Quaternary Science Reviews 186 (2018) 284–297

Contents lists available at ScienceDirect

Quaternary Science Reviews

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

The timing and cause of glacial activity during the last glacial in central Tibet based on ^{10}Be surface exposure dating east of Mount Jaggang, the Xainza range

Guocheng Dong [a, b, *], Weijian Zhou [a, b, c], Chaolu Yi [d, e], Yunchong Fu [a, b], Li Zhang [a, b], Ming Li [a, b]

[a] State Key Laboratory of Loess and Quaternary Geology, Institute of Earth Environment, Chinese Academy of Sciences, Xi'an 710061, China
[b] Xi'an AMS Center, Xi'an 710061, China
[c] Beijing Normal University, Beijing 100875, China
[d] Key Laboratory of Tibetan Environment Changes and Land Surface Process, Chinese Academy of Sciences, Beijing 100101, China
[e] Excellence Center for Tibetan Plateau Research, Chinese Academy of Sciences, Beijing 100101, China

A R T I C L E I N F O

Article history:
Received 26 August 2017
Received in revised form
27 February 2018
Accepted 5 March 2018

Keywords:
^{10}Be surface exposure dating
The last glacial
Heinrich events
Mount Jaggang
Central Tibet

A B S T R A C T

Mountain glaciers are sensitive to climate change, and can provide valuable information for inferring former climates on the Tibetan Plateau (TP). The increasing glacial chronologies indicate that the timing of the local Last Glacial Maximum (LGM) recorded across the TP is asynchronous, implying different local influences of the mid-latitude westerlies and Asian Summer Monsoon in triggering glacier advances. However, the well-dated sites are still too few, especially in the transition zone between regions controlled by the two climate systems. Here we present detailed last glacial chronologies for the Mount Jaggang area, in the Xainza range, central Tibet, with forty-three apparent ^{10}Be exposure-ages ranging from 12.4 ± 0.8 ka to 61.9 ± 3.8 ka. These exposure-ages indicate that at least seven glacial episodes occurred during the last glacial cycle east of Mount Jaggang. These include: a local LGM that occurred at ~61.9 ± 3.8 ka, possibly corresponding to Marine Isotope Stage 4 (MIS 4); subsequent glacial advances at ~43.2 ± 2.6 ka and ~35.1 ± 2.1 ka during MIS 3; one glacial re-advance/standstill at MIS3/2 transition (~29.8 ± 1.8 ka); and three glacial re-advances/standstills that occurred following MIS 3 at ~27.9 ± 1.7 ka, ~21.8 ± 1.3 ka, and ~15.1 ± 0.9 ka. The timing of these glacial activities is roughly in agreement with North Atlantic millennial-scale climate oscillations (Heinrich events), suggesting the potential correlations between these abrupt climate changes and glacial fluctuations in the Mount Jaggang area. The successively reduced glacial extent might have resulted from an overall decrease in Asian Summer Monsoon intensity over this timeframe.

1. Introduction

The behavior of mountain glaciers is a primary indicator of paleoclimate in high mountain ranges, where climate archives are relatively sparse, as compared with ocean basins or polar ice caps. Mountain glaciers react rapidly and markedly to changes in climate on sub-millennial timescales (Oerlemans, 2005), and thus glacial landforms, particularly moraines, have been widely dated to infer underlying climate changes in glaciated mountains (Balco, 2011), such as those on the Tibetan Plateau (TP).

