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Timing and climatic drivers for glaciation across semi-arid western Himalayan–Tibetan orogen

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ABSTRACT

Mapping and forty-seven new ^{10}Be ages help define the timing of glaciation in the Ladakh and Pangong Ranges in Northwest India. Five new local glacial stages are defined for the Ladakh Range. From oldest to youngest these include: the Ladakh-4 glacial stage at 81 ± 20 ka; the Ladakh-3 glacial stage (not dated); the Ladakh-2 glacial stage at 22 ± 3 ka; the Ladakh-1 glacial stage (not dated); and the Ladakh Cirque glacial stage at 1.8 ± 0.4 ka. Three local glacial stages are defined for the Pangong Range, which include: the Pangong-2 glacial stage at 85 ± 15 ka; the Pangong-1 glacial stage at 40 ± 3 ka; and the Pangong Cirque glacial stage at 0.4 ± 0.3 ka. The new ^{10}Be ages are combined with 645 recalculated ^{10}Be ages from previous studies to develop the first regional framework of glaciation across the dryland regions of the Greater Himalaya, Transhimalaya, Pamir and Tian Shan at the western end of the Himalayan–Tibetan orogen. Nineteen regional glacial stages are recognized that are termed semi-arid western Himalayan–Tibetan stages (SWHTS). These include: SWHTS 9 at 311 ± 32 ka; SWHTS 7 at 234 ± 44 ka [tentative]; SWHTS 6 at 146 ± 18 ka; SWHTS 5E at 121 ± 11 ka; SWHTS 5A at 80 ± 5 ka; SWHTS 5A- at 72 ± 8 ka; SWHTS 4 at 61 ± 5 ka; SWHTS 3 at 46 ± 4 ka; SWHTS 2F at 30 ± 3 ka; SWHTS 2E at 20 ± 2 ka; SWHTS 2D at 16.9 ± 0.7 ka; SWHTS 2C at 14.9 ± 0.8 ka; SWHTS 2B at 13.9 ± 0.5 ka; SWHTS 2A at 12.2 ± 0.8 ka; SWHTS 1E at 8.8 ± 0.3 ka [tentative]; SWHTS 1D at 6.9 ± 0.2 ka [tentative]; SWHTS 1C at 3.8 ± 0.6 ka; SWHTS 1B at 1.7 ± 0.2 ka; and SWHTS 1A at 0.4 ± 0.1 ka. Regional glacial stages older than 21 ka are broadly correlated with strong monsoons. SWHTS that are 21 ka or younger, have smaller uncertainties and broadly correlate with global ice volume given by marine Oxygen Isotope Stages, and northern hemisphere climatic events (Oldest Dryas, Older Dryas, Younger Dryas, Roman Humid Period, and Little Ice Age).

1. Introduction

Glaciation in high mountains, such as the Himalayan–Tibetan orogen, exerts a strong control on the development of topography (Brozović et al., 1997), influences tectonics (Zeitler et al., 2001; Willett, 2010) and climate (Molnar and England, 1990), can condition mountain systems and focus erosion (Norton et al., 2010), and may limit fluvial incision (Korup and Montgomery, 2008). Defining the timing and extent of glaciation both locally and regionally is a critical first step toward understanding landscape evolution and paleoenvironmental change in glaciated mountains. As a move towards developing a glacial framework within one of the world's most active and impressive orogens, the Himalayan–Tibetan orogen, we construct a glacial chronostratigraphy, defined using ^{10}Be terrestrial cosmogenic nuclides, for its western end. This includes 47 new ^{10}Be ages for the Ladakh region in northern India and reassessment of previous ^{10}Be studies across this part of the orogen.

