Journal of Palaeosciences 73(2024): 1–15
2583–4266/2024
https://doi.org/10.54991/jop.2024.1870

Space and field–based investigations towards understanding the characteristics and origin of an inhabited rock glacier in NW Himalaya

PRATIMA PANDEY[1], ATAULLAH RAZA KHAN[2] AND SHEIKH NAWAZ ALI[3*]

[1]Geosciences Department, Indian Institute of Remote Sensing, ISRO, Dehradun, India.
Email: pandeypreetu@gmail.com
[2]National Resources Data Management System, Soban Singh Jeena University, Almora, India.
Email: razamsc96@gmail.com
[3]Birbal Sahni Institute of Palaeosciences, 53 University Road, Lucknow 226 007, India.
Email: snawazali@gmail.com
**Corresponding author*

(Received 15 December, 2023; revised version accepted 04 March, 2024)

ABSTRACT

Pandey P, Khan AR & Ali SN 2024. Space and field–based investigations towards understanding the characteristics and origin of an inhabited rock glacier in NW Himalaya. Journal of Palaeosciences 73(1): 1–15.

The current space and field–based investigation of an important (inhabited) rock glacier (RG) in the north–western (NW) Himalaya aims to comprehend its morphological properties and genesis. Although the RG displays an inactive frontal lobe, small active lobes may be seen in the upper reaches, > 3900 m asl. The permafrost distribution map reveals that the rock glacier contains either discontinuous or sporadic permafrost. We propose that, while the rock glacier does not show indications of an active front, small RG lobes do show movement in the upper reaches. Furthermore, the presence of a well–preserved right lateral moraine implies that this RG originated from a previously glaciated valley and is supported and sustained by a constant supply of talus (rock debris) from the present sedimentary catchment to the northeast. The quick thawing of the RGs will significantly impact and perhaps lead to the complete migration of the inhabitants to other areas.

Key–words—Rock glacier, Morphology, Moraine, Relict lake sediments, NW Himalaya.

INTRODUCTION

ROCK glaciers (RGs) are perennially frozen debris (permafrost composition) that slowly moves down owing to gravitational pull and are found throughout the world's de–glacierized high latitude and altitude cold mountainous regions, including the high Himalayan region (Barsch, 1996; Kaab, 2013; Kaab *et al*., 2021). These landforms originate in the hinterlands and glaciated valleys, where vast amounts of debris from hill slopes and glacial weathering are available. During the initial stages of investigations, rock glaciers were thought to be a type of debris–covered glaciers. However, fundamental discrepancies were revealed in subsequent studies (Corte, 1976; Haeberli, 1985; Barsch, 1996; Kaab, 2013; Millar & Westfall, 2019). It has been suggested that after deglacial unloading or de–buttressing, paraglacial (landscape relaxation) processes may expose the steep valley rock walls for adjustments, resulting in a large volume of supra–glacial debris (Scherler *et al*., 2011; Rowan *et al*., 2015; Jones *et al*., 2019). The cold and arid meteorological conditions producing frost climates and exposed steep and unstable rocky cliffs combine to provide an abundant source of rock debris that falls on the glacier and its surroundings. As a result, a considerable proportion of the RGs are genetically linked to debris–covered mountain glaciers (Humlum, 2005; Benn & Evans, 2010). Whalley and Martin (1992), have presented a detailed description of the models and mechanisms of RG genesis, stating that there are three basic models of RG formation: permafrost (PM), glacier ice (GIM), and rockslide (RSM). The PM states that RGs can develop where there is permafrost and the flow is caused by internal ice creep in the weathered detritus. The GIM argues that permafrost is not required to form rock glaciers and claims that the flow of a small glacier ice core sheltered from significant ablation by the overlying

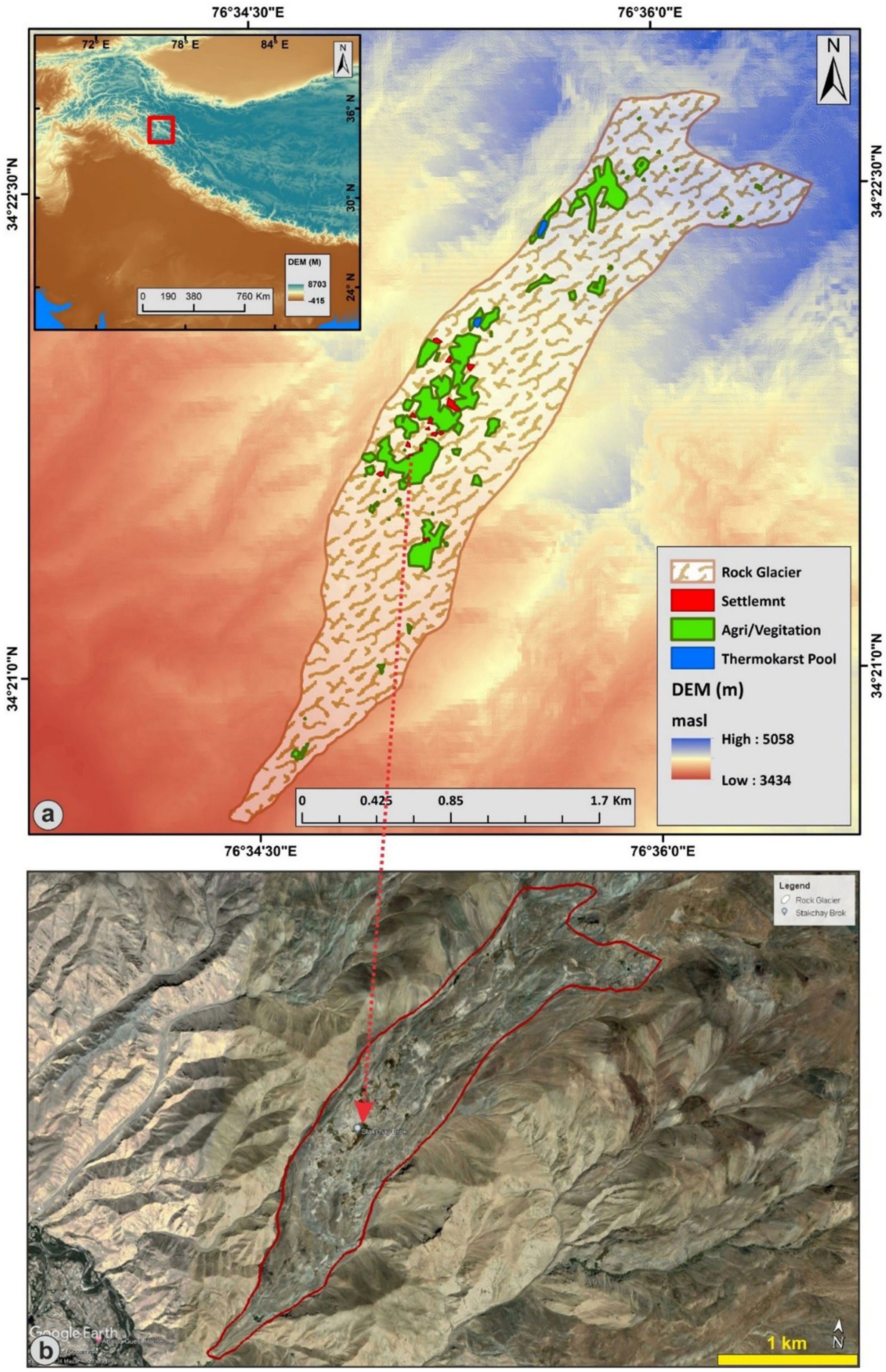


Fig. 1—(a) Shuttle Radar Topography Mission (SRTM) digital elevation model (DEM) showing the location of the study site (inset red rectangle) and the rock glacier super–imposed on it showing some prominent features, (b) Google Earth Pro image showing the Rock glacier (red boundary).

debris layer is sufficient to explain rock glacier features. Conversely, the RSM assets that certain RGs are produced by catastrophic rockslides (or talus collapse) and are often the consequence of a one–time occurrence. The movement might be produced by interstitial ice creep or hydrostatic pressure.

Understanding the relative importance of climatic and non–climatic controls on RG genesis and sustenance, as well as responses to changes in these controlling factors (such as precipitation patterns and seasonal variability; topography, sediment characteristics, vegetation cover, etc.), is critical for understanding the importance of RGs in palaeoclimatic studies and for future high mountain hydrology (Hassinger & Mayewski, 1983). Despite genetic variations, RGs typically have identical/similar morphological characteristics such as a lobate front, poorly sorted debris, transverse or longitudinal ridges and furrows, conical depressions, crevasses, and lobes, resulting in an extremely complicated topography. In a climate change scenario, RGs are considered a crucial source of water, particularly in arid or semi–arid regions where glacier cover is diminishing, leading to water shortages (Ali & Pandey, 2023). Because of their tolerance to continued warming due to extensive debris cover, RGs are an important water management resource in high mountain environments.

However, depending upon the type of the RG, the potential of water volume equivalent (WVEQ) stored within them may vary (Jones *et al*., 2021). The WVEQ for the Himalayan RGs has been estimated by Jones *et al*. (2021) using a thickness–area scaling relationship for an ice content ranging from 40–60% (median 50%), however, Wagner *et al*. (2021) lowered the lower range to 20% to account for the possibility of less ice content in inactive RGs in the Austrian Alps. Hence, depending on the genesis and the contemporary type of RG, the WVEQ can be roughly estimated.