For the past two decades in particular, a large number of studies have been devoted to defining the timing and extent of glaciations throughout the TP, and to assessing possible mechanisms behind glacial fluctuations (e.g. Heyman, 2014 and references therein). These efforts parallel recent refinements in cosmogenic ^{10}Be surface exposure dating techniques. A large number of glacial chronologies on the TP (>2000 individual ^{10}Be exposure-ages) show that glaciers reached their maximum extent of the last glacial cycle (*ca.* 110–10 ka) prior to the global Last Glacial Maximum (LGM; *ca.* 26.5–19 ka; Clark et al., 2009) in many regions, suggesting high sensitivity of glaciers to variations in precipitation and thus to orbital-driven monsoon intensity (e.g. Phillips et al., 2000; Owen

* Corresponding author. State Key Laboratory of Loess and Quaternary Geology, Institute of Earth Environment, Chinese Academy of Sciences, Xi'an 710061, China.
E-mail address: donggc@ieecas.cn (G. Dong).

https://doi.org/10.1016/j.quascirev.2018.03.007
0277-3791/

et al., 2002a, 2002b; Finkel et al., 2003; Owen et al., 2003; Wang et al., 2013; Li et al., 2014; Chen et al., 2015). However, inter-regional and intra-regional differences have been observed that are likely influenced by the mid-latitude westerlies and Northern Hemisphere climate oscillations (e.g. Zech et al., 2013; Dong et al., 2014; Blomdin et al., 2016; Hu et al., 2016; Lehmkuhl et al., 2016). Regional differences in the timing of the local LGM are not necessarily surprising because mid-latitude mountain glaciers around the world are known to have reached their respective maximum extent at different times during the last glacial cycles (Gillespie and Molnar, 1995; Hughes et al., 2013). However, this does indicate that our understanding of the last glacial advances on the TP is incomplete and robust last glacial chronologies are sparse considering the vast TP. More data are needed to fully understand the forcing mechanisms behind glacial advances.

Tackling these problems requires a full understanding of glacial activities through time in the transition zone between the mid-latitude westerlies and Asian Summer Monsoon. Mount Jaggang is located in the middle of this zone, in central Tibet (Fig. 1A), and is influenced both by the westerlies and the Asian Summer Monsoon. Previous research has shown that the intensity of these two climate systems has varied in the past, on glacial-interglacial and glacial millennial timescales (An et al., 2012). Therefore our study offers an opportunity to better understand their relative influences through time in central Tibet. We examine glacial fluctuations during the last glacial cycle based on cosmogenic ^{10}Be surface exposure dating. We then compare the glacial chronologies with terrestrial, marine, and ice core records to identify climatic controls on glacial fluctuations during the last glacial in the Mount Jaggang area.

2. Study area

The Xainza range is located on the southern part of the central TP (Fig. 1A). This range is ~150 km in length and trends along a south-north direction. It rises from ~4900 m above sea level (asl) to the highest peak, Mount Jaggang, at 6444 m asl (Fig. 1B). The climate of this region is dominated by the southwest monsoon in summer and the mid-latitude westerlies in winter (Dong et al., 2010). At the Xainza weather station, ~13 km northeast of Mount Jaggang (Fig. 1B), the modern (1981–2012) mean annual temperature is 0.55 °C and the mean annual precipitation is 316 mm (Li et al., 2015).

Our study centers on the eastern slope of Mount Jaggang, where one glacial catchment consisting of two glacial valleys stretches ~3 km eastwards to the catchment mouth at an altitude of ~5370 m asl (Fig. 2A). Glaciers in the two valleys terminate at 5505 and 5605 m asl. Seven sets of moraines are distributed within ~2.0 km beyond the catchment mouth (Fig. 2). These moraines have been reworked by the glacial meltwater, which is feeding Gyaring Co Lake, ~19 km northwest of Mount Jaggang (Fig. 1B).

