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Long-term glacier melt fluctuations over the past 2500 yr in monsoonal High Asia revealed by radiocarbon-dated lacustrine pollen concentrates

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ABSTRACT

Long-term records of glacier mass changes are important for improving our understanding of glacier dynamics and for predicting the response of glaciers to future climate change. In contrast to moraine sequences that only record isolated stages of glacier status, proglacial lake sediments may record long-term continuous glacier activities. The melt of old glacier ice releases old pollen that may affect the radiocarbon ages of pollen in proglacial lake sediments. We define the offset between the calibrated pollen ^{14}C ages and the sediment depositional age as the "old pollen effect" (OPE). In small catchments dominated by glaciers, the OPE may record variations in glacier melt intensity and extent, even though complex processes (e.g., modern pollen flux to a glacier or a proglacial lake, glacier flow velocities) may also impact the OPE. Using the sediments of a small proglacial lake on the southern Tibetan Plateau, we found that over the past 2.5 k.y., a weakened OPE occurred during three historical cool periods that coincided with regional glacier advances defined by moraine ages. Thus, we interpret the OPE as a new indicator of glacier melt intensity and its fluctuations. Our reconstructed glacier variability agrees well with glacier fluctuations in the European Alps and the global average temperature record, suggesting that hemispheric-scale temperature variations and/or mid-latitude Westerlies may have controlled the late Holocene glacier variability in monsoonal High Asia. We also show that the 20th century glacier melt intensity has exceeded that of two historical warm periods and is unprecedented over the past 2.5 k.y. This implies that current anthropogenic warming poses a serious threat to the survival of glaciers in monsoonal High Asia.

INTRODUCTION

Well-constrained late Holocene glacier chronologies have provided important clues for understanding the complex climate system (Solomina et al., 2015, 2016). The Tibetan Plateau (TP) and its surroundings contain the largest number of glaciers outside the polar regions and have shown spatially heterogeneous glacier responses to global warming (e.g., Yao et al., 2012). For glaciers in monsoonal High Asia, a recent study demonstrated that glacier variability was connected to changes in the strength of the mid-latitude Westerlies (Mölg et al., 2014). However, the above instrumental studies are limited to recent decades, and well-constrained late Holocene glacier chronologies are still sparse. Several studies have integrated sporadic moraine ages on the TP (e.g., Yang et al., 2008; Yi et al., 2008); however, some of the ages are questionable (Loibl et al., 2015), and temporal and spatial patterns of glacier fluctuations remain unclear (Solomina et al., 2015). Moraine sequences directly record ice margin change, but they are discrete low-resolution series and can be easily eroded by subsequent glacial advances of a larger extent (Kirkbride and Winkler, 2012). Multi-proxies (e.g., organic matter content, elements, and grain size) from proglacial lake sediments have been used to reconstruct continuous records of glacier change (e.g., Dahl et al., 2003; Liu et al., 2014; Matthews et al., 2000; Nesje et al., 2000), but nonglacial processes (e.g., rainfall events, colluvial activity, and debris flows) can confound the extraction of glacial signals.

Pollen preserved in Tibetan ice cores has been used to reconstruct past climate change (e.g., Liu et al., 1998), but no studies have focused on the effects of the melt of old ice in terms of the release of old pollen. According to a conceptual model of glacier flow, young ice containing modern pollen is formed in the accumulation area and then flows slowly to the ablation area and becomes a reservoir of old pollen (Fig. 1). Intensified glacier melt releases more old pollen from the old ice, which, together with overridden soil from beneath the glacier, enters proglacial lakes and results in a larger offset between the calibrated ^{14}C ages of pollen in lake sediments and the sediment depositional age. We define this offset as the "old pollen effect" (OPE) and propose that the OPE can be a new indicator of glacier melt intensity and fluctuations. Sediments from lake Qiangyong Co, China (Fig. DR1 in the GSA Data Repository[1]), were used to test our hypothesis through comparisons of the OPE against regional moraine ages. A 2.5 k.y. record of glacier variability is presented and is compared with other paleoclimatic and paleoglacial records in order to infer spatial correlations and dynamics of late Holocene glacier change in monsoonal High Asia.

