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Landforms and sediments developed during the recent recession of debris-covered Ponkar Glacier, Nepal

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Understanding the evolution of debris-covered glaciers in High Mountain Asia, the physical processes governing the effect of debris cover on mass balance, and the response of debris-covered glaciers to climatic change are key for assessing water resources, the contribution of glaciers to sea level rise and the potential for glacier related hazards such as glacier lake outburst floods (GLOFs) related to moraine-dammed lakes. Here we illustrate the effects of recent glacier recession on the development of landforms and sediments at Ponkar Glacier; a debris-covered glacier in the Manaslu area of the Nepal Himalaya using a combination of 2019 RapidEye satellite image (5 m spatial resolution), drone imagery (50 cm) and field observations. We describe the key features of the glacier and its ice-surface morphology, including size and extent of flow units and tributary glaciers, supraglacial features of the debris cover and vegetation. Geomorphological mapping is used to describe the moraines, proglacial geomorphology, outwash plains and proglacial streams, the development of new ice-marginal ponds and changes in vegetation. Moraines generally have steep and rapidly degrading inner faces and mature vegetation, including trees, on their outer flanks. They are typically composed of diamicton and silty or sandy boulder gravel. Large outer moraines are separated from the surrounding valley sides by 'ablation valleys'. We conclude by putting the landforms and sediments developed at Ponkar Glacier into a discussion of the likely future evolution of high-elevation debris-covered glaciers.

Introduction

Glaciers in high mountain environments such as the Hindu-Kush Himalaya are of great interest due to their importance for ecosystems, as a water resource for people living in the mountains and surrounding lowlands (Pritchard, 2019) and for glacier-related hazards (Richardson and Reynolds, 2000; Harrison et al., 2018). Glacierized basins

such as Indus and Ganges-Brahmaputra are among the most important globally but are also vulnerable to increases in population, ineffective governance and transboundary disputes (Immerzeel et al., 2020). Such issues are magnified by climate change, and continued glacier mass loss is projected throughout this century (Kraaijenbrink et al., 2017; Huss and Hock, 2018; Hock et al., 2019; Shannon et al., 2019). Under high-end climate scenarios driven by RCP8.5 forcing during the twenty-first century, models project HMA glacier volume loss of ~95% by 2100, relative to the present-day. Volume losses are driven by an average temperature change of + 5.9°C and a + 20.9% rise in average precipitation, the latter increasingly of rain rather than snow. Reductions in snow water equivalent have been reported for a number of catchments in HMA, particularly during spring and summer (Smith and Bookhagen, 2018).

One of the most notable characteristics of high mountain environments is the presence of debris-covered glaciers, prevalent in all the major high mountain regions of the world (Kirkbride, 2011) and most common in the Hindu Kush Himalayas (Nakawo et al., 2000; Shroder et al., 2000) and to a lesser extent in New Zealand (Kirkbride, 2000), the Andes (Racoviteanu et al., 2008; Glasser et al., 2016) and the European Alps (Smiraglia et al., 2000; Deline, 2005). Until recently, most of the field based glaciological research in the Himalaya has focused on debris-free ("clean") glaciers, which are easier to access and survey. Advances in the understanding of surface processes related to debris covered glaciers have been slow until recently not only due to their location in remote, high-altitude areas or the lack of proper field survey techniques, but also due to their dynamic surfaces, notably the presence of lakes and ice cliffs.

There are various definitions of debris-covered glaciers in the literature (Anderson, 2000; Kirkbride, 2011). In this paper, we adopt the definition of a debris-covered glacier as a body of ice that exhibits a largely continuous layer of supraglacial debris over most of the ablation area, typically increasing in thickness towards the terminus (Miles et al., 2020). The sources of debris on Himalayan glaciers vary individually but they generally include material supplied by rock and snow avalanches from surrounding valley slopes, as well as melt-out of englacial debris due to subglacial erosion processes such as ice regelation, (Jansson and Fredin, 2002), material elevated to the glacier surface by thrusting from the

glacier bed, and material supplied directly to the ice surface by collapsing lateral or terminal moraines (Hambrey et al., 2008; Kirkbride and Deline, 2013; Dunning et al., 2015; Rowan et al., 2015; Gibson et al., 2017; van Woerkom et al., 2019).

Debris deposited onto the glacier surface within the accumulation zone, for example from avalanches, is buried and transported englacially until it is exhumed by ice ablation within the ablation zone. Debris deposited directly onto the ice surface in the ablation zone, for example from collapsing lateral moraines, remains on the ice surface. Theoretical and modeling studies indicate that the specific location of debris input strongly influences the ensuing spatial pattern of supraglacial debris (e.g., Rowan et al., 2015; Anderson and Anderson, 2016; Wirbel et al., 2018; Scherler and Egholm, 2020). Once it appears on the glacier surface, debris is transported passively towards the terminus, where gradients in the ice surface velocity and resulting zones of compressive or extensional ice flow serve to thicken or thin the debris cover layer.

Debris-covered glaciers vary in terms of types of debris cover and their mean thickness. The surface debris layer can range from scattered particles to several metres in thickness, including large boulders (McCarthy et al., 2017; Nicholson et al., 2018). Debris on the glacier surface is affected by other processes such as gravitational reworking (Anderson, 2000; Kirkbride and Deline, 2013; Moore, 2018; Fyffe et al., 2020). Irregular englacial debris concentration and subsequent surface reworking causes local debris thickness variability (e.g., Moore, 2018; Nicholson et al., 2018; Westoby et al., 2020). This leads to strong small-scale variability in ablation rates and can cause the formation of pronounced surface relief, ice cliffs and supraglacial ponds (Benn et al., 2001; Mertes et al., 2017). Field measurements of debris cover thickness at various sites worldwide indicate that debris cover thickness increases generally towards the glacier margins and the terminus (Mihalcea et al., 2008; Zhang et al., 2011), but varies at local scales as shown in recent manual excavations or ground penetration radar surveys (Reid et al., 2012; McCarthy et al., 2017; Nicholson and Mertes, 2017). This variability in supra-glacial debris thickness has important implications for glacier mass balance, because of its control on ablation rates (Kayastha et al., 2000; Tangborn and Rana, 2000). Understanding the control of supraglacial debris on glacier ablation is therefore important for accurate predictions of melt rates from the world's mountain glaciers and estimating their contribution to sea-level rise (Huss and Hock, 2015; Immerzeel et al., 2020). Previous studies have shown that a thin debris layer (< few cm) initially increases rates of ice-surface melt (Østrem, 1959; Nicholson and Benn, 2006; Lambrecht et al., 2011; Lardeux et al., 2016) but that as the debris layer increases in thickness to several meters, ablation rates are reduced. This allows the termini of debris-covered glaciers to extend beyond those of their debris-free counterparts.

