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Geomorphic investigation of the Late-Quaternary landforms in the southern Zanskar Valley, NW Himalaya

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The Suru, Doda and Zanskar river valleys in the semi-arid region of Southern Zanskar Ranges (SZR) preserve a rich repository of the glacial and fluvial landforms, alluvial fans, and lacustrine deposits. Based on detailed field observations, geomorphic mapping and limited optical ages, we suggest four glaciations of decreasing magnitude in the SZR. The oldest Southern Zanskar Glaciation Stage (SZS-4) is inferred from glacially polished bedrock and tillite pinnacles. The SZS-4 is ascribed to the Marine Isotopic Stage (MIS)-4/3. The subsequent SZS-3 is represented by obliterated and dissected moraines, and is assigned to MIS-2/Last Glacial Maximum. The multiple recessional moraines of SZS-2 glaciation are assigned the early to mid Holocene age whereas, the youngest SZS-1 moraines were deposited during the Little Ice Age. We suggest that during the SZS-2 glaciation, the Drang-Drung glacier shifted its course from Suru Valley (west) to the Doda Valley (east). The study area has preserved three generations of outwash gravel terraces, which broadly correlate with the phases of deglaciation associated with SZS-3, 2, and 1. The alluvial fan aggradation, lacustrine sedimentation, and loess deposition occurred during the mid-to-late Holocene. We suggest that glaciation was driven by a combination of the mid-latitude westerlies and the Indian Summer Monsoon during periods of cooler temperature, while phases of deglaciation occurred during enhanced temperature.

Keywords. Zanskar Himalaya; Late Quaternary glaciation; Indian summer monsoon; Westerlies.

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1. Introduction

One of the major geomorphic expressions of the Quaternary climate variability in the northern latitude is the expansion and contraction of valley glaciers and the ice sheets (Lowe and Walker 2014). The multi-millennial scale climatic fluctuations are attributed to orbital forcings, which followed a distinct pattern with changes occurring at regular frequency. Superimposed on these were the abrupt short-term (centennial–millennial scale) climatic events that are well represented in the ice-core (Johnsen *et al.* 1992), marine (Bond *et al.* 2001;

Schulz *et al.* 1998), continental records (Street-Perrott and Roberts 1983; Gasse *et al.* 1990), and the mid-latitude glaciers (Owen and Dortch 2014; Sati *et al.* 2014; Bisht *et al.* 2015; Sharma *et al.* 2016). In the last century, anthropogenically-induced rise in global temperature (Hughton *et al.* 2001) led to ∼100 m increase in equilibrium line altitude of the mountain glaciers (Grove 2008). The Himalayan glaciers also suffered from both length and ice volume reduction since the 19th century (Bolch *et al.* 2012). The rate of retreat, however, varies and is also modulated by factors like morphology, elevation, percentage of debris cover, etc. (Brahmbhatt *et al.* 2017; Singh *et al.* 2016). Consequently, shrinking glaciers during the last century became iconic image of global climate change and present a stunning evidence of how climate shapes the face of the planet Earth (Mote and Kaser 2007).

One of the important pre-requisites in paleo-glaciation studies is the identification of glacial–deglacial landforms, and their detailed geomorphic mapping. However, identification of moraines is not always easy because besides, the difficulty in differentiating the moraines from the mass-wasted deposits (Hewitt 1999; Benn *et al.* 2005), challenge is posed by the discontinuous nature of moraines, obliteration by younger and larger glacial advances, and modification of landforms by flash floods (Singh and Mishra 2002; Benn *et al.* 2005; Singh 2014). However, in the semi-arid and arid Trans-Himalaya (Ladakh and Zanskar), the earth surface processes are relatively subdued; as a result, the terrain has relatively high preservation potential of sedimentary records of the past glaciations (moraines) and deglaciations (outwash terraces) (Owen *et al.* 2006; Dortch *et al.* 2013; Sharma *et al.* 2016).

Climatically, the SZR is influenced both by the ISM and mid-latitude westerlies (Owen and Benn 2005; Leipe *et al.* 2014). However, studies pertaining to paleo-glaciation suggested that in the western part of the SZR, glaciers were driven by the mid-latitude westerlies (Taylor and Mitchell 2000; Lee *et al.* 2014). Compared to this, recent studies from the eastern part of the SZR have suggested that the late Quaternary glaciation was driven by a combination of the ISM and mid-latitude westerlies (Saha *et al.* 2015; Sharma *et al.* 2016).

The present study investigates the central segment of the SZR, which is located between the Nun-Kun massif in the west and the Sarchu plain in the east. Since the terrain lies in the central segment, it is likely that the influence of the ISM and mid-latitude westerlies would have a cumulative influence in the evolution of the glacial and paraglacial landforms. Although the study is preliminary in nature, it would help in building the skeletal framework of the late Quaternary glaciation and landform evolution in the SZR. Hence the objectives are to document (i) the nature and distribution of glacial and paraglacial landforms, (ii) reconstruct the event stratigraphy, and (iii) suggest factors responsible for the late Quaternary landform evolution.

2. The study area

The study was carried out in the east–west trending Suru, Doda (Stod) and the upper Zanskar river valleys (elevation 3500–7000 m) covering an area of ∼7000 km^2 (Dèzes 1999). The Suru and Doda rivers originate from the Pensi-La (La=pass; 4400 m). The westward flowing Suru River meets the Dras River (at Kargil) before it joins the Indus River. The eastward flowing Doda River meets the Lingti or Tsarap Chu River at Padam (figure 1), and flows as the Zanskar River, which eventually meets the Indus river in Ladakh (near Nimu; Dèzes 1999). In the Suru river valley, we investigated the transverse Tangol, Shafat and Ringdom valleys (figure 1), and in the Doda and Zanskar river valleys, the study was carried out in Drang-Drung and the Seni glacier valleys.

2.1 *Climate*

In the complex mountain topography, there is a significant variation in precipitation and temperature over short distances (Beniston 2006). For example, at Leh, 30-yr climate record suggests ∼41% precipitation from the ISM (Benn and Owen 1998), while Dras and Kargil receive five times more winter precipitation than Leh (Lee *et al.* 2014). Similarly, the Zanskar Valley receives variable contribution of the ISM and mid-latitude Westerlies (Mayewski *et al.* 1984; Lee *et al.* 2014). The last 200-yr meteorological data from the NW Himalaya suggest a tele-connection between the North Atlantic Oscillations and winter precipitation (Bhutiyani *et al.* 2010). However, at local scale, 17-yr ice-core data from the Sentik glacier (Nun-Kun), located proximal to the northern fringe of the Higher Himalaya in the Suru River indicates dominance of the ISM (Mayewski *et al.* 1984). The topographic controlled rainfall gradient is manifested by relatively high precipitation (400–600

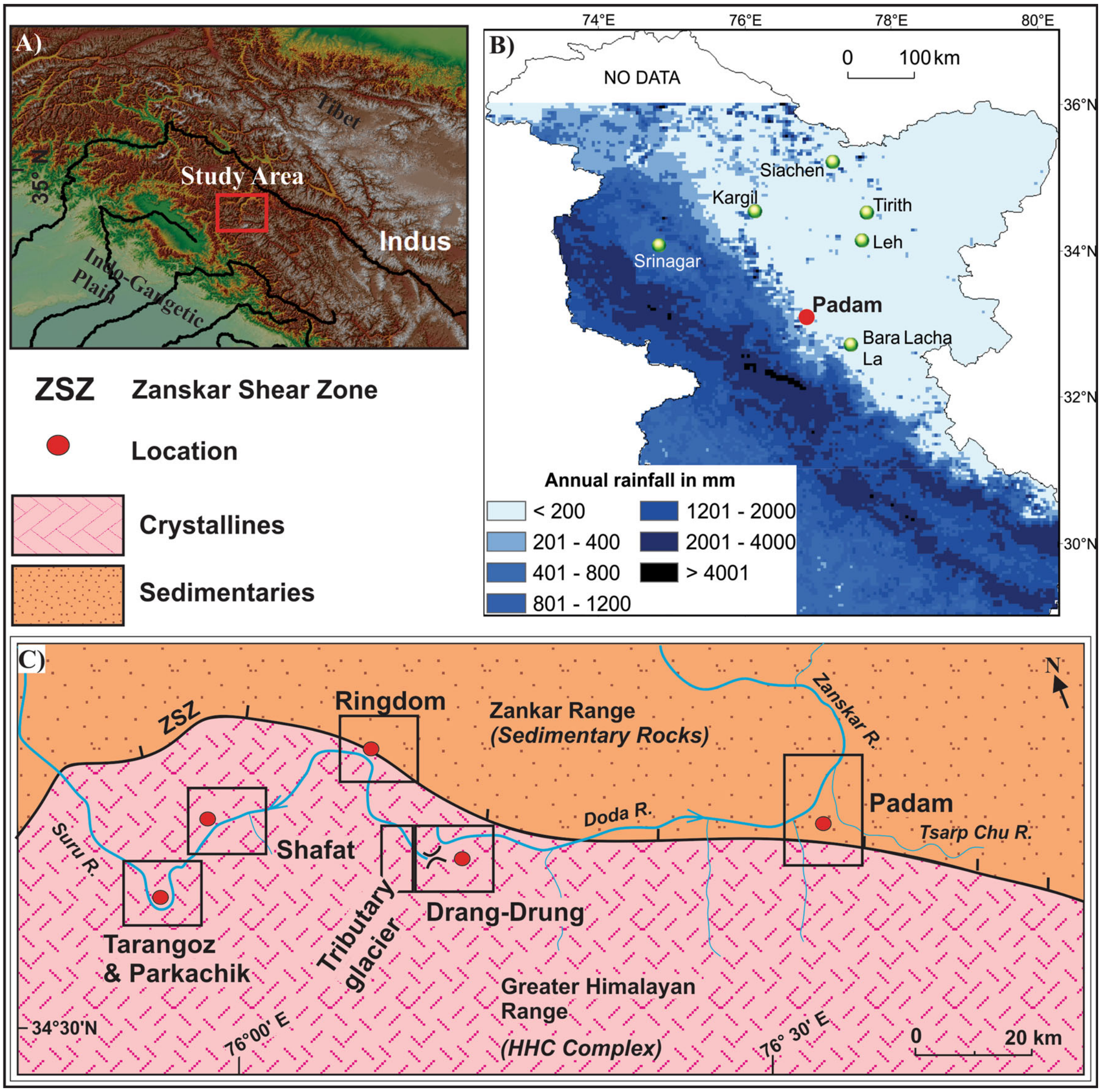

Figure 1. (**a**) Map showing location of the study area marked as red box. (**b**) The cumulative annual rainfall (mm) map of the western Himalaya (after Juyal *et al.* 2014). Padam (red dot) in the southern Zanskar Ranges is in climatically transition zone, where to the south of it rainfall is high, while in the north, arid conditions prevail. (**c**) Geological map along the Suru, Doda (Stod), and Zanskar rivers, where the square boxes mark the location of the investigated valleys. The catchment area of the glaciers is located in leeward side of the HHC.

mm) in the SZR as compared to the northern Indus valley and Ladakh ranges (Lee *et al.* 2014) (figure 1b).

