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Mass wasting and erosion in different morphoclimatic zones of the Makalu Barun region, Nepal Himalaya

Jan Kalvoda [a] and Adam Emmer [b]

[a]Department of Physical Geography and Geoecology, Faculty of Science, Charles University, Prague, Czechia; [b]Cascade | The Mountain Processes and Mountain Hazards Group, Institute of Geography and Regional Science, University of Graz, Graz, Austria

ABSTRACT

Mountain regions of the world face unprecedented climate-induced changes and associated sustainable development challenges. Retreating glaciers, degrading permafrost and rapid mass movements on the one hand and glacier-related disasters, on the other hand, are the sentinels of these phenomena. In this study, we focus our attention on the Makalu Barun region in the Nepal Himalaya, and characterize four main morphoclimatic zones, building on repeated field surveys and interpretation of remote sensing imagery. We distinguish four distinct zones: (i) extreme glacial zone; (ii) glacial zone; (iii) periglacial zone; and (iv) seasonally cold/warm humid zone. While extreme glacial zone is stagnant in its area, remaining three zones have been experiencing areal/location changes associated with changing climate, glacier extent and permafrost distribution. We describe dominant geomorphic processes and typical landforms of these zones in detail, highlighting the role of mass wasting processes and far-reaching process chains acting across distinct morphoclimatic zones. The study provides evidence of very dynamic landform evolution which indicates extreme geomorphological hazards in the Nepal Himalaya.

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Introduction

The environment of the High Asia mountain ranges is extremely sensitive to global climate change. According to Huss et al. (2017), general (global-scale) impacts of climate change on the cryosphere and cryospheric processes will consist of the shift of all components to higher altitudes and latitudes, decreasing area, volume and duration of snow and ice cover, resulting in: (i) Geo-hydrological effects; and (ii) Ecological and societal effects (see Table 1). A short-term runoff increase, medium- to long-term decrease and shift of melting season are expected in glaciers-dominated catchments and thaw/thermal alterations at depth are expected for permafrost areas. As a consequence, more variable flow will increase the risk of hydrological extremes such as are floods and droughts. Societal effects will be manifested by reduced and more variable water availability for domestic, agricultural and industrial use, decreasing biodiversity in glacier-fed rivers and lake and a loss of cultural and aesthetic ecosystem values of mountains. A better understanding,

CONTACT Jan Kalvoda jan.kalvoda@natur.cuni.cz Department of Physical Geography and Geoecology, Faculty of Science, Charles University, Prague 128 43, Czechia; Adam Emmer adam.emmer@uni-graz.at Cascade | The Mountain Processes and Mountain Hazards Group, Institute of Geography and Regional Science, University of Graz, Graz 8010, Austria

Table 1. Impacts of climate change on the components of the cryosphere and selected global and Himalayan studies. Geo-hydrological, ecological and societal effects are based on the overview of Huss et al. (2017); climate-change related hazardous geomorphic processes are quoted especially (Figures 2 and 3) from papers Evans and Clague (1994), Clague et al. (2012) and Wester et al. (2019).

	Example of a global study	Example of a study from Himalaya
Geo-hydrological effects:		
• glaciers	Zemp et al. (2019)	Bolch et al. (2012)
• snow cover	Riggs et al. (2017)	Xu et al. (2016)
• permafrost	Chadburn et al. (2017)	Fukui et al. (2007)
Ecological and societal effects:		
• biodiversity	Korner et al. (2017)	Shrestha et al. (2012)
• water availability	Huss and Hock (2018)	Immerzeel et al. (2010)
• ecosystem services	Palomo (2017)	Dong et al. (2010)
Climate change related hazardous geomorphic processes:		
• glacier avalanches	Alean (1985)	Richardson and Reynolds (2000), Shugar et al. (2021)
• rockslides, landslides and debris flows	Huggel et al. (2012)	Korup and Weidinger (2011), Götz et al. (2015), Uprety et al. (2017)
• GLOFs and jökulhlaups	Emmer (2018)	Ives et al. 2010; Veh et al. (2019)
• permafrost degradation	Haeberli et al. (2017)	Gruber et al. (2017)

anticipating of and preparing for these inevitable changes will help meeting sustainable development goals in mountain regions (Wester et al. 2019; Immerzeel et al. 2020).

As for the hazardous geomorphic processes, Evans and Clague (1994) listed main types of hazardous processes associated with post-Little Ice Age climate change in mountain regions, including (i) glacier and snow avalanches; (ii) landslides (especially rock avalanches, deep-seated slope deformations and debris flows); (iii) glacial lake outburst floods (GLOFs) (originating from moraine- and bedrock-dammed lakes) and jökulhlaups (originating from glacier-dammed lakes). Clague et al. (2012) published an extended list of these processes, further including permafrost degradation and deglaciation-induced seismicity. Recent research activities highlight process interactions (so-called cascade processes or process chains; e.g. Haeberli et al. 2017), which involve different types of environmental processes and may affect areas located far outside the cryosphere.

Research on the geological structure, lithologic features of rock assemblages and the landform patterns of the Himalaya has identified the extreme intensity of the geodynamic processes which, particularly during the Quaternary, remodelled these mountains to their present-day shape (e.g. Gansser 1964, 1983; Molnar and Tapponier 1977; Kalvoda 1992; Molnar et al. 1993; Valdiya 1998; Burbank 2005; Thiede et al. 2005; Bishop 2007; Searle 2013; Thiede and Ehlers 2013). This aspect of the Himalayan environment can contribute to the knowledge of a long-term integrity of climate-driven morphogenetic and active tectonic processes in dynamically evolving mountainous regions of collisional orogeny. The evidence and extent of the present-day orogenic activity, as well as the prognosis of the intensity of morphotectonic movements in the development of the lithosphere, is investigated by the systematic correlation and integration of observations obtained from several branches of the natural sciences (Wager 1937; Seeber and Gornitz 1983; Fort 2000, 2004; Avouac 2003; Burbank et al. 2003; Korup and Weidinger 2011; Owen 2011; Byers et al. 2013, 2019; Bilham 2019; Kalvoda 2020).

In the presented work we focus on the Makalu Barun region in the East Nepal Himalaya (Figure 1). The landform patterns between the Chomolongma and Makalu Massifs, Barun area and the wider surroundings of the Barun Khola valley form a natural section across the sequence of Himalayan rocks as well as varied high-mountain landscapes. Main topics examined during our geomorphic studies of the Makalu Barun region have been the dynamics of landform evolution and the Quaternary glacial history including the recent retreat of glaciers. The observation of landforms provides evidence of intensive landscape changes and indicates the extraordinary features of natural hazards in the East Nepal Himalaya. Therefore, the presented study deals with mass wasting and erosion in remarkable vertical morphoclimatic zones of the Makalu Barun region. Building on field observations and interpretation of satellite imagery, we aim at characterizing different morphoclimatic zones in the studied area, their dominant geomorphic processes and related hazards with regard to recently realized and also expected landform changes.

The East Nepal Himalaya represents a conspicuous climatic dividing range between the oceanic climate of India and that of continental semi-arid Tibet. The key feature determining the Himalayan climate consists in the seasonal system of monsoonal air flow along certain predominant wind directions. Moreover, the Himalayan belts are located within the subtropical climatic zone and their set of landforms intersects almost all the known vertical zones of the high-mountain climate (e.g.

