well agreement with temperature records of China and the Northern Hemisphere [*Christiansen and Charpentier Ljungqvist*, 2012; *Ljungqvist*, 2010; *Mann and Jones*, 2003; *Yang et al.*, 2002] , with glacial advance responding to low temperature and glacial retreat being correlated with high temperature. This good correspondence indicates that the glacial variations in western Tibetan Plateau are very sensitive to local and global temperature changes. Our results support the conclusion that the eastern Pamir glacier retreat is due to increases in air temperature, and increased precipitation would not be able to compensate for the mass loss [*Khromova et al.*, 2006] .

6. Conclusions

An 8.3m sediment core from Kalakuli Lake, a glacier-fed lake, is used to reconstruct a continuous and high resolution record of late Holocene glacier history in western Tibetan Plateau. Grainsize, magnetic susceptibility, Zr content, Zr/Rb and Rb/Sr ratio are used as proxy indicators of glacier advance and retreat. Our records show that four glacier expansion episodes can be identified in 4200-3800 cal yr BP, 2950-2300 cal yr BP, 1700-1070 cal yr BP, and 570-100 cal yr BP. These four glacier expansion episodes are generally in agreement with the glacial advances occurring at ca. 4.2 ± 0.3 ka, 3.3 ±

0.6 ka, 1.4 ± 0.1ka, and a few hundred years ago based on ^{10}Be terrestrial cosmogenic nuclide surface-exposure dating of boulders on the moraines in Muztag Ata and Kongur Shan of western Tibetan Plateau, and also possibly coincident with the Late Holocene ice-rafting events in the North Atlantic (i.e. Bond events 0 to 3)., , Reconstructed glacier advances and retreats of the last 2000 years correspond well with low and high temperature from other proxy records, which indicates that the glacial variations at centennial time scale in western Tibetan Plateau are very sensitive to local and global temperature changes.

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