2.2 *Geology*

The lithology of Zanskar Valley is represented by the rocks belonging to pre- and post-collision history. The sedimentary sequences span from Proterozoic to Eocene, while the Higher Himalayan Crystallines (HHC) dominated by migmatitic ortho/para-gneisses is extensively intruded by the leucogranitic dikes (Searle 1986). The sedimentary formations belonging to the Tethyan Sedimentary Sequence (TSS) contain rocks ranging from Late Carboniferous till the India–Asia continental collision around Eocene (Dèzes 1999). The Zanskar shear zone is one of the major structures that is represented by the normal sense of faulting and is equivalent to the South Tibetan Detachment System (STDS) (Searle 2013). The Suru and Doda rivers broadly follow the trace of the Zanskar shear zone (figure 1c).

The modern glaciers are preferentially located on the northern fringes of the HHC (southern part of the Zanskar hill ranges) and flow towards the north into the northeast–southwest trending river valleys. These glaciers invariably terminate in the vicinity of the Zanskar shear zone (figure 1).

3. Methodology

3.1 *Glacial and para-glacial landforms*

The geomorphological mapping was carried out using topographic sheets, field observations, hand held GPS, and the Google Earth images. Broadly, four major landforms were identified and mapped in the north facing tributary valleys of the Suru, Doda and Zanskar rivers. These are the (i) moraines, (ii) glacio-fluvial terraces, (iii) scree and alluvial fans, and (iv) pro-glacial lake deposits. At places, scanty occurrence of loessic silt is also observed.

Stratigraphy of the moraine is reconstructed using the conventional criteria such as morphology, sedimentary texture, relative elevation, degree of weathering, and extent of vegetation cover. The moraines are numbered from the youngest to oldest. For example, TGm-1 corresponds to the youngest moraine (m) of Tarangoz (TG) glacier. Likewise, outwash gravel terraces are identified and classified into different generations using sedimentary attributes like sorting, orientation, imbrication and texture, relative elevation, extent of weathering, and development of soil cover. These are also numbered from the youngest to oldest in each valley (e.g., SFt-1 stands for the youngest terrace (T1) in Shafat valley). Loess occur as thin drape over moraines and alluvial fans, and was identified in the field by its yellowish, friable, massive texture having hairpin pores with occasional presence of paleosols (Pye 1995; Pant *et al.* 2005). Lake deposits are buff coloured, laminated, silty-clay layers (Juyal *et al.* 2004, 2009) occurring as discrete patches that overlie moraines and/or terrace gravels. Alluvial fans and scree deposits were identified from their fan-shaped morphology with distal and proximal grading in sediment texture. Alluvial fans are differentiated from scree fans being associated with distinct catchments with streams and having finer grain size at the distal end (Blair and McPherson 1994; Hales and Roering 2005).

Besides the existing chronology obtained on glaciogenic sediments in the SZR by various workers, e.g., Taylor and Mitchell (2000); Lee *et al.* (2014); Saha *et al.* (2015) and Sharma *et al.* (2016), three new optically stimulated luminescence (OSL) ages are obtained in the present study on coarse grain quartz extracted from moraine and loess at Drang-Drung and lake deposits at Padam. Since the overdispersion in the equivalent dose is ≤32%, the ages were calculated using Central Age Model (CAM) (Bailey and Arnold 2006). The details regarding methodological aspects used in the optical dating are discussed in Sharma *et al.* (2016).

4. Results

4.1 *The Suru Valley*

4.1.1 *Tarangoz glacier (34°3′58.10″N, 75°55′25.89″E; 3370 m)*

Near Tarangoz village, two generations of lateral moraines and two levels of gravel terraces were identified on the southern valley flank. The oldest moraine (TGm-2), covered with shrubs and grasses, laterally extends down to the Suru River and is incised by the glacial melt stream. The moraine is represented by two recessional ridges. The sharp crested, crudely developed, curvilinear latero-frontal, younger moraine (TGm-1) terminates ∼1000 m above the older terminal moraine (TGm-2). It is devoid of vegetation and is fresh in appearance (figure 2a).

At the exit, along the Suru Valley (34°05′13.0″N, 76°00′29.0″E), two generations of glacio-fluvial terraces were observed. The older terrace (TGt-2) is ∼8 m thick, where the lithoclast assemblages are dominated by moderately sorted, crudely upward fining, sub-rounded to rounded boulders embedded in gritty-sand matrix (figure 2a). The less extensive younger terrace (TGt-1) is located ∼1.5 m above the present riverbed. It is composed of poorly organized lithoclast assemblages (not shown in figure). The terraces are incised by tributary streams, which have also deposited alluvial fan facies insets.

4.1.2 *Parkachik glacier (34°05′43.3″N, 76°00′0.01″E; 3100 m)*

This glacier has a catchment in the Nun-Kun massif. The snout has steep gradient; as a result, the snout is riddled with multiple transverse crevasses. The glacier has receded marginally in the recent times as indicated by the presence of proglacial lakes behind the recessional moraines (figure 2b).

Three generations of lateral moraines were identified along the western flank (figure 2b).

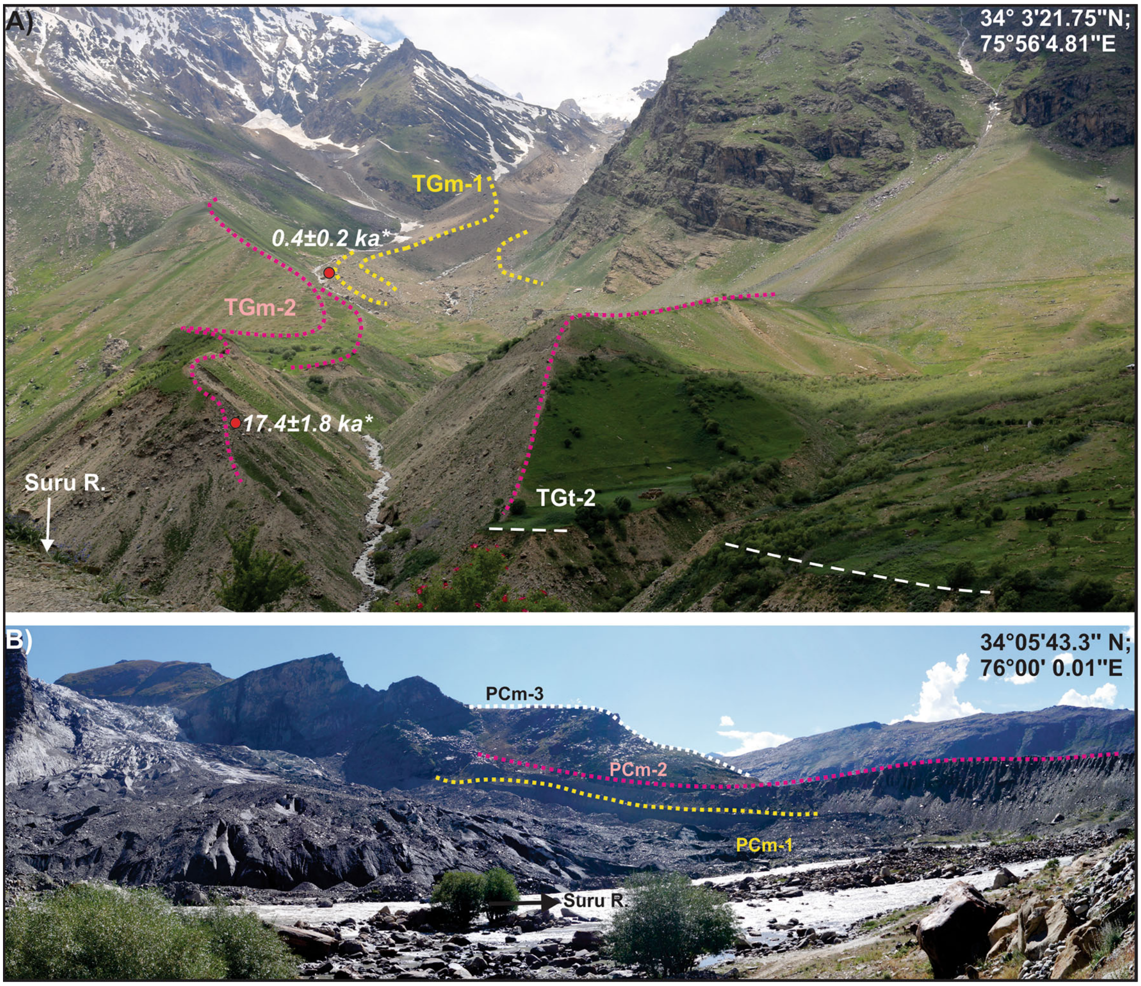

Figure 2. (**a**) Two generations of lateral moraines TGm-1 and TGm-2. The older terrace TGt-2 abuts the moraine TGm-2 in the Tarangoz glacier valley. The ages shown and marked with * are taken from Lee *et al.* (2014). (**b**) At Parkachik, three generations of moraines represent temporal changes in ice volume.

