Quaternary International xxx (2010) 1–13

Contents lists available at ScienceDirect

Quaternary International

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

Towards defining the transition in style and timing of Quaternary glaciation between the monsoon-influenced Greater Himalaya and the semi-arid Transhimalaya of Northern India

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A R T I C L E I N F O

Article history:
Available online xxx

A B S T R A C T

To help delineate the transition in pattern and timing of glaciation between two contrasting regions, Lahul to the south and Ladakh to the north, moraines in the Puga and Karzok valleys of Sanskrit in the Transhimalaya of northern India were mapped and dated using cosmogenic ^{10}Be. In Lahul, Late Quaternary glaciation was extensive with total valley glacial systems being >100 km in extent, whereas glaciation in Ladakh has been comparatively restricted, with glaciers advancing only ~15 km from the contemporary glaciers during the last 200 ka. In the Puga valley, glaciers advanced >15 km at ~129 ka and ~10 km at ~46 ka, ~4.2 ka, and ~0.6 ka. In the Karzok valley, glaciers advanced ~1 km at ~3.6 ka. Boulder exposure ages from a large moraine complex in Karzok indicate a glacial advance at ~80 ka of ~4 km from the present ice margin. The oldest moraine in Karzok is ~311 ka, indicating that glaciers advanced >10 km from the present ice margin during or before marine isotope stage 9. The glacial chronology of the two valleys shows a lack of early Holocene glaciation and generally asynchronous glaciation between them. Moraines in the Puga and Karzok valleys broadly correlate with previous studies in the Zanskar Range but the paucity of data for many of the glacial stages across the Zanskar region makes the correlations tentative. The lack of early Holocene glaciation in the Puga and Karzok valleys is in stark contrast to many regions of the Himalaya, including Lahul, and the restricted glacial extent in Zanskar is more similar to the style of glaciation in Ladakh. The similarity between the glacial records in the Puga and Karzok study areas suggests that the transition to Lahul style glaciation is to the south of the Karzok valley, showing that this geographical transition is abrupt.

1. Introduction

The Himalayan-Tibetan orogen is Earth's most glaciated realm, outside of its polar regions. The orogen has been extensively glaciated in the past, with Quaternary valley glacier systems extending >100 km beyond their present positions (Haeberli et al., 1989; Owen, 2009). This has resulted in impressive glacial landforms throughout the region, recording details of past glaciation and environmental change. Until recently, however, relatively few studies had established quantitative glacial chronologies in the Himalayan-Tibetan orogen. With the advent of surface exposure and luminescence dating, numerous studies illustrate the complexity of the glacial records. These studies are beginning to constrain the timing and extent of glaciation throughout the region (e.g. Sharma and Owen, 1996, Owen et al., 1997; Sloan et al., 1998; Phillips et al., 2000; Taylor and Mitchell, 2000; Owen et al., 2001; Owen et al., 2003; Richard et al., 2004; Seong et al., 2007; Owen et al., 2008, Seong et al., 2009).

Many of these glacial geologic studies are motivated by the desire to understand the interplay of two major climate systems, the south Asian monsoon and the mid-latitude westerlies (Benn and Owen, 1998). Variations in the strength of these two systems over time (Gasse et al., 1996; Bookhagen et al., 2005; Demske et al., 2009) as well as climatic gradients due to climate change and orographic effects has resulted in strong precipitation gradients across the orogen. These precipitation gradients change over time (Ives and Messerli, 1989; Owen and England, 1998), influencing glaciation throughout the region. Owen et al. (2008), for example, highlighted the contrast in the extent of glaciation across a stretch

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doi:10.1016/j.quaint.2010.07.023

of northern Pakistan and northern India during the Lateglacial (∼16–14 ka), showing that in the Hunza Valley in northern Pakistan, glaciers had only advanced a few kilometers from their present positions, whereas in the Central Karakoram, ∼100 km the east, glaciers formed an extensive valley glacier system that extended >100 km from their present positions.

To further examine the record of these strong climatic gradients and changes in the style and timing of glaciation, we focus on a zone of climatic transition between the monsoon-influenced Lahul Himalaya, which forms the high, southern margin of the orogen and the semi-arid continental interior of the Transhimalaya and spans the northeast margin of Lahul, Zanskar, and Ladakh in northern India (Fig. 1). To examine the records of timing and style of glaciation in the region, we utilize previous studies in Lahul, Zanskar, and Ladakh that employed optically stimulated luminescence (OSL) and ^{10}Be terrestrial cosmogenic nuclide (TCN) surface exposure dating methods; these studies reveal markedly different patterns of glaciation through time between Lahul and the Transhimalaya (Owen et al., 1997; Taylor and Mitchell, 2000; Owen et al., 2001; Owen et al., 2006). In Lahul, glaciation was very widespread during the Lateglacial with an extensive valley glacier system filling the main trunk valleys (Owen et al., 1997, 2001). In contrast, in Ladakh, glaciers only advanced a few kilometers from their present positions during the Lateglacial (Owen et al., 2006). Current studies in the Zanskar Himalaya indicate a gradual reduction in glaciation extent throughout the Quaternary, but the details of these glaciations are sparse (Taylor and Mitchell, 2000).

Our two main areas of study were the Puga and Karzok valleys located in the Zanskar Range (Fig. 1). Moraines and associated landforms were studied in these two valleys to elucidate the style and timing of glaciation in this transitional zone between Lahul and Ladakh. Our study areas are separated by ∼25 km (Puga to the north and Karzok to the south). This distance provides the spatial resolution that allows a test of whether there are any significant climatic gradients across the Zanskar Range. We also hoped to determine the location of the transition between more extensive ice systems, as were present in Lahul, to very restricted glaciation as in Ladakh. We utilize geomorphic mapping, remote sensing imagery, and ^{10}Be surface exposure dating to develop quantitative glacial chronologies that can be compared with previously established chronologies.

2. Regional setting

The Ladakh and Zanskar Ranges of the Transhimalaya, and the Pir Panjal and Greater Himalaya of Lahul are located at the western end of the Himalayan-Tibetan orogen. These mountain ranges rise from valleys with floors at ∼3500 m above sea level (asl) to summits extending >6000 m asl (Owen et al., 1997; Taylor and Mitchell, 2000; Owen et al., 2006). Closure of the Neo-Tethys Ocean and subsequent collision and partial subduction of the continental Indian plate beneath the Asian plate ∼55 Ma resulted in the formation of the Zanskar Suture Zone (ZSZ) and the Indus-Tsangpo Suture Zone (ITSZ) between the Ladakh and Zanskar Ranges (Schulp et al., 2003; Steck, 2003; Epard and Steck, 2008; Fig. 1). The ITSZ is the main boundary zone of the Indian and Asian plate collision (Searle et al., 1999). Lithotectonic units of the region are composed of metamorphosed sedimentary units of the Tethyan, Tetraogal, and Mata Nappes (Steck et al., 1998; Schulp et al., 2003; Epard and Steck, 2008) as well as granites and greenschist-facies lithologies of the Zildat and Nidar ophiolitic mélanges (Steck et al., 1998; Schulp et al., 2003).

Zanskar is a high-altitude desert (e.g. Bookhagen et al., 2005), but direct climate data measured from within the Zanskar Range are not available. Osmaston (1994) suggest that data from the Leh weather station (34° 09′N, 77° 34′E, 3514 m asl; Fig. 1) is most representative of Zanskar's climate. The thirty-year average annual precipitation at Leh is ∼115 mm/yr with ∼41% falling from July to

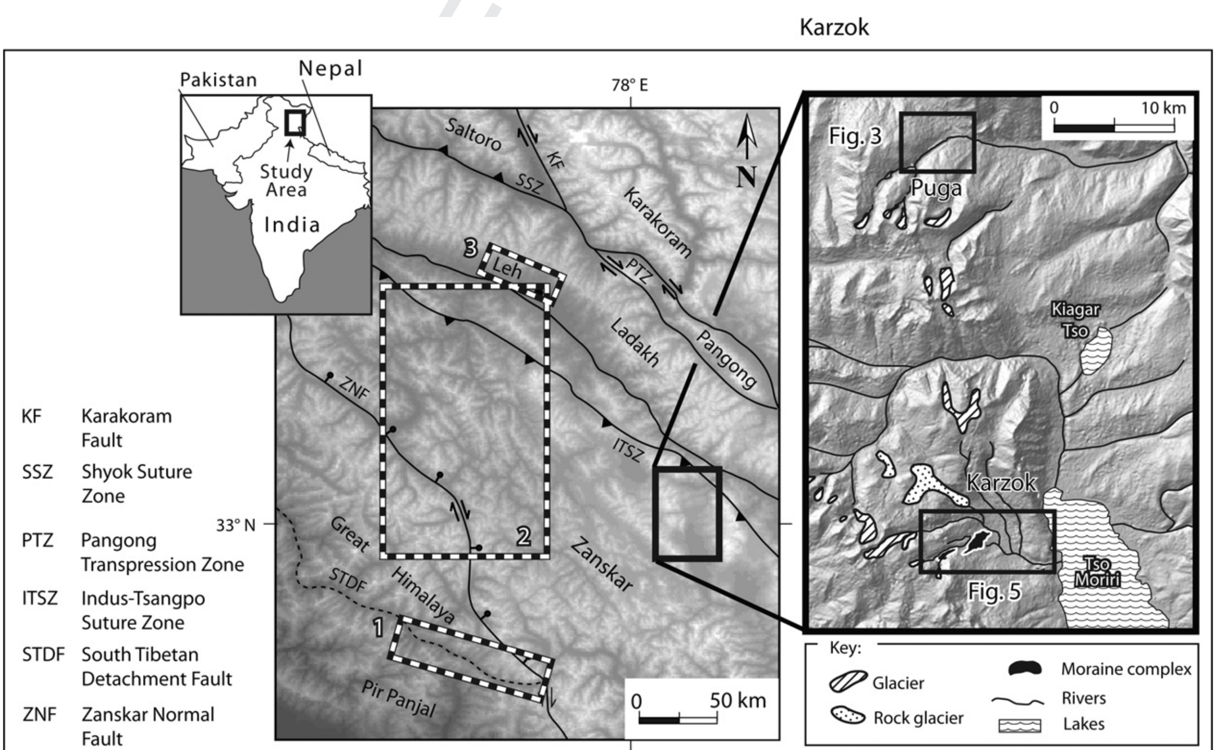

Fig. 1. Location of study area in the northwest Himalaya of northern India. Box 1–field area of Owen et al. (2006); box 2–field area of Taylor and Mitchell (2000); box 3–field area of Owen et al. (1997, 2001).