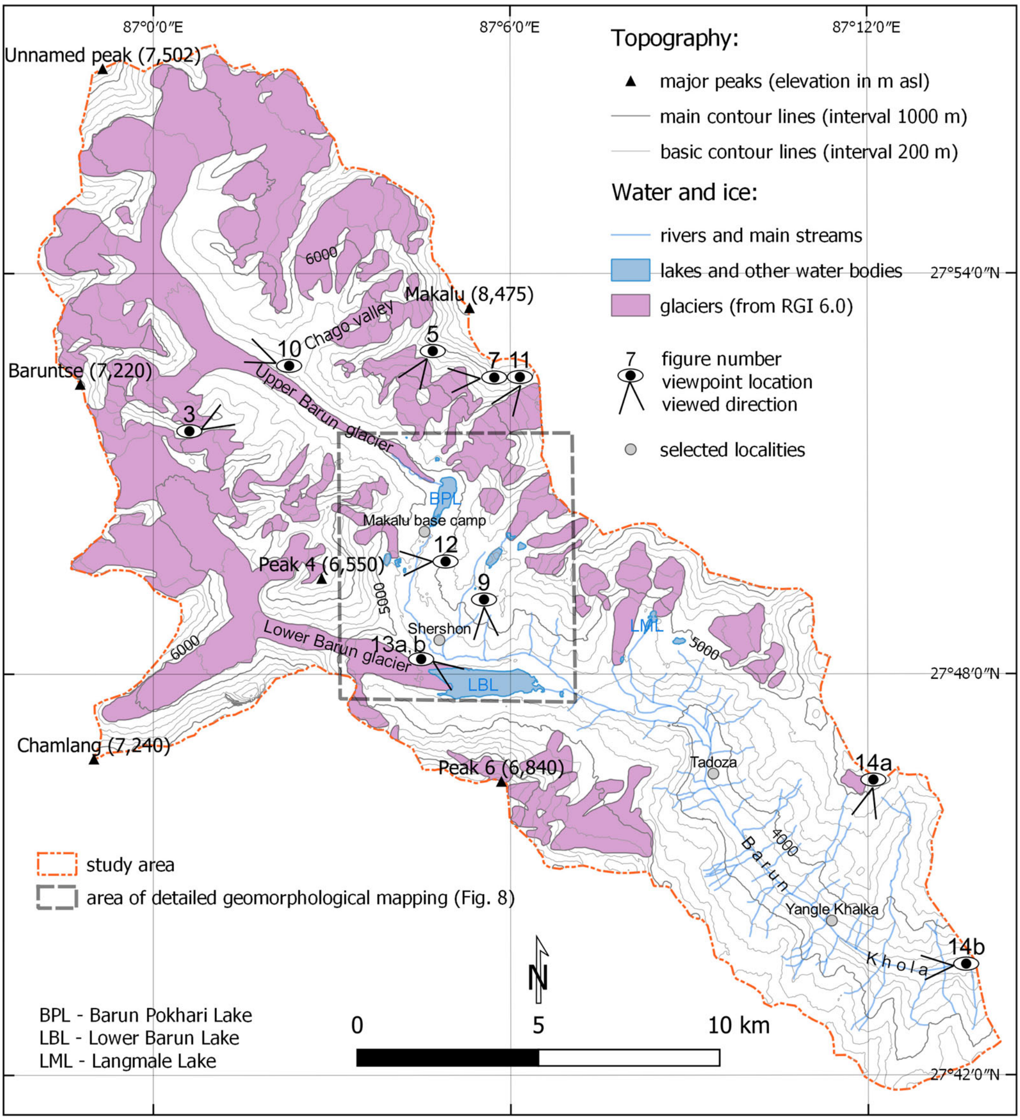

Figure 1. Geographical position and varied terrain of the Makalu Barun region in the Nepal Himalaya with locations of documented landform assemblages (Figures 2, 6 and 15 are located outside depicted area). The author of all photographs is Jan Kalvoda.

Figure 2. Impressive landscape of the Chomolongma Massif from the southwestern side (with indication of major peaks) and the Khumbu valley with group of glaciers in the foreground.

Kalvoda 1976, 1992). The distribution and dynamics of snow and glacial masses, the frequency of occurrence and discharge of rivers, the extent and volume of lakes and the properties of the mountain biosphere react very sensitively to the progressive changes in climatic conditions. The monsoon clouds blowing from the Indian Ocean across the Bay of Bengal and the Indian sub-continent carry 3000–4000 mm/yr of rainfall to the Nepal Himalaya, but with substantial variations depending on local geographical conditions.

The Makalu Barun region (Figure 1) is situated between the Chomolongma Massif (Mount Everest and/or Sagarmatha 8848 m a.s.l.; Figure 2) and the Arun valley (1350 m a.s.l.), in the morphotectonically active zone of the High Himalayan nappes. The Makalu (8475 m) is a distinct massif, partly isolated tectonically, as are the Baruntse (7220 m) and the unnamed peak reaching 7502 m elevation. The south-western side of the Makalu Massif has its foot at altitudes of 4900–5000 m. The vertical hierarchy of variable high-mountain reliefs is striking, and ranges from the extremely cold arête ridges of the Makalu Massif (Figure 3), through the heavily glaciated and periglacial areas, to the seasonally cold/warm humid area of the lower Barun Khola and Arun valleys.

Previous work, data and methods

Previous studies in the Makalu Barun region

The nature of the Makalu Barun region has been studied since the middle of the twentieth century and has mainly focused on (a) geology and geophysics (e.g. Bordet 1956, 1961; Schärer 1984; Searle et al. 2003, 2006; Corrie et al. 2010); (b) geomorphology (Kalvoda 1978, 1979, 2007, 2020; Kuhle 2005; Wagnon et al. 2013); and (c) biology and geoecology (Daniel 1979, 2015; Byers 1996; Chhetri et al. 2017). A remarkable feature of the present-day research on the Nepal Himalaya and its neighbouring regions is

Figure 3. The northwestern face of Makalu Massif (8475 m) consists of the Miocene leucocratic granite bodies and their injection zones into paragneisses. The extraglacial semi-arid zone above the Chago valley (5400 m) displays conspicuous landform patterns of intensive glacigenic, nival and cryogenic processes.

the attempts to reach an understanding of the evolution of their environment during the Quaternary. Numerous publications concentrated on this topic are quoted and evaluated by Kalvoda (1992, 2020).

Compared to generally well-studied Mount Everest region (e.g. Posch et al. 2015; Matthews et al. 2020; see also Table 1), Makalu Barun region has been a subject of limited amount of field observation-based geoscientific research studies in the past. Some of these studies address long-term geological evolution, metamorphism, melting and exhumation within the Greater Himalayan Sequence (Streule et al. 2010, 2012) and Quaternary glacial history (Kalvoda 1979, 1984; Owen et al. 2002; Kuhle 2005), while others address rather recent processes such as the controls and evolution of glacial lakes and associated hazards (Byers et al. 2013; Haritashya et al. 2018), including detailed description of the 2017 Langmale GLOF (Byers et al. 2019). Treeline patterns (Chhetri et al. 2017) and expansion of small terrestrial mammals and their parasites (Daniel 2015) have been studied in relation to topography controls, glacier retreat and human disturbances (Byers 1996).

Dynamics of landform evolution in the Makalu Barun region has been studied by Kalvoda (2007) and Kalvoda et al. (2004, 2013) and complex characterization of physical geographical conditions of the region has been recently provided by Kalvoda (2020). For example, on the geomorphological maps of the Khumbu and Barun glacier regions with mapping scales 1:50 000 (Kalvoda 1978, 1984, 1992, 2020), endogenous and exogenous landforms were indicated, together with the main glacial and hydrological features of the landscape.

Data

In the presented paper, we integrate field observations and photo-documentation with interpretation of satellite imagery in order to characterize complex physical-geographical conditions in diverse morphoclimatic zones of the Makalu Barun region. Four mountaineering and research expeditions with a total duration of 8 months have been conducted between 1971 and 2006, focusing on the reconnaissance, screening of geological and general environmental conditions, collecting of rock samples and detailed geomorphic mapping in varied terrains of elevational and morphoclimatic zones of the Makalu Barun region.

Remote sensing imagery analyzed in this work included Maxar Technologies / CNES / Airbus images available from Google Earth Digital Globe collection (period 2003–2017, down to 0.6 m spatial resolution; Google Inc. 2020). Further, we used radiometrically and terrain-corrected geocoded GeoTIFF ALOS PALSAR digital elevation model (spatial resolution 30 m; acquisition year 2011) accessed through the Alaska Satellite Facility webpage (ALOS PALSAR 2021). We used Randolph glacier inventory 6.0 (RGI Consortium 2017) for the visualization of glaciers in Figure 1.