In addition, at local scales, debris-covered glacier surfaces are complex. They are commonly characterised by hummocky, rugged topography but also present dynamic, ephemeral characteristics such as bare ice cliffs and supraglacial ponds (Miles et al., 2017; Steiner et al., 2019; Miles et al., 2020; Buri et al., 2021). These characteristics affect the local ice ablation rates, which are enhanced at supraglacial lakes or at ice cliffs (Buri et al., 2016; Irvine-Fynn et al., 2017; Steiner et al., 2017; Brun et al., 2018; Miles et al., 2018). Such patterns are reflected at regional scales. Recent studies based on satellite imagery report ice-surface lowering, glacier stagnation and mass loss on many debris-covered

glaciers across High Mountain Asia at rates similar to those of clean glaciers (Kääb et al., 2012; Gardelle et al., 2013; Brun et al., 2017). Understanding the style of recession of debris-covered glaciers is important because when these glaciers commonly recede, they form large lateral and terminal moraines behind which moraine-dammed lakes may be impounded (Westoby et al., 2015). This has important implications for glacier lake hazard assessment, since the sudden failure of a moraine-dammed lake can result in glacier lake outburst floods, with severe consequences for the populations downstream (Richardson and Reynolds, 2000; Reynolds, 2014; GAPHAZ, 2017).

Recent advances in high resolution satellite imagery, combined with field surveys has the potential to enhance our understanding of the surface of the debris cover surface glaciers, and their variability in less surveyed areas. The aim of this paper is to exploit the use of such new, high resolution aerial and satellite imagery combined with field surveys to update geomorphological mapping of debris-covered glaciers in the Manaslu region, a less studied area of the Nepal Himalayas. Specifically, we focus on: i) moraine characteristics; ii) ice surface characteristics and iii) the contribution of individual ice-flow units to geomorphology. The goal is to gain a better understanding of the surface characteristics and the current stage of evolution of the debris-covered glacier system in this area of the Himalaya in comparison with the rest of the Himalayas, and infer their influence on water resources or hazard potential.

The structure of this paper is as follows. First, we introduce the study area of Ponkar Glacier and describe the methods and data sets used. Second, we present our results concerning the mapped glacier morphology, its flow units and ice-surface morphology as well as the wider geomorphology. In the Discussion section, we discuss the implications of the mapped landforms and sediments in a landsystems context. Finally, we conclude with a discussion of the likely future evolution of high-elevation debris-covered mountain glaciers such as Ponkar Glacier.

Study Area

Our study area is Ponkar Glacier (28°37'49"N; 84°28'14"E), situated in the headwaters of Dudh Khola in the Manang district, Gandaki Province of Nepal (Fig. 1). Sapkota et al., (2016) reported a glacier area of ~30 km² with a mean elevation 5,679 m a.s.l.) Of the ~30 km², ~25 km² is clean ice and ~5 km² constitutes the debris-covered ablation area (Shrestha et al., 2020). The estimated average thickness of the glacier is 134 m (Bajracharya et al., 2014). Robson et al., (2018) reported 19 debris-covered glaciers in the area around Mt. Manaslu, with a mix of heavily debris covered, stagnating and lake-terminating glaciers. Compared to the Everest area for example, this region has not been surveyed systematically. The ablation area of Ponkar Glacier has been surveyed in the field since 2016 using ablation stakes and Unmanned Aerial Vehicle (UAV) (Shrestha et al., 2021), but published glaciological or geomorphological studies on this glacier are limited to a few (e.g., Sapkota et al., 2016; Thapa et al., 2019; Shrestha et al., 2020; Shrestha et al., 2021). A geomorphological map was produced on the basis of field observations and a 1:50,000 topographic map but data acquired were not published (Sapkota et al., 2016). A hydrological study characterized the chemistry of the melt water sources