Insightful information on the origin and evolution of these landforms through space and time may be gleaned from the present–day morphology of the RGs. In this work, we aim to provide detailed morphological characteristics and landscape evolution of one important RG that seems to be geomorphologically dynamic (inactive front, but active small lobes in upper reaches) and that has been giving certain ethnic groups in the Budhkarbu (Staksey Brok) region of Ladakh (Western Himalaya) refuge and a means of subsistence. With the help of this study, we intend to generate great interest in

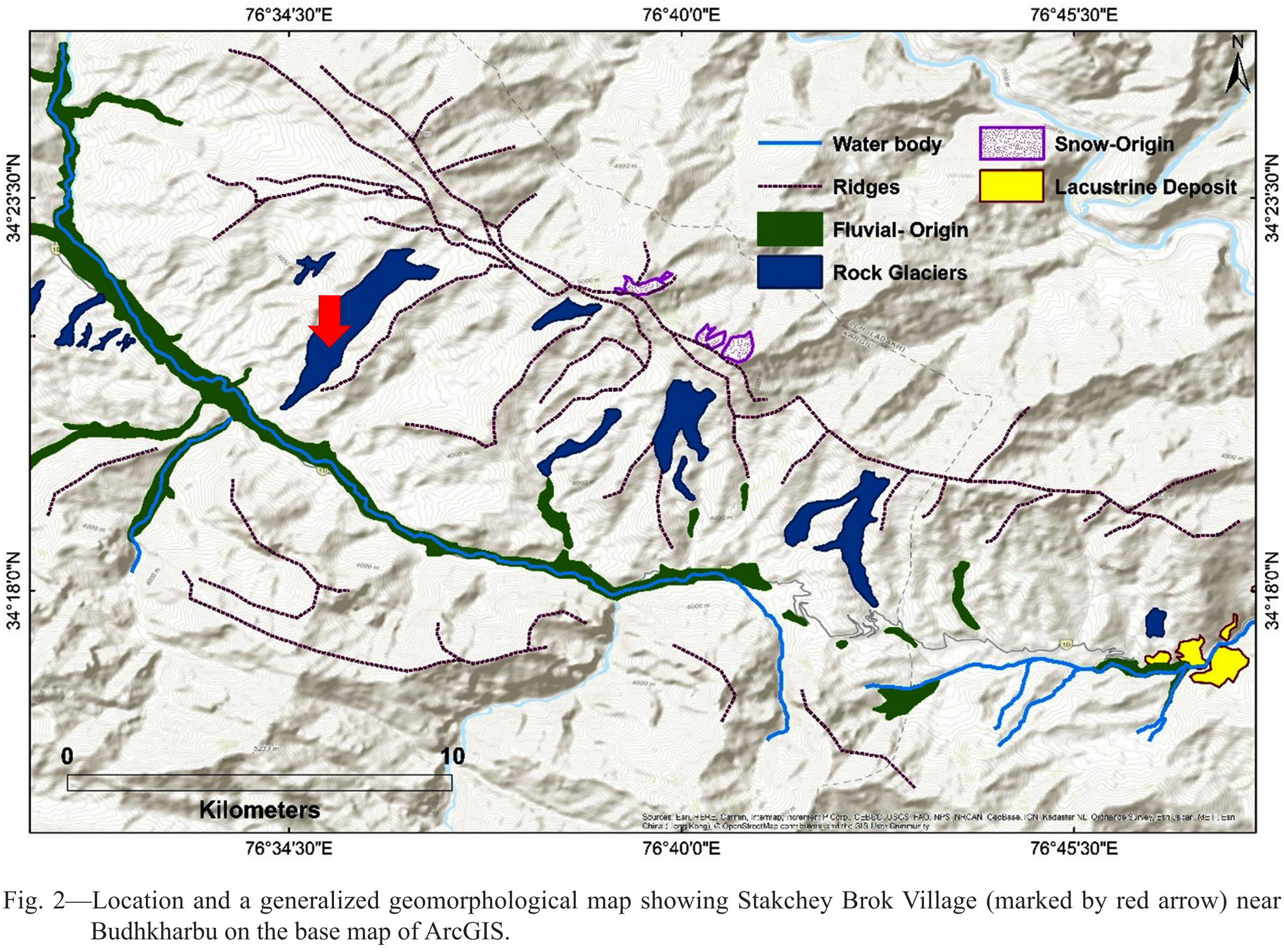


Fig. 2—Location and a generalized geomorphological map showing Stakchey Brok Village (marked by red arrow) near Budhkharbu on the base map of ArcGIS.

the investigation of inter–relationships among rock glaciers, permafrost, and the possibility of sustainable inhabitancy in cold and arid climates such as Ladakh.

STUDY AREA

The study site, i.e. the RG is located on the right flank of the Wakha River Valley, near the Budhkarbu Village in the district of Kargil, Ladakh. The rock geomorphology encompasses thermo–karst pools, agricultural fields, active crevasses, small active RG lobes, relict lake deposits, sediment–filled depressions, and lateral moraines. The RG is home to a small community (village–Stakchay Brok), with only a dozen dwellings, and provides the natives with livelihood and most basic requirement, i.e. freshwater (Figs 1, 2). The study area is located about 20 km west of Lamayuru also known as the Moon land of India. This RG bears evidence of the strategies of adaptation taken by high mountain people in the face of dramatic climate change, notably in the semi–arid to arid Ladakh region. It is situated on the Lamayuru Formation, and towards the south, it is bound by the Triassic–Cretaceous–Eocene rocks of the Zanskar Supergroup (Thakur, 1981; Mahéo *et al*.. 2004).

The region experiences a semi–arid to arid climate as it falls in the orographic exterior or rain shadow zone of the Indian Summer Monsoon precipitation. Considering its limited precipitation, scanty vegetation, and harsh climate, the region has been referred to 'cold desert' with the distinction of being the highest, coldest, and driest inhabited place on earth (Daultrey & Gergan, 2011; Hasnain, 2012; Ali *et al*., 2018, 2022). The harsh climate is evident from the fact that the temperatures range from 30°C in the summer to–50°C in the winter (Angeles & Tarbotton, 2001; Le Masson & Nair, 2012). The annual precipitation in this region which falls on the lee side of the Zanskar Range) is very low (~105 mm; Bhan *et al*., 2015) with major precipitation occurring during winter in the form of snow.

METHODOLOGY

A detailed field survey of the RG near Budhkarbu was carried out in June 2023. Detailed analysis of the RG was

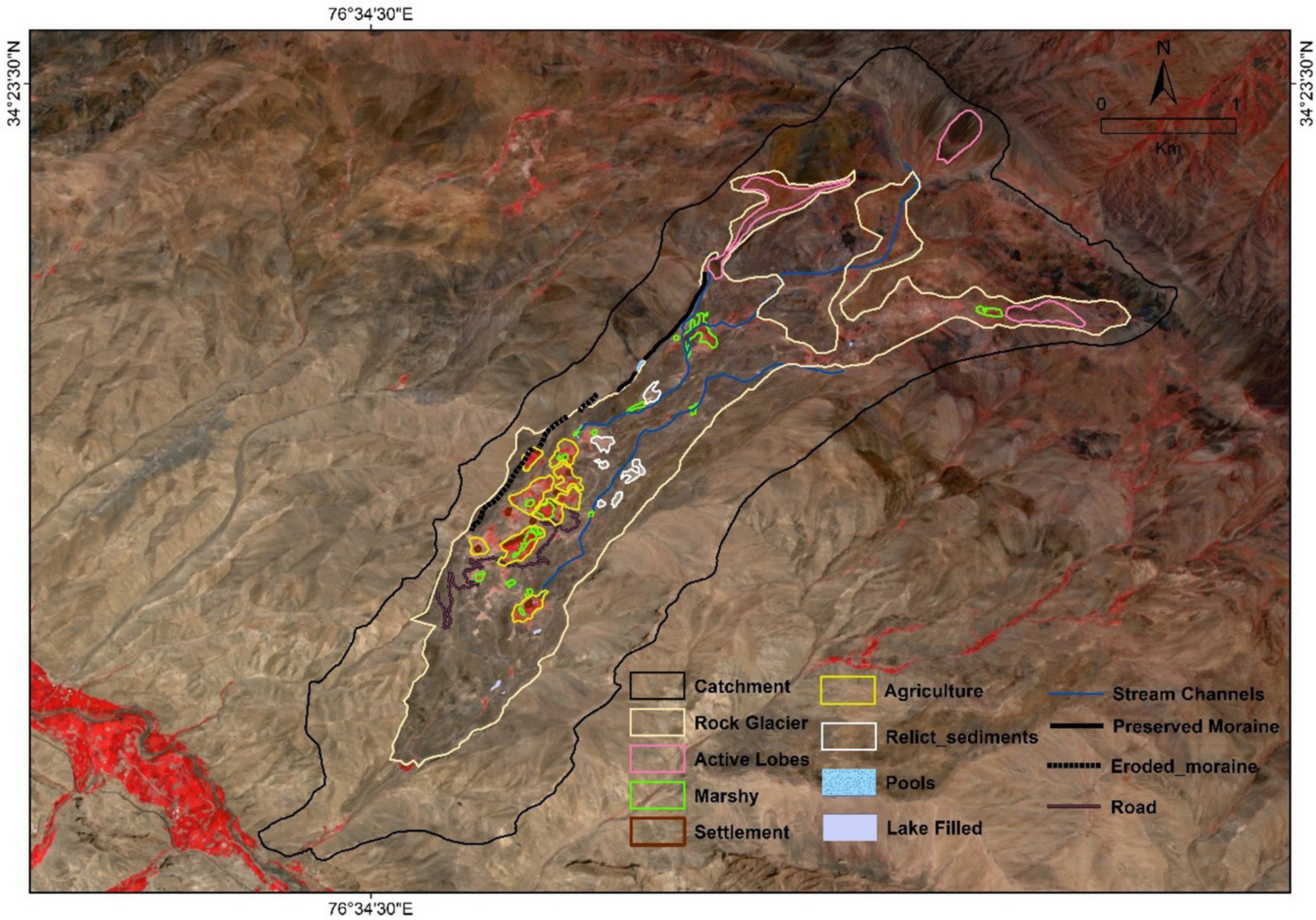


Fig. 3—Land use and land cover (LULC) map of the SBRG shown on the LISS IV image of July 2021 showing three different zones along with 100 m contours.