Geomorphological mapping and delimitation of morphoclimatic zones

Geomorphological mapping is based on the visual interpretation of Google Earth Digital Globe high-resolution optical imagery (mapping scale 1:10 000) with validation against field observations. Table 2 summarizes definition/description of the main mapped features. Table 3 summarizes the criteria used to divide the study area into four morphoclimatic zones and two transitional zones. All maps are prepared in the freeware QGIS 3.10.9-A Coruña software (www.qgis.org).

Results: recent geomorphic processes in the Makalu Barun region

Landforms in the East Nepal Himalaya and neighbouring regions provide evidence for the nature of very dynamic landscape evolution, including extensive tectonic movements, extremely high rates of denudation, sediment transfer and deposition (Kalvoda 1972, 1988). The long-term integrity of orogenic and climate-morphogenetic processes in the Himalayan terranes is also recorded in the present-day distribution of the mass (Kalvoda et al. 2010, 2013). We present our observation of mass wasting and erosion in four remarkable morphoclimatic zones (Figure 4): (1) Extreme glacial area; (2) Glacial area; (3) Periglacial area and (4) Seasonally cold/warm humid area.

Extreme glacial zone

The extreme glacial area with a remarkable landscape of alpine-type (arête) ridges displays an effective combination of deep cryogenic weathering with a complex of glacial and nival morphogenetic processes in the very cold and semi-arid environment. The intensity and duration of temperatures below freezing point have led to deep rock disintegration and macrogelivation. Avalanches and rockfalls are frequent, and aeolian erosion and stagnation of the volume of ice and snow masses are very

Table 2. A brief description of alpine-type (arête) relief, selected glacier types, main depositional and water-related landforms and morphogenetic features proved by evidence in the Makalu Barun region.

Landforms/features:	Description
Glaciers, glacigenic deposits and moraines:	
Debris-free glacier	Clean ice masses; glassy or crevassed surfaces
Debris-covered glacier	Hummocky surface, visual evidence of sub-surface ice (presence of supraglacial lakes, exposed ice cliffs); geomorphic activity
Rock glacier	Lobe-like morphology, hummocky surface, located in periglacial areas outside modern glaciation, source of the material from colluvium deposits/the lowermost parts of modern glaciers which cannot be classified as debris-covered glaciers because of the absence of visual evidence of sub-surface ice, geomorphologically less active compared to debris-covered glaciers
Glacigenic deposits of Holocene age and Upper Pleistocene age	Glacial accumulation landforms around- and in the fore-field of glaciers (morphostratigraphy of these landforms of Upper Pleistocene and Holocene age is presented in the Table 4)
Distinct moraine ridges	Topographically pronounced glacigenic deposits (typically lateral or frontal moraines)
Glacier-free mountain slopes:	
Alpine-type (arête) relief	Extensive faces of ridges and peaks with crystalline rocks; rocky slopes with none or thin sediment cover
Denudational slopes	Denudational slopes with weathering-generated sediment cover; above ca 4900 m a.s.l. likely with permafrost
Deposits:	
Ice avalanche deposits/regenerated glacier	Clean ice, detached from the accumulation zone of parental glacier
Landslide deposits/colluvial deposits	Various landforms of slope movement deposits, frequently located onto the or beneath steep side slopes of the valley
Glacifluvial deposits	Outwash fans located downstream a source area (typically moraine complexes/ rock glaciers in the fore-field of modern glaciers)
Fine-grained deposits	Typically located behind the relief obstacle (e.g. a moraine wall), suggesting possible lacustrine origin
Water-related:	
Dry gully	Parts of the stream network which do not have identifiable (permanent) streamflow, but exhibit clear signs of (seasonal) stream erosion
Gorge	Deeply eroded incision into the valley floor deposits formed by the main rivers

conspicuous. Glaciated platforms in the form of small altiplanos and relics of uplifted large glacial valleys provide an accumulation space for snow and glacier masses in the High Himalayan Range.

The intense destruction of the near-surface rock masses of the Chomolongma and Makalu Massifs, which occurs under semi-arid and extreme glacial conditions, is the principal cause of an amazing range of alpine-type (arête) relief (Figures 2 and 3). The steep cliffs lacking permanent snow and ice cover, underwent deep cryogenic disintegration, and were subjected to aeolian corrasion; the harder rocks and dykes being selectively carved out. Intensive block disintegration occurs *in situ*, and the loosened blocks are displaced throughout the slope, while portions of the walls are broken off along their surface. The sculptured peaks are especially conspicuous (Figure 5), furnishing evidence of the lithological pattern of morphostructural units in the walls and steep rocky slopes.

The landforms developed on the granites in the extreme glacial area are characterized by almost vertical, smooth, aeolized and ice-cracked sheets on the cliffs due to angular block disintegration of

Table 3. Definition of four morphoclimatic zones and two transitional zones in the Makalu Barun region.

Morphoclimatic zone	Definition
Seasonally cold/humid zone (CHZ)	delimited on a basis of the presence of compact vegetation cover (trees and rhododendron shrubs)
Transition zone between CHZ and PGZ	500 m upstream distance buffer from the limit of the Seasonally cold/humid area
Periglacial zone (PGZ)	located between transition buffer area of CHZ and transition area between PGZ and glacial zone (GZ)
Transition zone between PGZ and GZ	250 m downstream distance buffer from the 5200 m a.s.l. overlaid and combined with RGI6.0 glacial tongues reaching downstream this buffer
Glacial zone (GZ)	between 5200 m a.s.l. and 6400 m a.s.l.
Extreme glacial zone (EGZ)	above 6400 m a.s.l.

pinnacles and cliffs, and by numerous hanging glaciers on inclined rocky slopes. The granites often form the summits and arêtes of the isolated peaks. The largest area of this bedrock relief is occupied by the slopes and cliffs on the zones of granites injected into paragneisses, which are highly dissected with frequent ledges and troughs, and often displaying block disintegration of rocks with corresponding autochthonous slope debris. South of the structural denudation slopes below the elevation point 6170 m, and further across the exposures in the Chago glacier valley (Figure 3) and along the south-western face of the Makalu, a distinct, varicoloured, selectively ice-gauged, layer of migmatite, marking zones of intense tectonic deformations, has been exposed.

Cryogenic processes have played a substantial role in the lithological patterns of the rocky slopes and cliffs with strong physical weathering of rocks under the conditions of permanent severe frosts and also wide daily and seasonally variations in their surface temperatures (Kalvoda 2007, 2020). Intensive destruction of the mountain slopes is also indicated by variable tension gashes in scree slopes, which