The oldest lateral moraine (PCm-3) having a sub-rounded crest, is covered with grasses, and bifurcates into two linear moraine ridges. The second generation is represented by ∼300 m long, ∼50 m thick, paired, sharp crested, unstable lateral moraine ridges (PCm-2). The moraines are relatively fresh, comprise of matrix supported subangular to sub-rounded clast and are devoid of appreciable vegetation. The youngest PCm-1 is proximal to the modem glacier and represents the recent re-advancement (figure 2b).

4.1.3 *Shafat glacier* *(34°03′32.8″N, 76°10′27.2″E; 3940 m)*

The wide north trending Shafat glaciated valley is well graded and meets the Suru river valley near Shafat village. The valley has multiple cirque glaciers, the avalanche debris emanating from these glaciers have significantly obliterated the moraine stratigraphy, except around the valley mouth where relatively well preserved, but fluvially modified moraines are observed (figure 3). The oldest glacier advancement (SFm-4) is represented by a hanging half ‘U’-shaped ridge at the confluence of the Shafat River and Suru River (figure 3a). The younger advancements are represented by the lateral moraine (SFm-3) and the latero-frontal moraines (SFm-2 and SFm-1). The SFm-3 moraine is degraded and can be traced along the southern flank of the Shafat valley near the confluence (figure 3a). The paired latero-frontal moraine SFm-2 has moderate cover of grasses and shrubs (figure 3a). The moraines are incised into semi-circular mounds by multiple fluvial channels and are draped with stratified, fluvial sand and gravel. The SFm-1 is the youngest latero-frontal moraine that can be differentiated

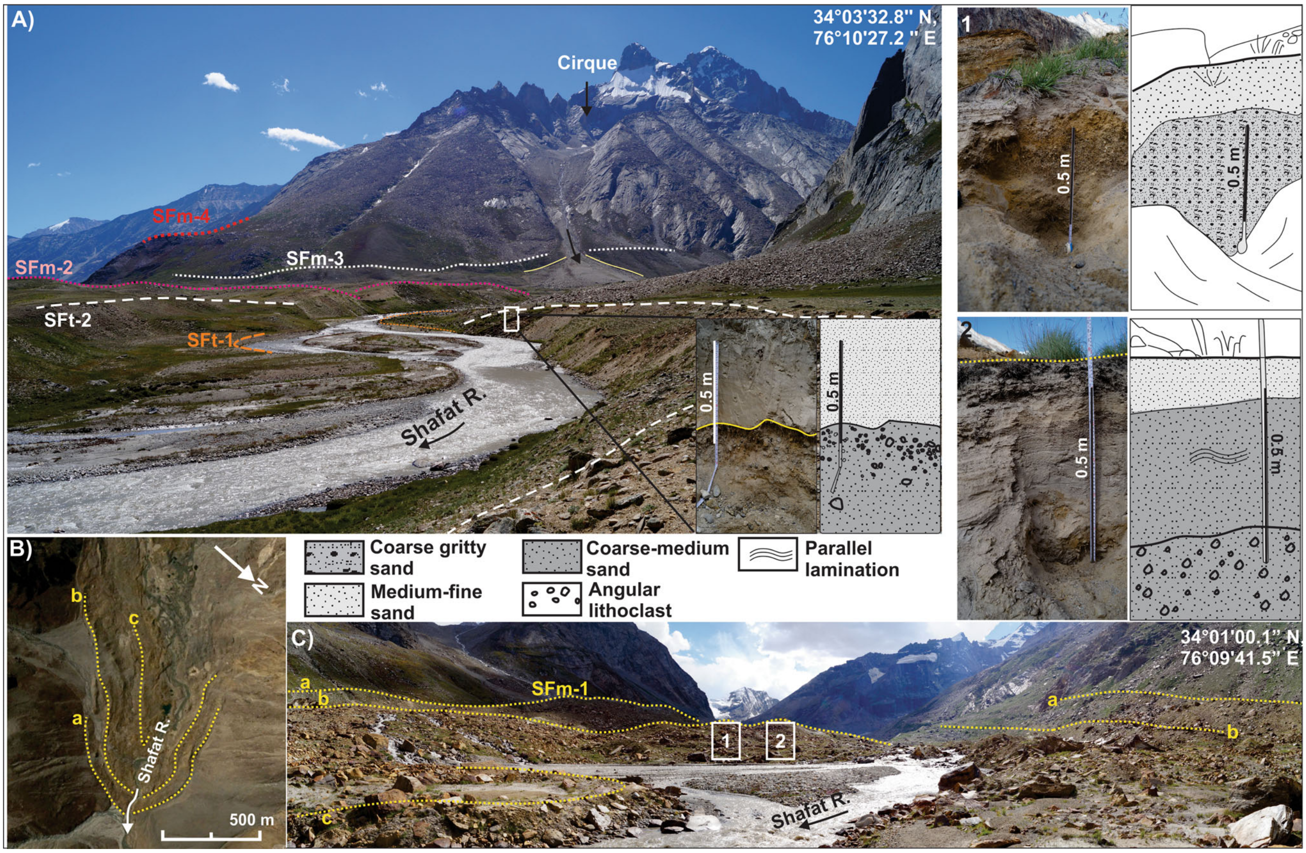

Figure 3. (**a**) Bedrock ridge corresponding to the oldest glaciation event (SFm-4) at Shafat. The SFm-3 moraine corresponding to the subsequent glaciation is obliterated by alluvial and scree fans, while the SFm-2 moraine is fluvially modified. SFt-2 and SFt-1 terraces represent the older and younger deglaciation events. Inset shows the sedimentary texture of the SFt-2 terrace. (**b**) The Google image shows three recessional moraines associated with SFm-1 glaciation. (**c**) Field photographs of SFm-1 moraine ridges, where 1 and 2 mark the location of insets showing the sedimentary texture details.

into three distinct recessional moraine ridges (figure 3b and c). These ridges, draped by laminated sediment, have fresh appearance and are devoid of vegetation.

At the confluence, the Suru river flows through an exceptionally wide channel containing point and braid bars. The SFt-3 terrace gravels can be laterally traced in the upstream along the SFm-3 moraines. Thus, suggesting that these are the oldest terrace gravel deposited following the recession of SFm-3 moraine. However, a definite inference would await the chronometric data. The terrace gravels are degraded and overlain by pedogeneised sandy-silt patches. Also, the outwash gravel terrace (SFt-2) (figure 4a and b; 34°03′54.9″N, 76°10′16.1″E; 3922 m) is incised into five surfaces having vertical offset ranging between 1 and 3 m that abut the moraines on either banks of the river. The sediment texture and lithoclast assemblage are dominated by pebbly sandy matrix containing poorly sorted, sub-angular to sub-rounded, crystalline lithoclast. The sandy horizon shows presence of planar and ripple laminated, crudely upward fining, medium-coarse sand, alternating with discontinuous clay layers. The younger terrace (SFt-1) is preserved along the meandering loops and is represented by ∼5 m thick, laterally impersistent gravel (figure 4c and d). The sedimentary structures and texture is suggestive of deposition during flashy, high energy fluvial discharge (Miall 2013; Bisht *et al.* 2015).

4.1.4 *Ringdom Gompa* *(34°00′21.4″N, 76°22′41.3″E; 4039 m)*

Around Ringdom Gompa, a lateral moraine (RIm-1), with three recessional ridges abuts the Suru Valley (figure 4e). The recessional moraines are draped by sub-rounded to sub-angular fluvial gravels. At places, active scree deposits concealed/eroded the moraines.