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September and ~35% falling from December to March (Osmaston, 1994; Taylor and Mitchell, 2000). However, Osmaston (1994) present anecdotal data that suggest precipitation is higher, possibly 200–250 mm/yr (Osmaston, 1994). Precipitation at altitudes <5500 m asl may fall as rain, but above this elevation, it falls as snow (Ives and Messerli, 1989).

Leh, on the southern slope of the Ladakh Range, has January mean maximum and minimum temperatures of −2.8 °C and −14.0 °C, respectively, with a July mean temperature maximum of 24.7 °C and a minimum of 10.2 °C (Osmaston, 1994; Taylor and Mitchell, 2000). There is a strong temperature gradient with altitude (~1 °C increase per 170 m) and an increase of precipitation (not quantified) (Derbyshire et al., 1991).

Satellite Tropical Rainfall Measuring Mission (TRMM) data are available for the entirety of the Himalayan-Tibetan orogen through the National Aeronautics and Space Administration's (NASA) Giovanni TRMM Online Visualization and Analysis System (TOVAS). Precipitation information plotted for the region outlined in Fig. 1 illustrates the strong precipitation gradient from the southern to northern ranges (Fig. 2). The Puga and Karzok valleys are located within different precipitation ranges: the Puga and Karzok valleys receive 500–600 mm/yr and 600–700 mm/yr precipitation, respectively. In contrast, the TRMM data shows that the annual precipitation in Lahul and the Ladakh Range is 800–900 mm/yr and 400–500 mm/yr, respectively.

Across the Transhimalaya, two-thirds of the annual precipitation is supplied by the south Asian monsoon during the summer, whereas the remaining one-third is brought by the mid-latitude westerlies during the winter (Murakami, 1987; Benn and Owen, 1998). Geochemical and paleontological studies of lake core records in Zanskar and Ladakh from Tso Kar (Demske et al., 2009) and Pangong Tso (Gasse et al., 1996), and in Tibet from Seling Co (Gu et al., 1993) and Sunxi-Longmu Co (Gasse et al., 1991; Gasse, 1993) indicate that the strength of the south Asian summer monsoon has fluctuated considerably during the Late Quaternary (Gasse et al., 1996; Bookhagen et al., 2005; Demske et al., 2009), and at times of increased intensity may have contributed 40–100% more precipitation than today (Shi et al., 2001).

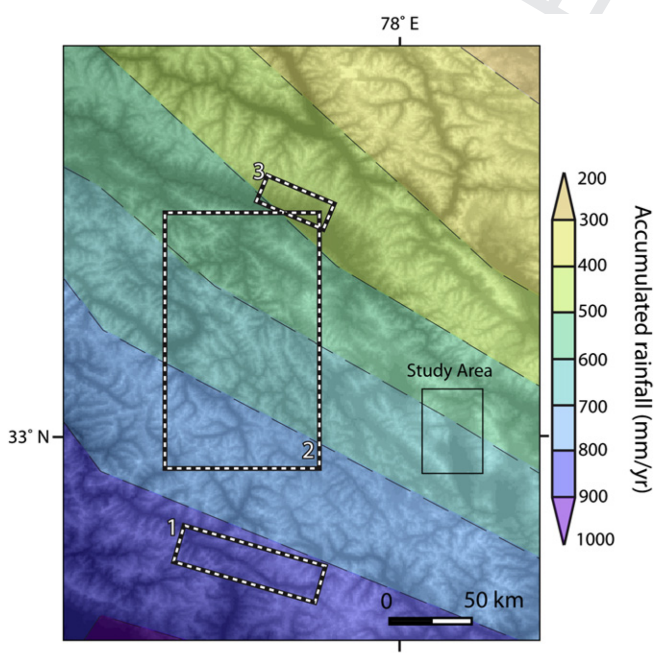

Fig. 2. Annual precipitation values for the overview map shown in Fig. 1, averaged over a 30-year period. Map generated using TRMM data from the NASA (2009) Giovanni TOVAS utilizing data from January 1979 to June 2009. Box 1 delineates field area of Owen et al. (2006); box 2 delineates field area of Taylor and Mitchell (2000); box 3 delineates field area of Owen et al. (1997, 2001).

2.1. Previous glacial geologic studies

Studies in Lahul utilizing OSL and ^{10}Be dating methods define four glacial stages: the Chandra, Batal (I and II), Kulti, and Sonapani (I and II) (Owen et al., 1995, 1997). During the Chandra glacial stage extensive valley glacier systems advanced to elevations <3800 m asl and extended >100 km, but an absolute age for this glaciation has not yet been determined. Batal glacial stage (15.5–12 ka) ice was also an extensive glacier valley system that stretched >100 km and reached below 4000 m asl. Kulti glacial stage (~11.4–10 ka) glaciers extended ~10 km from their present positions and were restricted to tributary valleys. The Sonapani glacial stage (a few hundred years ago) saw glaciers advancing <2 km from the modern-day ice margin. In the Zanskar Range, Osmaston (1994) used geomorphic methods to identify four glacial stages (M1, M2, M3, and M4) but did not undertake any numerical dating. Mitchell et al. (1999) and Taylor and Mitchell (2000) later examined the glacial record in Zanskar using geomorphic mapping and OSL dating. They adopted the glacial stage names proposed by Owen et al. (2001) for Lahul and argued for extensive glaciation during the Chandra glacial stage in Zanskar. Taylor and Mitchell (2000, 2002) cited the location of boulders on high rock benches >100 km from the present-day ice margin and suggested they are Chandra glacial stage erratics. Taylor and Mitchell (2000, 2002) also suggested that during the Batal glacial stage glaciers were confined to tributary valleys and were sourced by the High Himalaya and the Nimaling massif, requiring glaciers to have extended >30 km from their present-day positions. Taylor and Mitchell (2000) suggested that the Kulti stage glaciation was restricted to tributary valleys, reaching only ~15 km from present-day positions. Sonapani glacial stage moraines are located <2 km from present-day glacier termini, but Taylor and Mitchell (2000) did not undertake any numerical dating on these.

Taylor and Mitchell (2000) adopted Owen et al.'s (2001) Lahul-based glacial stage names for the Zanskar Range. However, the numerical dating of Owen et al. (2001) showed that this was not appropriate since the correlated landforms were of different ages (see Owen et al., 2002b for discussion). Owen et al. (2002b) pointed out that the "erratics" described by Taylor and Mitchell (2000, 2002) were derived locally and many are non-glacial in origin. Taylor and Mitchell's (2000) OSL dating of lacustrine sediments associated with Batal glacial stage deposits in the Zanskar Range provided an age of ~78 ka—markedly different from ^{10}Be ages of moraine boulders from the Batal glacial stage in Lahul. Taylor and Mitchell (2000, 2002) acknowledged this but did not take into account the possibility that glaciation was asynchronous between Lahul and Zanskar (Owen et al., 2002b). OSL dating of associated fluvioglacial sediments by Taylor and Mitchell (2000) date the Kulti glacial stage end moraines to ~16 and ~12 ka, which contrasts markedly with the early Holocene ^{10}Be ages for the Kulti glacial stage in Lahul (Owen et al., 2001). Using recessional moraines and associated landforms Taylor and Mitchell (2000) argued that the maximum extent of glaciers during the Kulti glacial stage occurred at ~13 ka with a late stage landform at ~10 ka. This contrast in ages, presuming the dating is robust, illustrates the problems of using morphostratigraphy to correlate glaciation across mountain ranges.

Damm (2006) extended the glacial chronology in the Zanskar Range using geomorphic evidence, and recognized eight glacial advances in the Markha Valley and northern Nimaling Mountains. From oldest to youngest, Damm (2006) called these glacial advances,

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the Skio I, Skio II, Chaluk, Hankar, Nimaling I, Nimaling II, Gapo Ri I/Dzo Jongo I/Kang Yaze and the Gapo Ri II/Dzo Jongo II/Tasken Ri II and correlated these with chronologies established by Fort (1983) in the Ladakh Range. Damm (2006) also compared them to landforms described in Osmaston's (1994) studies in the Zanskar Range and to chronologies in Lahul (Owen et al., 1995, 1997; Owen and England, 1998). However, Damm (2006) did not undertake any numerical dating.