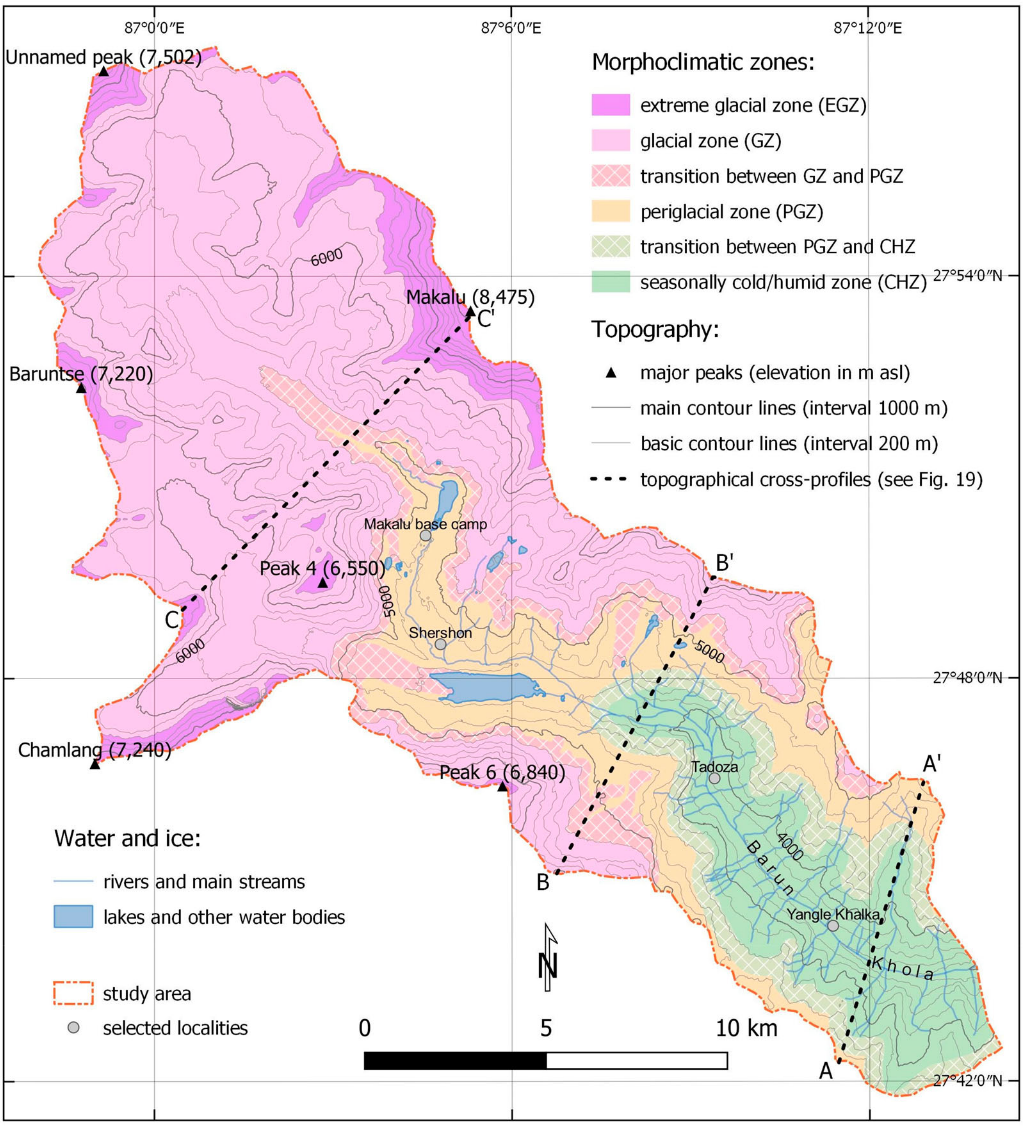

Figure 4. Delimitation of studied morphoclimatic zones in the Makalu Barun region.

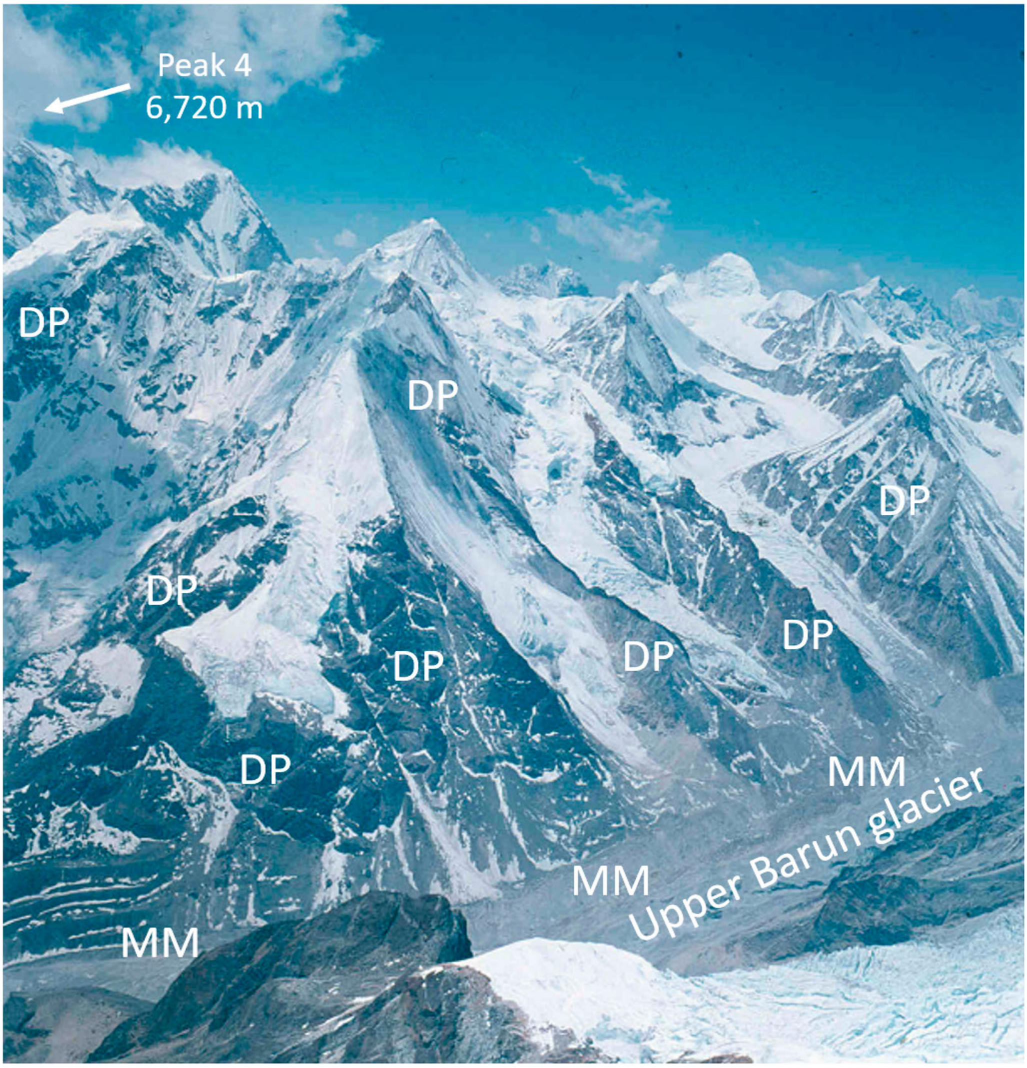

Figure 5. Himalayan-type landforms west of the Makalu Massif are developed on monoclinal structures of black gneisses. These crystalline rocks are interlayered with granite sills inclined to the west-northwest at ca 30° with an extent between 5200–7200 m a.s.l. Crests of the northern summit group of the Peak 4 Massif (6 720 m) terminate above the Upper Barun glacier by trapezoidal detachment planes (DP) of rockfalls between 5400–6000 m a.s.l., dipping up to 80°. The mostly blocky to coarsely sandy deluvia of steep rocky slopes pass into continuous accumulations of Holocene and modern moraines (MM).

may be hundreds of metres long, or by the sharp patterns of mostly glaciated crests. The glaciated passes of 6070–7400 m altitudes are covered by debris which separates the relics of rocky ridges. Desquamation surfaces at rocky slopes appear especially near and below the permanent snowline, and moreover, in the large periglacial zone a varied set of gelifluction and congelifraction microforms appear.

A unique feature of the extreme glacial zone of cliffs at Himalayan peaks consists in the aeolian polishing of the snow and ice surfaces (well known to mountain climbers), and the consolidation of solid precipitation into coarse-grained crystals. On these cliffs, firn- and ice ribs several hundred metres long and mostly vertical form spurs along the sides of small avalanches scars. The wind constantly blows snow into lee troughs, foot-of-slope depositional basins and glacial valleys. The numerous variants of sculptures on the ice and snow masses are controlled by their layering, plasticity, contamination by sand and dust, exposure to extreme insolation and prevailing wind currents. The maximum observed height range of surface features on glaciers is 10–30 m and the depth of vertical fissures in icefalls, often gaping down to the bedrock, can reach as much as 50 m deep. Field observations during the period 1971–2006 as well as later, together with present remote sensing data, have shown that conspicuous recent changes in the rock slope patterns and, especially, in the volume of ice masses accompanied by a recession of the frontal parts of hanging glaciers, are only in the lower parts of the mountain walls.