SITE DESCRIPTION

Qiangyong Co (Fig. 1B; 28°53′N, 90°13′E), with a maximum water depth of 30 m, is a small proglacial lake (0.8 km^2) at an altitude of 4875 m above sea level on the northern slopes of the Himalayas (Fig. 1). Glacier ice covers ~60% of the lake catchment (~12 km^2), and the other areas mainly comprise bare bedrock composed of limestone, dark carbonaceous slate, and granite, fresh moraines, and a small area of thin, weakly developed soils. Regional climate, with a mean annual precipitation of ~370 mm (Fig. DR2), is dominated by the Indian summer monsoon in summer and by the Westerlies in winter.

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[1]GSA Data Repository item 2017103, methodology, radiocarbon ages, and ^{210}Pb and ^{137}Cs ages, is available online at http://www.geosociety.org/pubs/ft2017.htm or on request from editing@geosociety.org.

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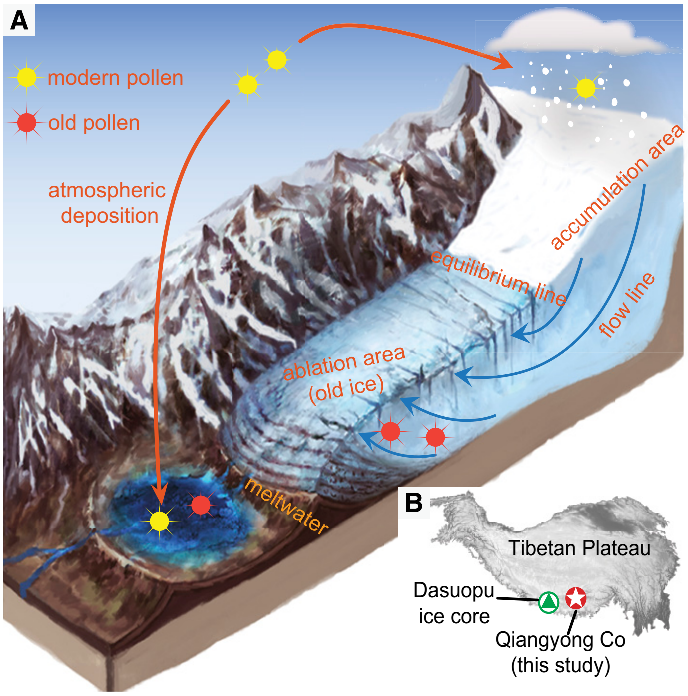

Figure 1. A: Conceptual model of glacier flow showing accumulation of old pollen in ablation area and its release to proglacial lake through meltwater. B: Location of lake Qiangyong Co, China (this study).

METHODS

A 3.06-m-long core (QYL09-4) and a 1.06-m-long parallel gravity core (QY-3) were retrieved from the depositional center of Qiangyong Co (see the Data Repository for details). Using a new composite extraction procedure (Fig. DR3), we obtained relatively pure pollen concentrates and plant residue concentrates (PRC; >125 µm; Fig. DR4) from the finely laminated sediments. Bulk organic matter and the PRC and pollen fractions were used for ^{14}C dating independently (Table DR1 in the Data Repository). All ^{14}C ages were calibrated with IntCal13 (Reimer et al., 2013). The age-depth model is based on ^{210}Pb and ^{137}Cs ages (Fig. DR5) and five ^{14}C ages of PRC (Fig. 2A). Only the youngest PRC ages were used for the age-depth model, whereas older ages that produce a stratigraphic reversal and are apparently influenced by redeposited or aquatic plant material were rejected. The deposition model was constructed using the P_Sequence algorithm in Oxcal 4.2 (Bronk Ramsey, 2008). For the calculation of the OPE, 2σ intervals for interpolated ages according to the deposition model were subtracted from calibrated pollen ages (2σ span) (Fig. 2B), resulting in the age offset between pollen and estimated sediment ages (ΔAge_{pollen}).

