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Quaternary glaciation of the Lato Massif, Zanskar Range of the NW Himalaya

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ABSTRACT

The glacial chronostratigraphy and history of the Lato Massif of Zanskar northern India is defined for the first time using geomorphic mapping and ^{10}Be surface exposure dating. Three local glacial stages, the Lato, Shiyul and Kyambu, are dated to 244–49, 25–15 and 3.4–0.2 ka, respectively. The Lato glacial stage was the most extensive period of glaciation, characterized by expanded ice caps with glaciers advancing to ~16 km from their present position. Large till deposits are associated with this glacial stage, which represent a time of heightened glacial erosion and localized incision, and increased rates of sediment transfer and deposition. The glacial style transitioned to entrenched valley glaciation during the Shiyul glacial stage. Hummocky moraine complexes reflecting fluctuating glacier margins characterize this glaciation. Glaciers have been confined to the cirques and headwalls of the massif during and since the Kyambu glacial stage. Equilibrium-line altitude (ELA) reconstructions help define the shifts in glaciation over time, with ELA depressions changing from 470 ± 140, 270 ± 80 to 100 ± 30 m for the Lato, Shiyul and Kyambu glacial stages, respectively. The change of glacial style during the latter part of the Quaternary is similar to other regions of the Transhimalaya and Tibet suggesting that this pattern of glaciation may reflect regional climatic forcing. The evolution of the Lato Massif from an isolated alpine plateau to a steeply incised massif over the last several glacial-interglacial cycles may have also influenced the shifts from ice cap to valley glaciation.

1. Introduction

Much attention has been paid to defining the extent and timing of glaciation throughout the Himalayan-Tibetan orogen over the past few decades (Owen and Dortch, 2014 and references therein). This has been mainly motivated by the desire to examine the relative roles of the Asian summer monsoon and mid-latitude westerlies in driving glaciation (Benn and Owen, 1998; Seong et al., 2007; Bookhagen and Burbank, 2010; Bolch et al., 2012; Sharma et al., 2016). These two dominant climatic systems create strong east-west and north-south precipitation gradients across the 2400-km-length and 300-km-breadth of the mountain belt, respectively (Burbank et al., 2003; Owen and Dortch, 2014). The southern and eastern extents of the mountain belt undergo enhanced summer precipitation by the advection of moisture from the Indian Ocean by the Asian summer monsoon (Benn and Owen, 1998; Owen, 2009). The mid-latitude westerlies bring maximum winter precipitation to the western end of the Himalaya from the Mediterranean, Black and Caspian seas (Benn and Owen, 1998; Owen, 2009). These climatic systems and the precipitation gradients they produce have varied significantly throughout the Quaternary as a result of changes in insolation (Finkel et al., 2003; Bookhagen et al., 2005; Owen et al., 2008). This, and microclimatic variations, are considered to have a strong influence upon the nature and timing of glaciation throughout the orogen, and likely responsible for the asynchronous behavior glaciation observed between individual mountain ranges (Benn and Owen, 1998; Bookhagen and Burbank, 2010; Dortch et al., 2011; Owen and

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Dortch, 2014).

Through the application of field mapping, remote sensing and numerical dating methods, modern glacial geologic studies across the Himalaya and Tibet provide evidence of significant glacier advances within the last several glacial cycles, with many valleys preserving confirmation for at least four of these advances during the late Quaternary (Owen and Dortch, 2014). Complex variations in the timing and extent of late Quaternary glaciation have been recognized over relatively short distances (10^{1-2} km). This is illustrated well at the western end of the Himalayan-Tibetan orogen, where the local last glacial maximum (lLGM) occurred at different times with vastly different glacier extents (Hedrick et al., 2011; Owen and Dortch, 2014). Within semi-arid regions of the Transhimalaya and Tibet, the style of glaciation has changed significantly over the last several glacial cycles, from expanded ice caps to entrenched valley glaciation (Seong et al., 2009a; Owen et al., 2010; Owen and Dortch, 2014). Rather than a single driver of Himalayan glaciation and its associated landscape change, the timing and extent of glaciation and the preservation of glacial evidence is likely governed by a complex combination of different factors specific to each locality, including climate and microclimate regimes, topographic controls and geologic setting (Bhutiyani, 1999; Hobley et al., 2010; Dortch et al., 2011; Dietsch et al., 2015).

Defining the changes in style and timing of glaciation throughout the Himalayan-Tibetan orogen is an essential component for understanding of the forcing factors behind glaciation and the associated landscape and paleoenvironmental change (Molnar and England, 1990; Brozovic et al., 1997; Barnard et al., 2004, 2006; Korup and Montgomery, 2008; Bookhagen and Burbank, 2010; Ali et al., 2013). The development of robust glacial chronostratigraphies is a prerequisite for examining the complex Quaternary glacial history of the Himalayan-Tibetan orogen. With this in mind, we examine an area of the Lato Massif, an unstudied region of Zanskar in northern India, at the climatic transition between the monsoon influenced Lahaul Himalaya and the semi-arid continental interior of the Transhimalaya (Hedrick et al., 2011). The Lato Massif is an interesting topographic high, which may have influenced the glaciation style over time from a small ice cap to cirque glaciers. Moreover, the Lato Massif is adjacent to several well-studied areas in northern Zanskar and Ladakh where key glacial chronostratigraphies have been developed (Owen et al., 2006; Hedrick et al., 2011; Sharma et al., 2016; Orr et al., 2017). The primary aim of this study is to examine the nature and timing of the late Pleistocene-Holocene glaciation of the Lato Massif. We develop the first glacial chronostratigraphy for this area using remote sensing, field mapping, geomorphic and sedimentological techniques, equilibrium-line altitudes (ELAs) and ^{10}Be surface exposure dating. We compare our glacial chronostratigraphy with studies from the adjacent regions to discuss possible controls upon the extent, style and timing of Quaternary glaciation for this region of the NW Himalaya.