During the late Quaternary, the width, position and thickness of glaciers and the abrasive action of their ice masses in the Makalu Barun region were influenced by changes of climatic conditions as well as morphotectonic activity with developing extreme dissection of mountain massifs. The largest areas of glaciation were concentrated in the upper end of the Barun glacier valley, which cuts between the Chomolongma and Makalu Massifs into the main ridge of the High Himalaya. This strongly glaciated area passes with a wide transfluence of ice masses into the Kangshung valley to the east of Sagarmatha. In this very cold and semi-arid region, the nunataks are developed in two types: (1) massive rocky crests, the heights of which exceed the maximum thicknesses of the fossil glaciers, e.g. ridges with debris eluvium in the environs of the 6140 m elevation point, and those in the Chago valley, and (2) steep exposed relics of pinnacles between slope and hanging glaciers, e.g. in the lower parts of the northwestern and southwestern cliffs of the Makalu.

Glacial zone

The present-day glaciation of the Makalu Barun region displays regression signatures due to the small amount of precipitation and the expansion of the periglacial zone by recent warming of monsoonal climatic conditions even in the close vicinity of the main High Himalayan range (Figures 5 and 6). The perpetual snowline oscillates on the southern slopes between 5400 and 5600 m, and on the northern slopes between 5700 and 5800 m. The glacial area is characterized by a recent regression of glaciers and a decrease in their volumes. The spreading of the periglacial zone to the detriment of lower areas of the cold glacial zone is striking (Kalvoda 1992, 2020). The valleys and ridges are fully filled with glacier masses at high altitudes above *ca* 6000 m. Large ice source areas often contrast with very narrow canyon-like lower parts of valleys. A remarkable phenomenon is also the occurrence of the relics of glacial and related sediments of Upper Pleistocene and Holocene age.

The present-day valley glaciers in the Makalu Barun region arose by the retreat of a large glacier and its splitting up into smaller flows (Figure 8). The junction of these flows has been preserved only in the glacier masses east of the Baruntse and below the north-western Makalu wall. In those sites where the dip of the bedrock does not exceed 40–45°, the slope glaciers form fans along the crests and ridges surrounding the valley axis. The largest slope glaciers are developed on broad ridges in the vicinity of the 6250 m and 6170 m peaks and below the southern Makalu face. Here hanging glaciers form discontinuous ice covers of a great areal extent on mountain cliffs and crests. They form, together with permanent firn fields above the snowline, the main feeding source for the lower-lying slope and valley glaciers and avalanche masses, especially in the Peak 4, Baruntse and Makalu Massifs (Kalvoda 1978, 1979).

The variety and dissection of glaciers and permanent firn fields reflect the mobility of the ice under the given relief and local climatic conditions (Figure 7). The most pronounced glacier surface patterns include ogives as well as a system of ice crevasses and fissures. Ice towers are striking as to height and volume because they occur at sites where the dip of the eroded bedrock suddenly steepens. In the ablation zones of glacier tongues they become also emphasized by the selective melting of ice. In the ablation process, at altitudes of over 5000 m, the decrease of ice by sublimation dominates. Below the permanent snowline, the water from melting ice forms rills, seasonally dry gullies, gorges, glacier lakelets and drain troughs. Outside and under glaciers, meltwaters form cascades and strongly influence the seasonal discharge of meltwater from the ice masses and permeate through the morainic material damming the lakes (Figure 8).

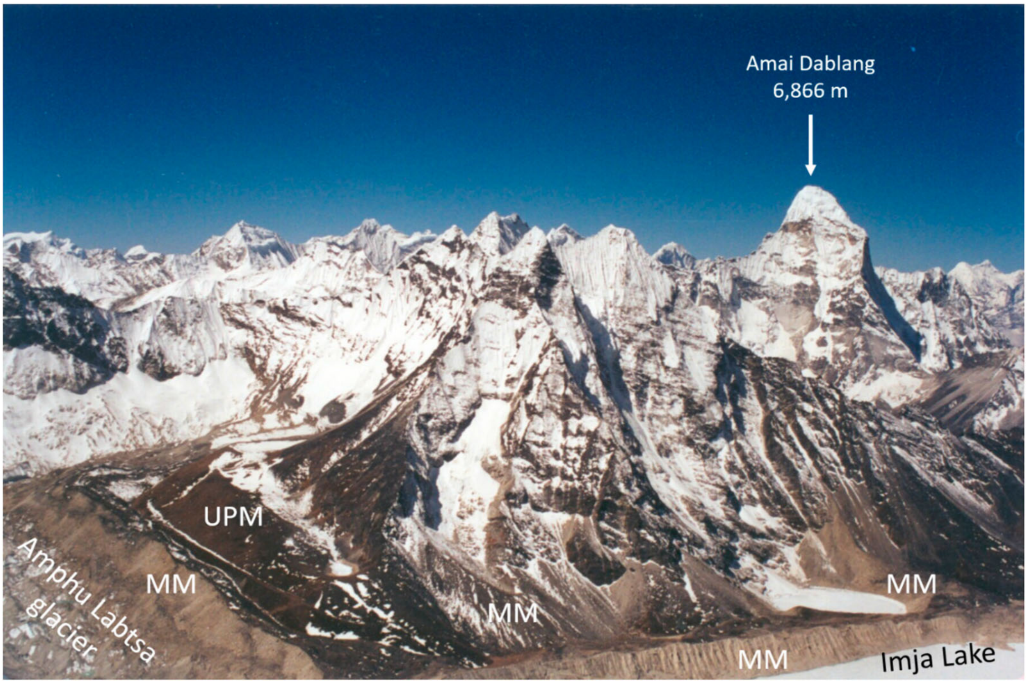

Figure 6. The group of the Upper Pleistocene (UPM) to modern moraines (MM) of the Amphu Labtsa and Imja glaciers situated north of the Baruntse Massif below remarkable ridges east of the Amai Dablang (6866 m).

Present-day glacier tongues in the Makalu Barun area and the neighbouring regions of the Nepal Himalaya are covered by surface morainic debris. The strong ablation resulting from the intense solar radiation and low relative humidity gives rise to various types of *nieves penitents* on the surface of glacier tongues, leaf-like and honeycomb structures, bolus-like ice forms and intermittent lakelets. Amongst ablation phenomena, crevasses, labyrinths of corridors, galleries and caves in the ice are found in localities where ice movement is slow.

On the basis of the spatial relationship of the moraines to the present-day relief and glaciers (e.g. Figures 5 and 6), their relative positions, lithology, degree of weathering and wear of detritus, detailed modelling and occasionally also their vegetation cover, the regional morphostratigraphy of these glacial deposits have been determined. In this paper, the morphostratigraphical classification of moraines is evaluated after dating of glacial accumulations in the Chomolongma Massif region situated in the close neighbourhood of the Makalu Barun region (Table 4).

An integrated pattern of morphostructural, glacigenous and related landforms provide also evidence of the existence of ancient glaciation of the Makalu Barun region during the Middle and/or Upper Pleistocene. However, these events were considerably older that preserved relics of glacigenic, cryogenic and glaciofluvial sediments. Remarkable geomorphic signatures of substantial loss in the volume of glaciers during the late Holocene are expressed by a variety of landforms as well as related expansion of the periglacial area.

During the recent retreat of the valley-, lateral-, slope- and hanging glaciers, only four of them contribute ice to the Barun glacier. The others are merely separated in individual mountain massifs and especially fill the basins between the steep peaks and their connecting crests. In the area where the Barun and Lower Barun glaciers joined in the past at the Shershon locality (Figure 8), the distribution of Upper Pleistocene morainic ridges suggests that the junction of both these glacier tongues ceased as early as during the course of the subsequent glacial retreat, and that it was never re-established during the Holocene.