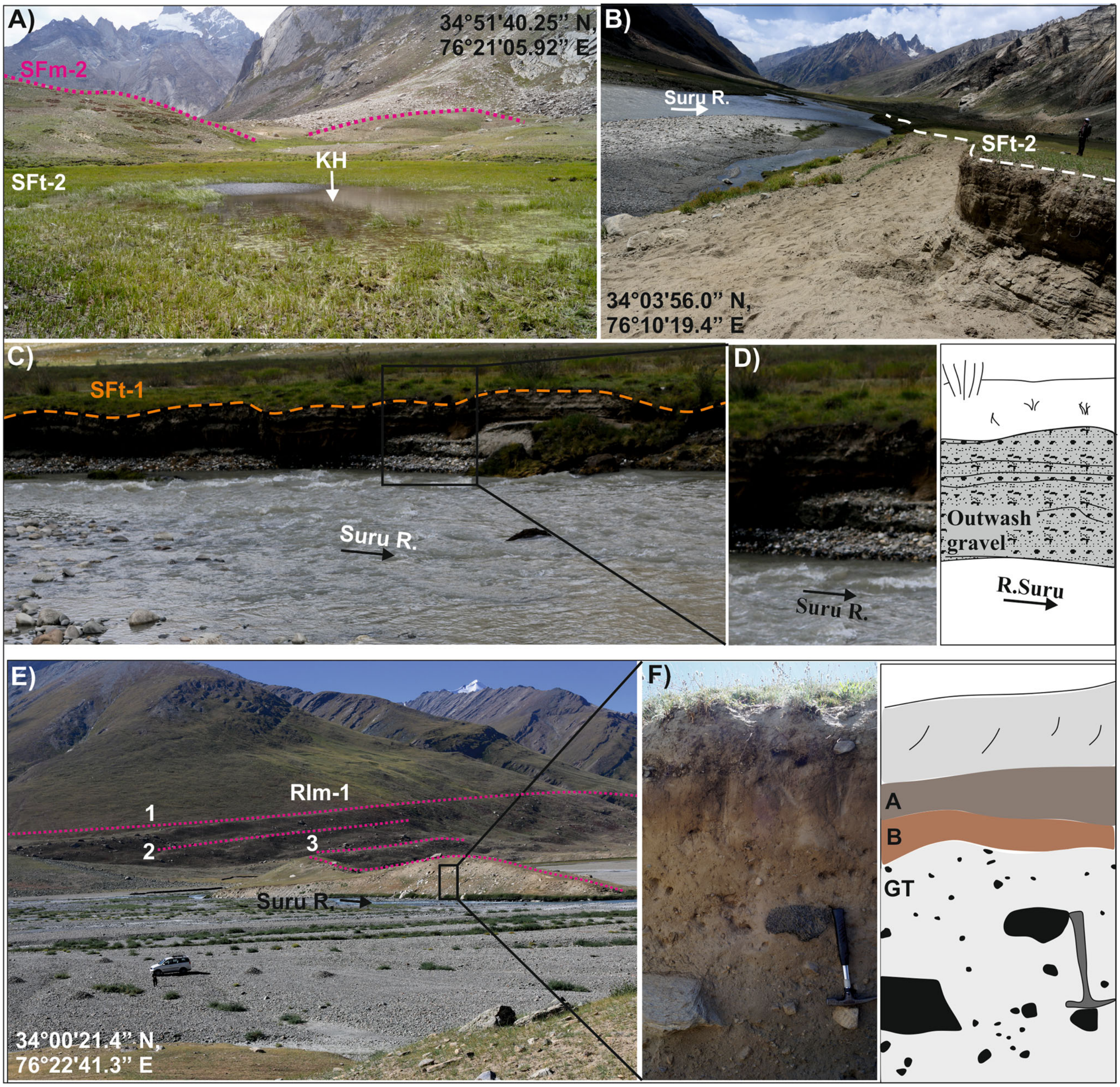

Figure 4. (**a**) The older terrace SFt-2 surface (at Shafat) is associated with kettle holes (KH) and (**b**) upward fining flood plain facies. (**c**) The younger terrace SFt-1 and (**d**) close-up of its facies, which comprises of matrix dominated, assorted gravel. (**e**) Three recessional ridges (1, 2, and 3) of lateral moraine at Rindgom (Rim-1) with inset (**f**) showing the detailed sedimentary texture. GT: glacial till, B: fine grain silty-clay horizon and A: humus-rich horizon overlain by slope wash.

4.1.5 *Tributary Glacier (33°53′14.5″N, 76°20′18.1″E; 4439 m)*

To the west of Pensi La, a major tributary glacier extends into the Suru Valley, and has deposited a prominent lateral moraine (TRm-1; figure 5a). The moraine is draped with gritty sand containing sub-rounded to angular lithoclast with occasional sand lenses implying short-lived fluvial activity. The moraine contains a modern and a buried soil (figure 5b). The modern soil has a 10 cm thick B-horizon of fine silty-sand, which is overlain by 10 cm thick humus horizon (A-horizon). The buried soil is ∼30 cm thick, containing 25 cm thick B-horizon that is dominated by light brown silty sand. It is followed by 5 cm thick humus/peat layer (A-horizon).

At the confluence of the Suru River, TRm-1 moraine is considerably modified by the fluvial activity. A fluvial terrace (TRt-1) incised into two surfaces, abuts the moraine. The sedimentary texture of the terrace comprises of crudely upward

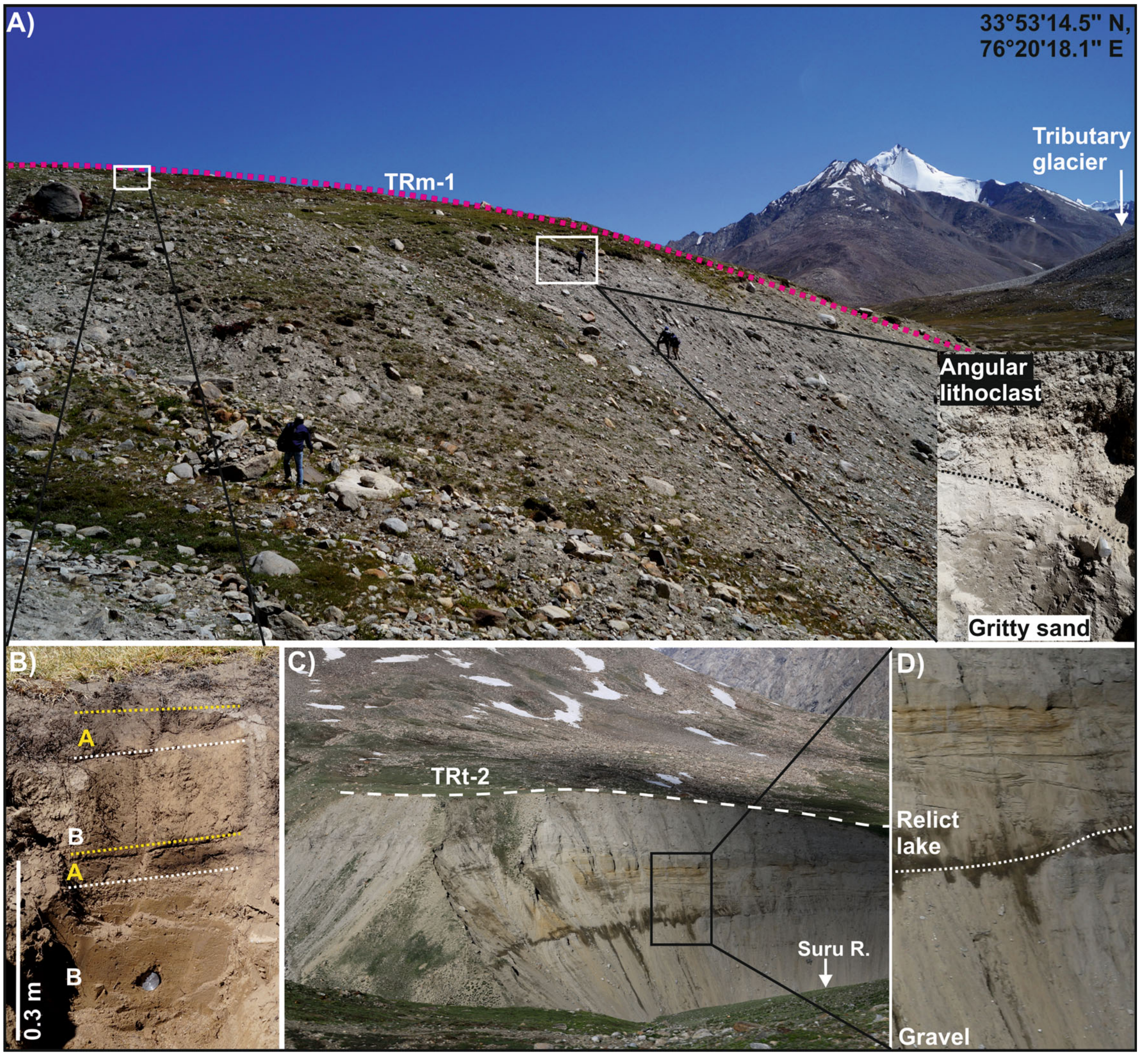

Figure 5. (**a**) The surface of tributary moraine TRm-1 is fluvially modified and draped with fluvial facies. (**b**) The crest of the moraine has preserved two soils having well-defined B-horizon and humus rich A-horizon. (**c**) In the downstream section, older terrace TRt-2 abuts the moraine and contains lacustrine facies representing the events of impounding during low discharge conditions. (**d**) A close-up showing of lacustrine deposits overlying the fluvial gravels of TRt-2.

fining, platy pebbles, oriented crudely parallel to the bedding surface. At places, the edges of the platy lithoclast are sub-rounded. The terrace TRt-1 contains ∼40 cm thick, coarse-medium, moderately rubified sand with dispersed angular lithoclast. The sandy horizon is overlain by angular to sub-rounded boulders. In the downstream, where the river channel is wider, presence of alternate lake and fluvial gravel sequence suggests multiple impounding and breaching events (figure 5c and d).

4.2 *Doda (Stod) and Zanskar Valley*

4.2.1 *Drang-Drung Glacier (33°52′08.4″N, 76°21′11.7″E; 4365 m)*

At Pensi La (La=pass; ∼4452 m), which is a water divide between the Suru and Doda River, three major glacial events can be discerned in the vicinity of Drang-Drung Glacier. The older events (DDm-3 and DDm-2) are represented by curvilinear, well-rounded moraine ridges, which are flanked by kettle holes. These have reasonably well-developed soil, are covered with grasses and can be differentiated into subsidiary (recessional) moraine ridges of decreasing elevation (figure 6). The last moraine ridge of DDm-2 terminates with a steep ∼50 m vertical scarp (figure 7). The third glacial advance, DDm-1, occurred after the glacier was deflected eastward into the Doda river valley. The DDm-1 glaciation is represented by around eight curvilinear, latero-frontal moraines (∼4410 m), which bifurcate towards east after trending S–N (parallel to Drang-Drung Glacier; figure 7). The eighth (youngest) paired lateral moraine ridge is dated to