carried out involving field–based information and satellite–derived parameters. The geomorphology of the region and land use land cover of the Stakchey Brok Rock Glacier (SBRG) were mapped using high resolution (5.8 m spatial resolution) Indian Remote Sensing Satellite (IRS) LISS IV data of July 2021 (LISS IV image ID is 2315981101). The morphometric parameters were extracted using Advanced Land Observing Satellite (ALOS) Digital Elevation Model (DEM) in the ArcGIS platform. The SBRG area and slope, upslope area and slope, hypsometry, maximum, minimum, and mean elevations, length, width, and headwall elevation were estimated using the ArcGIS tool employing remote sensing datasets. Previous information on the distribution of RG (Pandey *et al*., 2022; Khan *et al*., 2021) was also incorporated into the mapping. The local and regional lithologies of the bed rock and adjacent rock were collected from the available literature (Thakur, 1981; Mahéo *et al*., 2004). Small–scale topographic features such as lobate bulges, relict lacustrine sediment and debris flow deposits, moraines, marshy land, thermo–karst pools, settlement, etc. were recorded as used in the final maps. A permafrost map for the study area has been prepared following the earlier work in this region by Khan *et al*. (2021). The detailed field survey and information are expected to provide important insights into the origin of this rock glacier.

RESULTS AND DISCUSSION

Morphometry, Distribution, morphology, and Surface Features

The western Himalayan region is bestowed with plenty of rock glaciers (RGs) and some of them (frontal lobes) descend to an altitude of around 3550 m above sea level (m asl; Pandey *et al*., 2022). The regional setting of the study area is dominantly cold and arid and the landscapes are broadly characterized by glacial and periglacial landforms. The SBRG covers an area of about 4.4 km^2 and is about 5 km long, and 650 m broad. The actual trend or orientation of this SBRG is NNE to SSW and extends between 3500 and 4600 m asl. The slope of the front varies between 11° and 28° and the frontal lobe height is between 15 to 50 m. The mean slope of SBRG was 14° and the mean elevation was 4068 m asl. The SBRG has a distinct headwall with a relatively mean low height of 325 m and varies between 200 m to 800 m. The connection between the headwall and the rock glacier is not talus or slope connected but is more of a cirque type. The shape of the SBRG is very distinctly tongue–shaped and the front has a conical shape, which is dictated by the valley morphology (Fig. 3). The tongue–shaped landform has marked up–slopes from the three sides, covering an area of ~6.17 km^2 with an average slope of 26°. The gently sloping topography of the RG has a mean slope of 14° which is interrupted by some abrupt slopes at different locations.

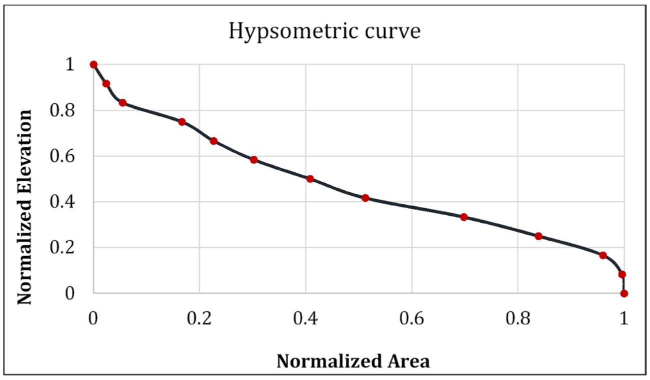


Fig. 4—Hypsometric curves of SBRG. The plots are between normalized area (A*) and normalized elevation (Z*).

The hypsometry of SBRG, which represents the area–altitude relationship (distribution of terrain area over its elevation range), was calculated using ALOS DEM. For the estimation of hypsometry, the SBRG was divided into 100 m elevation bins, and the area of each elevation bin was calculated. A normalized hypsometric curve was plotted using normalized area and elevation. A normalized hypsometric curve is the plot between normalized areas vs. normalized elevation and defines the distribution of the topographic character of the landscape (Pandey *et al*., 2017). The hypsometric curve analysis of SBRG suggested that the rock glacier be equidimensional with equal area distribution above and below the median elevation (Fig. 4). The equidimensional hypsometric curve also indicates that the landform is in equilibrium or mature stage of erosion and deposition activity.

The presence of vegetation cover on the surface of a rock glacier is one of the major indicators for remote sensing to categorize it as a relict rock glacier (devoid of movement and ice) (Seppi *et al*., 2005; Scotti *et al*., 2013; Lilleøren & Etzelmüller, 2011). Based on these criteria, SBRG is implied to be an inactive active rock glacier. However, it is also not unusual for vegetation–covered mountainous terrain to move with a displacement of 35 cm/year (Cannone & Gerdol, 2003). Based on the definition of rock glaciers, although in a satellite–based study, Pandey *et al.* (2022) suggested that this RG should be active; however, the field data suggest a complex nature of SBRG. Although in the field, the frontal zone shows an inactiveness, the presence of large crevasses/cracks in zone–II and active RG lobes near the headwall indicated that the landform is still potentially active and dynamic (Fig. 5).

Furthermore, the RG shelters several thermokarst pools of varying size, implying that the active layer of subsurface permafrost is, hence, thinning. The modelled permafrost map by Khan *et al.* (2021) also revealed the distribution of sporadic and discontinuous permafrost (Fig. 6). The thermokarst pools present on the SBRG are used for hydrating crops (agricultural land), and domestic purposes, and the gently sloping fine–grained grounds near these pools are used for agricultural purposes. Besides natural pools, artificial tanks/reservoirs have been constructed to tap the water during the early spring and summer, which is then used for domestic purposes. Figure 7 provides evidence of the thawing permafrost on the rock glacier.

Lithologically, the characteristic composition of the Lamayuru Formation (the bedrock of SBRG) is shales, phyllites, silty and calcareous shales, sand/siltstone, and blue platy limestones (Fuchs, 1975, 1979). According to Ikeda and Matsuoka (2006), the dynamics of RGs reflect the geology of the source rocks, which governs the way of debris delivery. As a result, the sedimentary source in the catchment of the SBRG provides good conditions for the same. This is because sedimentary rocks are softer and generally fracture before rock glacier development can begin (Johnson *et al*., 2007; Weidenaar, 2013). This is the possible reason that the SBRG predominantly consists of matrix–supported clasts as a result of fragile (less weathering resistant) shales, sand/siltstone, and platy limestones (Matsuoka & Ikeda, 2001; Ikeda & Matsuoka, 2006). As far as the clast size is concerned, it ranges from huge boulders (scattered) to fine sand matrices.

Based on prevailing surface clast distribution, slope, size, and elevations, the RG can be divided into four zones (Fig. 8). Depending upon the slope of the terrain and location of the thermokarst pools people are engaged in various agricultural activities. The need for such activities has been highlighted by Pandey *et al*. (2022). These flat areas seem to develop after finer sediments accumulated on the lee side of horizontal ridges on gentle slopes (Fig. 9a, b, c). These flat areas become marshy in the melt season and thus provide viable conditions for the hydration of flora (Fig. 9a, b, c, e, f). It has been observed that the local people have found some fossiliferous rocks in the catchment of the present Rock Glacier which are being used for religious activities (Fig. 9d).

Zone I

The lower–most zone–I (lower elevation; ~3542 to 3800 m asl) has relatively steeper slopes of up to 35° and is characterized by the presence of ridges and depressions that represent paleo–thermokarst pools. As per the permafrost distribution map, this zone is primarily devoid of any

Fig. 5—Longitudinal crevasses/cracks on the upper surface of the SBRG indicating dynamic activity of the landform.

underlying permafrost with some sporadic distribution of permafrost. The topography in this zone is uneven with the presence of lots of ridges and filled depressions. These filled depressions also serve as seasonal lakes. This zone is devoid of any grassland except confined dense bushes near the terminus of the rock glacier.