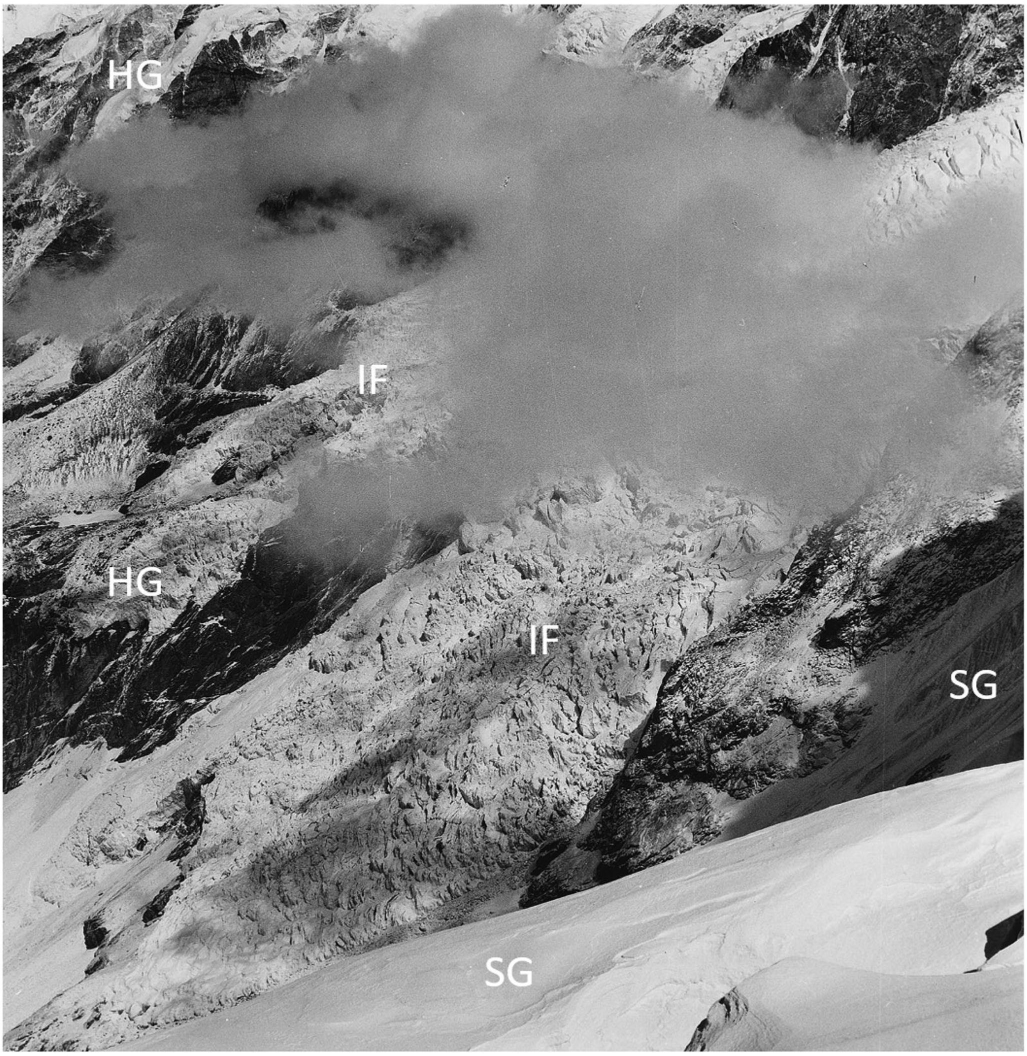

Figure 7. A view to extensively glaciated southwestern face of the Makalu Massif in vertical section at altitudes of ca 7800–6400 m shows numerous types of hanging glaciers (HG) and slope glaciers (SG), densely crevassed ice falls (IF) and their selectively eroded bedrock built of crystalline rocks and striking evidence of frequent ice- and snow movements.

Gravitational landforms include active talus fans developed at the foot of huge rock faces as well as older talus fans of great areal extent, and accumulation piles resulting from avalanches (Figure 9), rockfalls and landslides. A cover of sliding detritus, mostly consisting of boulders, originated on steep denudation slopes. The lateral moraines of glaciers are frequently overlained by accumulations of slope debris (Figure 10) ranging in size from coarse sand to boulders.

Periglacial zone

High rates of erosion and denudation have been observed in the periglacial environment around the lower part of glaciated area (Figure 11). Intense freeze–thaw activity of water is the basis of periglacial processes and related landforms. The intensity and duration of temperatures below the freezing point lead to deep rock disintegration and macrogelivation. By contrast, shallow freeze–thaw cycles

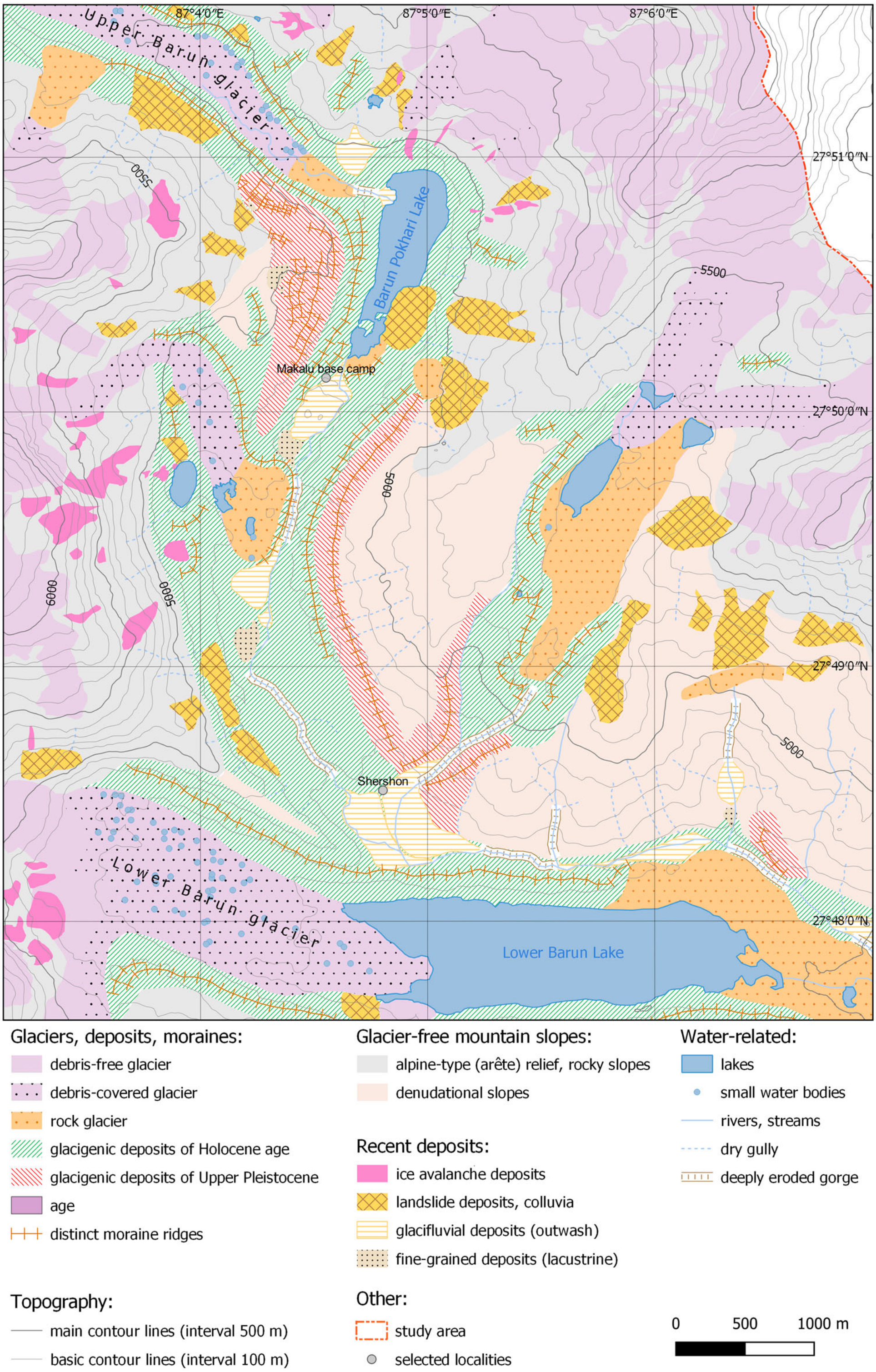

Figure 8. Geomorphological map of the central part of the study area (see Figure 1 for the location).

Table 4. Glacial stages, morphostratigraphy of glacial landforms and changes of climate-morphogenetic processes in the Chomolongma Massif and the Makalu Barun regions of the Nepal Himalaya from the Middle Pleistocene up today (simplified after Kalvoda 2020).