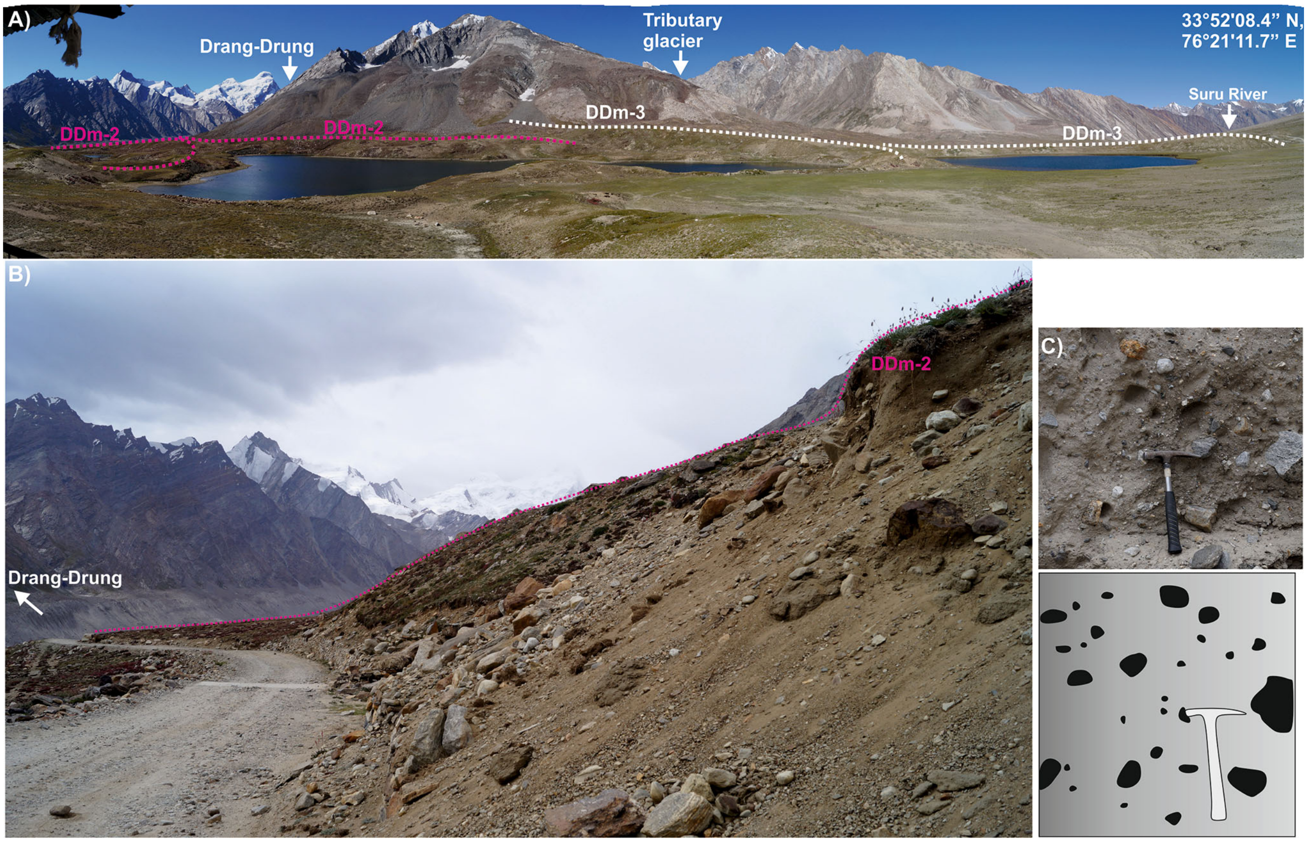

Figure 6. (**a**) Curvilinear, recessional latero-frontal moraines of DDm-3 and DDm-2 glaciations with kettle holes are preserved at Pensi La. (**b**) The lateral moraine corresponding to DDm-2 glaciation is located on the west of Drang–Drung glacier after which the ice-volume drastically decreased. (**c**) The sedimentary texture of glacial till comprising of angular boulders in the fine sandy matrix.

4.8±0.4 ka (∼4009 m; figure 7d). The moraines are fresh, loose, and contain no vegetation cover. A pro-glacial lake and push moraines with dead ice are also observed near the snout of the glacier.

About 1 m thick loessic-silt containing two paleosols, overlies the DDm-2 moraine mixed avalanche debris sediments (33°5′20.4″N, 76°21′51.2″E; 4410 m; figure 7a). The lower paleosol is divided into ∼40 cm thick, buff coloured, loess horizon, containing hairpin pores, and occasional pebbles (C-horizon). This is followed by ∼30 cm thick, weakly weathered B-horizon, which is capped by ∼15 cm thick, humus rich Ah-horizon. The upper soil profile does not have the parent C-horizon, instead it comprises of ∼10 cm thick B-horizon, and upper ∼10 cm thick A-horizon. The C-horizon (loess) of the lower paleosol is optically dated to 2.5±0.3 ka (figure 7a). A degraded relict lake deposit is also observed nestled between the curvilinear moraine ridges corresponding to DDm-2 glaciation at Pensi La (figure 7b).

4.2.2 *Padam Valley (33°29′39.5″N, 76°49′20.0″E; 3609 m)*

In the Padam Valley, four generations of moraines representing four glaciations are preserved. The moraines emanate from the western tributary and are named as PDm-4 (oldest) to PDm-1 (youngest). The PDm-4 moraine is highly degraded, indurated and comprises of isolated tillite pinnacles that overlie the rocky slopes particularly around Stongde village (figure 8a). This seems to be the oldest moraine observed so far in the SZR. The PDm-3 lateral moraines abut the valley flanks, and extend up to ∼15 km downstream in the Zanskar Valley, where these terminate as latero-frontal moraines. In the upstream (around Karsha village), the moraines are differentiated into five discontinuous lateral moraine ridges (figure 8c), suggesting pulsating recession of PDm-3 glaciation. The recessional moraines are draped by fluvial gravels and also obliterated by the large

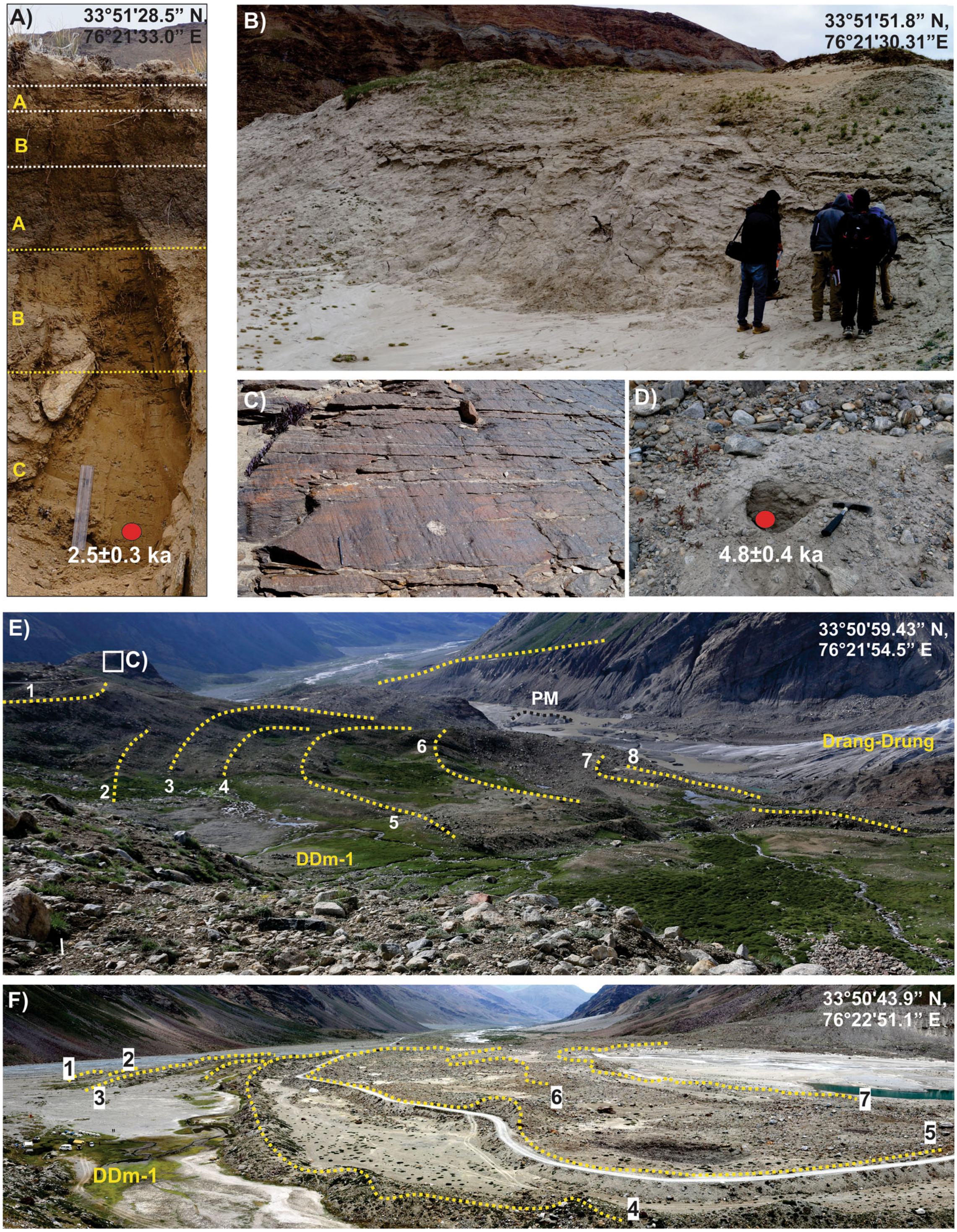

Figure 7. At Pensi La, (**a**) two loessic palaeosols with well-developed horizons (A, B, and C) are preserved on the DDm-2 moraines, (**b**) a relict proglacial lake is also associated with recessional moraines of DDm-2, (**c**) glacially striated bedrock. (**d**) The sedimentary texture of the youngest moraine ridge (8) of DDm-1 (shown in e) is dated to 4.8±0.4 ka. (**e** and **f**) Field photographs of recessional moraines corresponding to DDm-1 glaciation. In (**f**) latero-frontal ridges proximal to the snout are shown, where ridge eight is not visible.

alluvial fans, which are associated with relict or active cirques glaciers (figure 8b). The younger PDm-2 moraines preserved near the exit of the Seni Valley are dissected by the melt water streams and are draped with fluvial gravels giving rise to hummocky mounds (figure 8d). The youngest PDm-1 latero-frontal moraines are confined within the Seni Valley.

Figure 8. (**a**) The oldest moraine PDm-4 (red line) near Stongde in the Padam Valley is preserved as eroded pinnacles, which rest on the valley walls (shown in the inset). (**b**) Field photograph of the moraine PDm-3, which is obliterated by the extensive alluvial fans and river tributaries like the Tsarp Chu River and represent the successive younger glaciation. (**c**) The moraine PDm-3 receded in at least five phases that is represented by five recessional lateral moraines (white dotted lines). (**d**) Field photograph showing the paired lateral moraines PDm-2 (pink dotted lines), which are preserved on the flanks of the Seni River tributary. The moraine terminates at the confluence of the Seni and Doda rivers. The inset shows the sedimentary texture of the moraine.