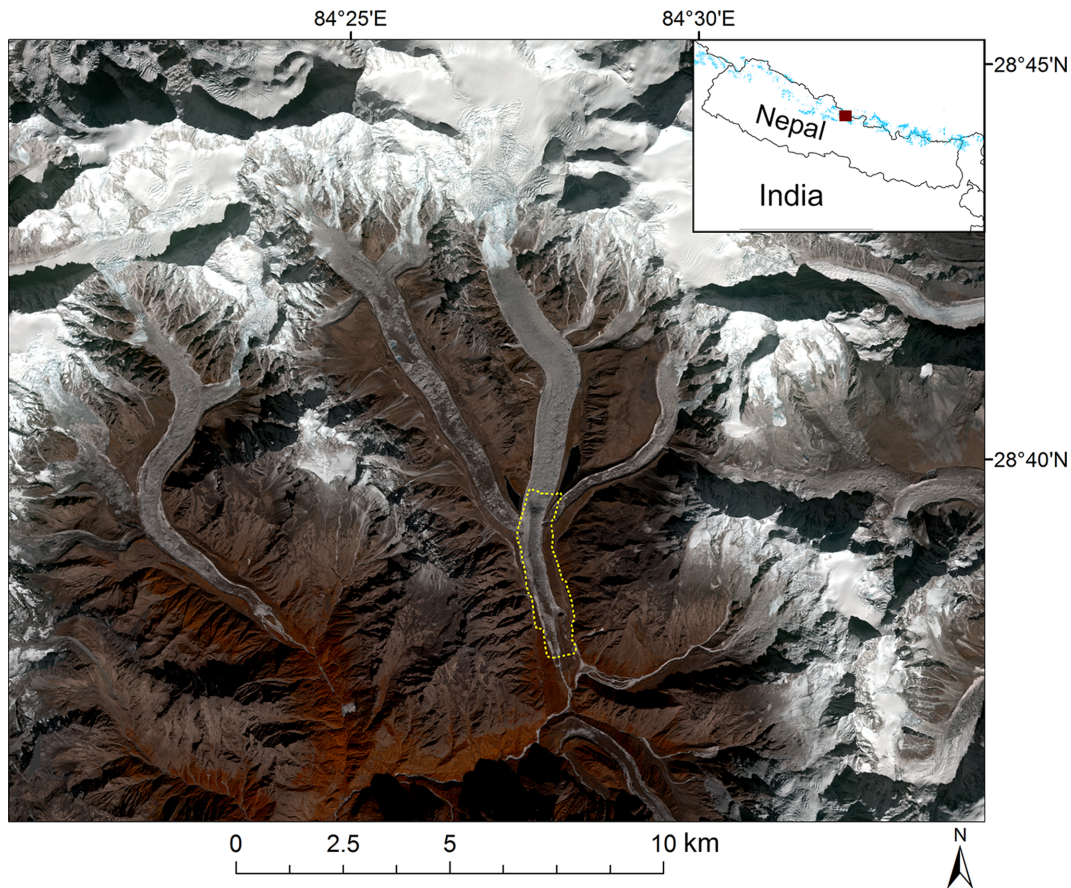


Figure 1. Location map of the study area (Manang district, in the Gandaki Province of Nepal) showing the location within Nepal and the wider Himalayas (red box). The figure is a false colour composite (bands 5,4,3) of the November 20th, 2019 RapidEye satellite image centered around Ponkar Glacier. Also shown is the extent of the drone flight survey (yellow polygon).

of Ponkar Glacier and its links with the local geology (Thapa et al., 2019) and reported calcium sulphate weathering as major source of dissolved ions in this region. Thulagi lake, a proglacial moraine-dammed lake located south of our study area has been surveyed in the field and using remote sensing with regards to GLOF potential (Haritashya et al., 2018).

Climatically, this region is located at the boundary between the south-west Asian summer monsoon-influenced region of eastern Nepal (Yanai et al., 1992; Benn and Owen, 1998), and the drier areas of the Tibetan plateau north (Benn and Owen, 1998). The last major advance of Ponkar Glacier was presumably in the Little Ice Age (LIA) (Rowan, 2017). Although the timing of LIA glacier advances varies spatially within the Himalayas, it appears that the peak period of moraine building occurred between 1300 and 1600 in the Common Era (CE), slightly earlier than the coldest period of Northern Hemisphere air temperatures (Rowan, 2017) and earlier than several regions in the Southern Hemisphere (Solomina et al., 2015).

Methods

Data Sources

In this study, we use a combination of high-resolution aerial and

remote sensing imagery combined with topographic data from digital elevation models (DEMs) for the geomorphology mapping. High-resolution stereo aerial photography at 50 cm spatial resolution was acquired over the ablation area of the glacier and its proglacial area over 3 days (November 10th – 12th, 2019) using two Phantom 4 drones, with a 30% overlap, covering an area of 3,362 km² (Fig. 2A). The image stripes were orthorectified using nine ground control points (GCPs) marked on the ground and were processed using point cloud procedures, yielding a 0.50 m drone orthoimage and DEM.

For the area that was not covered by the drone imagery, we relied on multi-spectral Planet RapidEye satellite imagery. The Planet constellation has been acquiring high-resolution daily images globally since 2009 (Planet_Team, 2017). The RapidEye sensor has the capability to acquire multispectral data with four or five spectral bands (Blue, Green, Red, Red edge and Near InfraRed), with a nominal spatial resolution of 6.5 m. The RapidEye level 3A provide orthorectified, multispectral surface reflectance data. We obtained a cloud-free RapidEye Level 3A analytic ortho tile for the closest date to the UAV flight (Nov 20th, 2019) covering the Ponkar Glacier and its surrounding region (Fig. 1). Image tiles were mosaicked using nearest neighbour resampling at 5 m spatial resolution.

We obtained surface topography needed for the geomorphological mapping from the drone DEM, combined with the freely available 8-m High Mountain Asia (HMA) DEM (Shean et al., 2016) for the areas out-

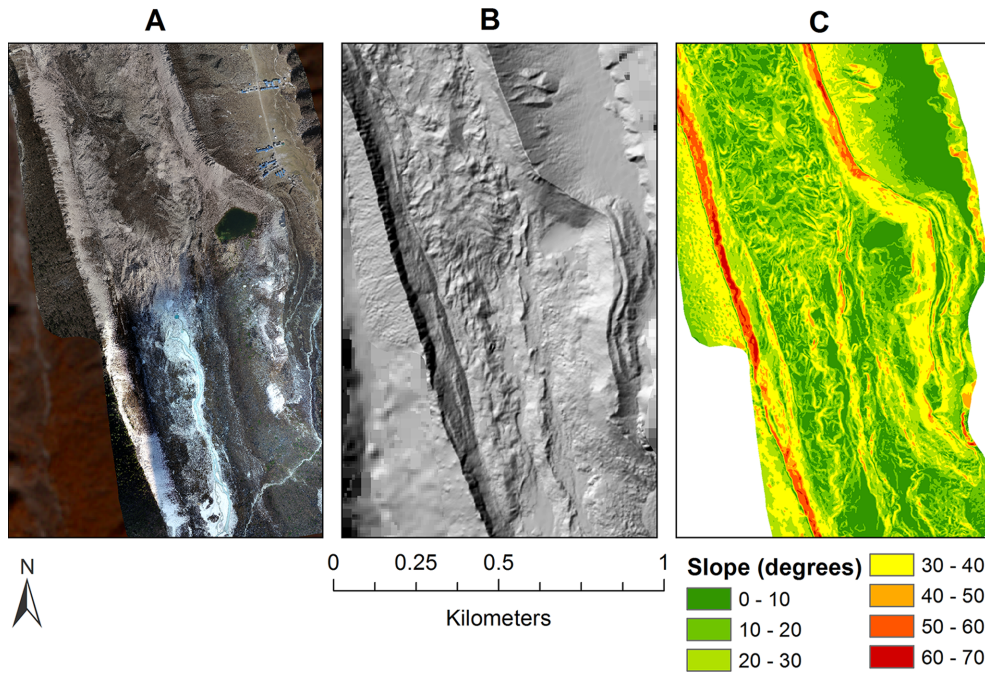


Figure 2. Data sources shown for the terminus of Ponkar Glacier: (A) drone image acquired in November 2019 (0.5 m spatial resolution); (B) shaded relief map of the drone DEM used for the interpretation of the contemporary glacier surface, and overlaid on the HMA and AW3D30 DEM for visual purposes; (C) slope map from the drone DEM. Note the sharp lateral moraines visible on the slope map.

side the area covered by the drone flight (Fig. 2B). The HMA DEM has significant holes in this area due to clouds, but these were mostly outside the glacierized area. Slope maps were derived from these two high-resolution DEMs (Fig. 2C), and were used to assist the manual digitization and feature interpretation.

