Quaternary Research 79 (2013) 439–451

Contents lists available at SciVerse ScienceDirect

Quaternary Research

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

Cosmogenic nuclide constraints on late Quaternary glacial chronology on the Dalijia Shan, northeastern Tibetan Plateau

Jie Wang [a,*], Christine Kassab [b], Jonathan M. Harbor [b], Marc W. Caffee [c], Hang Cui [a], Guoliang Zhang [a]

[a] Key Laboratory of Western China's Environmental Systems (Ministry of Education), Lanzhou University, Lanzhou, Gansu 730000, China
[b] Department of Earth, Atmospheric, and Planetary Sciences, Purdue University, West Lafayette, IN 47907, USA
[c] Department of Physics, Purdue Rare Isotope Measurement Laboratory, Purdue University, West Lafayette, IN 47907 1397, USA

ARTICLE INFO

Article history:
Received 13 September 2012
Available online 12 February 2013

Keywords:
Tibetan plateau
Cosmogenic nuclide
Glacial chronology
Dalijia Shan

ABSTRACT

Cosmogenic nuclide (CN) apparent exposure dating has become a widely used method for determining the age of glacial landforms on the Tibetan Plateau with > 1200 published ages. We present the first ^{10}Be exposure ages from the Dalijia Shan, the most northeastern formerly glaciated mountain range on the Tibetan Plateau. The moraine groups identified from field and remote sensing imagery mapping record four glacial events at 37.07 ± 3.70 to 52.96 ± 4.70 ka (MIS 3), 20.17 ± 1.79 to 26.99 ± 2.47 ka (MIS 2), 16.92 ± 1.49 to 18.76 ± 1.88 ka (MIS 2), and 11.56 ± 1.03 to 11.89 ± 1.06 ka (Younger Dryas). These ages indicate that glaciation in the northeastern Tibetan Plateau is much younger than previously thought. In addition, this record is consistent with many other regions on the Tibetan Plateau, with a local last glacial maximum during MIS 3 asynchronous with Northern Hemisphere last glacial maximum during MIS 2. The Dalijia Shan might also include an event of Younger Dryas age, but this needs to be tested in future studies.

Introduction

Mountain glaciers are sensitive indicators of climate change, so understanding past variations in glacial extent is important for reconstructing past climates and predicting future climate change (Oerlemans, 2005). The glacial history of the Tibetan Plateau is important (1) regionally, in understanding and modeling how climate change impacts a region of over 2.5 million km^2 with an average elevation of ~4000 m asl, and (2) globally because of the impact that this large, high-elevation region has on climate worldwide. Outside of the polar regions the largest concentration of glaciers today is located on the Tibetan Plateau (46,640 km^2 glaciated; Shi et al., 2000), making it critical to understanding how glaciers will react to changing climate and whether this may produce a feedback that changes regional climate patterns. Currently the precipitation of the Tibetan Plateau and the glacial extent is controlled in part by competing atmospheric systems: mid-latitude westerlies, the South and East Asian monsoon, and Mongolia–Siberia high pressure system with perturbations from the El Nino–Southern Oscillation (Lehmkuhl and Owen, 2005; Owen and Benn, 2005; Kirchner et al., 2011). These same climate drivers influenced the paleoclimate of the Tibetan Plateau via shifts in their relative locations driving spatial and temporal patterns of glacial advance and retreat (Lehmkuhl and Owen, 2005; Zhang et al., 2006; Owen et al., 2008). Thus, if past glaciations have been controlled mainly by precipitation, reconstructing the extent and timing of past glaciations is important in constraining past changes in the dominance and patterns of these climate drivers.

Over the past century there has been much debate over the paleoextent of glaciers on the Tibetan Plateau, with reconstructions ranging from a plateau-wide ice sheet synchronous with Northern Hemisphere glaciation (e.g., Han, 1989; Kuhle, 1998, 2004) to limited glacier and ice cap expansions that are not synchronous in timing and extent with Northern Hemisphere glaciation (e.g., Rost, 2000; Owen et al., 2002a, 2005; Zheng et al., 2002; Finkel et al., 2003; Zech et al., 2003; Zhang et al., 2005; Owen, 2009; Heyman et al., 2011a). Based upon a large body of research, including recent detailed studies focused on mapping glacial landforms in the field and with remote sensing, as well as absolute dating of landforms using a variety of methods, it is widely accepted that a large ice sheet did not cover the Tibetan Plateau during the past few glacial cycles. Rather, the glacial record of the Tibetan Plateau is dominated by the expansion and contraction of glaciers and small ice caps (e.g., Derbyshire et al., 1991; Shi et al., 1992; Lehmkuhl, 1998; Lehmkuhl et al., 1998; Zheng and Rutter, 1998; Schäfer et al., 2002; Zhou et al., 2004; Lehmkuhl and Owen, 2005; Owen et al., 2005, 2008, 2012).