Fort (1983) and Burbank and Fort (1985) undertook the first glacial geologic study of the southern slopes of the Ladakh Range and presented evidence for at least four glacial advances. Later work by Owen et al. (2006) confirmed the evidence for four glacial advances and recognized a fifth glacial advance, which they called the Bazgo glacial stage. Owen et al. (2006) summarized the evidence for glaciation on the southern slopes of the Ladakh Range and provided ^{10}Be exposure ages to define the timing of glaciation. Their data showed that glaciers filled the Indus Valley during the oldest glacial stage (>430 ka), the Indus Valley glacial stage, with an extensive valley system extending >100 km. Owen et al. (2006) showed that glaciers extended to the mountain front of the southern Ladakh Range at an altitude of 3300–3600 m asl, ~15 km from the present glaciers, during the Leh glacial stage, between ~130 and 200 ka. These ages confirmed earlier-determined ^{10}Be ages of Brown et al. (2002) on a moraine near Leh (recalculated to ~150 ka using the scaling models and production rates in our paper). A less extensive glacier advance, the Kar glacial stage, extended to 4300–4600 m asl, <7 km from present ice margins and was dated by Owen et al. (2006) to the last glacial cycle, but due to data scatter could not be better defined. The Bazgo glacial stage, was dated to 41–74 ka, and records a glaciation when glaciers extended to 4600–4800 m asl, ~5 km from the present glacier positions (Owen et al., 2006). Moraines of the Khalling glacial stage are present at 4950–5200 m asl, within <5 km from the present glaciers, and likely formed during an early Holocene glacier advance; however, insufficient data makes the age of the Khalling glacial stage tentative (Owen et al., 2006).

Reconstructions for former equilibrium-line altitudes (ELAs) for Lahul, Zanskar, and Ladakh are sparse owing to the lack of good topographic maps, the poor resolution on most remote imagery, and the lack of preservation of many of the glacial landforms. Nevertheless, Burbank and Fort (1985) presented ELA calculations for the southern slopes of the Ladakh Range and northern slopes of the Zanskar Range. Since they did not have any absolute dating they assigned moraines to stages based on position and characteristics such as boulder and moraine weathering. Burbank and Fort (1985) noted two major glacial moraines in both southern Ladakh and northern Zanskar and attribute them to the Leh glacial stage, suggesting that these formed during the late Pleistocene maximum advance, and the Kar glacial stage was the recessional stage representing a retreat of ice during the Lateglacial. Leh glacial stage moraines in Ladakh extend ~15 km downvalley from the 1985 ice margin and Kar glacial stage moraines reach ~8 km downvalley. Zanskar moraines indicate more restricted glaciation; Leh glacial stage moraines are located at ~10 km from the 1985 glacial margin with the Kar glacial stage moraines located ≤5 km from the 1985 ice margin. ELA depressions for the Ladakh Range and the Zanskar Range calculated from the Leh stage moraine by Burbank and Fort (1985) are 900–1000 m and only 500–600 m, respectively.

Damm (2006) also reconstructed ELAs within the Zanskar Himalaya but they are difficult to directly compare with exact dating of glacial moraine boulders. Damm (2006) showed ELA depressions >1000 m in the Skio I and Skio II stages with progressively lower values through time: 670 m during the Chaluk, 510 m during the Hankar, 400 m during the Nimaling I, 350 m during the Nimaling II, and ELA depressions <70 m for the Gapo Ri I/Dzo Jongo I/Kang Yaze and Gapo Ri II/Dzo Jongo II/Tasken Ri II stages. These ELA depression values chronicle progressively more restricted glaciation over time in Zanskar.

Former ELAs were not calculated for the Puga or Karzok valleys because appropriate glacial landforms (e.g. terminal moraines) are not preserved. Furthermore, it is difficult to use ELA to quantify the magnitude of glaciation in high mountain regions due to complicating factors on mass balance such as snow input from avalanching, debris cover, and topographic effects (Benn and Lehmkuhl, 2000). Future studies might utilize better-preserved moraines in order to reconstruct former ELAs.

3. Methods

3.1. Field methods

Landforms in the Puga and Karzok valleys were identified and mapped in the field aided by topographic maps generated from a 3 arc-second (~90 m) Shuttle Radar Topography Mission (SRTM) digital elevation model (DEM) (Jarvis et al., 2006). Present-day glacier locations and extents were observed in the field or determined by analysis of NASA Worldwind (NASA, 2006) and Google Earth imagery (Google and Google Earth, 2009).

Moraines were divided on the basis of morphostratigraphy in both study areas. Well-defined, high-relief moraines with sharp ridge crests were chosen in preference to degraded moraines for ^{10}Be dating. Three to seven moraine boulders were sampled for ^{10}Be dating from each moraine to help determine their age. Most of the sampled boulders are composed of granite, but other quartz-rich lithologies were also sampled such as granodiorite and augen gneiss, and where possible, large, unweathered, tabular boulders >1 m long with well-developed rock varnish and inset into the moraine were chosen in preference to those that showed any possible signs of weathering and/or toppling. Horizontal, flat-topped and debris-free boulders were selected to avoid the need for shielding corrections; however, five boulders (India-45, India-47, India-52, TM-B, and TM-C) required shielding corrections for sloping surfaces.

Using a hammer and chisel, ~500 g of rock was collected from each boulder; the sampled depth was 1–5 cm. The characteristics of the boulder, including lithology, size, shape, emplacement, rock varnish, angle of sampled surface, and topographic shielding were recorded. Topographic shielding was determined by taking inclination measurements from the boulder surface to the surrounding summits and ridges. Photographs were taken of the boulders and sampling sites (Data Supplement Item). The location of each boulder was recorded using a hand-held Garmin GPS60.

3.2. ^{10}Be surface exposure age dating

Purification of quartz, chemical separation of Be, and cathode preparation followed the methods described in Kohl and Nishiizumi (1992) and Dortch et al. (2009). Puga samples (India-10 to India-20 and India-45 to India-55) were processed in the geochronology laboratories at the University of Cincinnati. Karzok samples (TM-B to TM-F and TM-1 to TM-20) were processed at Korea University. All samples were loaded into steel cathodes. The Puga valley samples were measured at the Purdue Rare Isotope Measurement (PRIME) Laboratory and the Karzok valley samples were measured at the Accelerator Mass Spectrometry Laboratory at the Korea Institute of Geosciences and Mineral Resources using Accelerator Mass Spectrometry (AMS).

^{10}Be exposure ages were calculated using the CRONUS ^{10}Be-^{26}Al exposure age calculator (version 2.2, Balco, 2009; Table 1 and data supplement item Table DS1), which utilizes Lal's (1991) and Stone's (2000) scaling factors and a density value of 2.75 g/cm^3.

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Table 1
Locations of sampled boulders, boulder size, weathering, lithology, sample thickness, shielding, and ^{10}Be measurements and surface exposure ages.