Zone II

The zone–II represents the middle elevation part (~3800 to 4000 m asl) of the SBRG and is characterized by relatively flat slopes that are used by the natives for agro–pastoral activities and settlement (Fig. 10). The agricultural activities and the houses are concentrated in this zone mainly. As per the permafrost distribution map, this zone is devoid of any underlying permafrost. This zone II shelters several thermokarst pools that usually fill in the melting season that starts around the month of May. Depending upon the slope of the terrain and location of the thermokarst pools people are engaged in various agricultural activities. As per the permafrost distribution map, this zone comprises underlying permafrost that falls in the category of sporadic to discontinuous. The flat areas in this zone become marshy in the melt season and thus provide viable conditions for the hydration of flora. The subsurface permafrost melt replenishes temporary lakes and streams and now artificial tanks have been constructed to retain the water in summer and use it for various purposes (Fig. 11d). This highlights the hydrological significance of RGs and permafrost in the semi–arid to arid Himalayan region. Since a complete glacier ice loss is predicted by the end of the century in mid–latitude areas, the resilience of these ice–rich bodies to climate change makes them a key water management resource, with implications for future freshwater management (Ali & Pandey, 2023; Pandey *et al*., 2022; Arenson *et al*., 2022; Grosse *et al*., 2013). While some researchers and policymakers claim that these changes are normal, however, the pace and extent of current ecological and societal transformations are unprecedented

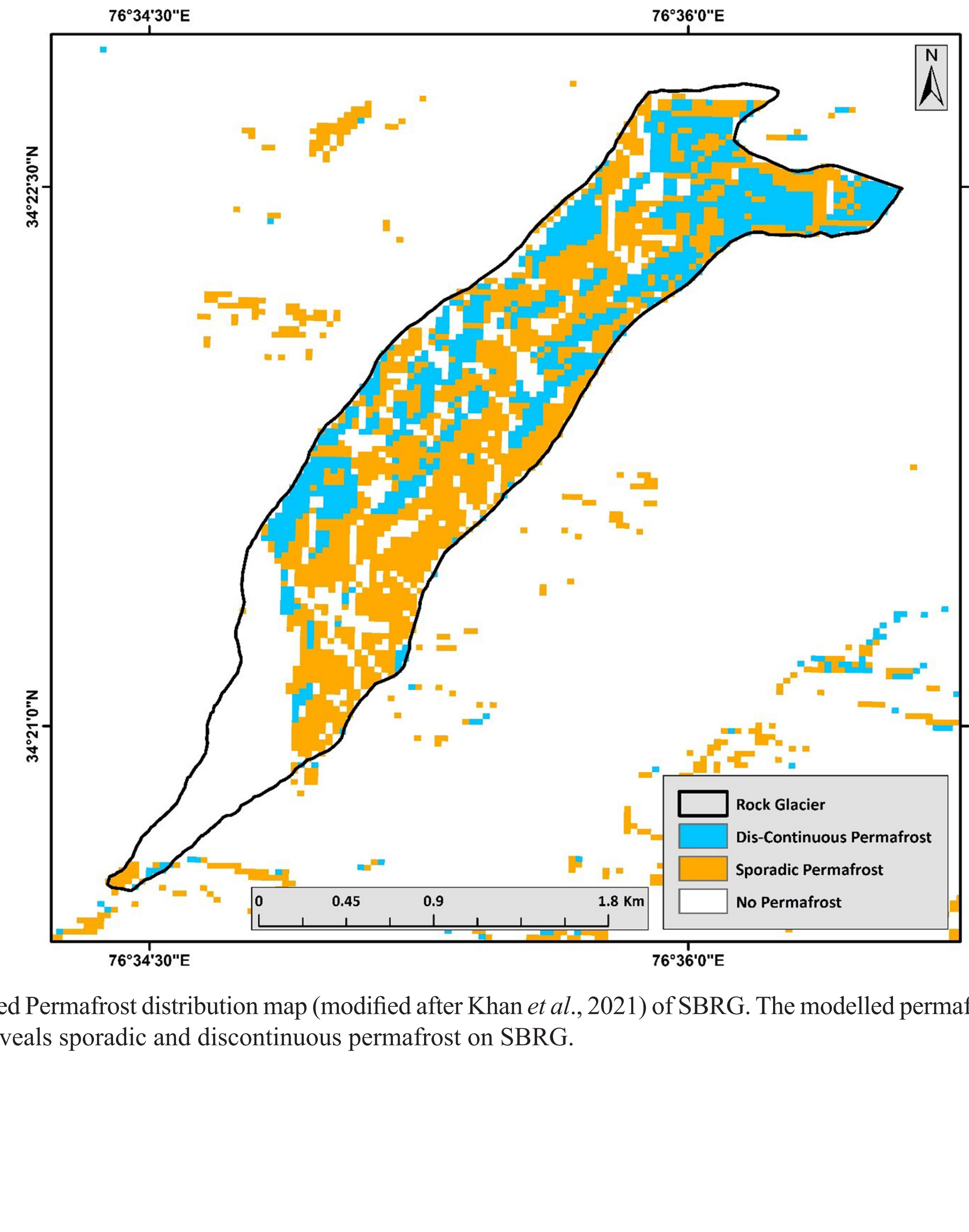


Fig. 6—Modelled Permafrost distribution map (modified after Khan *et al*., 2021) of SBRG. The modelled permafrost distribution map reveals sporadic and discontinuous permafrost on SBRG.

(Stephen, 2018; Abbass *et al*., 2022; Reidsma *et al*., 2009). Considering that the RGs are a component of the permafrost, which is extremely sensitive to climate warming and has degraded widely and quickly during the past few decades, so is the case with RGs. The quick thawing of the ice–rich RGs significantly changes soil moisture content, alters soil nutrient availability, and will have catastrophic impacts on the agro–pastoral activities in semi–arid to arid regions (Jin *et al*., 2022; Zhao–ping *et al*., 2010; Nelson *et al*., 1993). Therefore, it is just a matter of time before these high mountain communities that rely on these vulnerable RGs for their livelihoods are severely impacted perhaps leading to widespread migration to other regions that provide basic life–sustaining necessities. This makes them (RGs) crucial since they are the primary issues that demand a basic investigation to determine how much water is truly/actually locked up in such features and how long it will be sustained (Pandey *et al*., 2022).

One of the peculiar features observed in this zone is the relict lake sediments of a few to several meters in thickness (Fig. 11a, b). Besides these, at places, mud cracks that form as the finer sediment dries and contracts are also present (Fig. 12a, b). This would imply that these previously hydrated or water–filled depressions are now lacking water/dry (Goehring *et al*., 2010). These relict lake sequences (Fig. 11a, 12a) suggest that there were several thermokarst lakes. The relict lake sediments are layered and range in size from grit to silt. Such palaeo–thermokarst lakes reveal the thawing processes in the past. Their breaching and subsequent deformation would imply that the RG became active and its movement has given rise to the contemporary relict lake sedimentary sequences at different places. Detailed palaeo–climatic and chronological investigations on these relict lake sediments will shed more light on their time of formation and the prevailing climate (Phartiyal *et al*., 2022). Therefore, multi–proxy palaeoclimatic investigations aided with luminescence and exposure dating techniques will provide some crucial information about them.

Zone III

Zone III is between 4000 and 4200 m asl. The frequency of large boulders is relatively (Zone–I) higher and the overall clastic size is also high. Although except for a few agricultural

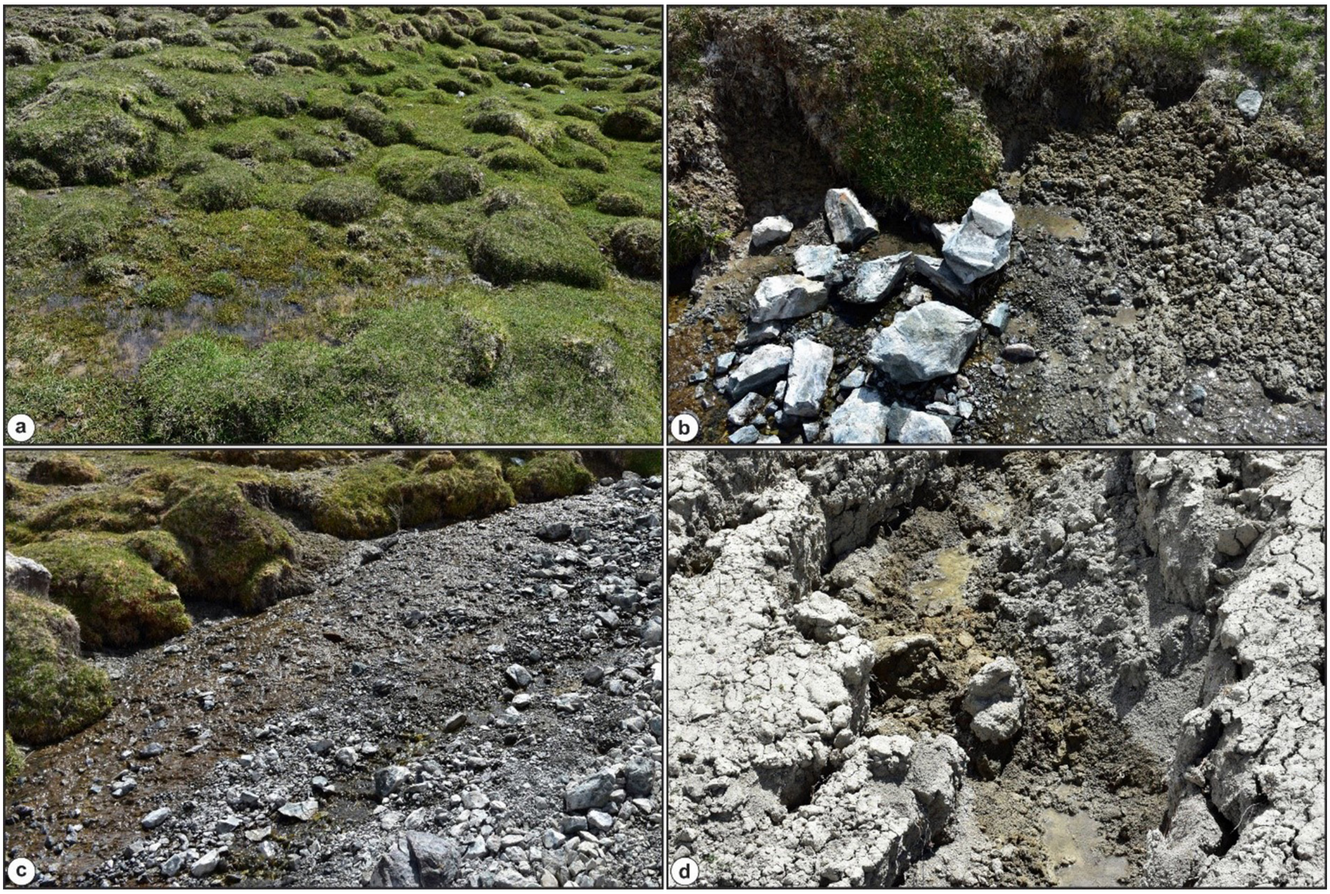


Fig. 7—Field photographs showing the evidences of thawing of the RG interstitial ice at various locations of zone II and III on the SBRG.

fields, this zone is predominantly used as pasture land (Fig. 9e, f). The melt–water streams and the marshy land provide enough hydration during the summer and shelter some small lush green grasslands usually covered by earthern hummocks (Fig. 10 a-c, 11c). The melt–water streams often end up in flat, broad, flatter sections and give rise to debris fans.