Various methods have been used to date glacial deposits and landforms on the Tibetan Plateau, including relative age control from stratigraphy or morphostratigraphy, organic radiocarbon (^{14}C), thermoluminescence (TL), optically stimulated luminescence (OSL), electron spin resonance (ESR), and cosmogenic nuclide (CN). The earliest work relied on the general global model of

* Corresponding author.
E-mail addresses: wangjie@lzu.edu.cn (J. Wang), ckassab@purdue.edu (C. Kassab).

0033-5894/$ – see front matter © 2013 University of Washington. Published by Elsevier Inc. All rights reserved.
http://dx.doi.org/10.1016/j.yqres.2013.01.004

glaciation chronology to assign relative ages to various landforms and deposits. Low abundance of organic matter within glacial deposits provided a few absolute radiocarbon ages for young events, but care had to be taken when interpreting the results because of the possibility of a considerable time lapse between the demise of the organism being dated and the glacial event it is associated with (Richards, 2000). The sparseness of suitable sediments and the inability to correlate some glaciofluvial sediments with specific glacial events limit the applicability of TL and OSL methods. Where successful, these methods have provided ages that represent the timing of deposition of sediment associated with a glacial event (Richards, 2000; Owen and Benn, 2005). Currently the most widely used technique to date glacial advances is CN exposure dating. Unlike TL and OSL methods that provide the timing of deposition, exposure dating methods provide a minimum age of deglaciation (Owen and Benn, 2005). All three of these methods extend the chronological control to identify older glaciations and allow for the dating of rocks and sediments that do not have organic matter or are beyond the traditional ^{14}C range.

Over the past two decades, multiple studies have used exposure dating methods to constrain the timing of glaciation across the Tibetan Plateau and have produced more than 1200 published exposure ages (discussed in Chevalier et al., 2011; Heyman et al., 2011b). Several glacial advances in various regions across the Tibetan Plateau can be identified based upon the exposure ages: the Little Ice Age, Neoglacial, mid-Holocene, early Holocene, late glacial interstadial, global last glacial maximum (LGM; MIS 2), mid-last glacial (MIS 3), and early last glacial (MIS 4). Based mainly on the absence of dated landforms in some areas, not all of these glaciations appear to have occurred in every region (Owen et al., 2005) or they have very different relative magnitudes in different areas. Spatial variations in timing and magnitude of glaciation can be linked to the different climate systems that impact the Tibetan Plateau. Regions that are primarily affected by the monsoonal systems recorded glacial advances during interstadial periods as a result of increased precipitation due to increased insolation during these periods. Precipitation in these regions decreased during glacial periods, resulting in a smaller glacier advance if any (Shi et al., 2001; Owen et al., 2002a,b; Shi, 2002). Regions that are primarily affected by the winter westerlies typically experience glacier advances during glacial periods because precipitation is not influenced by changes in insolation (Owen et al., 2005, 2012; Seong et al., 2009).

The Dalijia Shan (Shan = mountain), along the northeast boundary of the Tibetan Plateau, is not presently glaciated. However, during the glacial–interglacial cycles of the Quaternary, it was extensively and repeatedly glaciated. Glacial landforms from multiple glaciations are well preserved, especially in the Dalijia Pass area (e.g., Deheisui Valley). The Quaternary glacial landforms and moraines of the Dalijia Shan have been studied since the late 1980s and have been assigned to three glacial stages with local names: Wulongguan (oldest), Pass, and Dalijia (youngest; Li and Pan, 1989; Shen et al., 1989; Pan, 1993). To date, there is little absolute age control on the glacial landforms; researchers have only used relative age dating techniques to interpret a glacial history for this region. These studies are based on correlation of loess deposited on top of the moraines with loess deposits within terraces along the Daxia River and weathering profiles of soils that have developed on top of the moraines (Li and Pan, 1989; Shen et al., 1989; Mahaney and Rutter, 1992; Pan, 1993).