Sample name	Relative age	Location		Altitude (m asl)	Boulder size			Weathering characteristics	Lithology	Sample t hickness (cm)	Topographic shielding factor	^{10}Be (104 atoms/g)	Minimum ^{10}Be exposure age (ka)
		Latitude (°N)	Longitude (°E)		Length (cm)	Width (cm)	Height (cm)						
Puga													
India-45	PM-3	33.226	78.166	5266	175	110	120	SW	granite	3	1.00	4.45 ± 0.30	0.46 ± 0.05
India-46	PM-3	33.226	78.167	5263	170	190	170	SW/MB	metagranite	3	1.00	1.82 ± 0.21	0.19 ± 0.03
India-47	PM-3	33.226	78.167	5257	170	130	135	SW	granite	3	1.00	11.74 ± 0.47	1.22 ± 0.12
India-48	PM-3	33.226	78.167	5267	185	90	95	SW/SB	granite	2	1.00	10.22 ± 0.48	1.05 ± 0.10
India-49	PM-3	33.226	78.167	5260	155	110	125	SW	granite	4	1.00	2.40 ± 0.31	0.25 ± 0.04
India-50	PM-3	33.226	78.167	5265	~80	~50	~100	SW	granite	3	1.00	2.55 ± 0.34	0.26 ± 0.04
India-10	PM-2	33.245	78.200	4910	250	180	135	SW/SB	leucogranite	3	1.00	62.54 ± 3.21	7.59 ± 0.77
India-11	PM-2	33.245	78.201	4905	270	220	140	MW/SB	granite	3	1.00	42.94 ± 2.96	5.22 ± 0.58
India-12	PM-2	33.245	78.201	4904	450	420	170	SW/MB	granite	2	1.00	20.84 ± 1.97	2.51 ± 0.32
India-13	PM-2	33.245	78.201	4899	200	170	80	SW/DB	granite	2	1.00	307.50 ± 7.55	37.46 ± 3.41
India-14	PM-2	33.244	78.202	4886	270	120	100	MW	metagranite	2	1.00	5.45 ± 1.22	0.66 ± 0.16
India-56	PM-2	33.244	78.198	4924	170	110	90	SW/DB	granite	3	1.00	29.04 ± 0.75	3.50 ± 0.32
India-57	PM-2	33.245	78.199	4921	~100	~50	~90	SW	granite	3	1.00	17.76 ± 0.70	2.14 ± 0.21
India-51	PM-1	33.237	78.182	5104	150	100	65	SW/MB	leucogranite	5	1.00	1005.93 ± 26.57	116.89 ± 10.93
India-52	PM-1	33.237	78.182	5092	121	~80	70	SW/MB	granite	2	0.98	435.00 ± 5.50	49.57 ± 4.41
India-53	PM-1	33.237	78.182	5091	170	150	60	SW/DB	granite	3	0.97	469.51 ± 5.37	54.76 ± 4.86
India-54	PM-1	33.237	78.182	5094	200	155	45	SW/DB	granite	2	0.96	308.02 ± 3.85	35.59 ± 3.15
India-55	PM-1	33.237	78.182	5093	165	~60	150	HW/SB	granite	3	0.98	365.30 ± 4.26	42.21 ± 3.74
India-15	PM-0	33.247	78.203	4863	330	190	120	SW/MB	granite	5	1.00	1010.61 ± 39.47	131.43 ± 12.94
India-16	PM-0	33.248	78.202	4802	310	130	100	SW/DB	quartzite	4	1.00	967.04 ± 33.11	128.16 ± 12.36
India-17	PM-0	33.248	78.202	4861	270	160	65	SW/SB	quartzite	2	1.00	844.49 ± 26.40	106.50 ± 10.10
India-18	PM-0	33.248	78.202	4863	210	110	70	MW	quartzite	3	1.00	947.18 ± 29.91	120.79 ± 11.51
India-19	PM-0	33.249	78.200	4875	400	220	110	SW/SB	granite	2	0.99	1292.66 ± 54.78	165.85 ± 16.71
India-20	PM-0	33.249	78.200	4876	410	270	140	MW/DB	granite	5	0.99	925.43 ± 23.46	120.38 ± 11.23
Karzok													
TM-B	KM-4	32.971	78.182	5306	170	252	160	SW/DB	augen gneiss	2	1.00	47.04 ± 8.73	4.75 ± 0.97
TM-C	KM-4	32.971	78.182	5309	180	160	70	HW/MB	granite	3	1.00	207.93 ± 15.08	21.31 ± 2.43
TM-D	KM-4	32.971	78.182	5309	290	180	90	MW/DB	metagranite	3	1.00	33.21 ± 6.28	3.39 ± 0.71
TM-F	KM-4	32.971	78.181	5318	170	170	100	MW/DB	metagranite	1	1.00	26.54 ± 3.79	2.65 ± 0.44
TM-1	KM-3	32.977	78.203	5010	70	100	124	SW/MB	gneiss	5	1.00	577.43 ± 74.55	69.51 ± 11.01
TM-2	KM-3	32.977	78.203	5010	66	90	68	MW/MB	gneiss	5	1.00	497.33 ± 26.32	59.73 ± 6.17
TM-3	KM-3	32.978	78.203	5011	81	101	126	MW/DB	granite	5	1.00	735.84 ± 33.76	88.97 ± 8.94
TM-4	KM-3	32.978	78.203	5013	84	80	163	MW/DB	gneiss	5	1.00	274.10 ± 35.09	32.65 ± 5.09
TM-6	KM-2	32.982	78.211	4859	86	75	121	MW/MB	gneiss	5	1.00	574.07 ± 30.26	74.10 ± 7.67
TM-7	KM-2	32.982	78.211	4858	100	152	185	MW/MB	gneiss	5	1.00	212.26 ± 9.20	27.09 ± 2.65
TM-8	KM-2	32.982	78.212	4855	74	174	225	HW/MB	gneiss	5	1.00	162.28 ± 15.27	20.71 ± 2.67
TM-9	KM-2	32.982	78.212	4851	73	138	136	MW/SB	gneiss	5	1.00	748.47 ± 18.34	97.54 ± 9.02
TM-10	KM-2	32.983	78.212	4850	123	174	290	SW/MB	gneiss	5	1.00	184.97 ± 23.68	23.68 ± 3.69
TM-11	KM-2	32.984	78.212	4849	127	138	205	MW/MB	gneiss	5	1.00	648.59 ± 20.25	84.32 ± 7.95
TM-12	KM-1	32.983	78.214	4785	76	192	113	SW/SB	gneiss	5	1.00	108.61 ± 12.63	14.29 ± 2.08
TM-13	KM-1	32.983	78.214	4785	52	103	197	MW/SB	gneiss	5	1.00	407.05 ± 34.90	54.10 ± 6.69
TM-14	KM-1	32.983	78.214	4782	97	123	278	MW/SB	gneiss	5	1.00	95.15 ± 7.52	12.53 ± 1.48
TM-15	KM-1	32.983	78.214	4781	121	57	143	SW/SB	leucogranite	5	1.00	994.66 ± 35.32	135.13 ± 13.12
TM-16	KM-1	32.984	78.215	4768	123	78	147	SW/SB	granite	5	1.00	563.29 ± 17.46	75.86 ± 7.13
TM-17	KM-1	32.984	78.216	4762	137	85	192	MW/MB	gneiss	5	1.00	176.24 ± 12.43	23.49 ± 2.64
TM-18	KM-0	32.961	78.254	4712	52	58	49	HW/DB	quartzite/quartz vein	5	1.00	2099.91 ± 17.71	307.58 ± 29.02
TM-19	KM-0	32.961	78.254	4713	61	52	57	HW/SB	quartzite/quartz vein	5	1.00	2137.69 ± 25.29	313.41 ± 29.74
TM-20	KM-0	32.961	78.258	4710	38	35	42	HW/MB	quartzite/quartz vein	5	1.00	1385.25 ± 29.56	197.72 ± 18.59

Boulder weathering characteristics: SW—Slightly weathered, MW—Moderately weathered, HW—Highly weathered, SB—Slightly buried, MB—Moderately buried, DB—Deeply buried.
Production rate for the CRONUS calculator is a sea level low-latitude production rate of 4.5 ± 0.3^{10}Be atoms/grams SiO_2/year and a ^{10}Be half-life of 1.36 Ma.
Isotope measurements were calibrated using KN Standard Be 0152 with a ^{9}Be/^{10}Be ratio of 8.558 × 10−12 (c.f. Nishiizumi et al., 2007).

Q3

CRONUS also allows ^{10}Be exposure age calculations based on the scaling factors of Dunai (2001), Lifton et al. (2005), and Desilets et al. (2006). In this paper, we use the Lal (1991) and Stone (2000) time-independent model. Owen et al. (2008) and Balco et al. (2009) have recently discussed scaling models, and their effects on ^{10}Be ages highlighting that the range of different scaling models can change calculated ^{10}Be ages significantly. The maximum difference between the exposure ages using the Stone (2000) and Lal (1991) scaling algorithms compared to exposure ages calculated using the Dunai (2001), Lifton et al. (2005), and Desilets et al. (2006) scaling models for our study area is large; for example, at 1 ka the ages can vary by ~8%, at 15 ka by ~10%, at 25 ka by ~20%, at 50 ka by ~43%, at 100 ka by ~40% and at 150 ka by ~47%. However, systematic corrections for scaling models would not likely affect correlation between landforms within adjacent regions considered in our study. No correction is made for boulder erosion or snow cover, so ^{10}Be ages are minimum ages.

AMS measurements report both internal (essentially analytical) and external (analytical and production rate uncertainty) error at 1σ. The larger of the two errors (external) was taken for each sample to ensure greatest certainty in the reported ages. To examine ages consistently, a 2σ error was used to statistically determine boulder outliers within a moraine sample set. Boulders with ages that did not overlap with a 2σ error were considered outliers and were removed from the dataset. The average of the remaining data points was taken to determine the moraine surface age, and the standard deviation of the viable samples is reported as the error. The ^{10}Be ages for each moraine boulder were also assessed using the Mean Square Weighted Deviation (MSWD) methods of McDougall and Harrison (1999) to test whether they could statistically represent one population or event. McDougall and Harrison (1999) remove outliers from the dataset until a statistical indicator of ~1 is reached, with a minimum of three data points required to constitute a population. In our MSWD analyses, we use a statistical indicator of ≤ 1 as the cutoff value for a viable population.

4. Study areas

Both the Puga and Karzok valleys are located in western Zanskar, southeast of Leh, south of the Indus River along the southeastern side of the Zanskar Range. The Puga valley is located within the northwest–southeast trending Tso Moriri dome along the dome's northeastern margin. The Tso Moriri dome exposes ultra-high pressure metamorphic rocks (de Sigoyer et al., 1997; Guillot et al., 1997) composed principally of granite and granodioritic orthogneisses and meta-basic rocks. The Puga valley forms a half-graben, one of a series of grabens and half-grabens extending across the Transhimalaya in Zanskar, recording post-middle Miocene extension (Steck, 2003; Thiede et al., 2006) and marked by asymmetric valley walls, lakes, and hot springs. The Karzok valley is located along the southwestern flank of the dome in metasedimentary rocks of the Mata nappe that overlie orthogneisses exposed in the dome core.