Geomorphological Mapping

Geomorphological mapping was undertaken using on-screen digitization using standard criteria for identifying and mapping glacial landforms (adapted from Glasser et al., 2005) (see Table 1) on the RapidEye colour composite and the aerial drone imagery. Mapped landforms include the extent of the contemporary glacier, terminal and lateral moraines, and large areas of outwash. On the glacier surface we also mapped areas of vegetation, supraglacial ponds and areas with ogives and crevasses. shows some of the key elements of the landscape at the glacier. For the ablation area, we refined the maps using the very high resolution (50 cm) drone imagery acquired in the field.

Results

Glacier Morphology, Flow Units and Ice-surface Morphology

An ice-surface and geomorphological map of the glacier was compiled using the Rapid Eye and drone images and informed by fieldwork at the glacier in November 2019.

Ponkar Glacier comprises three main ice-flow units (labelled 1 to 3 on Fig. 4), which converge at a single confluence. Ice-flow unit 1 originates from a tributary glacier on the true right-hand side and is largely debris-covered in its lower reaches, upstream of the confluence. Flow is pinched out where it joins Ponkar Glacier and this can be seen in the surface structures (Fig. 4).

Ice-flow unit 2 is the central Ponkar Glacier flow unit. Ice flow can be traced uninterrupted all the way to the contemporary glacier terminus. The main Ponkar flow unit is largely free of debris above the confluence.

Table 1. Criteria used in geomorphological mapping to identify ice-surface and proglacial landforms. Adapted from Glasser et al. (2005)

| Feature | Morphology | Colour/structure/texture | Possible identification errors | Glaciological significance |
|-------------------------------|--|---|--|--|
| Contemporary glaciers | Bare ice, snow and debris. Surface structures (e.g. crevasses) may be visible | White to light blue Surface smooth to rough | Minor over-estimate in glacier extent possible where confused with snow cover | Glaciers are the foci for ice discharge |
| Terminal and lateral moraines | Prominent cross-valley single or multiple ridges with positive relief Linear, curved, sinuous or saw-toothed in plan. Lateral moraines follow glacier margins | Shadowing due to change in relief and change in colour where moraines are vegetated | Possible, but unlikely, confusion with trimlines where moraines have low relative height | Moraines mark the former terminal and lateral position of glaciers |
| Glacial outwash | Valley floor accumulations of sediment, commonly dissected by a braided stream pattern | Flat, mainly grey areas where there is thin vegetation cover Erosional scars and sharp boundaries with surrounding terrain | Possible, but unlikely, confusion with deltas or ice-contact deposits | Areas of outwash mark major drainage routes from contemporary glaciers and other glacier-fed streams |

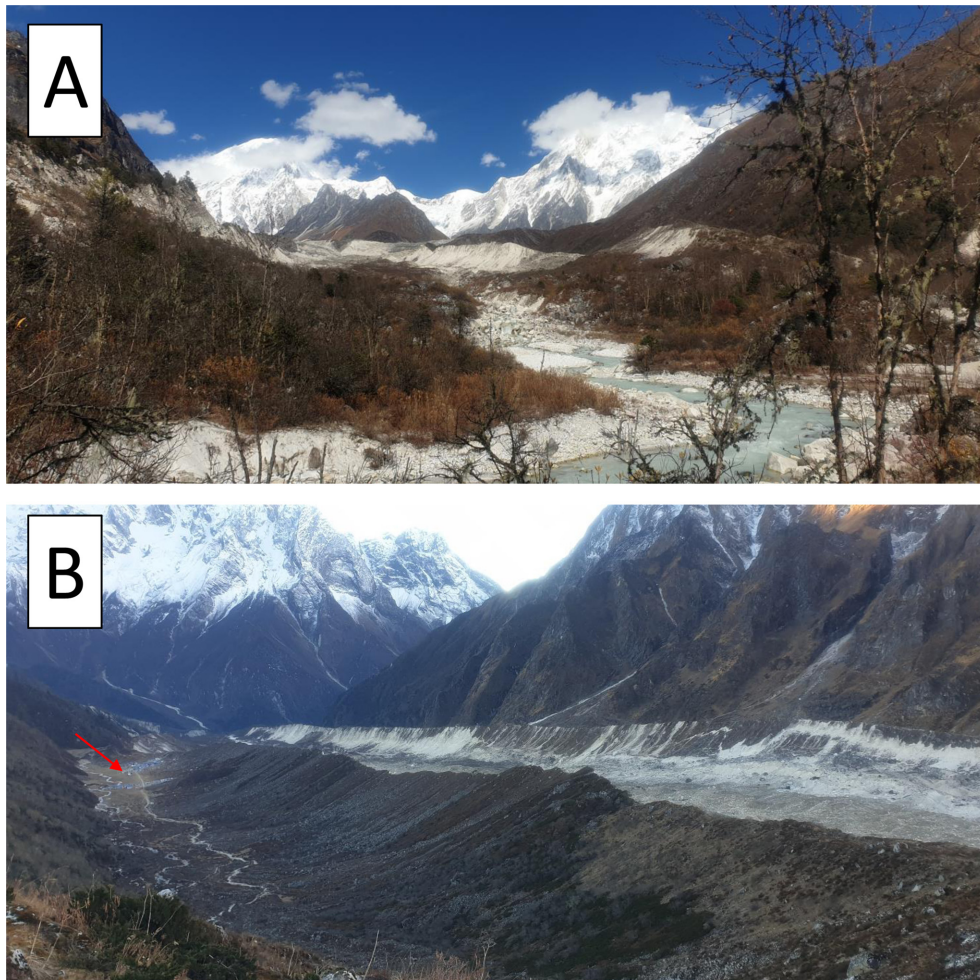


Figure 3. Overview photographs of Ponkar Glacier taken in November 2019. (A) View up-glacier from the terminal moraine showing steep inner faces of the outer lateral moraines and breach in terminal moraine. The contemporary glacier surface (just visible in the photograph) is 90–100 m below the elevation of the outer moraines; (B) View down-glacier from near Ponkar Lake. Note the steep inner faces and more gentle outer face of the lateral moraines. The large ‘ablation valley’ containing the village of Bimthang (arrowed) is on the left of the photograph.

ence but becomes debris-covered below this point. Below the confluence, Ponkar Glacier is covered with a supraglacial debris mantle, which exhibits isolated small supraglacial ponds and a few visible ice cliffs. In the lower reaches, parts of the glacier surface support surface vegetation. An area of transverse crevasses just above the confluence marks the transition from clean ice to debris-covered ice. The Ponkar flow unit is the most dynamic unit, as indicated by its relatively clean ice surface. Ice-flow unit 3 originates in a true left-hand side tributary glacier. In a similar manner to ice-flow unit 1, it is debris-covered in its lower reaches, upstream of the confluence. Flow Unit 3 is now detached from the main Ponkar Glacier system and no longer contributes active flow. Its surface is debris-covered and a series of inter-connected supraglacial ponds have developed on the ice surface, indicating it has no little or no forward velocity. The glacier surface appears to have lowered below the elevation of the surrounding lateral moraines.