Numerous studies, including cosmogenic nuclides and luminescence, show the complexity of the glacial records in the Himalayan–Tibetan orogen (Phillips et al., 2000; Richards et al., 2000a,b; Taylor and Mitchell, 2000; Owen et al., 2001, 2002, 2003, 2006, 2008, 2012; Seong et al., 2007, 2009a,b,c; Dortch et al., 2010a; Hedrick et al., 2011). These studies indicate that in some regions, particularly monsoon-influenced areas, Quaternary glaciation was extensive, while in others, primarily semi-arid areas, glaciation was relatively restricted over time (Owen et al., 2005, 2008 and references therein). In the monsoon-influenced regions extensive Quaternary glacial advances, high precipitation, and the associated runoff have conspired to destroy much of the evidence for past glaciation. In contrast, in the semi-arid regions of the Himalayan–Tibetan orogen, such as the Transhimalaya, old glacial landforms and well-preserved multiple sets of moraines are common (Owen

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et al., 2005, 2008 and references therein). Semi-arid regions have a greater potential for preserving more complete glacial chronologic records. We accordingly focus on the semi-arid regions at the western end of the Himalayan–Tibetan orogen; directing our efforts on several valleys in the Ladakh and Pangong ranges of Ladakh, Northern India.

In addition to the impressive successions of moraines in Ladakh, the region also contains some of the oldest preserved moraines in the Himalayan–Tibetan orogen (Owen et al., 2006). Ladakh has become one of the most well studied regions in the Transhimalaya with research focusing on glaciation (Fort, 1983; Burbank and Fort, 1985; Brown et al., 2002; Damm, 2006; Owen et al., 2006; Dortch et al., 2010a), the development of asymmetrical topography (Jamieson et al., 2004; Kirstein, 2011; Dortch et al., 2011a) and valley morphology (Hobley et al., 2010; Reynhout et al., 2013), the importance of large landslides in landscape development (Dortch et al., 2009), exhumation histories (Dunlap et al., 1998; Kirstein et al., 2006, 2009; Kumar et al., 2007), strath terraces development, and catastrophic flooding (Brown et al., 2003; Dortch et al., 2011a,b; Hobley et al., 2012). A common theme in many of these studies is the underlying importance of glaciation in influencing landscape development (Hobley et al., 2010; Dortch et al., 2011a; Reynhout et al., 2013).

To produce a coherent glacial chronostratigraphic framework for an extensive region of the Himalayan–Tibetan orogen we present a new glacial chronostratigraphy for Ladakh using cosmogenic ^{10}Be dating. We compare this chronology with published chronologies for semi-arid regions to the north and south. This framework provides a foundation for future Quaternary paleoenvironment, landscape development and tectonic studies.

2. Study area

The study region spans the semi-arid mountain regions at the western end of the Himalayan–Tibetan orogen and includes the Transhimalaya, greater Himalaya, Pamir, and Tian Shan (Fig. 1). Within this region there are several relatively isolated massifs, which include Mustag Ata, Kongur Shan, and Nun-Kun. The mountains are among the highest in the world and include five 8000 m-high peaks (K2 at 8611 m above sea level [asl], Nanga Parbat at 8126 m asl, Gasherbrum 1 at 8068 m asl, Broad Peak at 8047 m asl, and Gasherbrum II at 8035 m asl). The high topography was produced by the collision of the Indian–Asian continental lithospheric plates starting at $\sim$50 Ma, which resulted in $\sim$2000 km of crustal shortening (Dewey et al., 1989; Johnson, 2002). This is one of the most glaciated regions outside of the polar realm and includes glaciers that exceed many tens of kilometers in length. The climate of the region is influenced by both the mid-latitude westerlies and Indian monsoon (Benn and Owen, 1998). Lehmkuhl and Owen (2005), Owen et al. (2005, 2012) and provide overviews of the Quaternary glaciation of the Himalayan–Tibetan orogen.

The detailed study area focuses on the Ladakh and Pangong ranges that trend NE–SW within the Transhimalaya. The Ladakh and Pangong ranges rise from about 3500 m asl to peaks reaching $>$6000 m asl, and contain deeply incised valleys with 1–3 km of relief. The Ladakh Range is bounded to the south by the Indus-Tsangpo suture zone and to the north by the Shyok suture zone and Karakoram Fault. The range experienced rapid exhumation during the Oligocene, and slow exhumation on the northern side of the range since the Miocene (Kirstein et al., 2006, 2009, 2011; Dortch et al., 2011a). The Pangong Range is bounded by two strands of the Karakoram fault and has undergone exhumation during two periods of transpression at 13–17 Ma and 7–8 Ma (Dunlap et al., 1998).