The Puga valley is located ~115 km southeast of Leh and rises from a valley floor at ~4500 m asl to high peaks at ~6000 m asl (Figs. 1 and 3). Tso Kar (Tso = lake), a salt lake which drains east through the Puga valley in times of high water (e.g. Rawat and Adhikari, 2005) is located to the west of the Puga valley. The Puga valley is ~15 km long and contains the Puga River, a small river that drains to the east. The Puga River joins with an un-named river draining Kiagar Tso to form a freshwater lake located to the south of the village of Sumdo. The Puga River continues to flow east, where it joins with the Indus River. Within the Puga valley, the Puga River helps form marshes and low-flow areas due to the contribution of various hot springs in the valley floor in central Puga (e.g. Singh et al., 2005; Azeez and Harinarayana, 2007). River flow intensifies daily and seasonally with snow and ice melt from tributary valleys.

The Puga valley and its tributaries contain abundant glacial and fluvial landforms including moraines, polished bedrock, glacial benches, hummocky terrain, and alluvial fans. In the east, the valley floor is level and is ~1 km wide, while to the west the valley floor becomes progressively narrower and uneven due to accumulations of unconsolidated debris. At its western end the Puga River has incised ~30 m through debris to form a deep gorge and ~2 km to the west of this point a large (~10 km long) tributary valley on the southern side of the main valley contains an impressive set of moraines where boulders were sampled (Fig. 4).

The Karzok valley is located ~25 km south of the Puga valley. The primary drainage of the Karzok valley follows the southern valley wall and is joined by tributary meltwater streams. These streams converge in the south-central portion of the valley and flow from west to east into Tso Moriri, a high-altitude, brackish lake set in a glacial depression (Negi, 2002). This lake has no outlet. The valley is bounded on its western side by a normal fault. Springs are present in many areas of the Karzok valley, primarily in the main east–west trunk valley, that also contribute to the valley's primary river. At its longest (trending southeast to northwest) the valley stretches for ~11 km. The Karzok valley floor is at an altitude of ~4500 m asl and surrounding peaks rise to ~6000 m asl. Glacial and fluvial landforms dominate the landscape; the most common are large alluvial fans and extensive hummocky moraines. Moraines were sampled near the town of Karzok at the mouth of the valley and in a 4-km-long tributary valley located ~4 km to the west of Karzok.

Modern glaciers are present in many of Puga's and Karzok's tributary valleys at elevations >5000 m asl. Most glaciers are <3 km and commonly <2 km long. Glaciers in the tributary valleys of Puga are typically smaller than those in the tributary valleys of Karzok. Some glaciers in the tributary valleys of Puga are debris-mantled and extend down to 4600 m asl.

5. Landform descriptions

5.1. The Puga valley

The Puga valley contains four distinct moraines. From the oldest to youngest we name these moraines: PM-0; PM-1; PM-2; and PM-3. The PM-0 moraine (Fig. 3, location A) trends generally northwestward and is located at the confluence of a tributary and the main Puga Valley. The PM-0 (Figs. 3 and 4) moraine is sharp-crested and stretches for ~60 m along its length. PM-0 has low relief; it is ~2 m high and ~3 m wide across the crest with side slopes of ~4°. PM-0 is most likely a lateral moraine due to its nearly straight morphology and its position adjacent to the valley wall. The moraine is composed of a high concentration of large boulders 1- to 2-m-long at ~1 large boulder per 5 m moraine length, as well as abundant smaller boulders (40- to 60-cm-long). The PM-0 moraine overlies alluvial outwash fan deposits. Less distinct, discontinuous ridges appear on either side of the PM-0 moraine. The PM-0 moraine was formed when a glacier advanced down the main valley from the northwest.

The PM-1 moraine is a lateral moraine (Fig. 3, location B, and Fig. 4) and forms a distinctive southwest-trending ridge, which rises ~3 m. The sampled section of the moraine is ~200 m long and ~6 m wide. Up-valley from the sampling locations, the moraine ridge becomes less distinct as it onlaps the valley wall and downvalley as it trends into hummocky terrain. Boulders on the PM-1 moraine are generally smaller than those on the PM-0 and PM-2 moraines (<2 m) and the PM-1 moraine has larger boulders

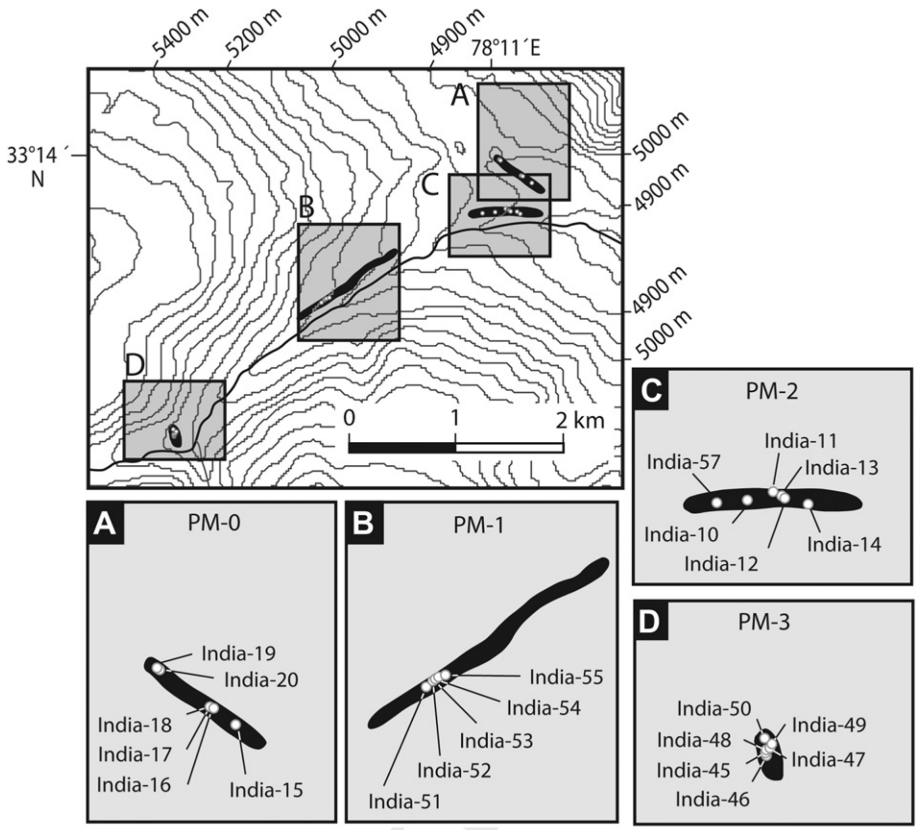

Fig. 3. Puga Valley moraine locations and sampling sites.

Fig. 4. Puga Valley moraines and sampled boulders. A) PM-0 moraine showing sample India-13, viewed to the north showing surrounding moraines, B) PM-1 moraine, sample India-54, viewed to the west showing typical boulder size and abundance, C) PM-2 moraine, viewed to the south (no boulders were sampled in this view), D) PM-3 moraine showing the boulder for sample India-48 viewed to the west and showing valley profile in background.

with an axis >1.5 m long and are less abundant than on the PM-0 and PM-2 moraines. Moraine PM-1 has ~2 large boulders per 10 m of moraine length.

The PM-2 moraine (Fig. 3, location C, and Fig. 4) is located ~200 m up-valley from PM-0 and ~0.5 km downvalley from the PM-1 moraine, and is <2 m high and ~4 m wide, and slopes at ~4° to the north. PM-2 most likely represents a latero-frontal moraine. The moraine stretches for ~60 m and is covered with large, 2- to 3-m-long boulders. The moraine becomes difficult to distinguish as it onlaps the northwestern valley wall. Boulders become generally larger and more abundant farther from the valley walls, near sample locations India-12, India-13, and India-14. The PM-2 moraine was formed by a glacier that originated from the southwest.

The PM-3 moraine (Fig. 3, location D, and Fig. 4) is an arc-shaped ridge that rises ~2 m and is ~8 m wide, and is broadly perpendicular to the valley walls. Large boulders on the PM-3 moraine are more abundant than on the PM-1 moraine, and boulders in general (small, moderate, and large) are more abundant than on all other moraines. The northwestern edge of the moraine onlaps the valley wall and becomes less distinct up-valley. The moraine is located in the same tributary valley as the PM-1 and PM-2 moraines, and was sourced from the same up-valley glacier.

5.2. The Karzok valley

The Karzok valley contains a distinct moraine, which is the most extensive preserved glacial landform in the valley and provides evidence for the most extensive glaciation — named KM-0 —, and two large moraine complexes. The KM-0 moraine (Fig. 5, location A, and Fig. 6) is located ~4 km to the east of the younger moraine complex, near the village of Karzok at the far eastern end of Karzok valley, ~600 m west of Tso Moriri (Fig. 5). The KM-0 moraine is a lateral moraine located on a gently sloping ridge ~30 m above the valley floor. The moraine is intensely weathered with low relief, rising to ~0.5 m. Several streamlined bullet-shaped boulders are present on the surface of the moraine. The larger moraine complex was sampled on three moraines that form distinct ridges (KM-1, KM-2, and KM-3) (Fig. 5, location B). The KM-1 moraine (Figs. 5 and 6) is a sharp-crested lateral moraine ~1 km long, ~10 m high and ~13 m wide. Large boulders >1.5-m-long, smaller boulders, and cobbles are present on its surface. Most of the boulders are highly weathered and are covered with abundant lichen.