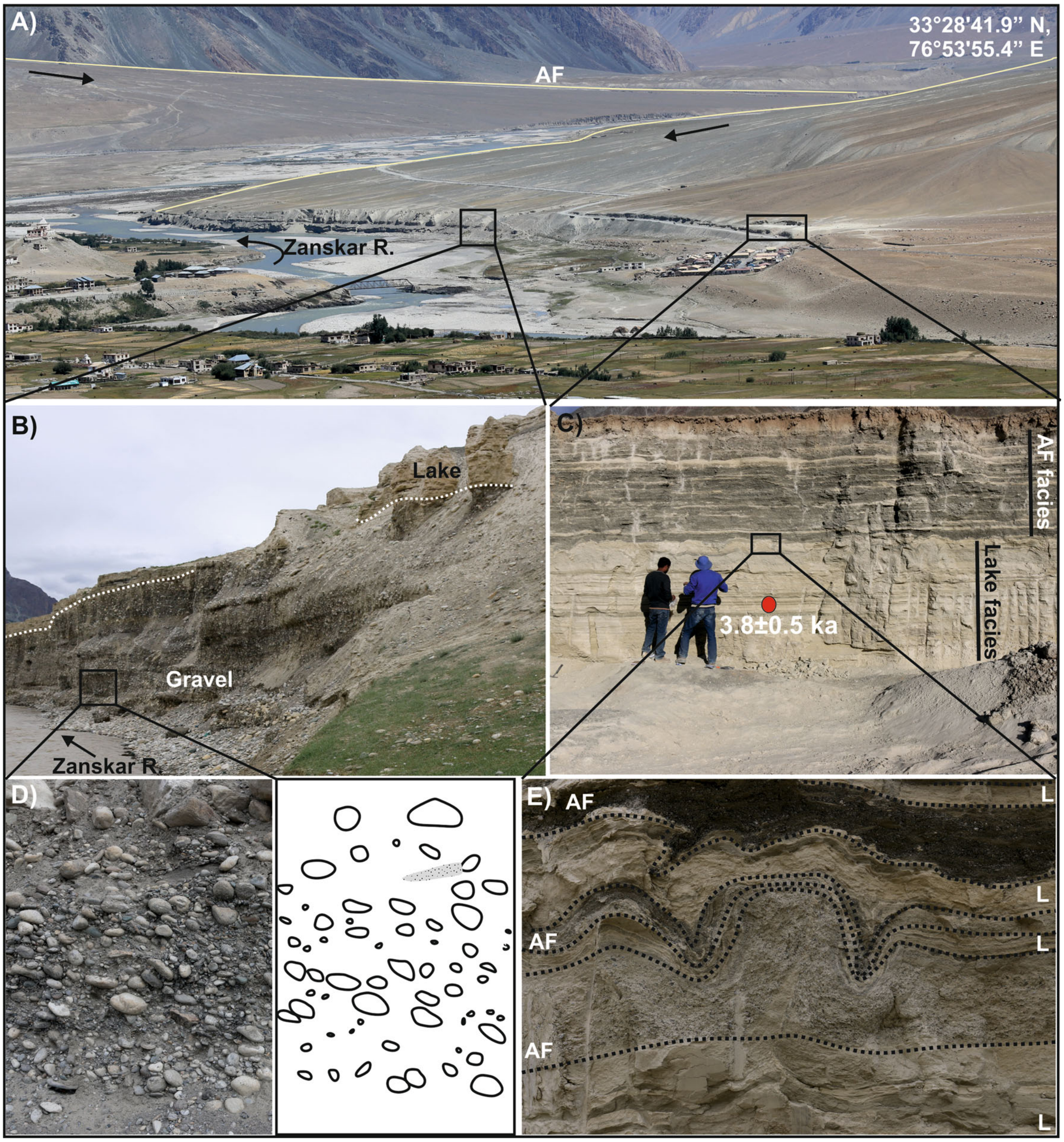

Figure 9. (**a**) Alluvial fans (AF) emanating from the eastern and western mountain flanks extending into the Zanskar river valley suggesting that they coalesced to temporarily dam the Zanskar River. (**b** and **c**) The evidence of impounding is preserved as the relict lake deposits along with intervening alluvial fan facies. The lake deposits overlie the PDmt-2 terrace gravels. Note the frequency of alluvial fan facies increase from the middle part of the lake succession. (**d**) A close-up of terrace gravel PDt-2 which extends down to the present river. (**e**) A close-up of the relict lake where the lacustrine facies (L) alternating with the alluvial fan facies (AF) along with the ice-wedge structures.

The two generations of outwash gravel terraces are also identified in the Padam Valley (figure 8b). The older PDt-2 outwash terrace gravel (33°28′41.9″N, 76°53′55.4″E; 3551 m) is ∼15 m thick and has sub-rounded, clast supported deposit. It is overlain by laterally persistent relict lake sediments (figure 9a–c), which are preserved along the eastern flank of the Padam village (33°28′41.9″N, 76°53′55.4″E; 3551 m). Based on the texture and sedimentary structures, the relict lake succession can be differentiated into two broad units. The lower 2 m thick unit-I is dominated by parallel laminated silty-clay (varves and rhythmites), alternating with coarse-gritty sand. The upper part of this unit show convolute bedding (cryoturbated?, figure 9c and e). The upper ∼2.5 m thick unit-II is dominated by crudely laminated, angular lithoclast with sub-ordinate silty-clay layers suggesting their deposition as alluvial fan facies. The frequency of clayey-silt layers decreases towards the top and weakly developed soil is also observed. The relict lake sediment overlying the fluvial gravel indicates that the lake came into existence following the obstruction caused by the alluvial fans (figure 9a and b). The middle part of the lake sediment is dated to 3.8±0.5 ka (figure 9c), implying that the lake probably represents the late Holocene climatic instability (aridity/cooling).

The younger outwash terrace (PDt-1) is ∼10 m thick and abuts the older terrace. Scree fans are present all along the valley slopes and at places drape the moraines and gravel terraces, thus suggesting them to be the youngest geomorphic feature in the study area (figure 9).

4.3 *Composite stratigraphy*

The composite alluvial stratigraphy is reconstructed based on the field relationship of the multiple generations of moraines, outwash gravel terraces, alluvial fans and lacustrine deposits observed in the seven glacier valleys. The inferred glacial stages are named using a common nomenclature, *viz.*, the Southern Zanskar Glaciation Stage (SZS) (table 1). This allowed us to identify four major glacial stages – the SZS-4 (oldest) to SZS-1 (youngest) and three deglaciation events that broadly correlate with the SZS-3, 2, and 1. Detailed description is given in table 1 and figure 10.

5. Discussion

The semi-arid Ladakh and Karakoram ranges preserves the oldest record of glaciation in the Himalayan orogen (>430 ka; MIS-6/3; Phillips *et al.* 2000; Richards *et al.* 2000; Owen *et al.* 2006; Seong *et al.* 2007). Dortch *et al.* (2013) have summarized the existing chronology from the NW Himalaya and suggest that the terrain has preserved a record of around nine major glaciations starting from MIS-10/9, which they called the semi-arid Western Himalayan Tibetan stages (SWHTS). However, in the Zanskar Himalaya, the studies so far indicate five major glaciations. The oldest glaciation is dated to ∼311 and 116 ka in the northern Zanskar valleys and corresponds to the MIS-9/5 (Hedrick *et al.* 2011). This is equivalent to SWHTS 9/5E regional stages defined by Dortch *et al.* (2013). During this phase, the glaciers are suggested to expand >10 km from the present day ice margin into the main valleys. The next glacial advance is represented by subdued, highly eroded and obliterated moraines or the bedrock trim lines, which are dated/correlated to the MIS-4/3 (∼80–40 ka; SWHTS 5A/3) in the southern Zanskar (Dortch *et al.* 2013). During MIS-4/3, it is suggested that trunk valleys were extensively glaciated (Taylor and Mitchell 2000; Damm 2006; Dortch *et al.* 2013; Lee *et al.* 2014; Sharma *et al.* 2016). The ELA was lowered between >1000 (north) and 350 m (south) with a corresponding temperature decrease of ∼3°C (Taylor and Mitchell 2000; Damm 2006; Hedrick *et al.* 2011; Orr *et al.* 2016). The third glaciation in Zanskar occurred during MIS-2 (equivalent to SWHTS 2B/C) and LGM in response to the mid-latitude westerlies (∼20–16 ka) which is represented by well-preserved, vegetated moraines having rounded crests. The glaciers, however, did not expand beyond the exit of the tributary valleys (Taylor and Mitchell 2000; Lee *et al.* 2014; Sharma *et al.* 2016). The Zanskar glaciers also expanded during MIS-1 in late Pleistocene/early Holocene (14–7 ka; SWHTS 2B-1D), and lastly during early-mid Holocene (<6 ka; SWITS 1C-1A) in response to the North Atlantic Oscillations (Damm 2006; Lee *et al.* 2014; Saha *et al.* 2015; Sharma *et al.* 2016).

In order to provide the chronostratigraphy of the various glacial stages, we used the stratigraphically equivalent published ages from the Nun-Kun Massif in SZR by Lee *et al.* (2014) and three new optical ages obtained during the present study. The oldest age given by Lee *et al.* (2014) is from the bedrock trim line of the Sentik glacier (Nun-Kun massif), which they ascribe to the MIS-4/3 glacial stage (Achambur glaciation). In Padam Valley, Mitchell *et al.* (1999) and Taylor and Mitchell (2000) dated moraine dammed lake in the Tsarp Chu River to ∼80 ka and assigned it to the above glaciation. Stratigraphically equivalent moraines of SZS-4 glaciation would correspond to the MIS-4/3, which in the study area are represented by glacially polished ridges at Shafat and tillite pinnacles in Padam Valley. Thus, it would imply that the SZS-4 glaciation was driven by a combination of enhanced mid-latitude westerlies during the MIS-4 and/or strengthened ISM during the earlier part of pluvial MIS-3 (Owen *et al.* 2001; Juyal *et al.* 2006). This looks reasonable considering that the SZR is located in the transitional climatic zone and is influenced both by the ISM and mid-latitude westerlies (Owen and Benn 2005; Leipe *et al.* 2014).

