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Timing and nature of Holocene glacier advances at the northwestern end of the Himalayan-Tibetan orogen

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ABSTRACT

Holocene glacial chronostratigraphies are developed for four glaciated valleys at the northwestern end of the Himalayan-Tibetan orogen using geomorphic mapping and cosmogenic ^{10}Be surface exposure dating. The study areas include the Hamtah valley in the Lahul Himalaya, and the Karzok, Lato and upper Stok valleys in Zanskar. Five local glacial stages are dated to ~10.4, ~6.1–3.3, ~2.1–0.9, ~0.7–0.4, and ~0.3–0.2 ka based on 49 new moraine boulder ages. Large age dispersions are evident for each of the local glacial stages. This is especially the case for ~6.1–3.3 and ~2.1–0.9 ka, which is likely a result of prior and/or incomplete exposures in very young moraine boulders. An additional compilation of 187 published ^{10}Be moraine boulder ages help define seven Himalayan Holocene regional glacial stages (HHs) for the northwestern end of the Himalayan-Tibetan orogen. These HHs date to ~10.9–9.3, ~8.2–7.4, ~6.9–4.3, ~4.5–2.8, ~2.7–1.8, ~1.8–0.9, and <1 ka. Early Holocene glacier advances were generally more extensive and had larger equilibrium-line altitude depressions (ΔELA = ~425 ± 229 m) than glacier advances during the mid-Holocene (ΔELA = ~141 ± 106) and late Holocene (ΔELA = ~124 ± 121 m). The early Holocene glacier advances likely correspond to orbitally-forced northerly migration of the Intertropical Convergence Zone and enhanced summer monsoon. The timing of the majority of HHs during mid- and late Holocene corresponds well with the North Atlantic cooling that is likely teleconnected via mid-latitude westerlies, particularly during ~8 ka and after ~5 ka. These chronostratigraphies suggest that Holocene glaciation in the northwestern part of the Himalayan-Tibetan orogen is largely influenced by long-term orbital forcing amplified by large-scale migration of the Earth's thermal equator and the associated hemispheric oceanic-atmospheric systems.

1. Introduction

Over the past decade, several compilations of young glacial chronologies have been used to help reconstruct and understand the nature of Holocene glaciation on a global scale (Grove, 2008; Davis et al., 2009; Solomina et al., 2015, 2016). Most of these studies conclude that glacier advances during the Holocene in extratropical regions are broadly the consequence of climatic change driven by long-term orbital forcing, with occasional forcing by explosive volcanic eruptions and El Niño-Southern Oscillations (Solomina et al., 2015). Changes in oceanic-atmospheric circulations in the North Atlantic (Denton and Broecker, 2008; Chiang and Friedman, 2012, 2014; Wanner et al., 2015) represent another possible amplification mechanism. By way of contrast, long-term forcing behind Holocene glacier variability in the Himalaya has been attributed to distinct regional teleconnections, and do not correlate directly with orbital forcing (Solomina et al., 2015, 2016). Despite the impressive preservation of glacial landform assemblages throughout the Himalaya, this view has not been adequately tested due to the lack of well-defined Holocene glacial chronostratigraphies (Fig. 1A).

To examine the nature of Holocene glaciations and possible forcing factors behind glacier advances in the Himalaya, we developed Holocene glacial chronostratigraphies for four glaciated valleys at the northwestern end of the Himalayan-Tibetan orogen using remote sensing and field mapping, geomorphic techniques, and cosmic-ray-produced (cosmogenic) ^{10}Be surface exposure age dating. We also compare these new studies with existing glacial chronostratigraphies developed using ^{10}Be dating in adjacent