The KM-2 moraine (Figs. 5 and 6) is a latero-frontal moraine that is located ~30 m to the southwest of the KM-0 moraine. The moraine is sharp-crested but the outer (northern) side is much more subdued, and gentler than the inner, southern side. Most of the boulders are severely weathered and low-lying. Large boulders (>1.5 m) are relatively common on the western end of the moraine where there is ~1 boulder per 5 m of moraine length, but boulders become rarer east of the sampling site TM-8 (Fig. 5). Moderate sized boulders ~0.5 m long are much more common and persist over the entirety of the moraine.

The KM-3 moraine (Figs. 5 and 6) is a latero-frontal moraine, located ~2.5 km from the present glacier. The moraine is ~1 m high and ~6 m wide. Large boulders are rare, with the most common boulder size being ~1 m long. Moderate sized boulders, cobbles, and pebbles are also abundant on this moraine, and are very weathered.

The KM-4 moraine (Fig. 5, location C, and Fig. 6) is a sharp-crested frontal moraine and is located ~0.5 km from the present glacier. Large boulders (>1 m long), small angular boulders and cobbles are present on the surface of the moraine and most do not show any significant signs of weathering.

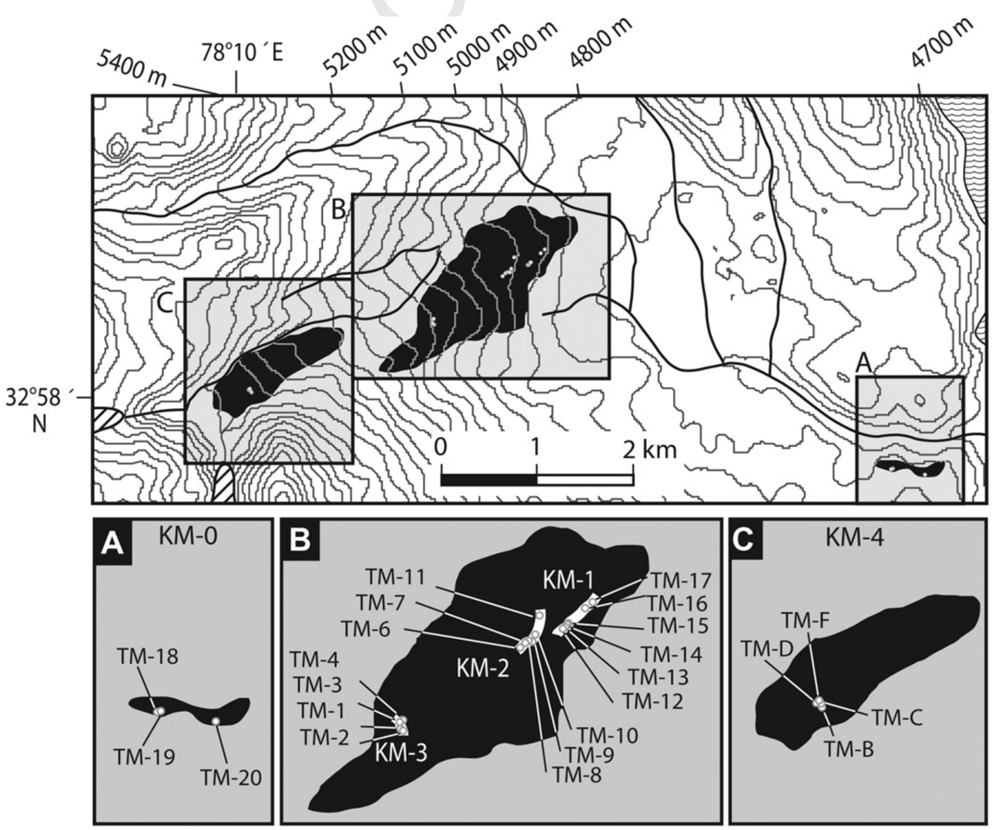

Fig. 5. Karzok Valley moraine locations and sampling sites.

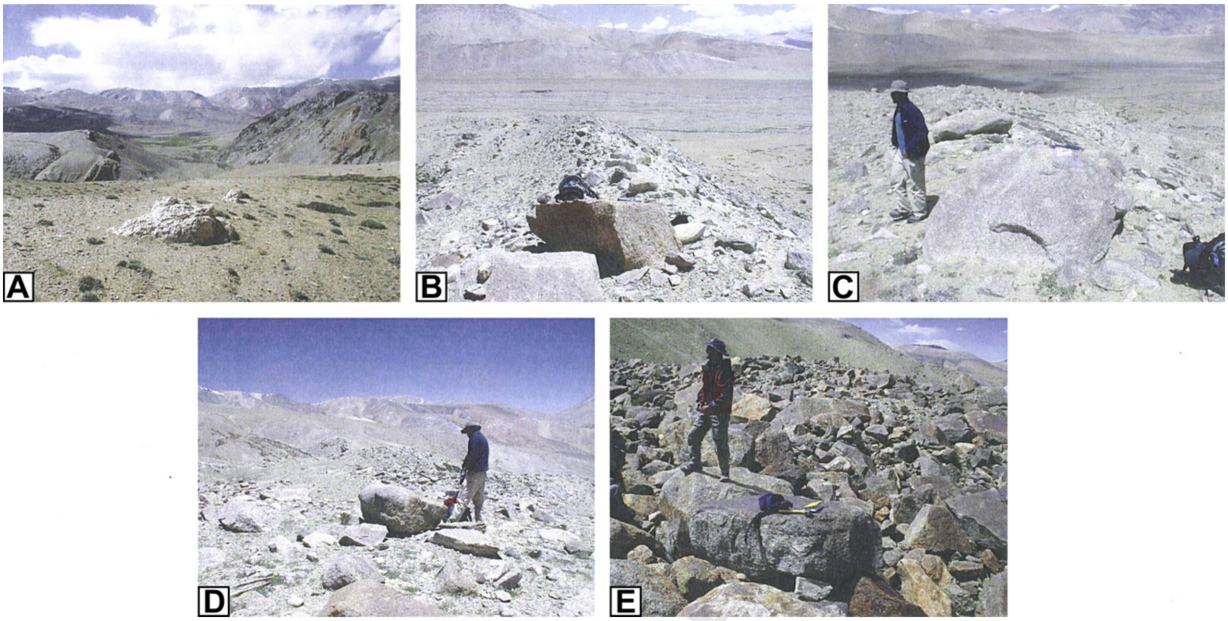

Fig. 6. Karzok Valley moraines and sampled boulders. A) KM-0 moraine showing the boulder for sample TM-18 viewed to the north showing low relief and deflated nature of moraine, B) KM-1 moraine showing the boulder for sample TM-14 viewed to the west showing steep moraine sides, C) KM-2 moraine showing the boulder for sample TM-7 viewed to the south, D) KM-3 moraine showing the boulder for sample TM-1 viewed to the west, E) KM-4 moraine viewed to the west illustrating typical boulders.

6. Ages of landforms

Sample data and exposure age results and are listed in Table 1 and presented in Fig. 7. These data are grouped by the age of each moraine.

6.1. The Puga valley

Moraines sampled in the Puga valley are distinct and physically separate, with many large boulders available for sampling. ^{10}Be ages for the Puga samples cluster well within each moraine, with

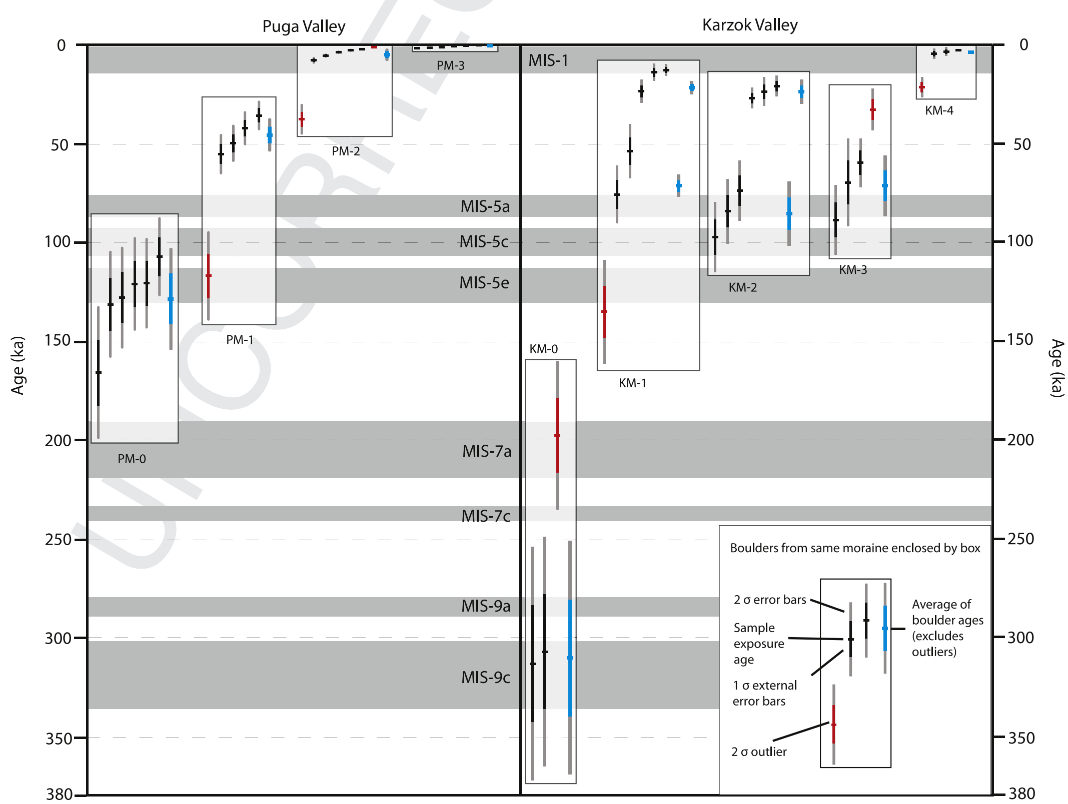

Fig. 7. ^{10}Be boulder age plotted by relative age and study area.

few outliers. The data agree with the morphostratigraphy of the moraines, with the outermost moraines having the oldest ages and successive moraines up-valley having progressively younger ages. The PM-1 lateral moraine, although farther up-valley than the younger PM-2 end moraine, is located closer to the valley wall and is thus morphostratigraphically older than PM-2. Moreover, the PM-1 moraine is more denuded, and has smaller (generally <1 m diameter cf. 1–2 m diameter) and lower relief surface boulders than the PM-2 moraine. The ^{10}Be ages support this stratigraphic interpretation.