Table 1. *Composite stratigraphy reconstructed from the moraines, outwash gravel terraces, alluvial fans and scree fans, and relict lake deposits, is discussed along with their depositional environment. The glacial stages are named from the oldest Southern Zanskar Glaciation Stage (SZS-4) to the youngest (SZS-1).*

Glacial stage	Glacial landforms	Outwash gravel terraces	Alluvial and scree fans	Relict lake deposits
SZS-4	Shafat Valley (SFm-4): U-shaped valley morphology, polished bedrock. Padam Valley (PDm-4): Highly eroded, moraine pinnacles.			
SZS-3	Parkachik (PCm-3), Shafat (SFm-3), Tributary (TRm-1), Drang–Drung (DDm-3) and Padam (PDm-3) (figures 2, 3, 5, 6 and 8). The moraines abut the valley flanks of the tributary glaciers and the main valleys; terminate at the confluence of the tributary/ trunk valleys except at Drang–Drung (DDm-3) Padam (PDm-3), where five sets of lateral moraines indicate pulsating recession (figures 6a and 8c)	Shafat Valley (SFt-3): Highly degraded and pedogeneised.		
SZS-2	Shafat Valley (SFm-2); Padam Valley (PDm-2); Parkachik (PCm-2); Tangol (TGm-2); Ringdom (RIm-1): Latero-frontal moraines. Drang-Drung: DDm-2: Two curvilinear recessional moraine ridges with kettle holes. DDm-1: Eight curvilinear lateral and terminal moraines indicate recessional pulses (figure 7e–f).	Shafat Valley (SFt-2), Ringdom (RIt-2), and Padam (PDt-2) Valley. The outwash gravel terraces abut and drape the SZS-2 moraines (figures 3a, 4, 8).	The older alluvial fans show a cross-cutting relationship with the SZS-2 (figures 3a, 8b and 9a) and overlie older outwash terraces.	Relict lake deposits at Pensi La nestled between the (DDm-2) moraines (figure 7b). Depositional environment: The varve and rhythmites dominated sediment suggest deposition under proglacial-lacustrine environment (Juyal *et al.* 2004, 2009).

Table 1. *(Continued.)*

Glacial stage	Glacial landforms	Outwash gravel terraces	Alluvial and scree fans	Relict lake deposits
SZS-1	Shafat (SFm-1), Padam Valley (PDm-1), Parkachik (PCm-1), Tangol (TGm-1): Paired, lateral and latero-frontal moraines	Shafat terrace (SFt-1) corresponds to the deglaciation event of SZS-1. Depositional environment: SFt-3, SFt-2 and SFt-1 terrace gravel are matrix supported fabric, poorly sorted, non-imbricated implying deposition under high energy flows, probably catastrophic glacial lake outburst floods associated with events of deglaciation (Dadson and Church 2005; Miall 2013; Bisht *et al.* 2015). The surface of SFt-2 terrace is cut into five levels representing pulsating decrease in sediment/water ratio (Brodzikowski and Loon 1991; Juyal *et al.* 2010).	The active younger fans inset within the older alluvial fans. Depositional environment: Alluvial fans are associated with relict or active cirques glaciers whereas, the scree deposits, associated with the valley slopes form an apron of unconsolidated angular lithoclasts.	Alluvial fan obstructed lake at Padam (figure 9). Depositional environment: The lake overlies the fluvial gravel indicating that the lake came into existence following the obstruction caused by the alluvial fans (figure 9). Dominance of clayey-silt with intervening sand in the lower half of the succession followed by the dominance of crudely laminated angular driven lithoclasts (scree fan deposits) with subordinate sitly-clay (figure 9) indicate fluctuating hydrological conditions during period of deglaciation (Miall 2013).

The SZS-3 moraines terminate as poorly defined ridges at the tributary valley mouths, except in the case of relatively wide Padam Valley, where the moraines were deposited down to an elevation of 3500 m (∼15 km from the snout). Also, at Drang-Drung these are preserved as curvilinear latero-frontal moraines (DDm-3). Stratigraphically, the moraines are equivalent to Tongul stage of Lee *et al.* (2014) that is dated between ∼14 and ∼19 ka. We suggest that the SZS-3 stage probably began around the LGM (mid MIS-2) and continued till the later part of the MIS-2, although a conclusive statement should await chronometric data. Unlike the east–west trending Doda and Suru valleys, the SZS-3 moraines in the north–south trending Padam Valley extended down into the Zanskar river valley implying that valley orientation (N–S) perhaps played an important role in glacier expansion. The SZS-3 glaciation in Padam Valley is represented by five linear moraine ridges of decreasing heights, suggesting pulsating reduction in ice volume (figure 8). Studies from the northwestern (Nagar *et al.* 2013; Sharma *et al.* 2016) and monsoon dominated western and central Himalaya (Ali *et al.* 2013; Bali *et al.* 2013; Bisht *et al.* 2015; Eugster *et al.* 2016) indicate that valley glaciers expanded during the LGM. However, compared to its older counterpart, the LGM glaciation was less extensive (Dortch *et al.* 2013 and references therein). Therefore, we suggest that the SZS-3 glaciation probably represent a period of intensified mid-latitude westerly corresponding to LGM (Benn and Owen 1998; Sharma *et al.* 2016) or later part of MIS-2 during which a gradual strengthening of ISM is suggested (Duplessy 1982; Schulz *et al.* 1998).

The SZS-2 moraines terminate marginally above the exit of the tributary valleys. Stratigraphically and morphologically the moraines are equivalent to ST1; TG2; and RT1 glaciers in Nun-Kun massif that are dated to early part of the late glacial (Amantick stage; Lee *et al.* 2014). In the eastern Zanskar Valley, the early Holocene advancement was suggested to be ∼8 ka (Sharma *et al.* 2016). Speculatively, we tend to suggest that SZS-2 glaciation occurred during the early to mid-Holocene – a period known for moderate ISM and cooler air temperature (Gasse *et al.* 1990; Thompson *et al.* 1997; Sati *et al.* 2014). Here it is important to mention that until around SZS-3, Drang-Drung Glacier was flowing westward into the Suru river valley. It was during the deposition of SZS-2 moraines, the pulsating decrease

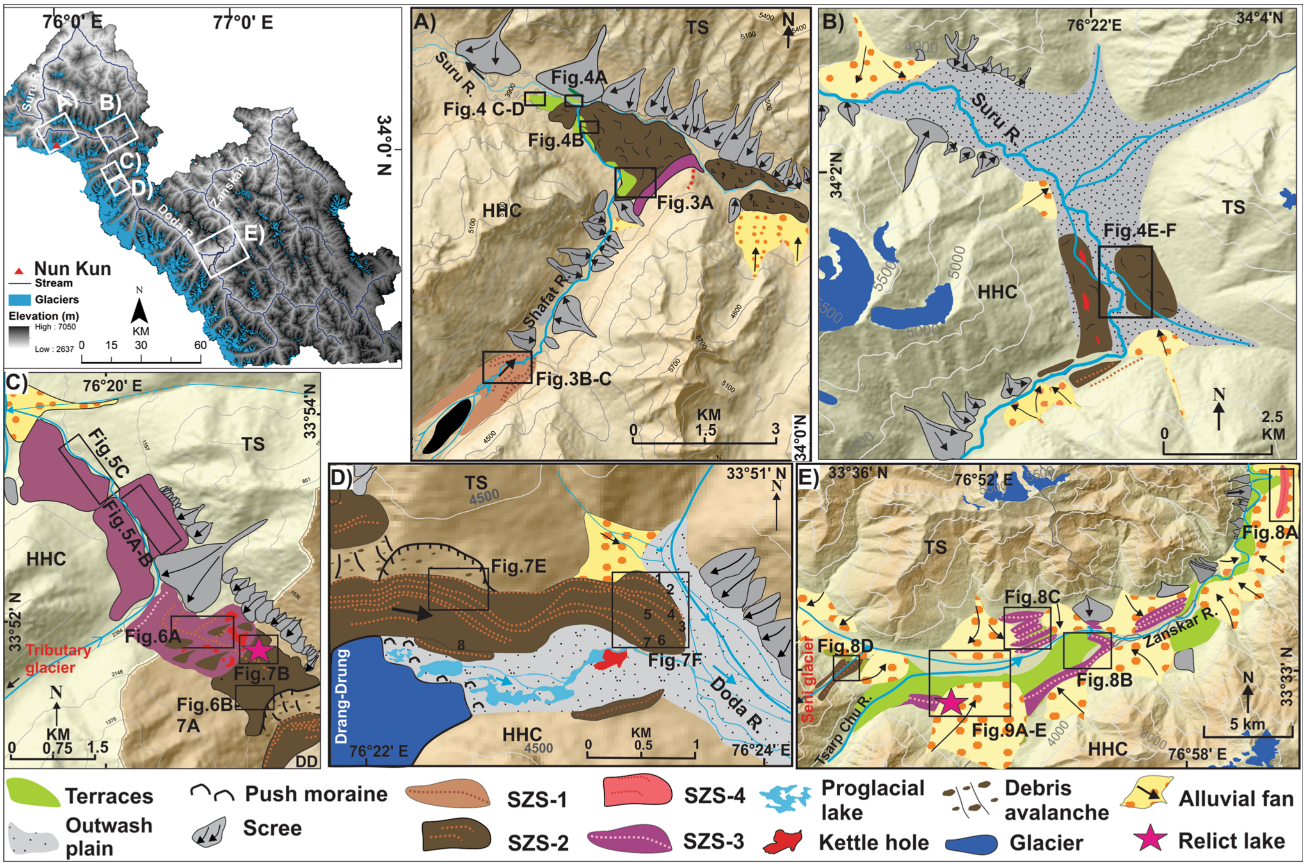

Figure 10. Map showing the summary of the landforms investigated in the present study in different sub-catchments of the Suru and Doda rivers. Inset is the digital elevation model (DEM) of the study area where locations of the valleys investigated are marked. The geomorphic maps (**A**–**E**) are drawn from the Google Earth images, topographic maps and field observations on the georeferenced SRTM–DEM. The four Southern Zanskar Glaciation stages (SZS) are observed in the Shafat Valley (**A**). In the Parkachik (not shown here) and Padam valleys (**E**), we could identify moraines corresponding to three glacial stages whereas, around Drang-Drung (**C** and **D**), two glacial stages are preserved. Near the Tributary Valley (**C**) and Ringdom (**B**), only one glacial stage could be discerned. In addition to this, distribution of outwash gravel terraces, relict lake deposits, alluvial fans and scree slopes are also marked. The locations of field photographs are marked on the maps.

in ice volume led to the eastward deflection of the glacier snout (towards the Doda Valley). This is manifested by the presence of around eight curvilinear recessional moraine ridges (figure 7e and f). The youngest eighth moraine ridge is dated to ∼5 ka.