Stratigraphical divisions of the Quaternary *Marine isotope stages (MIS)*	Main glacial stages in the Chomolongma Massif and the Makalu Barun regions inclusive their approximate dating	Preserved glacial landforms and corresponding key geomorphological phenomena
– 0.00 Ma Holocene Epoch		Rapid retreat of glaciers
	Little Ice Age (Historical, Recent, ca 1000–850 years ago)	Recent advance- and retreat moraines
	Lobuche (2000–1000 years ago)	Lingten-type moraines (short glacier advance)
~MIS 1 (warm period)		Retreat of glaciers (3000–2000 years ago)
	Thukhla (Mid-Holocene, ca 4900–3600 years ago)	Khumbu-type moraines (rapid glacier advance)
		Retreat of glaciers (8000–4000 years ago)
– 0.0117 Ma	Chhukung (Early Holocene, 10 000–8000 years ago)	Changri-type moraines (mild glacier advance)
Pleistocene Epoch: Upper Pleistocene		Retreat of glaciers (13 000–10 000 years ago)
	Pheriche II (13 600 years ago)	
(MIS 2 – maximum of cold period)	Pheriche I (Late Glacial Maximum, 25 000–16 000 years ago)	Dusa-type moraines (considerable advance of glaciers)
(MIS 3 – cold period)	Thyangboche II (36 000–25 000 years ago)	Development of conspicuous and well preserved glacial valleys Origin of the oldest preserved U-shaped valleys and high situated flat glacial valleys
(MIS 4 – cold period)	Thyangboche I (Late MIS4-Early MIS3, 74 000-(top 57 600)—36 000 years ago)	
– 0.126 Ma		
Middle Pleistocene *(MIS 5, warm oscillation)*	Later (Upper Pleistocene and Holocene) climate-morphogenetic processes probably may have destroyed erosional and accumulation landforms which could be considered as evidence of an earlier glaciation in the East Nepal Himalaya	Long-term erosion and denudation was intensified by orogenic uplift and heavy rainfall at southern windward side of the Himalaya caused by the strengthening of summer monsoon
(Brunhes Chron normal)		
– 0.781 Ma *(MIS 19, warm oscillation)*		
(Matuyama Chron reverse)		

are effective for rock microgelivation. A remarkable enlargement of the active periglacial zone accompanies the recent retreat of the glaciers in the Himalaya (Table 4). It increases the volume of transported products of erosion and denudation and the level of geomorphological hazards, including frequent mass movements (triggered also by earthquakes; compare e.g. Kalvoda 1972, 1976; Fort 2000; Avouac 2003; Bilham 2019), avalanches, landslides (Figure 8) and flash as well as outburst floods (Byers et al. 2019). The current decrease in the distribution of permafrost has implications for landscape stability, which is reflected in solifluction movements, rock-glacier evolution (Figure 8 and Figure 12) and sediment release into streams and rivers.

In the foreland of glaciers in the Barun valley a system of slope, glaciofluvial, lacustrine and fluvial accumulation landforms have developed (Figures 8, 11 and Figure 12). The Late Holocene to modern terraces and cones of outwash sediments represent the earlier of two generations of glaciofluvial landforms which occur in the depressions between individual moraine ridges. They occur on the floor of the valley between the Holocene frontal moraines of the Barun glacier and the left lateral sub-recent moraine of the Lower Barun glacier near the Shershon site. In the vicinity of the Shershon, flood terraces can be seen, displaying the meandering nature of the streams depositing the alluvium, while terraces of coarsely sandy to gravelly alluvia occur along the small Barun Khola river. Erosional gulleys up to 3 m deep have developed along intermittent and perennial streams in moraines and on the surface of lacustrine terraces.

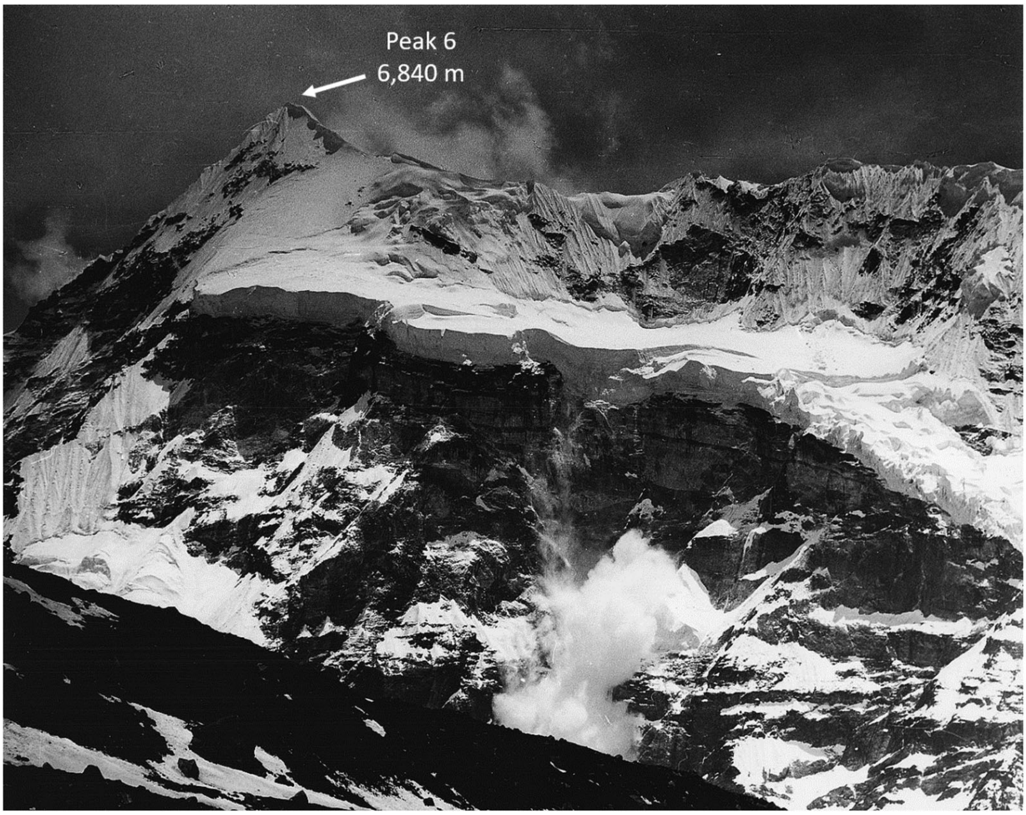

Figure 9. An ice avalanche swiping down the north face of Peak 6 (6840 m) with conspicuous structural planes covered by ice and snow masses.

From the Lower Barun icefall south of the Peak 4 Massif to the Tadoza site, the valley floor is filled with chaotic ridges of fossilized oscillation moraines, rockfalls, talus fans and the retreating glacier tongue (Figure 13a). The small Barun Khola river was deflected to the northeast for several hundreds of metres from the centre of the valley by the ice masses of this glacier as well as the lateral moraines and huge landslide deposits. In the Barun Khola river valley, glacial, nival and periglacial landforms, which reflect the existence of former cirque and slope glaciers, occur especially to the east of the Lower Barun glacier. Here they are located above the Yangle Khalka site and the Arun river canyon-like valley in the foreland of structurally controlled denudational slopes which have developed along the frontal part of the Main Central Thrust. These landforms occur only in the lateral, mostly hanging, valleys and on the intervening crests.

The base of the rock cliffs is frequently concealed behind taluses and debris cones which are often hundreds of metres high. These are developed only below the snowline, since the slope deposits in the catchment areas of the glaciers fuse with the recent glacial moraines (Figure 13). On the sides of the main glacial valleys, polygenetic slope-debris deposits formed after the retreat or disappearance of slope- or hanging firn field and glaciers. In these polygenetic accumulations recent angular boulders derived from the valley sides predominate, mixed with basal moraines. The shapes of the talus fans and debris cones change rapidly under the constant removal of scree from the walls and steep denudational slopes. Fossil talus fans stabilized by vegetation have also been identified.