The ^{10}Be ages for the PM-0 moraine boulders range from ~107 to ~166 ka with a tighter cluster between ~107 and ~131 ka and a mean exposure age of ~128.8 ± 20.1 ka. Four of the five dated boulders for the PM-1 moraine cluster between ~36 and ~55 ka with an average of ~45.5 ± 8.4 ka, with an outlier (India-51) of ~117 ka. The ^{10}Be ages for PM-2 moraine boulders cluster between 2.1 and 7.6 ka, with two outliers at 37 ka (India-13) and 0.7 ka (India-14). For the PM-2 moraine, the boulder average exposure age is 4.2 ± 2.2 ka. The PM-3 moraine boulders have ^{10}Be ages that cluster range from 0.2 to 1.2 ka with no outliers. The average of the boulder ages for moraine PM-3 is 0.6 ± 0.5 ka.

6.2. The Karzok valley

The moraines in the Karzok valley are large and complex. ^{10}Be ages for boulders on the moraine complexes do not conform well to a singular, defined age. However, sample sets from well-defined and separate, single moraines (KM-0 and KM-4) cluster relatively well.

The three boulders sampled from the geomorphically distinct moraine KM-0 contain one outlier; the mean age (excluding the outlier) is 310.5 ± 4.1 ka, with an outlier (TM-20) age of 198 ka. Boulders were sampled from the distinct ridges on the moraine complex: six from KM-1, six from KM-2, and four from KM-3. When considered separately, boulder ages from these moraine ridges cluster poorly. KM-1 has a two-boulder cluster at ~54 ka to ~76 ka, and a three boulder cluster at 12.5 to 23.5 ka with an outlier (TM-15) age of ~135 ka. KM-2 has two clusters of three boulders at ~74 to ~98 ka and ~21 to ~27 ka, with no outlier ages. KM-3 shows a three boulder cluster at ~60 to ~89 ka with the youngest boulder as an outlier (TM-4) age of ~33 ka. Four boulders were sampled from the sharp-crested frontal moraine KM-4 and age results show a cluster of three boulders from 2.7 to 4.7 ka with an outlier (TM-C) age of 21.3 ka. The average for these boulders returns an age of 3.6 ± 1.1 ka.

6.3. Further considerations

The Puga valley exposure ages after removing 2σ outliers return approximate average moraine ages of 128.9 ± 20.1 ka, 45.5 ± 8.4 ka, 4.2 ± 2.2 ka, and 0.6 ± 0.5 for moraines PM-0, PM-1, PM-2, and PM-3, respectively (Table 1). ^{10}Be ages after removing 2σ outliers for the KM-3, and KM-4 moraines in the Karzok valley are, 72.7 ± 14.9 ka and 3.6 ± 1.1 ka, respectively (Table DS2). Only 3 boulders were sampled from the KM-0 moraine, and removal of 2σ outliers results in 2 boulders, which give an average age of 310.5 ± 4.1 ka. Although 6 boulders were sampled from the KM-1 moraine, the boulder ages do not display a valid population of 3 or more boulders, and the KM-2 moraine has two populations of 3 or more boulders with average ages 85.3 ± 11.8 ka and 23.8 ± 3.2 ka. The ^{10}Be age distributions for the KM-1, KM-2, and KM-3 ridges are complex and a separate age for each of these moraines cannot be assigned with confidence.

Of the Puga valley moraines, only PM-0 passes MSWD analysis with an average age of 121.4 ± 9.6 ka (compared to 128.6 ± 20.1 with 2σ analysis). Karzok valley moraines KM-1, KM-2, and KM-3 show apparent clusters represented on each moraine at ~20 ka and ~80 ka (Fig. 7). Considered separately, Karzok valley moraines do not pass MSWD analysis, however, when considered together boulders from the large moraine complex containing moraine ridges KM-1, KM-2, and KM-3 pass MSWD analysis with two populations at 78.6 ± 7.9 ka and 23.7 ± 2.6 ka. These ages overlap with the 2σ averages for KM-3 (72.7 ± 14.9 ka) and KM-2 (85.3 ± 11.8 ka and 23.8 ± 3.2 ka) and provide a compelling pattern. Older boulders (~80 ka) may represent the initial moraine stabilization as remnants of a glacial advance ~80 ka, but with cosmogenic inheritance and younger boulders (~24 ka) representing deposition by a subsequent glacial advance at ~24 ka.

Older 2σ ^{10}Be age outliers in both valleys may be due to incorporation and reactivation of remnant boulders from previous glacial advances in younger glacial deposits. Of the two younger outliers located on the KM-0 (TM-20) and KM-3 (TM-4) moraines, the KM-3 moraine boulder (TM-4) fits into MSWD-deduced population at 23.7 ka (as compared to 23.8 ± 3.2 with 2σ analysis). This boulder could also represent an unearthed boulder through moraine settling or a boulder more susceptible to erosion, however, greater erosion is not likely on the TM-4 boulder because it is the same lithology as moraine boulders TM-1 and TM-2, which return much older ages.

7. Discussion

^{10}Be ages for moraine boulders in the Puga valley show clear age clusters for each sampled moraine. In contrast, the ^{10}Be age distribution for boulders collected from the Karzok valley moraines are complex with a large range of ages on individual moraines. KM-4 and PM-2 correlate well between the valleys with ages at 3.6 ± 1.1 and 4.2 ± 2.2 ka, respectively. However, the record of the oldest Karzok moraine (TM-0, ~311 ka) is asynchronous with the oldest Puga moraine (PM-0, ~116 ka). Correlation of moraine ages between the valleys is limited.

Boulder ages for the moraine complex in the Karzok valley (KM-1, KM-2, and KM-3) suggest that glaciers advanced at ~80 ka and/or ~24 ka (using 2σ mean and MSWD values). However, given the spread of ages on individual moraines, it is not possible to provide precise and accurate ages for these moraines. Nevertheless, Taylor and Mitchell (2000) showed that a glacial advance occurred elsewhere in the Zanskar at ~78 ka, and it seems reasonable to argue that our ~80 ka also argues for a glacial advance at ~80 ka. Moraines dated in Ladakh (Owen et al., 2006) also have some boulders from ~80 ka, but once again, scatter in their dataset does not allow for confident definition of glacial advance/retreat at that time, although the coincidence in ~80 ka is striking.

Current data for the Puga and Karzok valleys suggest a gap in the glacial record during the early Holocene (Fig. 8). The obvious gap in the Puga and Karzok records also contrasts markedly with the glacial record for Lahul to the south. Kulti and Batal stage glaciations in Lahul (Owen et al., 1997) show glacial advances at 11.4 to 10 ka and 15.1 to 12 ka, respectively, during which time there is no evidence for glacial advance in either the Puga or Karzok valleys. Taylor and Mitchell (2000), however, discuss records indicating advance between 16 and 12 ka, which overlaps with ages of moraines in Lahul. In the Ladakh Range to the north, the Khalling stage moraine could not be confidently dated to the early Holocene due to an inadequate number of sampled boulders (Owen et al., 2006).