2. Regional setting

The Lato Massif is located in the north-central region of Zanskar. Bounded by the Ladakh Range to the north and the High Himalaya to the south, the Zanskar Range is a semi-arid mountain range within the Transhimalaya of northern India. Zanskar is characterized by discrete west-northwest trending mountain ranges that rise from elevations of ~3500 m above sea level (asl) within the Indus River valley to peaks in excess of 6000 m asl. However, the trend of the Lato Massif which is part of the Mata nappe, is oblique to Zanskar's main ranges, trending northwest and rising from ~4000 to 6150 m asl (Fig. 1).

The formation and development of the Zanskar Range is the result of the on-going continental collision and partial subduction between the Indian and Eurasian lithospheric plates that commenced at ~55 Ma (Schlup et al., 2003). This large-scale tectonism secured the closure of the Neo-Tethys Ocean and the establishment of major geologic structures including the Indus-Tsangpo Suture Zone (ITSZ) and the Zanskar Suture Zone (ZSZ) (Steck et al., 1998, Fig. 1A). The lithotectonic units of the Tethyan Himalaya, Tso Moriri Nappe and North Himalayan crystalline sequence characterize the Zanskar Range. The Lato Massif is a core complex composed of granite and orthogneiss, surrounded by late Cenozoic-Precambrian metasedimentary rocks (Searle, 1986; Steck et al., 1998; Schlup et al., 2003).

Geomorphic studies have described a broad range of valley types in Zanskar, which include steep relief valleys with narrow valley floors and fluvial gorges, to broad and gently sloping valleys with wide cultivated floors (Osmaston, 1994). These valleys have been shown to retain evidence of glacial, fluvial, paraglacial and periglacial landforms and deposits, which include moraines, mass movements, debris flow/alluvial fans and cones, terraces, and outwash and till deposits (Mitchell et al., 1999; Taylor and Mitchell, 2000; Sharma et al., 2016; Orr et al., 2017). Many studies have focused on investigating the past and present glaciation of the mountain range enabled by the excellent preservation of geomorphic evidence (*ibid*). Moreover, with parts of Zanskar remaining unglaciated during the late Quaternary, the Zanskar Range has become a desirable location to understand the role and interplay of geomorphic processes including fluvial and glacial erosion, within semi-arid landscapes (Osmaston, 1994; Hedrick et al., 2011; Jonell et al., 2018).

Climatic and weather records from Leh's Meteorological Station are considered representative of Zanskar's semi-arid climate (Osmaston, 1994). Approximately 40% of the 113 mm a^{-1} of precipitation that falls in Leh occurs between July and September (Osmaston, 1994; Damm, 2006). The Tropical Rainfall Measuring Mission (TRMM) 12-year mean total annual rainfall data shows that Zanskar's mean annual rainfall is < 100 mm (Bookhagen and Burbank, 2006, 2010). Based upon the proposed environmental lapse rate of Derbyshire et al. (1991; ~1 °C/170 m), at the elevations of the contemporary glaciers in Zanskar (5500–6150 m asl), the summer (-7– -1 °C) and winter (–16– -10 °C) temperatures are likely to be significantly lower than in Leh at ~3300 m asl (January [-2.8–14 °C], June [10.2–24.7 °C]).

The desert steppe vegetation and sandy-gravel soils of Zanskar are mostly restricted to elevations below 5000 m asl. Alpine desert vegetation including small leafed shrubs and grasses are present, or no vegetation exists at all, at higher elevations (Osmaston, 1994).

Glacial studies of the Zanskar and Ladakh region have recognized evidence for three to four glacier advances within most investigated valleys, many of these advances occurring during the last few glacial cycles (Owen et al., 2006; Dortch et al., 2010; Hedrick et al., 2011; Lee et al., 2014; Sharma et al., 2016; Orr et al., 2017). Low erosion rates (at the lower end of 0.7–127 m/Ma determined by Dietsch et al., 2015) in parts of this region allow moraines to be preserved for many thousands of years in some valleys (Owen et al., 2010). Through numerical dating methods and existing nomenclature, the glacier advances are commonly assigned to: the lLGM, the global last glacial maximum (LGM as ~ 26–19 ka in MIS 2 as defined by Clark et al., 2009), the late glacial, the neoglacial and the little ice age (LIA) (Owen, 2009; Owen and Dortch, 2014). Orr et al. (2017) provides a summary of the glacial studies for the Zanskar Range. Of particular relevance is the glacial chronostratigraphy for southeast Zanskar produced by Hedrick et al. (2011) who identified four glacial stages extending to >300 ka. Four glacial stages were also defined within the Stok valley of northern Zanskar dating back to 124 ka (Orr et al., 2017).