The outermost moraine (referred to as moraine JM1) forms a ~1.4 km-wide platform (Fig. 2). This moraine platform, ~70–140 m above the present river floor, extends downward to an altitude of ~4930 m asl where it forms a flat terminal-moraine crest. The surface of the moraine crest is mantled by a thin veneer of turf, on which boulders of >1 m in diameter are scattered. Some of these boulders contain cavernous pits up to 30 cm in diameter (Fig. 3H). Moraine JM1 is partially overlaid by a latero-frontal moraine (named moraine JM2) (Fig. 3A). Moraine JM2 is comprised of two latero-frontal crests, which can be traced upstream to the catchment mouth (Fig. 2). The crest of moraine JM2 rises ~130 m over that of moraine JM1. Those boulders embedded in the crest of moraine JM2 feature surficial knobs with diameters up to 20 cm (Fig. 3G). Inside of moraine JM2, another latero-frontal moraine (named moraine JM3) extends ~1 km eastward from the range-front to an altitude of 5120 m asl. The distal part of moraine JM3 is characterized by a series of hummocks with a height of ~1–2 m (Fig. 3B and C). On the top of these hummocks, boulders protrude through sparse vegetation and reach 3 m in diameter.

A discontinuous inset moraine (named moraine JM4) can be distinguished along the proximal margin of moraine JM3 (Figs. 2 and 3B). In addition, three sets of moraine relics (referred to as moraine JM5, JM6, and JM7) are distributed between moraine JM4 and the dated Little Ice Age (LIA) moraine (Dong et al., 2017b) (Figs. 2A, C and 3D). The four moraines are characterized by crests with gentle relief of no more than 2 m, which commonly represent recessional moraines (Benn and Evans, 2010). The surface of these crests is sparsely vegetated, with emerging granitic boulders up to 3 m in diameter (Fig. 3D–F).

3. Methods

3.1. Mapping and sampling

Prior to the fieldwork, we identified the glacial features on the eastern slope of Mount Jaggang using oblique Google Earth imagery. These glacial features were then checked during field study in 2014–2016 to determine whether they might yield meaningful exposure-ages. After field investigations, we delineated the moraine sequences on the eastern slope of Mount Jaggang using a 30 m resolution ASTER GDEM (Global Digital Elevation Model; www.gscloud.cn) (Fig. 2A). Also, we illustrated these moraine sequences on the Google Earth images (Fig. 2B and C).

Forty-three glacial boulders were sampled from seven moraines (Moraine JM1-JM7) east of Mount Jaggang for ^{10}Be surface exposure dating. We preferentially selected the largest granitic boulders that were embedded in the moraine crest and characterized by rock varnish on the surface (Fig. 3F and supplementary material). Samples were collected from the top and flattest boulder surfaces using a hammer and chisel. The locations and elevations of all samples were recorded using a handheld GPS (global positioning system) instrument. The detailed geomorphic context was recorded through notes and photographs of sample locations (Supplementary material). Detailed sample information is provided in Table 1.

3.2. ^{10}Be surface exposure dating

Laboratory processing and ^{10}Be/^{9}Be ratio measurements were all performed at the Xi'an Accelerator Mass Spectrometry Center (Xi'an-AMS Center). After sample crushing and sieving (250–500 μm), quartz was isolated from the sample using the modified procedures of Kohl and Nishiizumi (1992), which were described in detail by Dortch et al. (2009) and Dong et al. (2014). The isolation of Be and precipitation of BeO were carried out following the procedure of Zhang et al. (2016). AMS measurements were made at the Xi'an-AMS Center based on the revised ICN standard (Nishiizumi et al., 2007, 07KNSTD). The measured ^{10}Be/^{9}Be ratios were corrected using four chemical procedural blanks (4.96×10^{-15}-20.13×10^{-15}) and converted to ^{10}Be concentrations for exposure-age calculation. Quartz weights, ^{9}Be carrier masses, measured ^{10}Be/^{9}Be ratios, and procedural blanks are shown in the Supplementary material.

Cosmogenic ^{10}Be exposure-ages were calculated using the CRONUS-Earth online calculator version 3 (Balco et al., 2008; http://hess.ess.washington.edu/), based on an assumption of zero erosion. In the interpretation, we focus on exposure-ages derived from the time- and nuclide-dependent scaling scheme LSDn (Lifton et al., 2014) on the basis of considerations as follows: Borchers et al. (2016) have demonstrated that the Lal (1991)/Stone (2000) time-