RESULTS AND DISCUSSION

Chronology

Excess ^{210}Pb of core QY-3 showed a variable decay trend (Fig. DR5a), and sediment ages were calculated using the constant rate of supply (CRS) model (Appleby, 2001). Two ^{137}Cs peaks at 5.25 and 3.25 cm were found (Fig. DR5b) and were ascribed to the maximum of global nuclear tests in A.D. 1963 and the Chernobyl nuclear disaster in A.D. 1986 (Kasper et al., 2012). The initial increase of ^{137}Cs activity at 7.75 cm is probably related to the onset of global nuclear tests in A.D. 1953 (Kasper et al., 2012). The ^{210}Pb age model agreed well with the ^{137}Cs-based ages (Fig. DR5c).

We obtained a total of 37 radiocarbon ages for core QYL09-4 (Table DR1). The ^{14}C ages of bulk organic matter (23,585–26,490 yr B.P.) are not in chronological order and are too old, revealing a significant and complex reservoir effect in the proglacial basin. This phenomenon may be explained by the complex impact from the two main kinds of local bedrock, carbonate and dark carbonaceous slate (containing dead carbon). The five youngest calibrated ages of PRC—among them one sample consisting of terrestrial Cyperaceae fruits (Fig. 2C)—document that ~2500 yr is covered by the 306-cm-long sequence from Qingyong Co. The sedimentation rate based