The youngest SZS-1 moraines are preserved as curvilinear ridges in Shafat Valley. Stratigraphically, the moraine is equivalent to the TG3 and TG4 moraines of the Nun-Kun massif that are dated to the Little Ice Age (LIA) (Lomp and Tanak stages; Lee *et al.* 2014). Though at Drang-Drung, Osmaston (2001) had suggested moraines near the snout to be few centuries old, the youngest lateral moraine ridge discerned by us is dated to ∼5 ka (late mid-Holocene; Walker *et al.* 2012).

Evidence of deglaciation is represented by the outwash gravel terraces. In the absence of absolute chronology, it is difficult to assign the glacial stages to individual outwash gravel terraces. However, given the fact that ISM fluctuated since MIS-2 (Thompson *et al.* 1997; Schulz *et al.* 1998, figure 11), the outwash gravel terraces would represent the phases of warm climatic intervals, which led to the mobilization of glacial and paraglacial sediment as also recently suggested by Jonell *et al.* 2017) in the Doda river valley. The alluvial fans show cross-cutting relationship with older terraces, and suggest that these were activated at the end of deglaciation events. Based on their stratigraphic position with respect to the lake deposits (dated to ∼4 ka), it would be reasonable to suggest that the alluvial fan aggradation would have occurred after mid-Holocene transitional climate. The loess deposits represent the drier conditions whereas, the intervening humus rich horizons imply temporary wetness (Pant *et al.* 2005). Lee *et al.* (2014) have dated the loess-paleosols in the adjoining valleys

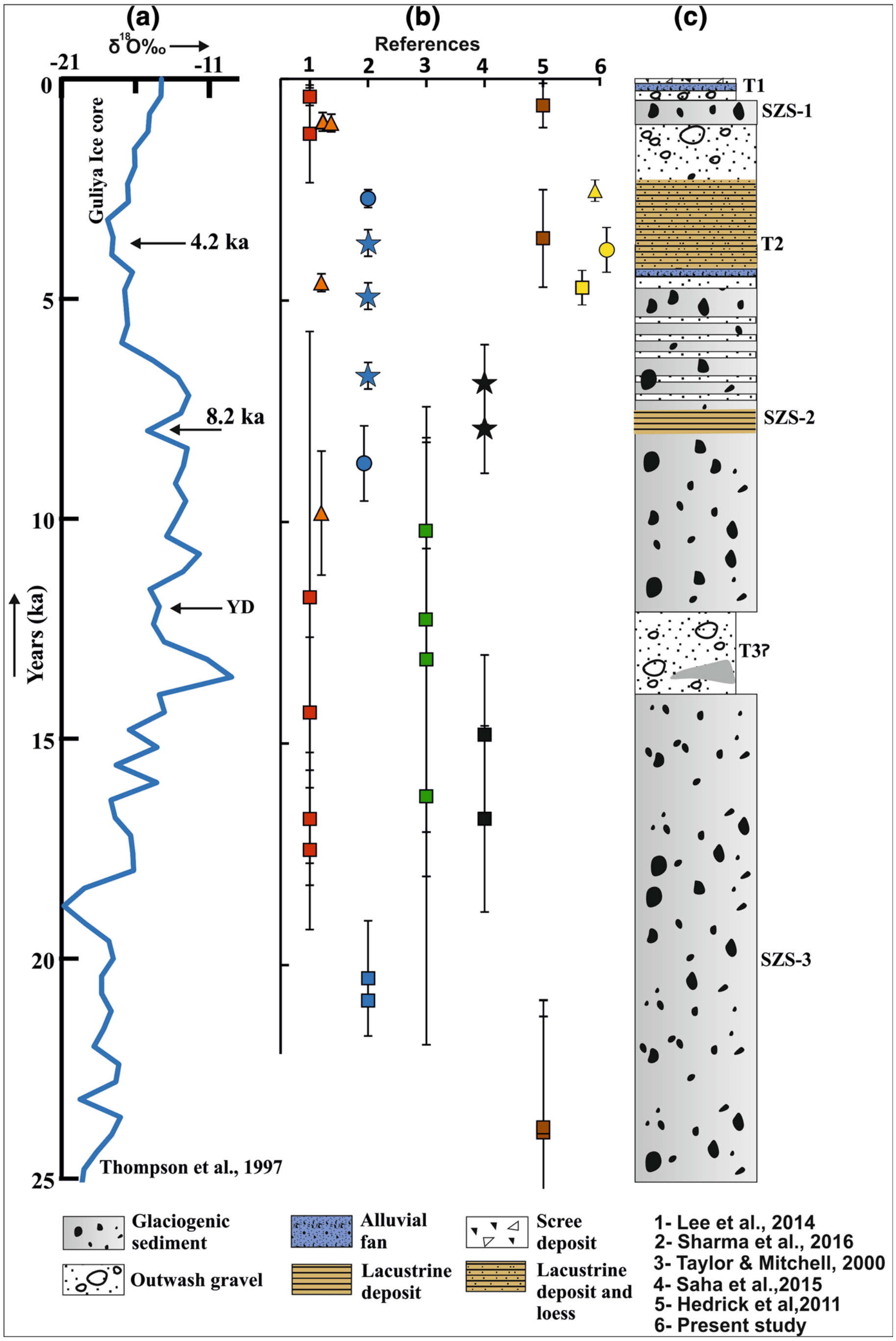

Figure 11. (**a**) δ^{18}O of Guliya ice core plotted for the last 25 ka (Thompson *et al.* 1997). (**b**) Chronology from the present study and the other studies in the Zanskar ranges, where the ages of moraines are shown by squares, triangles represent the loess deposits, stars show the ages of the drumlins, and the circles represent the outwash gravel/lake ages. Chronology from Lee *et al.* (2014) and the present study show that the glaciers in the south Zanskar advanced during the SZS-4 (∼80 ka; not shown); SZS-3 (MIS-2/LGM); early-mid Holocene (11–4 ka); and LIA. (**c**) Event stratigraphy of the south Zanskar ranges since 25 ka, where the deglaciation events (outwash sediments) largely correspond with the warmer climate and the glaciation events (glacial sediments) correspond with cooler climate conditions.

to c.1.5, c.3.4, and c.5.2 ka, and Sharma *et al.* (2016) have dated drumlins and lake deposits (representing deglaciation and warming) from eastern Zanskar to ∼4 and ∼3 ka. In the present study, the paleosol at Pensi La is dated to ∼2.5 ka that broadly lies within the above age brackets.

Figure 11 summarizes the observations made in the present study. The existing chronology from various studies including the present study in the Zanskar ranges is plotted against the δ^{18}O values from Guliya ice core (Thompson *et al.* 1997), which serve as a proxy for ISM intensity. The isotopically light values indicate weaker monsoons with cooler temperature and *vice versa*. The event stratigraphy from the present study is also plotted in the last panel. The study suggests that SZR responded sensitively to variability in both the ISM and mid-latitude westerlies. The glaciation seems to have occurred during wet phases when the temperature was low while the deglaciation perhaps occurred during warm pluvial phases. However, more definitive inferences towards the factors responsible for driving glaciation and deglaciation should await a detailed chronometric study.

6. Conclusions

The SZR has preserved at least four phases of glaciations (SZS-4 to SZS-1) and three phases of deglaciation since the last 80 ka. The oldest SZS-4 glaciation is assigned MIS-4/3 and the subsequent phases, *viz.*, SZS-3, SZS-2, and SZS-1 are assigned MIS-2/LGM, early-mid Holocene, and the LIA, respectively.

The stratigraphic correlation of the glacial stages with that of the chronologically dated sequences in the region indicates a broad synchronicity in glacial advancements across the Zanskar Himalaya since the MIS-4. It seems that the most extensive glaciation in the southern Zanskar Valley was initiated during the strengthened mid-latitude westerlies (MIS-4) and sustained by the enhanced moisture contribution during the early phase of the pluvial MIS-3. The initiation of the SZS-3 glaciation is ascribed to the global LGM and MIS-2 implying the role of strengthened mid-latitude westerlies whereas, for the younger glaciations, *viz.*, SZS-2 and 1, seems to be driven by a favourable combination of temperature and precipitation (ISM and mid-latitude westerlies). Our study suggests that the Drang-Drung Glacier that was feeding the Suru river valley in the west was deflected eastward into the Doda (Stod) river valley due to the decrease in ice volume after SZS-3.

The study identifies three phases of deglaciation that are ascribed to the post-LGM, insolation driven, strengthened ISM. The termination of the deglaciation is marked by alluvial fan sedimentation, which impounded the Zanskar River and created a temporary lacustrine condition during periods of low discharge. This phase corresponds to the late-Holocene aridity which is also indicated by the deposition of loess around Pensia La.

Although preliminary in nature, the study suggests that the SZR glaciers, being in transitional climatic zone, are likely to respond sensitively to even the minor changes in both ISM and the mid-latitude westerlies.

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