The location of the current Ponkar Glacier terminus is difficult to determine with certainty even with high-resolution imagery, as it is the case with many other debris covered glaciers due to the spectral similarity between non-glacierized terrain and supra-glacial debris

(Paul et al., 2004; Racoviteanu and Williams, 2012). We identified the terminus on the Rapid Eye satellite images and then we checked the location against the terminus identified in the field in November 2019 where it is marked by stream emerging from a portal in the glacier.

Geomorphology

The primary geomorphological features of Ponkar Glacier are its moraines, which can conveniently be divided into the large outer lateral moraines and smaller inner lateral moraines. The large outer moraines are up to 100 m in height and have steep, degrading inner faces and gentle, vegetated outer faces (Fig. 5). They are separated from the main valley walls by large ‘ablation valleys’; depressions between the glacier moraines and the adjacent valley wall. The moraines enlarge progressively in both width and height down-ice, particularly after a point around the confluence of the three glaciers. Moraines have mature vegetation including fully grown trees on their outer flanks. Because the main glacier trunk has thinned below the outer moraines, their inner faces are no longer supported and are rapidly degrading (Fig. 6).

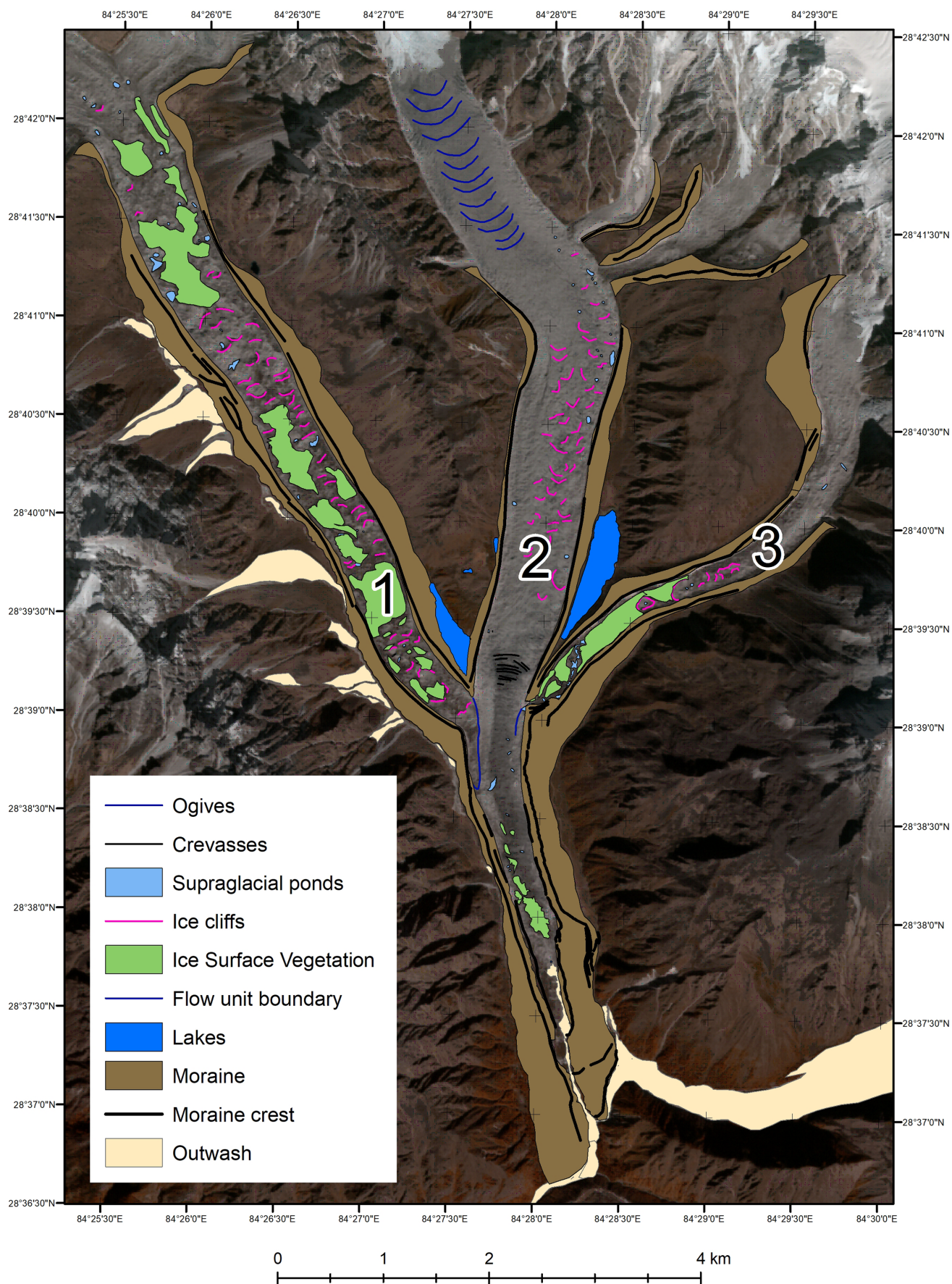


Figure 4. Geomorphological map of Ponkar Glacier and its tributaries showing the main ice-surface features and proglacial geomorphology. Numbers 1 to 3 indicate glacier flow units. The main trunk of Ponkar Glacier is Flow Unit 2.