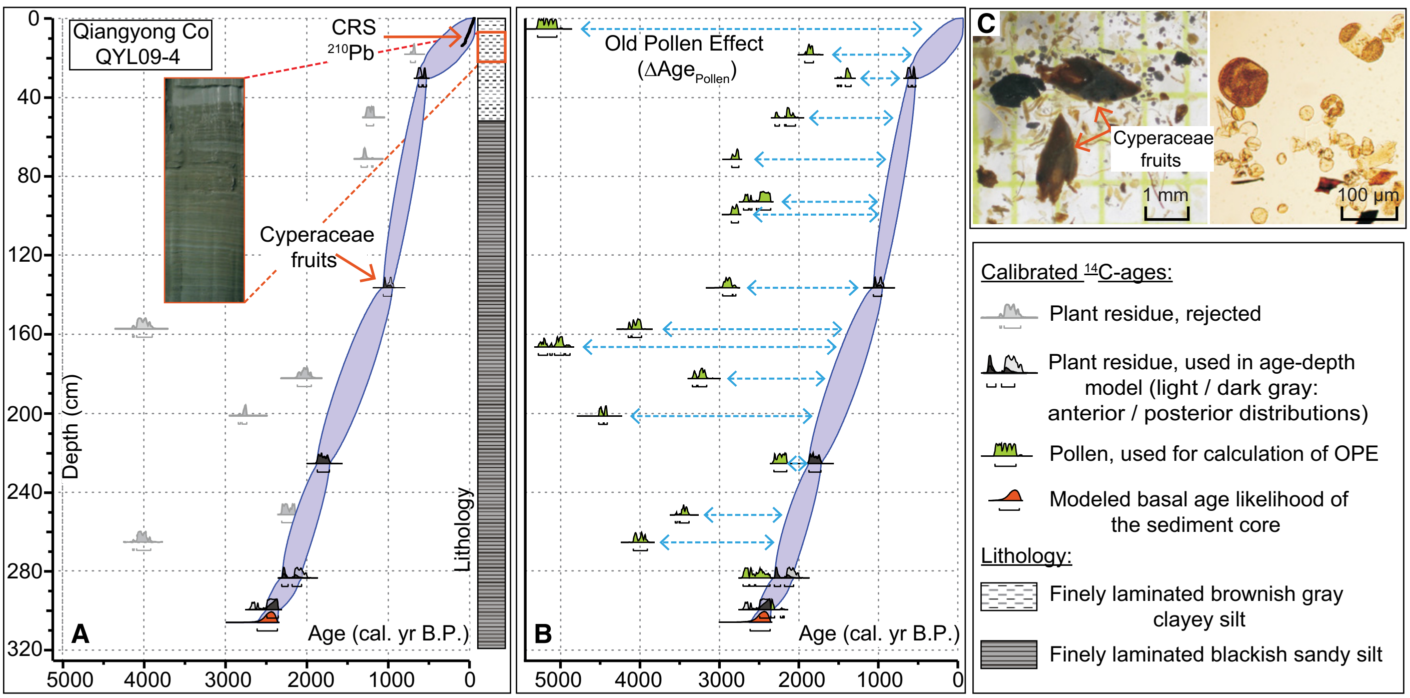

Figure 2. A: Age-depth model based on youngest calibrated ^{14}C ages of plant residues, lake Qiangyong Co, China. B: Calculation of "old pollen effect" (OPE, blue arrows; offset between calibrated ^{14}C ages of pollen concentrates and sediment depositional age). Shaded blue areas represent 2σ probability age ranges constructed with OxCal software (Bronk Ramsey, 2008). CRS— constant rate of supply model; cal.—calendar. C: Images of pollen concentrates and terrestrial macrofossils.

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on the selected (youngest) ^{14}C ages is consistent with the sedimentation rate based on the ^{210}Pb analysis (Fig. 2A), and the modeled relatively constant accumulation rate over the past 2500 yr agrees well with the continuously and finely laminated nature of the sediments (Fig. 2). Considering the depositional characteristics, we rejected several other, too-old PRC ages that are reversed stratigraphically (Fig. 2A). These samples may partly consist of redeposited materials or remains of aquatic macrophytes that are easily affected by the reservoir effect. Although the youngest ages produce a reasonable looking age-depth model, there is no way to discern if there remains a minor old carbon effect on the ages. Large error of the age-depth model, however, can be excluded because of its consistency with the sedimentary characteristics and the terrestrial macrofossil and ^{210}Pb ages.

OPE as a Proxy for Glacier Melt Intensity

The calculated ΔAge_{pollen} varies from values ~0 to a maximum of 5080 yr (Fig. 2B) and exhibits high values at A.D. 1850–present, A.D. 600–1250, A.D. 300–400, and 200–50 B.C., and low values at A.D. 1250–1850, A.D. 400–600, A.D. 100–300, and 520–300 B.C. (Fig. 3). The three periods of higher OPE at A.D. 1850–present, A.D. 600–1250, and 200–50 B.C. appear to be related to the Current Warm Period (CWP), the Medieval Warm Period (MWP), and the Iron/Roman Age Optimum (I/RAO) (Lamb, 1977), while lower OPE values at A.D. 1250–1850, A.D. 400–600, and B.C. 520–300 may be associated with the Little Ice Age (LIA), the Dark Ages (DA), and the Iron Age Cold Epoch (IACE) (Lamb, 1977), respectively. Although there are some differences in timing and amplitude of temperature change, these historical warm-cold events have also been recorded in other parts of the TP (Liu et al., 2006; Liu et al., 2014; Yang et al., 2003).