Zone IV

The zone–IV or the uppermost zone >4200 m asl) of the RG is characterized by uneven topography, varied lithology and unstable steeper slope (Fig. 12c, f). The frequency of large boulders is high and the overall clastic size also increased. As per the permafrost distribution map, this zone comprises underlying permafrost that falls in the category of dis–continuous to sporadic. This zone is mostly barren, however a few flat to gentle sloping parts are used for grazing the animals during the summer season. One of the important characteristics of this zone is the presence of active RG lobes (Fig. 12c, e). At least three active RG lobes have been identified which suggests that this RG is still an active one. Furthermore, at some places, water is seeping out of the steep slopes and the people locally call them springs. These water seepages would imply that the underlying permafrost is melting in the summer and provides an indispensable resource for the people living there. Another important landform present in this zone is the well–preserved moraines (Fig. 12d). These moraines run parallel to the present–day valley and are more prominent on its

DISCUSSIONS ON THE EVOLUTION OF SBRG

The presence of moraines in the upper reaches gives the fundamental idea about the origin and evolution of this rock glacier. As per the basic models of RG Formation (i.e. PM, GIM, and RSM), this glacier falls under the GIM category. We back up our hypothesis on the possible evolution of this RG with maps, field observations, photographs, and satellite data. As per the suggestions of Humlum (1998, 2005), the amount of ice in the RGs may vary, but the majority of RGs in

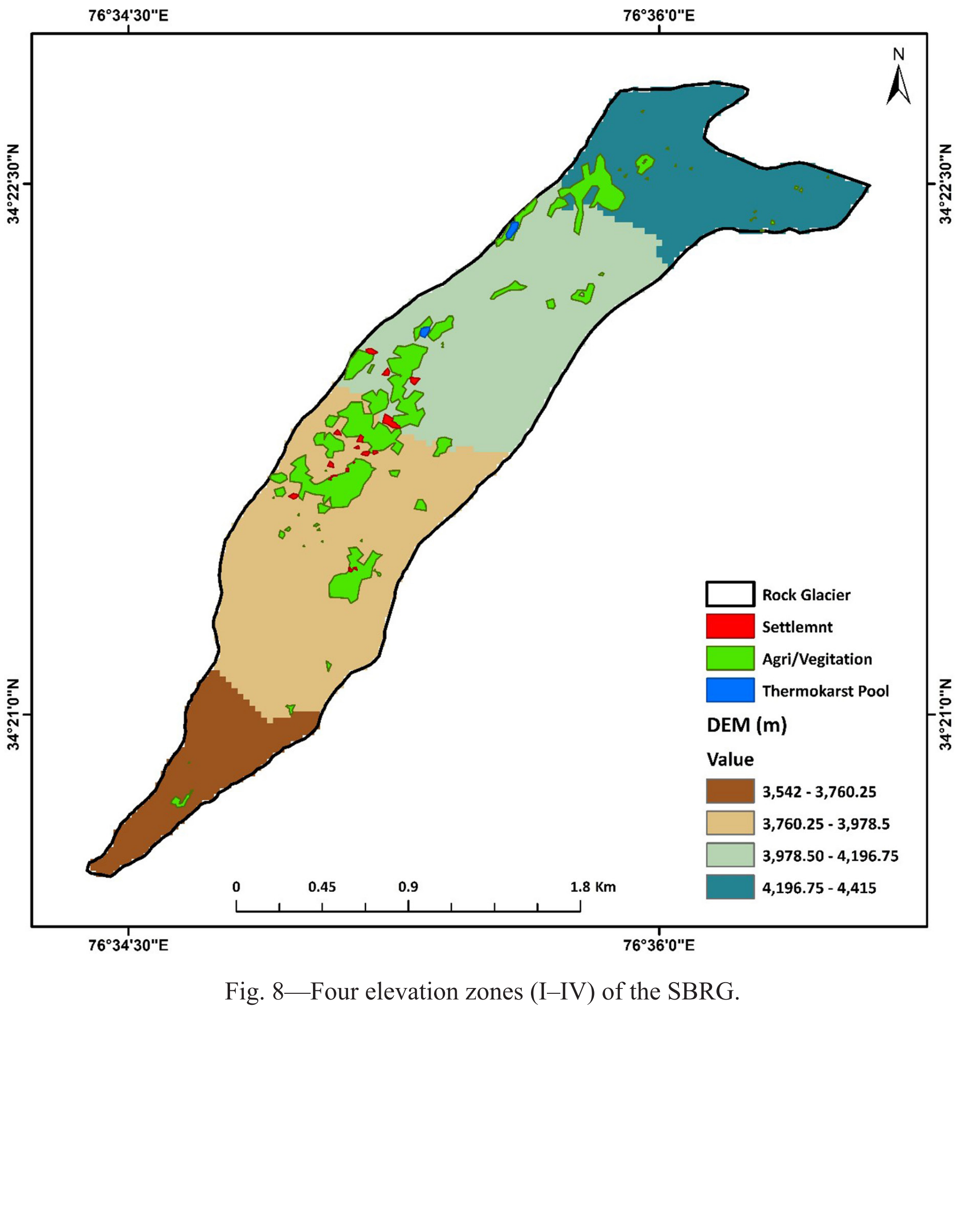
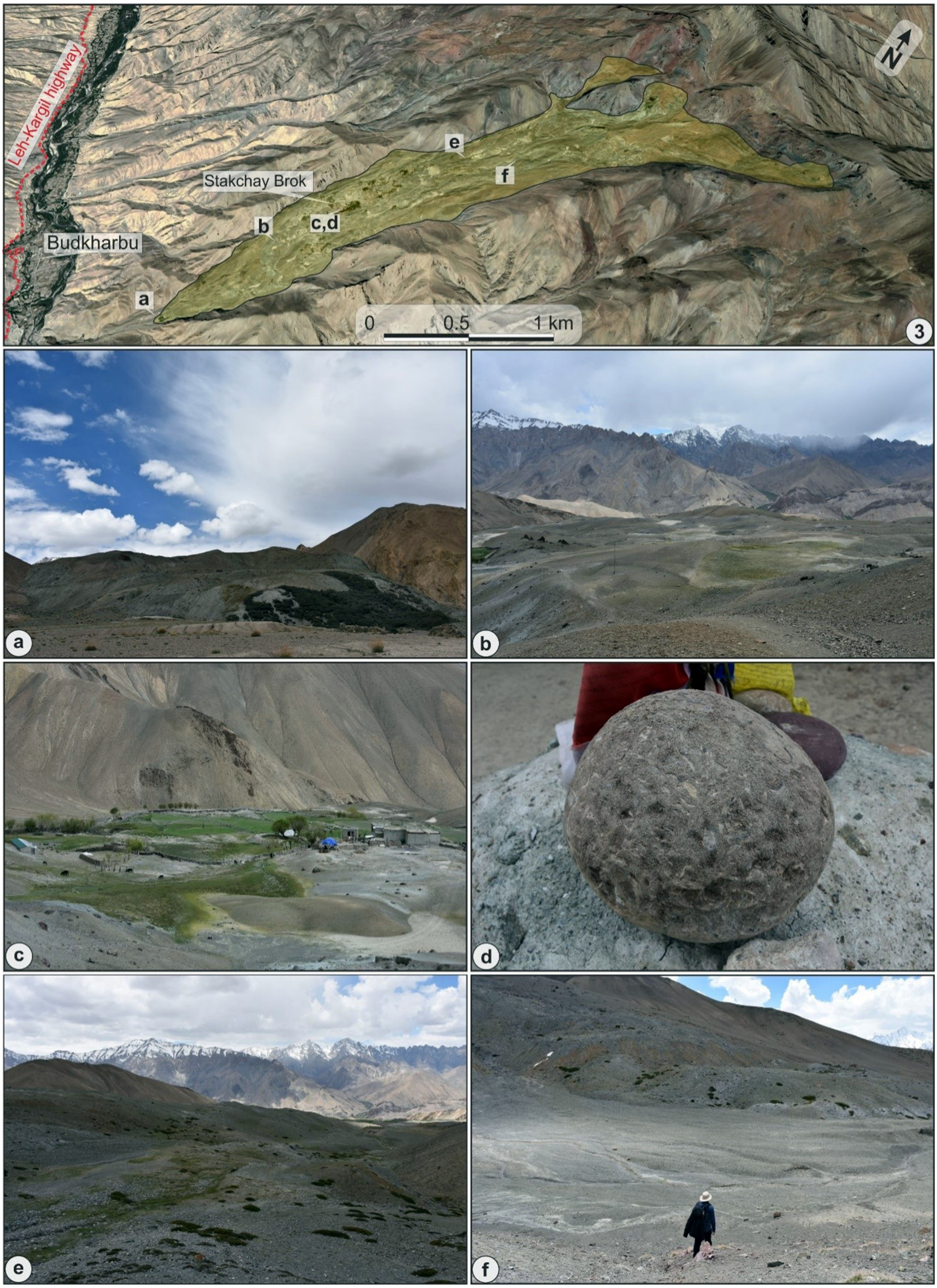


Fig. 8—Four elevation zones (I–IV) of the SBRG.