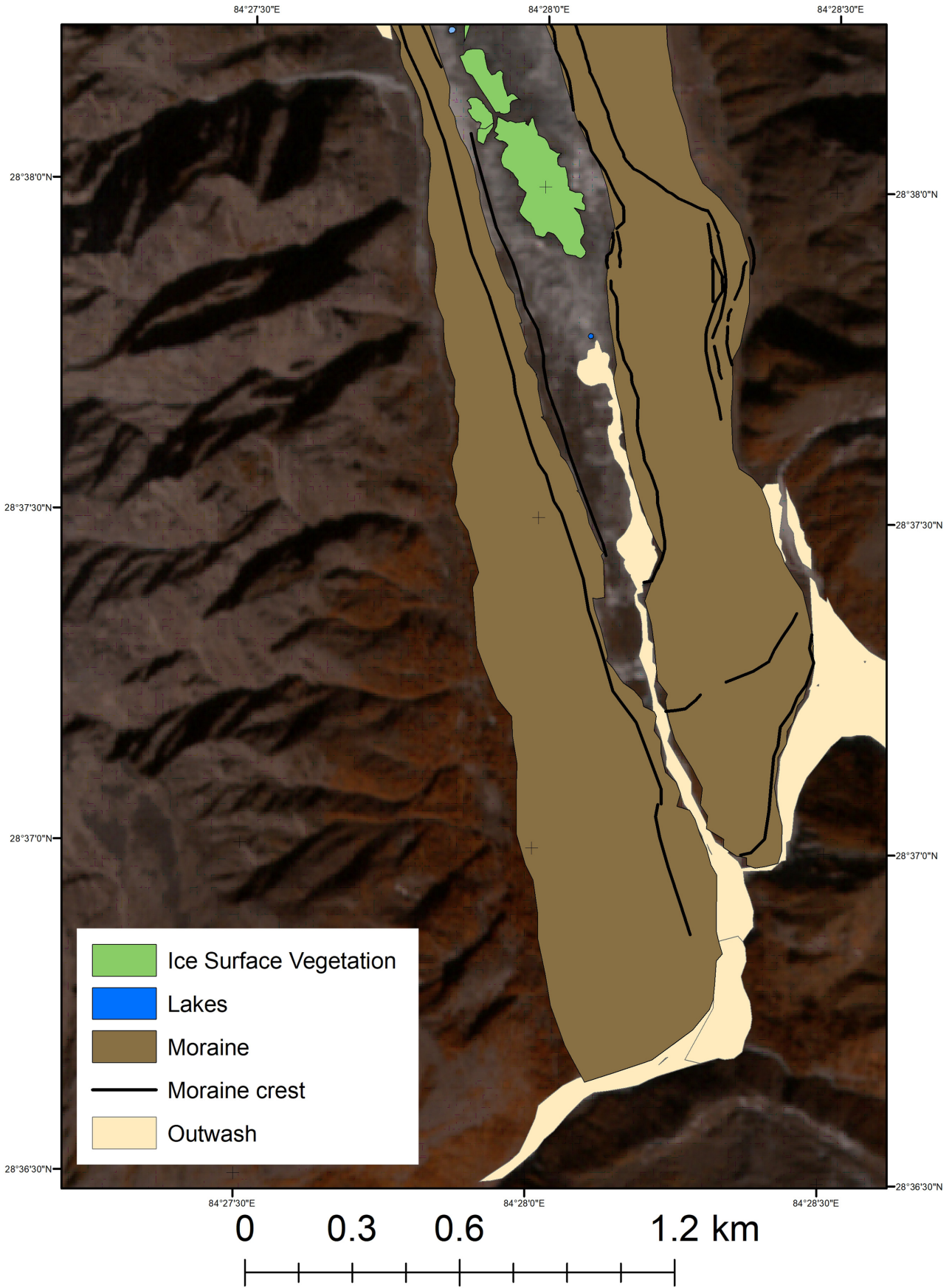


Figure 5. Detail of the geomorphological features at the snout area of Ponkar Glacier showing large lateral moraines, as well as active and abandoned outwash plains.

The true-left lateral moraine opens into a large embayment close to the current glacier terminus (Fig. 5). The outer moraine here consists of multiple crests. Sedimentologically, the outer moraines are composed of a pale-coloured, clast-rich diamicton with clay or silt matrix (A). Clasts are typically subangular and subrounded and dominated by local lithologies.

The inner moraines are visible only near the terminus of Ponkar Glacier (Fig. 5). They are low (5–10 m) ridges (Figs. 2 and 6). Lines of boulders typically mark their crests. They are composed of sandy boulder gravel and where unsupported they have steep, rapidly degrading inner faces. Clasts are typically subangular and subrounded and dominated by local lithologies.

A proglacial stream originating at a portal in the glacier (Fig. 6C) drains the contemporary glacier. The outwash plain (sandur) has both active and abandoned components. In some places, the outwash plain is topographically defined and in others it forms an extensive spread over the valley floor. A thin ribbon of abandoned outwash, related to a former terminal position of the glacier, is also visible at an elevation of 10–15 m above the present outwash stream (Fig. 5).

A number of ice-marginal ponds are developed around the glacier margins. The largest sits within the embayment in the true-left lateral moraine close to the current glacier terminus.

Discussion

Glacier Morphology and Flow Units

Multiple flow units are a common feature of cirque-fed mountain glaciers. Individual flow units typically have their own characteristic structural assemblage (Jennings et al., 2014). Flow units that narrow rapidly down-glacier are dominated by primary stratification that has evolved into longitudinal foliation. In contrast, wider flow units preferentially develop an axial planar foliation. The Ponkar flow units do not change much in width down-ice, i.e., the glaciers maintain a relatively consistent width down-ice; they are long and thin.

Glacier structure plays a limited role in the entrainment of debris. For example, there are no obvious links between the ogives on Ponkar Glacier and debris structures near the snout as has been observed in other settings (Evans, 2003). Instead, debris appears to be more strongly influenced by ice-marginal rockfall and avalanche inputs onto the glacier surface and this manifests itself in large lateral moraines.