As there are no other apparent nonglacial sources of old pollen in the catchment, and aquatic microfossils such as coenobia of green algae that could cause a reservoir effect were virtually absent in samples (Fig. 2C), we interpret the OPE (ΔAge_{pollen}) as a new indicator of glacier melt intensity and its fluctuations. High ΔAge_{pollen} values may represent intensified glacier melt and retreat, and low values may represent weakened glacier melt and advance. On millennial time scales, low ΔAge_{pollen} values generally occurred during the two regional glacial advances at 3.5–1.4 ka and 1.0–0.13 ka in Tibet (Yi et al., 2008; Fig. 3C). On centennial time scales, our reconstructions are coherent with the several regional glacial stages (0.4 ± 0.1 ka; 0.7 ± 0.1 ka; 1.5 ± 0.2 ka; 2.3 ± 0.1 ka) defined by ^{10}Be ages (Murari et al., 2014; Fig. 3D) and with two of the three main synthesized glacial stages (A.D. 200–600 and A.D. 1400–1920) defined by ^{14}C and other evidence (Yang et al., 2008) on the monsoonal TP. Lower OPE values at B.C. 520–300 at this site are consistent with glacier advances occurring in Gonggashan, Qilianshan, and East Kunlun (Yi et al., 2008). Although moraine sequences younger than 2.6 ± 0.6 ka have not been dated in this valley (Owen et al., 2005), lower OPE values at A.D. 100–300, A.D. 400–600, and A.D. 1250–1850 coincide with glacier advances in some other parts of monsoonal TP (Yang et al., 2008) and central Asia (Solomina et al., 2015, 2016). Overall, lower OPE values at this site generally correspond to regional glacier advances defined by moraine ages. Thus, although the pollen deposition in a proglacial lake comprises complex processes (e.g., modern pollen flux to a glacier or a proglacial lake, glacier flow velocities, and young ice melt), we are in favor of an interpretation that the OPE is mainly modulated by variations of glacier extent and melt intensity and that other complex processes play a limited role.

To evaluate wider correlations and implications, we compared our record with the temperature variations indicated by the Dasuopu ice core $\delta^{18}O$ record from the southern TP (Yao et al., 2002; Fig. 3B), two high-resolution records of glacier fluctuation from the European Alps (Holzhauser et al., 2005; Fig. 3E), and central Europe (Büntgen et al., 2011) and global average temperature records (PAGES 2k Consortium, 2013) (Fig. 3F). The centennial-scale glacial advances at this site and other sites in monsoonal High Asia are generally correlated to low values of $\delta^{18}O$ (indicating low temperature) in the Dasuopu ice core, glacier expansions