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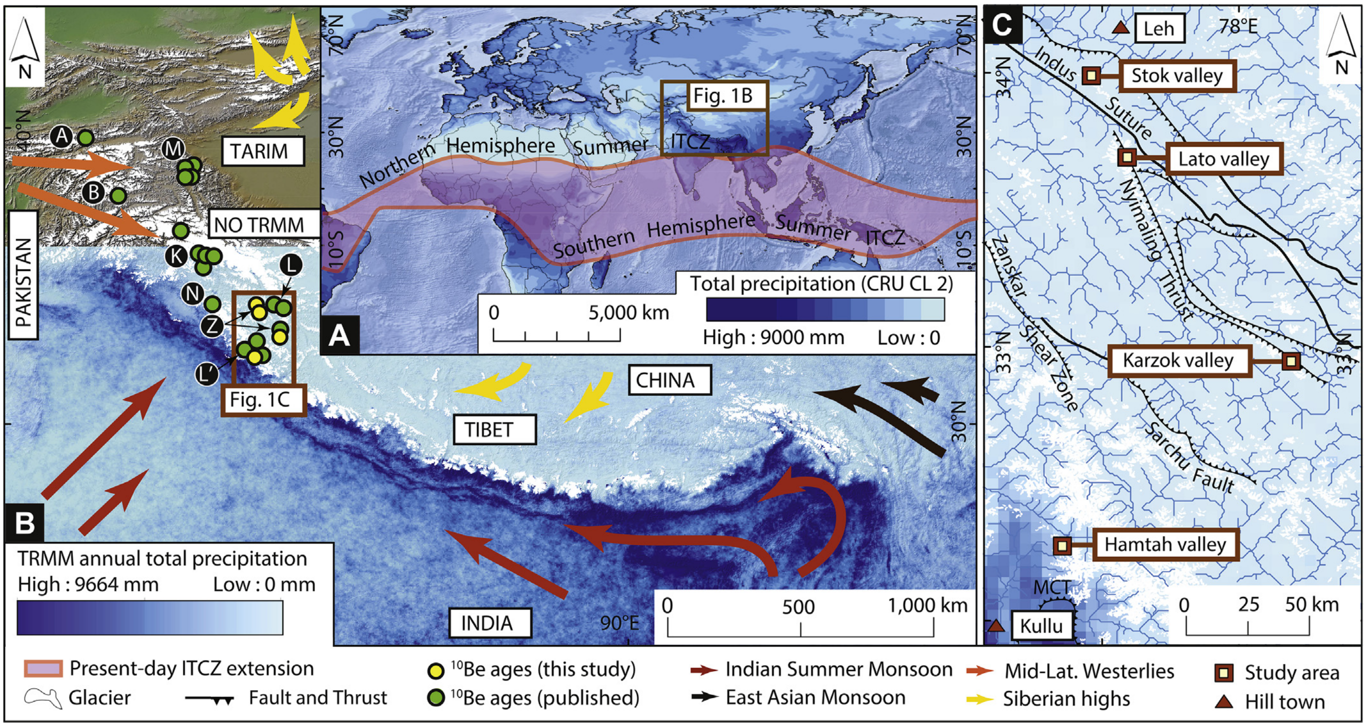

Fig. 1. Regional context and location of the study areas. (A) Present-day seasonal distribution of the Intertropical Convergence Zone (ITCZ) with respect to the Himalayan-Tibetan orogen (in brown rectangle). (B) Tropical Rainfall Measuring Mission (TRMM) precipitation imagery (averaged from 1998 to 2005) superimposed on a hillshade map, showing the study area (brown rectangle) and locations of new (yellow circles) and published (green circles) ^{10}Be ages. New and published study areas are highlighted in black circles as A = Alay Range (Koksu), B = Great Bogchigir, M = Muztag Ata, K= Karakoram, L = Ladakh (Chang, Pang), N= Nun Kun, Z = Zanskar (Stok, Lato, Karzok), L′ = Lahul Himal. The region is dominated by four major climate systems: the Indian summer and East Asian monsoons (during the summer), the northern mid-latitude westerlies, and the Siberian high-pressure system (during winter). (C) Locations of the new study areas showing TRMM derived strong annual total precipitation regimes from south to north. See the text for regional geology. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