Glacial Landsystems at Ponkar Glacier

Like many other debris-covered glaciers, Ponkar Glacier is domi-

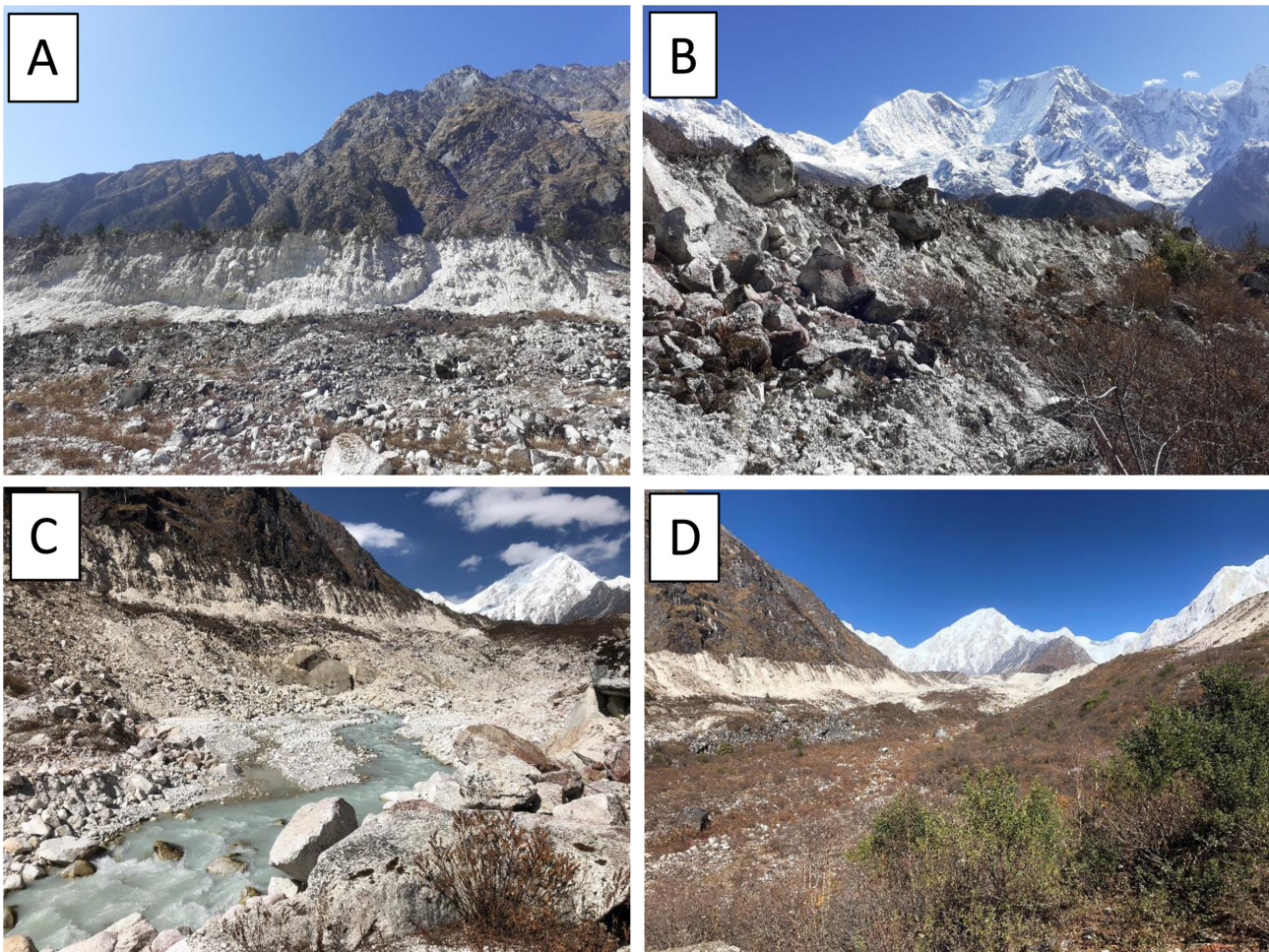


Figure 6. Photographs of landforms at Ponkar Glacier. (A) Large lateral moraines with rapidly degrading inner faces. (B) Smaller, more recent inner moraines close to the contemporary ice surface. (C) Proglacial outwash plain with active river channel. (D) Abandoned proglacial outwash plain related to a previous ice-front position.

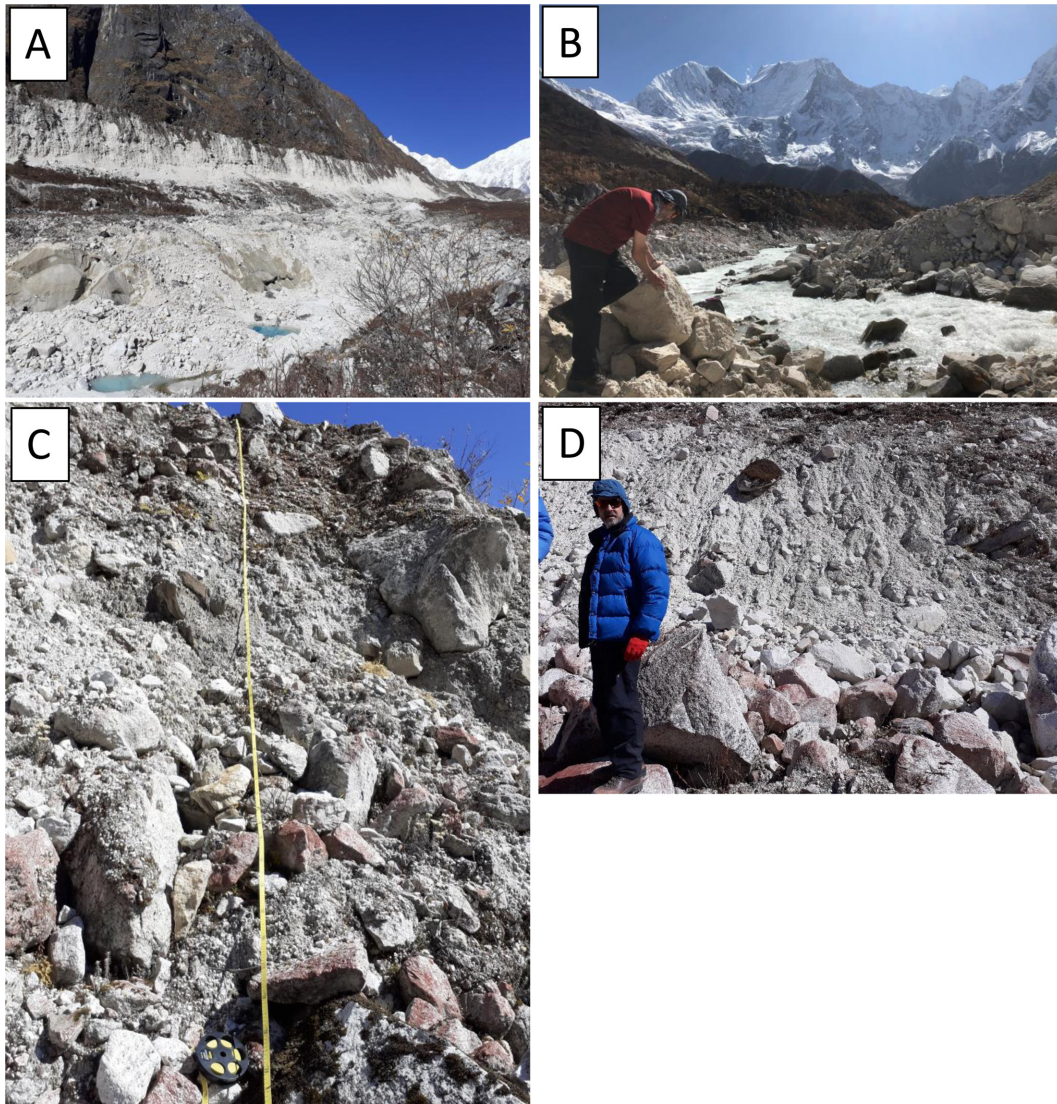


Figure 7. Photographs of sediments at Ponkar Glacier. (A) Coarse, angular supraglacial debris at the glacier snout. (B) Glaciofluvial sediment at location of subglacial meltwater emerging at the glacier snout (C) boulder moraine. (D) diamicton exposed in inner face of true-left lateral moraine.