Owen et al. (2006) and Owen (2009) discuss early Holocene advances in other regions of the Himalaya, including the studies of Barnard et al. (2004a, b) in the Garhwal to the south of Lahul, Khumbu Himal to the far east of Lahul (Finkel et al., 2003), and the

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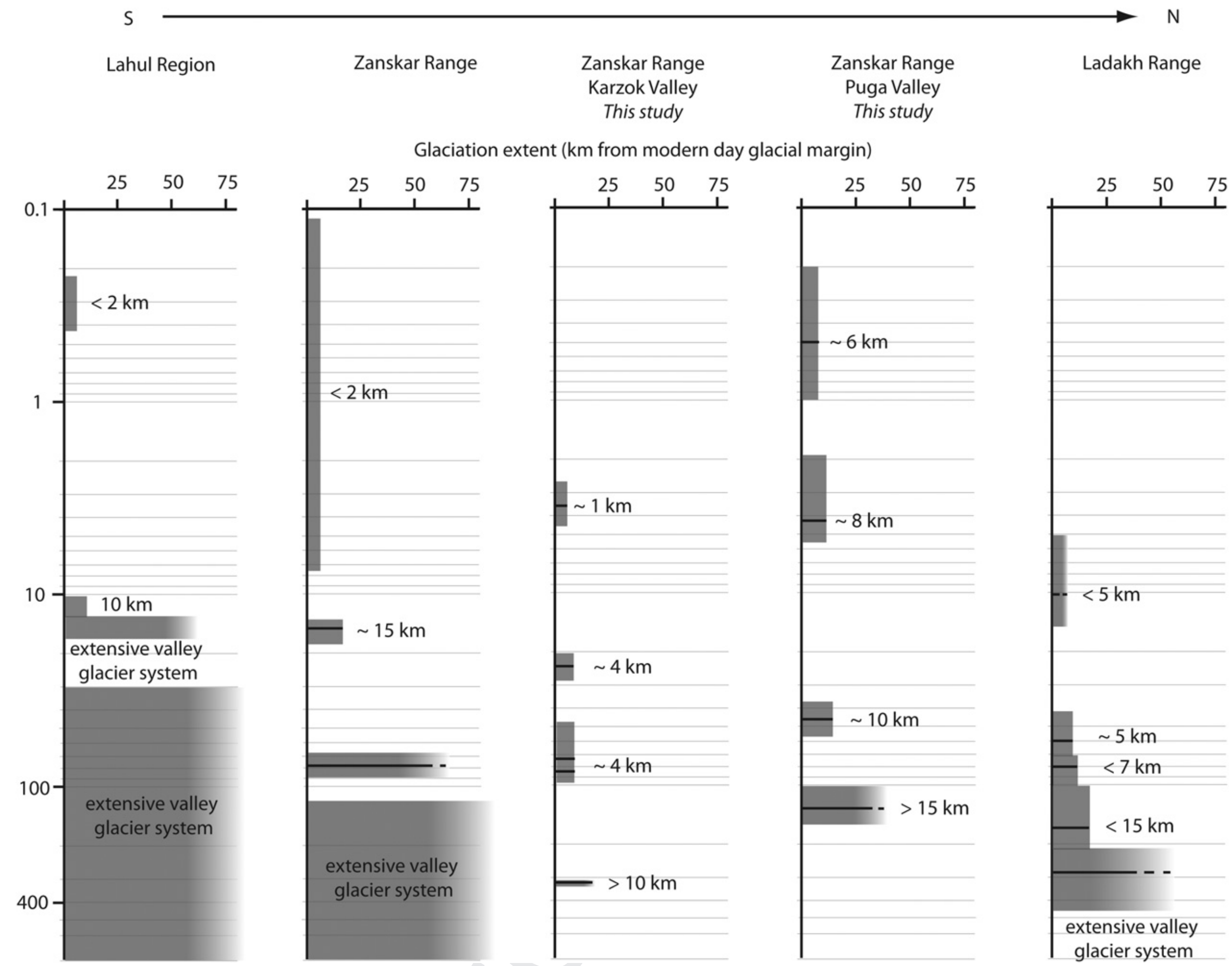

Fig. 8. Comparison of timing and extent of glaciation in Lahul, Zanskar, and Ladakh. Lahul data are from Owen et al. (1997, 2001), Zanskar data from Taylor and Mitchell (2000) and this study, and Ladakh data are from Brown et al. (2002) and Owen et al. (2006). Solid black lines indicate average age of a single landform (this study) or multiple landforms of a single glacial stage (Owen et al., 2006). Gray bars indicate standard deviation uncertainty in ages (this study, Owen et al., 2006), range of ^{10}Be boulder ages (Owen et al., 1997, 2001), or range in OSL ages (Taylor and Mitchell, 2000). Dashed black lines and gray bars with a gradient indicate uncertain extent of glacial advance.

Karakoram located to the north of the Ladakh Range (Owen et al., 2002a). Early Holocene glaciation is common in many Himalayan records but is not apparent in the Puga or Karzok valleys and may or may not have occurred in the Ladakh Range. Although further study is needed to define the timing of the Khalling stage Ladakh glaciation, the records at Puga and Karzok suggest no extensive glaciation at that time. Evidence for early Holocene glaciation is also lacking on the northern side of Mount Everest in the Rongbuk Valley (Owen et al., 2009). Although it is possible that early Holocene glacial landforms have not been preserved, Owen et al. (2009) suggest this is not likely and argue that the topography was too great to allow penetration of an enhanced monsoon north of Mount Everest during the early Holocene. The lack of an early Holocene glacial advance in Zanskar might reflect similar topographic controls. However, Owen et al. (2006) argue that the Khalling glacial stage in the Ladakh Range is early Holocene and this is clearly to the north of our study area and more distance from monsoon influences.

Glacial records in Lahul and the Zanskar Range indicate a major change in style in glaciation from Lahul to Zanskar: Lahul glaciations were very extensive in the Chandra and Batal glacial stages as valley glacial systems extended ≥100 km before decreasing dramatically in extent (~10 km) during the Kulti glacial stage. Our study and that of Taylor and Mitchell (2000) shows that glacial advances became progressively less extensive over time, but throughout the region glaciers extended similar distances for any one glacial time. Zanskar glacial timing may be more similar to glaciation in Ladakh (Owen et al., 2006), however, the deposition dates of the moraines need to be better defined for more robust comparisons (Fig. 8).

The glacial records in our study areas are more similar in both extent and timing to those of the Ladakh Range (Fig. 8). This greater similarity between the glacial records in our study areas suggest that the transition to the pattern of glaciation that characterizes Lahul must be to the south of the Karzok valley and that this transition is geographically very abrupt.

8. Conclusions

This study presents the first quantitative glacial chronology for the Puga and Karzok valleys along the southeastern flank of the Zanskar Range of northern India. This study provides an initial framework for understanding the glacial records south of the Indus River in eastern Zanskar and will aid in understanding the nature of glaciation in the Himalayan-Tibetan orogen as a whole. While it is not possible to determine precisely the existence or location in climatic gradient across the Himalaya based on this study alone, comparison with previous studies in the Ladakh and Zanskar

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Ranges and in Lahul to the south indicates similarities and notable differences in the glacial records among these areas. Our study suggests that such a transition occurs south of the Karzok valley and that it is geographically very abrupt.

Current records of glacial advances in the Puga and Karzok valleys suggest glaciation in the two valleys may be asynchronous, although data from key moraines (KM-1, KM-2, and KM-3) are difficult to interpret. A correlation of glacial advances between the valleys at ~3.6 ka and 4.2 ka (KM-4 and PM-2) is apparent, but the record based on ^{10}Be exposure age dating otherwise shows few similarities. More accurate dating of the KM-1, KM-2, and KM-3 moraine complex may result in a better understanding of the relationship in glaciation style between the two study valleys.

Moraine ages for the Karzok valley largely agree with the established glacial record in the Zanskar Range as studied by Taylor and Mitchell (2000), whereas ages from the Puga valley do not correlate as well. Additionally, the distinct lack of early Holocene glacial advances in both the Karzok and Puga valleys contrasts with studies in many other areas of the Himalaya (Owen et al., 2001; Finkel et al., 2003; Barnard et al., 2004b). Additionally, the pattern of glaciation in the Puga and Karzok valleys differs markedly from the southern ranges of Lahul and the Ladakh Range. Lahul glaciers advanced extensively with valley-fill glacial systems >10 ka with evidence for only a few glacial stages, which rapidly decrease to 10 km in length and there were possibly large gaps in time between glaciations. Glaciation in the Ladakh Range was restricted to small advances of <15 km beyond the present ice margins during the past ~430 ka, but prior to this glaciers were much more extensive filling valleys to produce valley glacier systems >100 km in length.

Both the Puga and Karzok valleys of the Zanskar Range, as well as Zanskar Range locations studied by Taylor and Mitchell (2000), reveal glacial advances ≥10 km from the present-day ice margin, but evidence for more extensive glaciation within 100 ka is sparse. Despite their relatively short advance distance, these are moraines of significant antiquity (>300 ka), possibly exceeding the age of the oldest dated materials in Lahul and Ladakh.

These data suggest that the region from northern Lahul northwards across the Zanskar and Ladakh Ranges are of further interest and importance in investigating former climatic gradients and their influence on glaciation. In particular, detailed glacial chronologies throughout the whole Zanskar Range need to be improved to more adequately discuss and understand the influences of topography and the relative roles of different climatic systems in the Himalayan-Tibetan orogen.

Uncited reference

Q2 Owen et al., 2005.

Acknowledgments

We should like to thank Jakob Heyman and an anonymous reviewer for their very careful and constructive comments on our manuscript. KAH would like to thank the University of Cincinnati's Department of Geology for funding and support of this work as an M.S. thesis. Additionally, KAH would like to thank the Geological Society of America and Sigma Xi for funding grants 8773-08 and G200803150407, respectively. The chemical preparation and AMS measurement of Karzok samples in this study were supported by the Korea Polar Research Institute project PE10010 for YBS. All authors thank Discover Ladakh Adventure for logistical support in the field, as well as Karan Thakur for field support, Jason Dortch for his reviews and comments, and to Tim Phillips for his suggestions and aid in drafting figures. LAO, CD, and MWC thank the University of Cincinnati for helping to fund their fieldwork.

Appendix. Supplementary material

Supplementary data associated with this article can be found in the online version, at doi:10.1016/j.quaint.2010.07.023.

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