Leh-Kargil highway
Budkharbu
Stakchay Brok
N
a
b
c,d
e
f
0
0.5
1 km
3
a
b
c
d
e
f

mountainous environments are genetically associated/linked to debris–covered glaciers. The transformation of debris–covered glaciers to RGs in the de–glacierized mountains like the tectonically active Himalayas is dictated by decreasing snow and increasing debris accumulation. The steep valley walls, physically weathered and frost–thaw–shattered rocks, and geologically weaker sedimentary rocks are prone to be eroded during intense rain and snow events. This huge amount of debris is then deposited on the glacier's surface.

Due to a warmer climate and contemporary glacier shrinkage, the debris that is generally supplied to the glacier accumulation area via snow avalanches and rock fall keeps on accumulating and covers the glacier surface (Benn & Evans, 2010; Humlum, 1998; Shroder *et al*., 2000). Once the glacier surface is covered by a thick pile of supra–glacier debris and the motion due to lesser ice is slow, RG may evolve (Shroder *et al*., 2000). Based on field investigations in the western Himalayan region (i.e. Chandra Valley and the Wakha Valley; western Himalaya) and the observations and field validation of the satellite data, it is evident that the snow and debris mixed avalanches are one of the dominant sediment/debris transfer ways. Other sources and processes that play an important role are mass transport from the pre–existing moraines, hillslope sediment transport, headwall erosion, and basal processes

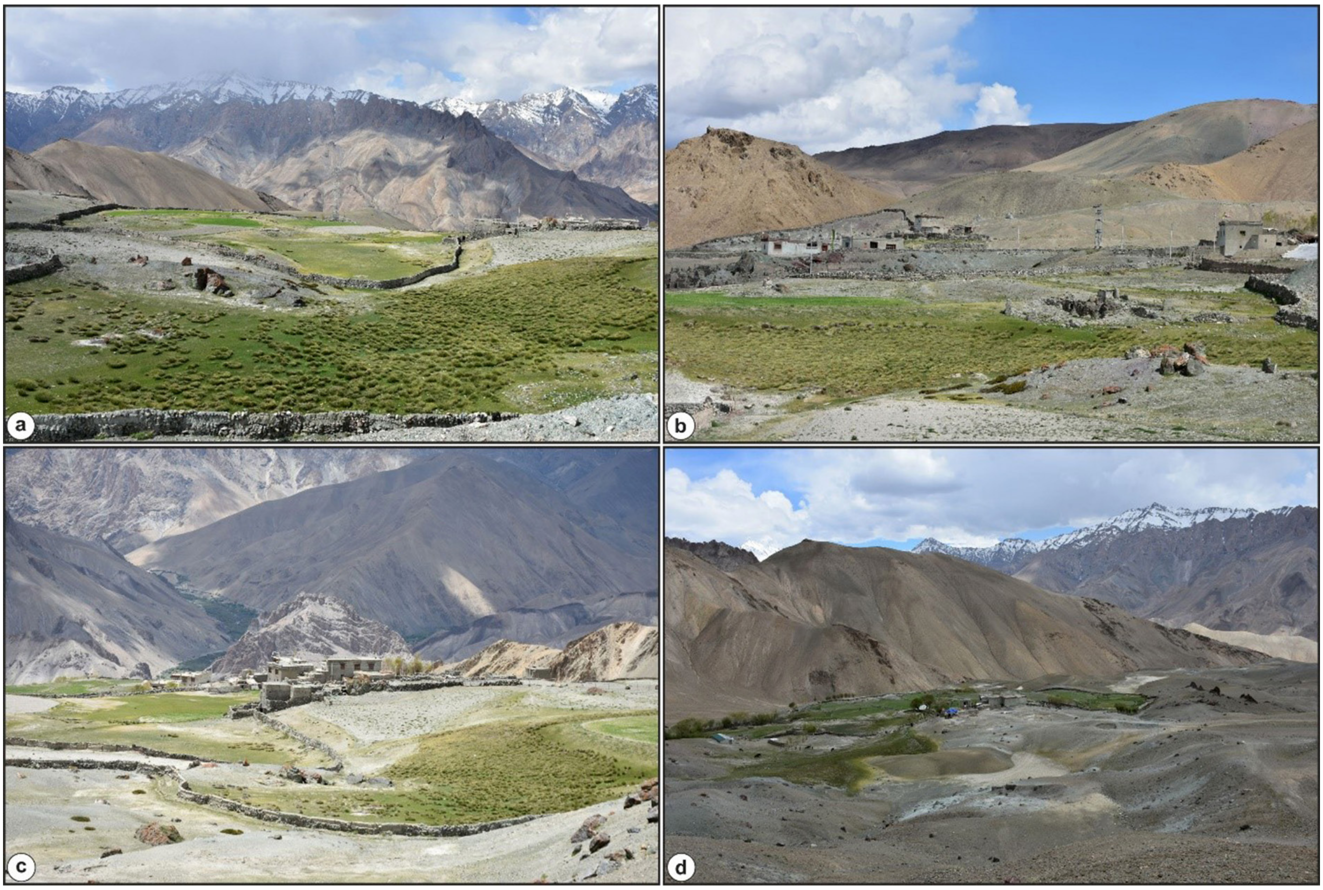


Fig. 10—(a–d) Field photographs showing the glimpses of the Skachey Brok Village settled on the elevation zone–II (~3760 to 3980 m asl) of the rock glacier.

Fig. 9—Google Earth Pro image showing the rock glacier boundary (highlighted area) and its surroundings. The location of different field photographs is also marked on the image showing (a) the frontal lobe of the rock glacier, the green patch is the bushy vegetation growing along the seepages, (b) a downstream view of the rock glacier showing the Zone–II, which has a relatively gentle slope and is used for agro–pastoral activities, (c) Stakchay Brok Village present on the rock glacier and the surrounding agricultural fields, (d) a fossiliferous rock (sandstone) collected from the local hills which is being for religious activities, (e) a downstream view of the rock glacier showing the Zone–III which is characterized by multiple uneven ridges, and (f) view of the active outwash and melt streams in Zone–III.

(Benn & Owen, 2002; Anderson & Anderson, 2016; Woerkom *et al*., 2019). That is why rock glaciers may represent the last stage of an evolutionary process in which certain glaciers shift to debris–covered glaciers, a part of which eventually transitions to rock glaciers (Jones *et al*., 2019; Knight *et al*., 2019). As a result, it is critical to research deeper facts about the Himalayan rock glaciers since they give a window into the future of debris–covered RGs.

CONCLUSION

In this paper, we provide field and remote sensing–based characteristics of a dynamic rock glacier in Ladakh that is especially inhibited by a small local settlement known as Stakchey Brok. The RG frontal lobe appears inactive and has acquired scattered vegetation cover, which may be ascribed to the moisture availability in such an arid