nated by its large lateral moraines composed of diamicton and silty or sandy boulder gravel. The large embayment close to the current glacier terminus in the true left-hand moraine was presumably formed at a time when the true-left hand tributary was more dynamic and contributed a larger ice flux to the overall glacier complex. At other glaciers in the Everest Region of Nepal, terminal moraines of this size have been described by Hambrey et al. (2008). The large moraines originally grew by accretion of multiple sedimentary facies of basal glacial and supraglacial origin, probably by folding and thrusting when the glaciers were more dynamic during the Little Ice Age (Hambrey et al., 2008).

The origin of the lateral embayment is unclear but it may be the remnant of a breach-lobe moraine (Benn et al., 2003). These form as inset loops or lobate moraines where a glacier exploits a gap in a major moraine ridge, either in lateral or latero-terminal positions, and they may evolve either into large superposed moraine complexes or into accreted suites of individual ridges. Similar feature have been observed at Tasman Glacier in New Zealand (Kirkbride, 2000). The age of the large lateral moraines is

unknown but by analogy with other Himalayan glaciers, they probably date from the Little Ice Age (LIA). The peak period of moraine building occurred between 1300 and 1600 in the Common Era (Rowan, 2017).

Since the terminal moraine is breached and the proglacial stream is currently freely draining through the outer moraines there is no potential for a moraine-dammed lake to develop behind the terminal moraine. Finally, the large lateral morainic troughs or ‘ablation valleys’ are of note. Lateral morainic troughs were originally termed *ablationsschlucht* (‘ablation valleys’) by Oestreich (1906), and are features of many large valley glaciers in the Hindu-Kush Himalaya (Iturrizaga, 2001). They separate lateral moraines from valley side slopes and act as gutters trapping slope debris transported by processes including rock fall, debris flow, snow avalanche and fluvial transport (Hewitt, 2011), and may contain ponds between debris cones (Benn et al., 2003).

Our results confirm existing observations concerning glacial landsystems from other debris-covered glaciers in the Himalaya. These debris-

covered glaciers tend to form large, impounding latero-terminal moraine complexes (e.g., Benn and Owen, 2002; Hambrey et al., 2008) while, less commonly, other debris-covered glacier termini end in outwash plains without substantial terminal moraines (e.g., Mayer et al., 2006). The sedimentological, geomorphological and dynamic context of debris-covered glaciers in the eastern Himalaya was discussed by Hambrey et al. (2008), who presented a conceptual model, applicable to other Himalayan glaciers to explain the development of large, lateral-terminal moraine complexes and associated moraine dams. The presence or absence of confining moraine dams has been highlighted, in addition to declining ice content and prevailing thermal regime as a condition favouring the transition of debris-covered glaciers to rock glaciers or other ice-debris landforms (Whalley and Martin, 1992; Jones et al., 2019). In terms of their sedimentology, Hambrey et al. (2008) identified similar prominent lateral-terminal moraine complexes, comprising sandy boulder-gravel on other glaciers in Nepal such as Khumbu Glacier.

Summary and Wider Implications

Geomorphological mapping conducted at the receding Ponkar Glacier, Nepal from high resolution satellite images and field surveys indicates a landsystem composed of:

- Moraines, which can be divided into large outer lateral moraines and smaller inner moraines. The large outer moraines are separated from the valley side by ‘ablation valleys’. Moraines generally have steep rapidly degrading inner faces and mature vegetation, including trees, on their outer flanks. Moraines are typically composed of diamicton and silty or sandy boulder gravel.
- A large proglacial stream with both active and abandoned outwash plains.
- Ice-marginal ponds and supraglacial ponds developed in and around the glacier.

The landforms at Ponkar Glacier fit well with existing descriptions of debris-covered glacier landsystems (Benn and Owen, 2002; Benn et al., 2003; Hambrey et al., 2008). These suggest that large fronto-lateral moraine complexes dominate because of the abundance of supraglacial debris, which is deposited at the glacier terminus and margins during maximum advances. It is also important to note that the sediments and landforms developed at the glacier are closely related to the debris transport history in each of the three ice-flow units.

The development of Ponkar Glacier presented in this paper should also be seen in the context of glacier evolution in High Mountain Asia and its impact on future water supplies in surrounding lowlands mentioned previously. Given this general context of glacier change, the behaviour of glaciers in the wider HMA region is of great interest. While glacier-climate modeling projects considerable reduction in glacier mass balance for all areas of HMA by the end of this century (e.g., Shannon et al., 2019), a more considered assessment of how mountain glaciers respond to climate warming suggests that many of these will evolve in ways that are currently difficult to model. For instance, paraglacial processes during deglaciation lead to enhanced rock falls and debris flows from deglaciating mountain slopes and these deliver rock debris to glacier surfaces (Ballantyne, 2002; Knight and Harrison, 2009; Jones et al., 2019; Shannon et al., 2019). This produces the

kind of debris-covered glacier response we have described at Ponkar Glacier. The reduction in ice ablation due to the thick debris cover reverses the mass balance gradient, with comparatively higher ablation rates upglacier than at the debris-covered terminus, as observed in the Khumbu region of Nepal Himalaya (King et al., 2017). This significantly influences glacier dynamics (Benn et al., 2003), and with inefficient sediment evacuation eventually leads to the transition from debris-covered glaciers to rock glaciers (Shroder et al., 2000). This is important because rock glacier response may therefore be seen as the end-member of glacier evolution in HMA, as clean ice glaciers transition to debris-covered glaciers and then, finally, to rock glaciers. Further studies of the geomorphology associated with receding glaciers in high mountain areas such as the Himalaya are required to understand better this potential glacier to rock glacier transition.

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