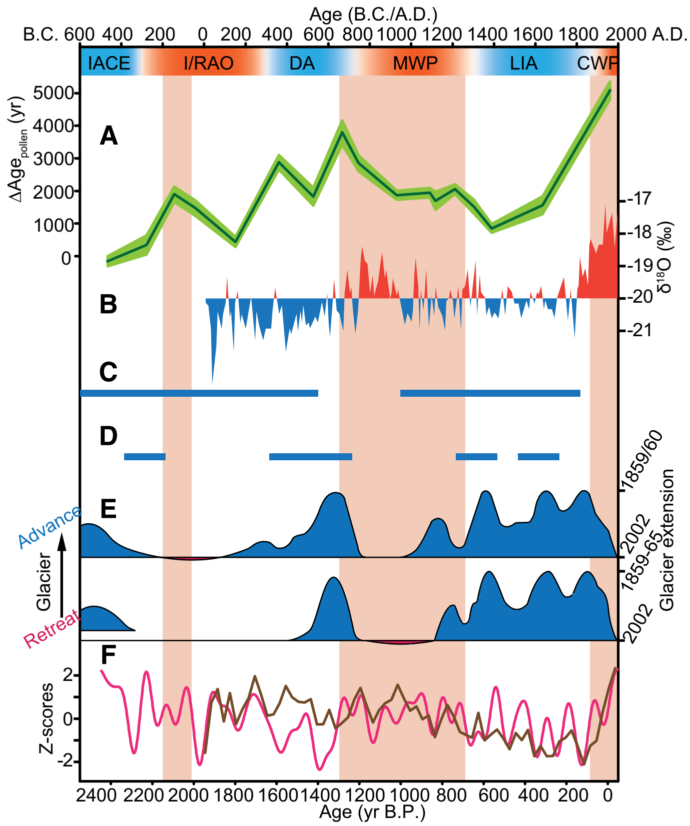

Figure 3. A: ΔAge_{pollen} (age offset between pollen and estimated sediment ages; ±2σ uncertainties, shaded areas). B: Dasuopu (Tibet) ice core $\delta^{18}O$ record (Yao et al., 2002). C,D: Regional glacial advances based on moraine ^{14}C ages in Tibet (C) (Yi et al., 2008) and on moraine ^{10}Be ages on monsoonal Tibetan Plateau (D) (Murari et al., 2014). E: Fluctuations of Great Aletsch Glacier (top) and Gorner Glacier (bottom) in European Alps (Holzhauser et al., 2005). Numbers on the "Glacier extension" axis represent years (A.D.; the glacier extents in those years were used as references). F: Standardized (Z-score) values of global average (brown curve; PAGES 2k Consortium, 2013) and central Europe (pink curve; 80 yr low-pass filtered; Büntgen et al., 2011) temperature reconstructions. IACE—Iron Age Cold Epoch; I/RAO—Iron/Roman Age Optimum; DA—Dark Ages; MWP—Medieval Warm Period; LIA—Little Ice Age; CWP—Current Warm Period.

in the European Alps, low temperature in central Europe, and low global average temperature. This extra-regional correlation suggests that hemispheric-scale temperature variations may have played an important role in the late Holocene centennial-scale glacier fluctuations. Meanwhile, a recent study indicated that the strength of westerly waves, affecting May–June precipitation and summer air temperatures, explains 73% of the interannual mass-balance variability of a glacier on the monsoonal southern TP (Mölg et al., 2014). Thus, our study suggests that the interval when the Westerlies acted as a driver of glacier variability in monsoonal High Asia can be extended at least to the late Holocene, which explains its roughly synchronous glacial behavior to records from the European Alps.

The ΔAge_{pollen} reaches a maximum (~5080 yr) near the sediment surface (Fig. 3A), suggesting that the current melt of Qiangyong glacier is so intense that a large amount of old pollen is being released. Our results show that the 20th-century glacier melt intensity exceeded that of two historical warm epochs (MWP and I/RAO) and is unprecedented at least for the past 2.5 k.y. (Fig. 3). Although warm climatic conditions during these periods have been reported in many parts of the TP (e.g., Liu et al., 2006; Liu et al., 2014) and the Asia-Pacific region (Ge et al., 2013; Yan et al., 2015), available records in High Asia comparing the glacier melt intensity during the CWP with those of the MWP and I/RAO are

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still lacking. Our results indicate stronger glacier melt intensity during the CWP, which implies that the current anthropogenic warming poses a serious threat to the survival of glaciers in monsoonal High Asia.

CONCLUSIONS

This study demonstrates that, although multiple factors (e.g., glacier melt intensity, modern pollen flux to a glacier or a proglacial lake) may control the pollen deposition in a proglacial lake, the radiocarbon ages of pollen in proglacial lake sediments may serve as a new indicator of glacier melt intensity and its fluctuations. A 2.5 k.y. record of glacier variability has been reconstructed, and we found three periods of intensified melt (glacier retreat) at A.D. 1850–present, A.D. 600–1250, and 200–50 B.C., corresponding to the CWP, the MWP, and the I/RAO, respectively. Three periods of reduced melt (glacier advance) also occurred at A.D. 1250–1850, A.D. 400–600, and 520–300 B.C., related to the LIA, the DA, and the IACE, respectively. Our reconstruction agrees well with glacier fluctuations in monsoonal High Asia and the European Alps and also with records of southern TP, central Europe, and global average temperatures. This spatial correlation suggests that large-scale temperature variations and/or mid-latitude Westerlies may have controlled the late Holocene centennial-scale glacier variability in monsoonal High Asia. Our record also indicates that the 20th century glacier melt intensity is the strongest, at least for the past 2.5 k.y., suggesting the serious impact of recent anthropogenic warming on the rapidly shrinking glaciers in monsoonal High Asia.

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