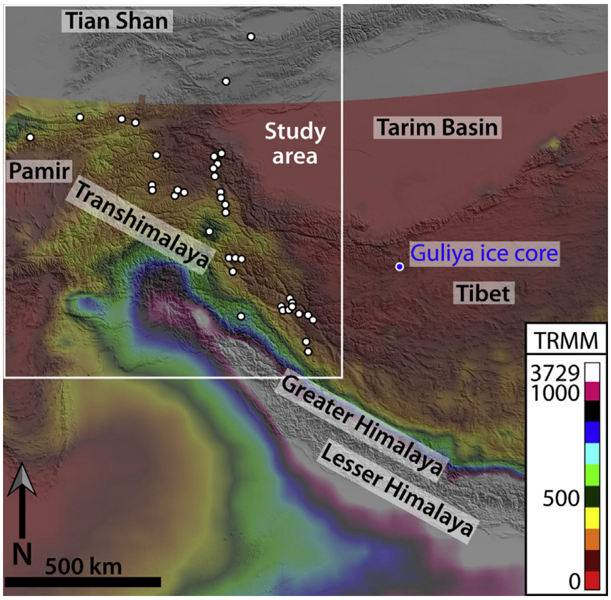

Fig. 1. Shuttle radar topography mission (SRTM) hillshade digital elevation model (DEM) of the western portion of the Himalayan–Tibetan orogen. Tropical Rainfall Measurement Mission (TRMM) average annual precipitation data for 1998–2008 (from Bookhagen and Burbank, 2006; Bookhagen, 2013) is superimposed on the DEM. Sample locations for all studies are denoted by white dots while the location of Guliya ice core is denoted by a blue dot. Location of Fig. 12 is outlined by a white box. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

The Ladakh and Pangong ranges, and the Zanskar Range to the south, receive most of their precipitation from the Indian summer monsoon (Gasse et al., 1996; Brown et al., 2003; Owen et al., 2006). In contrast, the Karakoram Range and the Pamir to the north receives the majority of its precipitation from the mid-latitude westerlies (Miehe et al., 2001). The strength of the monsoon and mid-latitude westerlies, along with precipitation gradients, have changed over time due to changes in insolation influenced by variations in the Earth orbital parameters (Gasse et al., 1996; Benn and Owen, 1998; Bookhagen et al., 2005; Demske et al., 2009). Currently, the region is characterized as semi-arid, and receives $\leq$200 mm of precipitation per year (Bookhagen and Burbank, 2006; Bookhagen, 2013).

Brown et al. (2002) and Owen et al. (2006) defined the timing of glaciation for the southern side of the Ladakh Range using cosmogenic ^{10}Be dating, and Dortch et al. (2010a, 2011a,b) made tentative correlations of glacial landforms across the Ladakh Range and the Nubra, Shyok, and Tangtse river valleys. To the north and south of the study area, Owen et al. (2002, 2012), Zech et al. (2005a, 2013), Abramowski et al. (2006), Seong et al. (2007, 2009c), Koppes et al. (2008), Hedrick et al. (2011), Zech (2012), Röhringer et al. (2012) and Lee et al. (2013) defined the timing of glaciation using ^{10}Be methods.

3. Methods

3.1. Field methods

All landforms were mapped in the field aided by remote sensed imagery, which included panchromatic merged 15 m Landsat ETM+ and 3 arc-second [90 m] Shuttle Radar Topography Mission [SRTM] DEMs (CGIAR-CSI, 2007; USGS EarthExplorer, 2011; Fig. 2). Five valleys in the Ladakh Range and one valley in the Pangong Range were traversed and mapped in detail.