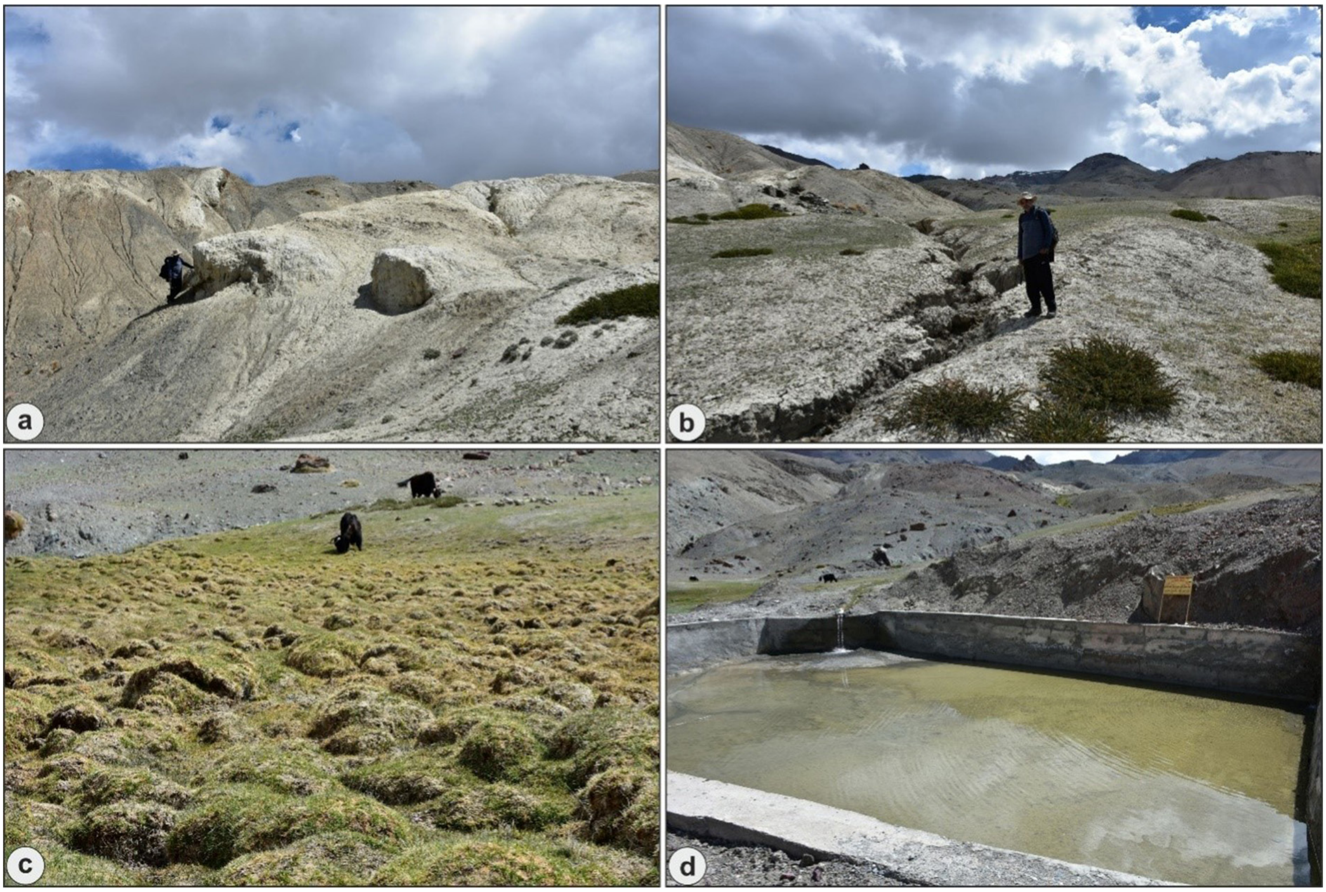
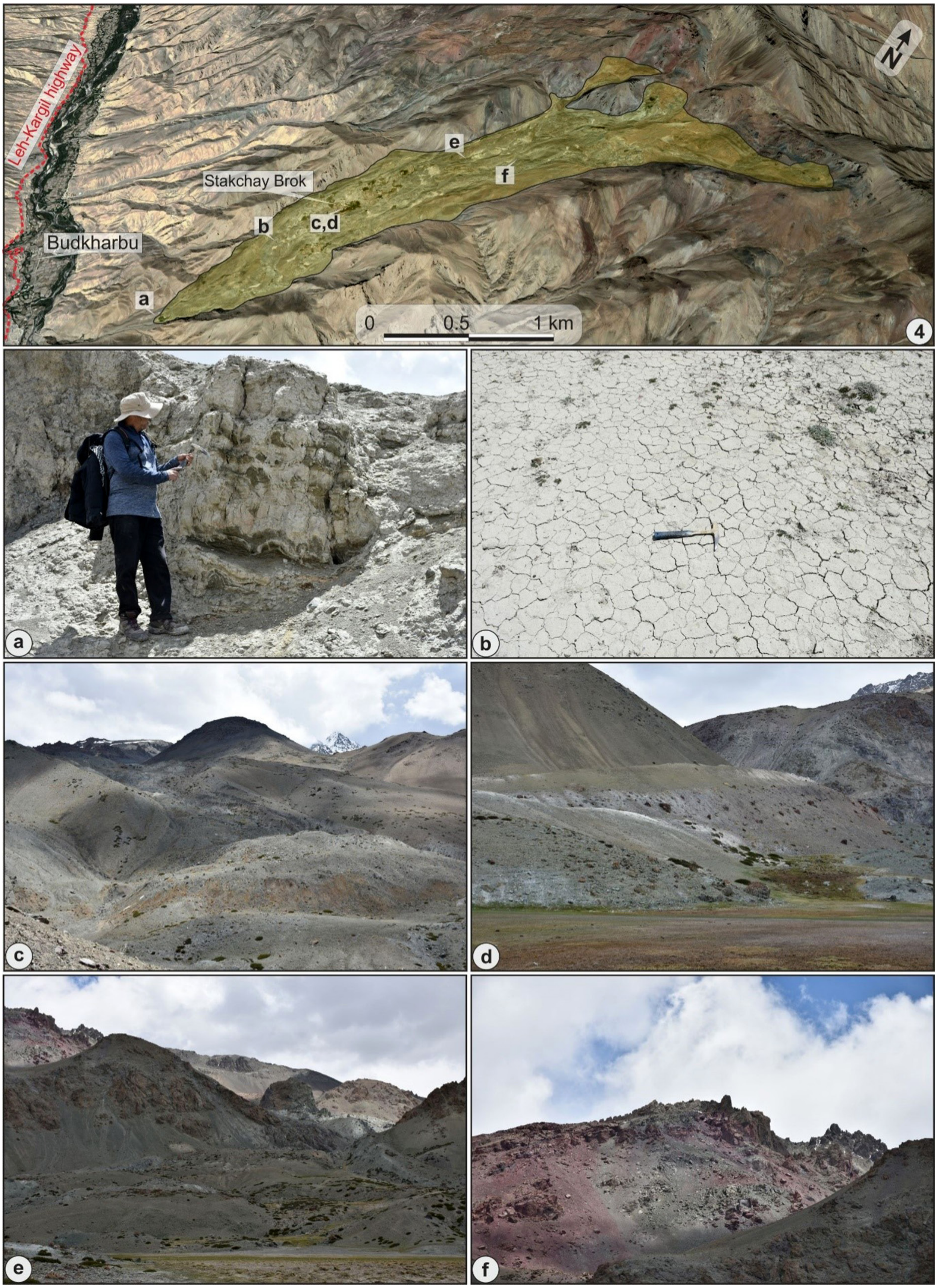


Fig. 11—Field photographs showing (a) relict lake sediments in Zone–III of the rock glacier, (b) a ~1.5 m deep longitudinal rift/ crevasse implying recent activity in the rock glacier, (c) earthen hummocks that are a representation of cryogenic mounds formed on finer sediments affected by cryoturbation (Tarnocai & Zoltai, 1978), and (d) an artificial water tank used for meltwater storage.

Fig. 12—Google Earth Pro image showing the rock glacier boundary (highlighted area) and its surroundings. The location of different field photographs is also marked on the image (Zone–II) showing (a) a succession of relict lake sediments that is a represent of sedimentation in some paleo–thermokarst lake or depression, (b) mud–crack structures that develop as a consequence drying and contracting of fine sediments, (c, e) an active rock glacier lobe present on the left and central portion of the rock glacier in Zone–IV, (d) right lateral moraine ridge and a swampy ground present on the right flank of the rock glacier (Zone–III), and (f) head–wall of the rock glacier showing different lithologies and loose sediments, a pre–requisite for rock glacier formation and sustenance.


Leh-Kargil highway
Budkharbu
Stakchay Brok
a
b
c,d
e
f
N
0
0.5
1 km
4
a
b
c
d
e
f

environment. However, there is evidence of small active RG lobes in the upper part, suggesting that the RG has a dynamic nature. Furthermore, the existence of crevasses with water (oozing out) indicates that the subsurface ice is thawing. These crevasses/cracks/fissures originate by the differential movement of the rock–ice and thawing. The existence of lateral moraines in the upper portion of the RG suggests that it had a glacial origin, which would have been supported by a steady supply of rock and ice in the accumulation zone. The cooler climate of Ladakh, enough winter snow, and therefore the availability of ice, and the weatherable sedimentary rocks (surrounding geology) appear to be the regulating causes of this RG Formation. Despite the fact that RGs are essential indicators of permafrost, permafrost distribution modelling indicates a discontinuous or sporadic occurrence of permafrost. Nonetheless, this RG supports a small high mountain habitation, and other peri–glacial landforms like SBRG have the potential to serve as water supplies in other cold and semi–arid areas.

Acknowledgements—*The authors are thankful to the Directors of the Indian Institute of Remote Sensing (ISRO), Dehradun, and Birbal Sahni Institute of Palaeosciences (BSIP), Lucknow for providing infrastructure, encouragement, and support. Funding for PP: The fieldwork to Budhkharbu was carried out under an ISRO–sponsored TDP Project entitled "Automated detection of rock glaciers in Western Himalaya, India".*

REFERENCES

Abbass K, Qasim MZ, Song H, Murshed M, Mahmood H & Younis I 2022. A review of the global climate change impacts, adaptation, and sustainable mitigation measures. Environmental Science and Pollution Research 29(28): 42539–42559.

Ali SN & Pandey P 2023. Crucial, But not systematically investigated: Rock glaciers, the concealed water reservoirs of the Himalayas: An Opinion. Journal of Atmospheric Science Research 6(2): 33–41.

Ali SN, Quamar MF, Phartiyal B & Sharma A 2018. Need for permafrost research in Indian Himalaya. Journal of Climate Change 4(1): 33–36.

Ali SN, Singh R, Morthekai P, Sharma A, Phartiyal B, Quamar MF, Kumar R & Arora P 2022. Perception of climate change from the Himalayan 'cold desert'Ladakh, India. Journal of Palaeosciences 71(1): 89–111.

Anderson LS & Anderson RS 2016. Modelling debris–covered glaciers: response to steady debris deposition. The Cryosphere 10(3): 1105–1124.

Angeles LC & Tarbotton R 2001. Local transformation through global connection: Women's assets and environmental activism for sustainable agriculture in Ladakh, India. Women's Studies Quarterly 29(1/2): 99–115.

Arenson LU, Harrington JS, Koenig CE & Wainstein PA 2022. Mountain permafrost hydrology—a practical review following studies from the Andes. Geosciences 12(2): 48.

Barsch DR 1996. Rock glaciers: Indicators for the permafrost and former geoecology in high, mountain environment. Series in the Physical Environment. Berlin, Germany: Springer, p. 331. ISBN: 978–3–642–80095–5

Benn DI & Evans DJ 2010. Glaciers and glaciation (2nd edition). Hodder Education, London, 2010: ISBN 978–0–340–90579–1

Benn DI & Owen LA 2002. Himalayan glacial sedimentary environments: a framework for reconstructing and dating the former extent of glaciers in high mountains. Quaternary International 97: 3–25.