^{10}Be exposure ages of 22 samples collected on four moraine groups in the Dalijia Shan presented here provide the first absolute age control for Dalijia Shan glacial landforms that can be compared with ages from other regions on the Tibetan Plateau. These ages from the northeasternmost region of the Tibetan Plateau that is known to have been glaciated add to the growing database of numerical ages from across the Tibetan Plateau, contributing to a better understanding of the chronological framework.

Geologic setting

The Dalijia Shan is located in a transition region between the northeastern border of the Tibetan Plateau and the Loess Plateau (Fig. 1A; Li and Pan, 1989; Pan, 1993). Average elevation is approximately 3600 m asl with Dalijia Peak reaching 4636 m asl. There is a planation surface between 4000 and 4300 m asl on top of the Dalijia Shan, which slopes ~4° from north to south (Fig. 1B). Bedrock in this region consists mainly of intensely folded and faulted Precambrian crystalline complexes of granite and schist. Deformation is mainly a result of late Neogene orogenic events (Mahaney and Rutter, 1992).

The climate of this region is semi-arid, and dominated by the East Asia and South Asia monsoons. Moisture is derived mainly from the South Asia monsoon (Indian Ocean and Bengal Bay; Wang et al., 2005; Zhang et al., 2011). At Linxia Station (35°34′N, 103°11′E; 1917 m asl) on the eastern slope of Dalijia Shan (~40 km east of Dalijia Peak), the mean annual temperature is 7.1°C, and the mean annual precipitation is 499 mm (for the period 1951–2011) (http://cdc.cma.gov.cn). Precipitation between May and October accounts for >85% of the annual total; winter and spring are very dry. Many types of glacial landforms and deposits (planation surfaces, U-shaped valleys, moraines, tills, and rouche mountonnées) have been identified above 3000 m asl in the Dalijia Shan, with the majority located around Dalijia Peak (elev. ~4600 m asl; Li and Pan, 1989; Pan, 1993). Based on the presence of glacial landforms and deposits, Li and Pan (1989) and Pan (1993) hypothesized that a 150 km^2 ice cap covered the planation surface.

Moraines characterized by deeply weathered tills were identified by Li and Pan (1989) at Wulongguan (~2700 m asl) and provide the basis for the Wulongguan glacial stage. Our own field investigations at Wulongguan did not identify any unequivocal glacial deposits or landforms and so the Wulongguan glacial stage is not included in our analysis.

In the Dalijia Pass region, the oldest moraine set, group A, is a lateral moraine that is only preserved at altitudes of 3600–3900 m asl (Figs. 1C and 2). It is ~400–600 m above the valley floor, and cannot be continuously traced to an end moraine, possibly due to post-depositional glacial and fluvial erosion of the landform. The tills at this site are gray and sub-angular, with clasts of granite and overlie schistose bedrock. Many weathered, erratic granite boulders, 2–4 m in diameter, and a thick loess layer are present on the platform surface. The glacial advance associated with this deposit was referred to as the Pass glacial stage by Li and Pan (1989) and Pan (1993).

Another lateral moraine, moraine group B, is present on the eastern and western sides of the Deheisui valley. These moraines are adjacent to and slightly lower than the group A moraines and represent a younger, less extensive glacier configuration. Moraine group C includes well-developed right and left lateral moraines that join end moraines at altitudes of 3180–3400 m asl in the Qitai valley. These end moraines consist of three distinct moraine ridges, ~20–40 m above the valley floor with ~0.5-m thick meadow soils. The sediments of these ridges are poorly sorted, with granite clasts ranging in size from fine-grained sands to boulders of ~1 m in diameter. Boulders present on the surface of this moraine exhibit slight granular weathering. The two moraine sets, groups B and C, were assigned to the early and late Dalijia glacial stage by Li and Pan (1989) and Pan (1993).

Near the head of the valley is the group D moraine, a latero-frontal moraine ridge that rises ~20–40 m above the valley floor at an altitude of 3800 m asl. The till includes granite clasts and areas of fine sand, and a soil profiles that is several cm thick.

Glacial deposits in the actual pass area (Dalijia Pass moraine) have been previously assigned to the Pass glacial stage and have been linked to moraine group A deposits in past studies. However the elevation of these moraines is more consistent with moraine group B deposits. One of the goals of this study is to determine whether these deposits are equivalent in age to moraine group A or B.