regions of the Himalayan-Tibetan orogen (Fig. 1B). These include: the Chandra valley in Lahul, (Owen et al., 2001); the Yunam (Saha et al., 2016), Puga (Hedrick et al., 2011) and Stock valleys (Orr et al., 2017) and Nun Kun massif (Lee et al., 2014) in Zanskar; the northern slopes of the Ladakh range (Dortch et al., 2013); several valleys in the eastern and central Karakoram (Owen et al., 2002; Seong et al., 2007); Muztag Ata (Seong et al., 2009) and the Great Bogchigir valley in the Pamir (Röhringer et al., 2012); and the Koksu valley in Alay Range (Abramowski et al., 2006) (Fig. 1B). These study areas are within the contemporary transition between the Indian summer monsoon and mid-latitudinal westerly climate systems. Together these represent a key natural laboratory for investigating the relative influence of these climate systems in the region (Fig. 1B).

Previous studies of Quaternary glaciation, utilizing optically stimulated luminescence (OSL) and cosmogenic ^{10}Be surface exposure ages, have shown that glacier advances at the northwestern end of the Himalayan-Tibetan orogen are likely influenced by both oscillations in the Indian summer monsoon and mid-latitude westerlies (Taylor and Mitchell, 2000; Owen et al., 2001; Hedrick et al., 2011; Dortch et al., 2013; Lee et al., 2014; Saha et al., 2016; Eugster et al., 2016; Sharma et al., 2016; Orr et al., 2017, 2018). Dortch et al. (2013) and Owen and Dortch (2014 and references therein) using ^{10}Be dating have summarized the regional Quaternary glacier advances in the northwestern end of Himalaya and Tibet. Their semi-arid western Himalayan–Tibetan stages (SWHTS) date to 311 ± 32 (SWHTS 9), ~234 ± 44 (SWHTS 7), 146 ± 18 (SWHTS 6), 121 ± 11 (SWHTS 5E), 80 ± 5 (SWHTS 5A), 72 ± 8 (SWHTS 5A), 61 ± 5 (SWHTS 4), 46 ± 4 (SWHTS 3), 30 ± 3 (SWHTS 2F), 20 ± 2 (SWHTS 2E), 16.9 ± 0.7 (SWHTS 2D), 14.9 ± 0.8 (SWHTS 2C), 13.9 ± 0.5 (SWHTS 2B), 12.2 ± 0.8 (SWHTS 2A), ~8.8 ± 0.3 (SWHTS 1E), ~6.9 ± 0.2 (SWHTS 1D), 3.8 ± 0.6 (SWHTS 1C), 1.7 ± 0.2 (SWHTS 1B), and 0.4 ± 0.1 ka (SWHTS 1A). Recently, new moraine chronologies using ^{10}Be (Saha et al., 2016, Eugster et al., 2016; Orr et al., 2017, 2018) and OSL (Sharma et al., 2016) are also added to further improve and corroborate the existing regional stages of Quaternary glacier advances. While detailed Pleistocene chronologies are reconstructed in several valleys in the northwestern Himalaya, only a few attempts have been made to reconstruct Holocene glacial chronostratigraphies in the Lahul and Zanskar regions (see Owen and Dortch, 2014). These studies have delineated how small temperate to sub-polar glaciers in these regions oscillated throughout the Holocene. We, therefore, selected areas across the northwestern end of the Himalayan-Tibetan orogen which have a strong precipitation gradient, ranging from ~800 to ~40 mm a^{-1}, to help examine Holocene glacier oscillations. From wettest to driest, our study areas include the Hamtah valley in the Lahul Himalaya, and the Karzok, Lato, and upper Stok valleys in Zanskar (Fig. 1). We use ^{10}Be dating because this method has been applied extensively due to scarcity of suitable organic materials necessary for radiocarbon dating and/or the lack of well-bleached non-glacial sediments suitable for OSL dating (Owen and Dortch, 2014). The primary goals of our study are to refine previously proposed regional glacial stages (Dortch et al., 2013; Owen and Dortch, 2014; Solomina et al., 2015) and to assess whether Holocene glacier advances at the northwestern end of the Himalayan-Tibetan orogen were driven by regionally unique forcing factors that are not directly be influenced by long-term orbital trends, and/or global changes in the oceanic-atmospheric circulation system.