Bhan SC, Devrani AK & Sinha V 2015. An analysis of monthly rainfall and the meteorological conditions associated with cloudburst over the dry region of Leh (Ladakh), India. Mausam 66(1): 107–122.

Cannone N & Gerdol R 2003. Vegetation as an ecological indicator of surface instability in rock glaciers. Arctic, Antarctic, and Alpine Research 35(3): 384–390.

Corte A 1976. The hydrological significance of rock glaciers. Journal of Glaciology 17(75): 157–158.

Daultrey S & Gergan R 2011. Living with change: adaptation and innovation in Ladakh. Journal of Climate Adaptation 2011: 1–11.

Fuchs G 1975. Contributions to the Geology of the North–Western Himalayas. Geologische Bundesanstalt, Vienna: 65pp.

Fuchs G 1979. On the Geology of Western Ladakh. Jahrbuch Geologische Bundesanstalt (Wien) 122/2: 513–540.

Goehring L, Conroy R, Akhter A, Clegg WJ & Routh AF 2010. Evolution of mud–crack patterns during repeated drying cycles. Soft Matter 6(15): 3562–3567.

Grosse G, Robinson JE, Bryant R, Taylor MD, Harper W, DeMasi A, Kyker–Snowman E, Veremeeva A, Schirrmeister L & Harden J 2013. Distribution of late Pleistocene ice–rich syngenetic permafrost of the Yedoma Suite in east and central Siberia, Russia. US Geological Survey Open File Report 2013(1078): 1–37.

Haeberli W 1985. Creep of mountain permafrost: internal structure and flow of alpine rock glaciers. Mitteilungen der Versuchsanstalt fur Wasserbau, Hydrologie und Glaziologie an der Eidgenossischen Technischen Hochschule Zurich, (77).

Hasnain M 2012. Climate vulnerability and resilience assessment of mountain communities living in the Ladakh Region in India. GERES India. https://www.geres.eu/wp–content/uploads/2019/10/cvra–india–2012.pdf.

Hassinger JM & Mayewski PA 1983. Morphology and dynamics of the rock glaciers in southern Victoria Land, Antarctica. Arctic and Alpine Research 15(3): 351–368.

Humlum O 1998. The climatic significance of rock glaciers. Permafrost and Periglacial Processes 9(4): 375–395.

Humlum O 2005. Holocene permafrost aggradation in Svalbard. Geological Society, London, Special Publications 242(1): 119–129.

Ikeda A & Matsuoka N 2006. Pebbly versus bouldery rock glaciers: Morphology, structure and processes. Geomorphology 73(3–4): 279–296.

Jin H, Huang Y, Bense VF, Ma Q, Marchenko SS, Shepelev VV, Hu Y, Liang S, Spektor VV, Jin X & Li X 2022. Permafrost degradation and its hydrogeological impacts. Water 14(3): 372.

Johnson BG, Thackray GD & Van Kirk R 2007. The effect of topography, latitude, and lithology on rock glacier distribution in the Lemhi Range, central Idaho, USA. Geomorphology 91(1–2): 38–50.

Jones DB, Harrison S & Anderson K 2019. Mountain glacier–to–rock glacier transition. Global and Planetary Change, 181: p.102999.

Jones DB, Harrison S, Anderson K, Shannon S & Betts RA 2021. Rock glaciers represent hidden water stores in the Himalaya. Science of The Total Environment, 793: p.145368.

Kääb A 2013. Rock glaciers and protalus forms. *In:* Elias SA (Editor)—Encyclopaedia of Quaternary Science, 2nd Edition, Volume 3. Elsevier, Amsterdam: 535–541.

Kääb A, Strozzi T, Bolch T, Caduff R, Trefall H, Stoffel M & Kokarev A 2021. Inventory and changes of rock glacier creep speeds in Ile Alatau and Kungoy Ala–Too, northern Tien Shan, since the 1950s. Cryosphere 15(2): 927–949.

Khan MAR, Singh S, Pandey P, Bhardwaj A, Ali SN, Chaturvedi V & Ray PKC 2021. Modelling permafrost distribution in western Himalaya using remote sensing and field observations. Remote Sensing 13(21): p.4403.

Knight J, Harrison S & Jones DB 2019. Rock glaciers and the geomorphological evolution of deglacierizing mountains. Geomorphology 324: 14–24.

Le–Masson V & Nair K 2012. Does climate modeling help when studying adaptation to environmental changes? the case of Ladakh, India: 75–94. *In:* Lamadrid A & Kelman I (Editors)—Climate change modelling for local adaptation in the Hindu Kush–Himalayan region. Emerald Group Publishing Limited.

Lilleøren KS & Etzelmüller B 2011. A regional inventory of rock glaciers and ice-cored moraines in Norway. Geografiska Annaler: Series A, Physical Geography 93(3): 175–191.
Mahéo G, Bertrand H, Guillot S, Villa IM, Keller F & Capiez P 2004. The South Ladakh ophiolites (NW Himalaya, India): an intra–oceanic tholeiitic arc origin with implication for the closure of the Neo–Tethys. Chemical Geology 203(3–4): 273–303.
Matsuoka N & Ikeda A 2001. Geological control on the distribution and characteristics of talus–derived rock glaciers. Annual report of the Institute of Geoscience, the University of Tsukuba 27: 11–16.
Millar CI & Westfall RD 2019. Geographic, hydrological, and climatic significance of rock glaciers in the Great Basin, USA. Arctic, Antarctic, and Alpine Research 51(1): 232–249.
Nelson FE, Lachenbruch AH, Woo MK, Koster EA, Osterkamp TE, Gavrilova MK & Cheng GD 1993. Permafrost and climate change. *In:* Proceedings of the Sixth International Conference on Permafrost 2: 987–1005.
Pandey P, Ali SN, Ramanathan AL & Venkataraman G 2017. Regional representation of glaciers in Chandra Basin region, western Himalaya, India. Geoscience Frontiers 8(4): 841–850.
Pandey P, Ali SN & Simon A 2022. Rock glacier Oasis: An alternative for agro-pastoralism in a changing environment in the Himalayan cold desert. The Geographical Journal 188(4): 585–590.
Phartiyal B, Ali SN, Sharma A, Agrawal S, Nag D, Tiwari P, Kumar M, Morthekai P, Govil P, Thakur B & Bhushan R 2022. Palaeoclimatic variability during last eight millennia from a morainal lake in Zanskar, northwest Himalaya, India. Journal of Palaeosciences 71(1): 75–88.
Reidsma P, Ewert F, Oude–Lansink A & Leemans R 2009. Vulnerability and adaptation of European farmers: a multi–level analysis of yield and income responses to climate variability. Regional Environmental Change 9: 25–40.
Rowan AV, Egholm DL, Quincey DJ & Glasser NF 2015. Modelling the feedbacks between mass balance, ice flow and debris transport to predict the response to climate change of debris–covered glaciers in the Himalaya. Earth and Planetary Science Letters 430: 427–438.
Scherler D, Bookhagen B & Strecker MR 2011. Spatially variable response of Himalayan glaciers to climate change affected by debris cover. Nature geoscience 4(3): 156–159.
Scotti R, Brardinoni F, Alberti S, Frattini P & Crosta GB 2013. A regional inventory of rock glaciers and protalus ramparts in the central Italian Alps. Geomorphology 186: 136–149.
Seppi R, Zanoner T, Carton A, Bondesan A, Francese R, Carturan L, Zumiani M, Giorgi M & Ninfo A 2015. Current transition from glacial to periglacial processes in the Dolomites (South–Eastern Alps). Geomorphology 228: 71–86.
Shroder JF, Bishop MP, Copland L & Sloan VF 2000. Debris-covered glaciers and rock glaciers in the Nanga Parbat Himalaya, Pakistan. Geografiska Annaler: Series A, Physical Geography 82(1): 17–31.
Stephen K 2018. Societal impacts of a rapidly changing Arctic. Current climate change reports 4(3): 223–237.
Tarnocai C & Zoltai SC 1978. Earth Hummocks of the Canadian Arctic and Subarctic. Arctic and Alpine Research 10(3): 581–594.
Thakur VC 1981. Regional framework and geodynamic evolution of the Indus–Tsangpo suture zone in the Ladakh Himalayas. Earth and Environmental Science Transactions of the Royal Society of Edinburgh 72(2): 89–97.
Van–Woerkom T, Steiner JF, Kraaijenbrink PD, Miles ES & Immerzeel WW 2019. Sediment supply from lateral moraines to a debris–covered glacier in the Himalaya. Earth Surface Dynamics 7(2): 411–427.
Wagner T, Seelig S, Helfricht K, Fischer A, Avian M, Krainer K & Winkler G 2021. Assessment of liquid and solid water storage in rock glaciers versus glacier ice in the Austrian Alps. Science of the Total Environment. https://doi.org/10.1016/j.scitotenv.2021.149593.
Weidenaar M 2013. Rock Glaciers in the eastern Cascades, Washington. Ph.D. Thesis, Central Washington University, Science Honors Research Program.
Whalley WB & Martin HE 1992. Rock glaciers: II models and mechanisms. Progress in physical geography 16(2): 127–186.
Zhao–ping YANG, Yang–hua OU, Xing–liang XU & Wen–bin YANG 2010. Spatial heterogeneity of soil moisture and vegetation coverage of alpine grassland in permafrost area of the Qinghai–Tibet Plateau. Journal of Natural Resources 25(3): 426–434.