Samples of slope, glacial and glaciofluvial sediments representing the weathered and transported products of the granites, paragneisses and migmatites of the High Himalayan crystalline complexes,

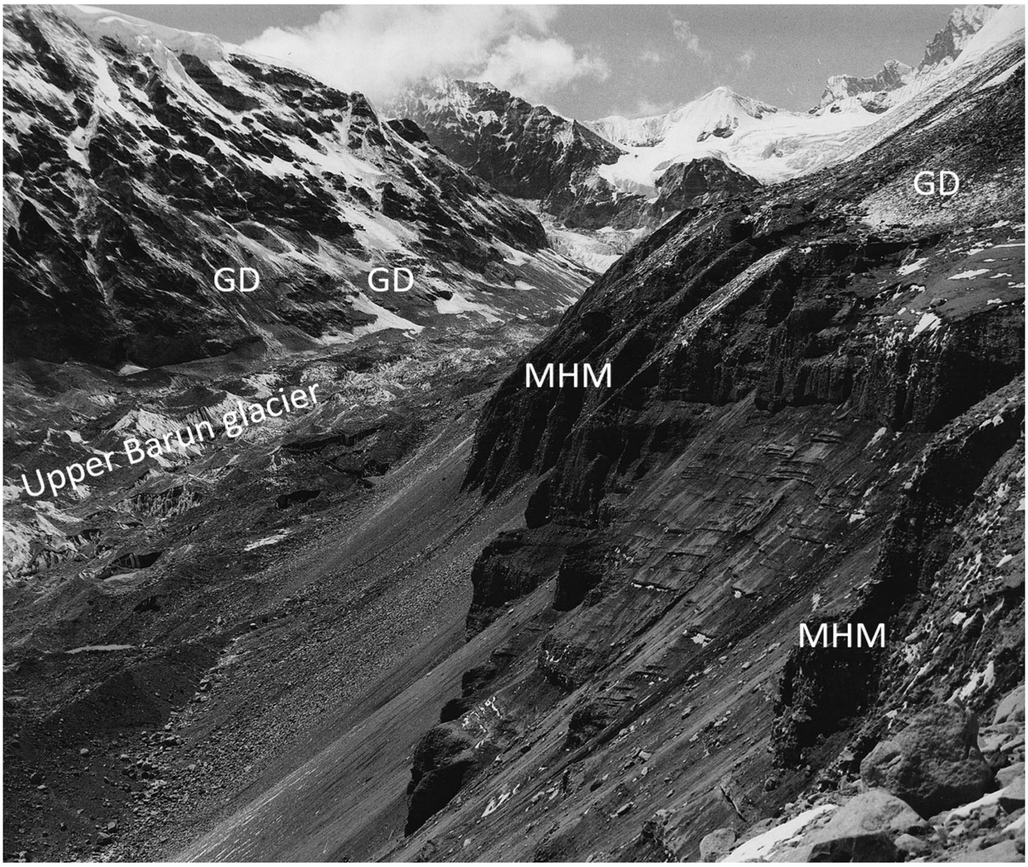

Figure 10. Relics of almost 100 m high left-lateral moraine of Middle Holocene age (MHM) are situated above the main Barun glacier tongue at 5400 m a.s.l. along the foot of partly glaciated slopes with recent granite block detritus (GD). Volume of the Upper Barun glacier is rapidly decreasing even near the confluence of its partial tongues. Conspicuous is also a high dissection of the glacier surface covered almost continuously by moraines' debris of strongly weathered crystalline rocks.

contain in their lutite fraction a proportion of clay minerals, especially illite and chlorite. For the rock fragments from altitudes above 6000 m, only sericitization of feldspars, sagenite in biotite, limonization and chloritization of biotite have been found. The nature of the transport mechanism is also inferred: the fragments making up slope and glacial sediments have sharp edges and show no wear; they originated by mechanical disintegration and partly by crushing of the source rock; the fragments of glaciofluvial sediments are relatively well worn. Ice-transported psammitic quartz grains are extremely angular with clear traces of mechanical disturbance of the primary structures and joint planes. During consecutive fluvial transport large pits develop on the curved surface of quartz grains, as well as V-shaped pits on the primary planes of minerals. The chemical weathering of quartz grains in the periglacial and humid zones, which takes place in the presence of organic substances, produces depressions and cavities resulting from etching along the weakened primary structures of these grains.

Between the Lower Barun and Barun glacier tongues extend a vegetation zone of alpine shrubs and meadows with typical representatives of *Rhododendron* species, *Juniperus* and *Lonicera*. Sporadic flowering plants appear in protected places on steep scree-covered slopes even in the vicinity of the snowline. The density of vegetation increases with decreasing altitude. The upper boundary of the alpine steppe is in some places modified by rock outcrops. At altitudes of 4500–5000 m, the granular character and occasional movements of sub-recent to modern lacustrine and glaciofluvial

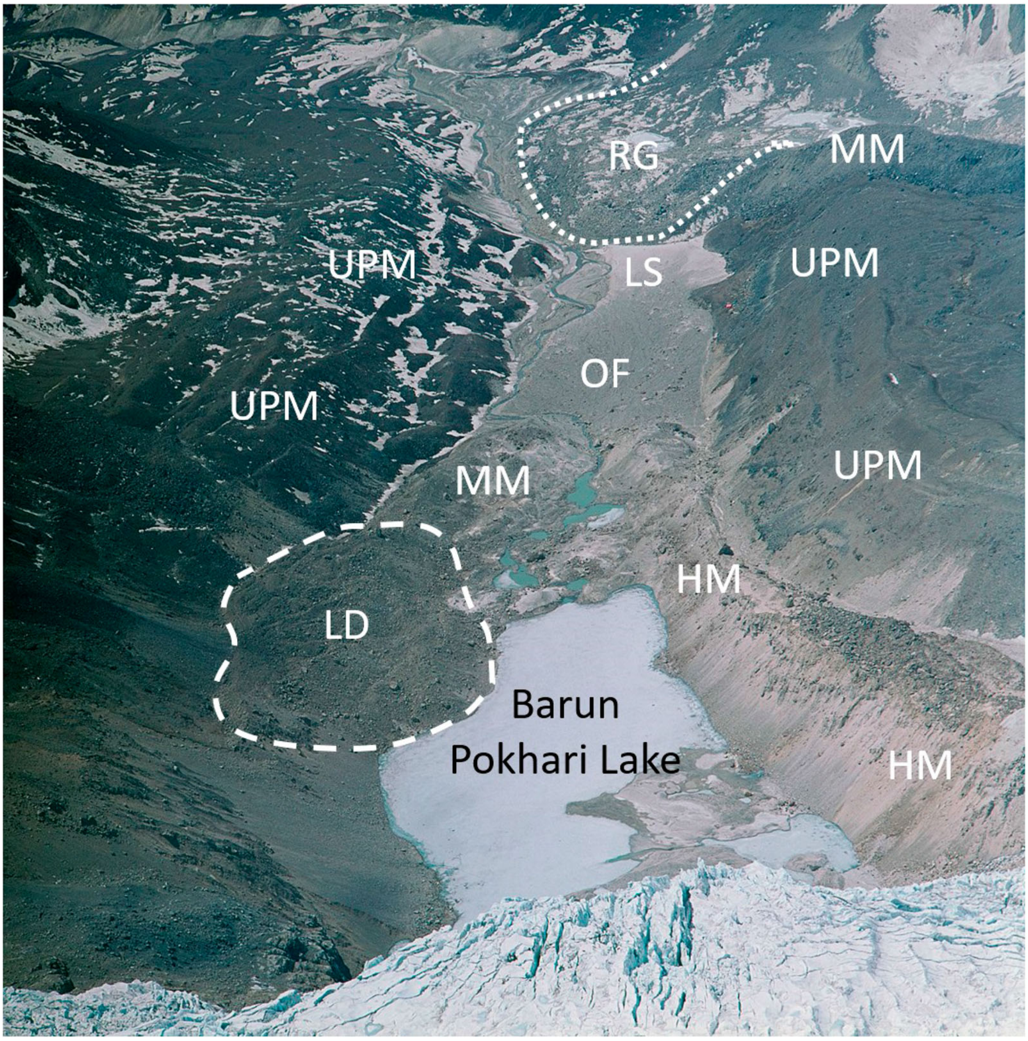

Figure 11. Landforms in the foreland of the Upper Barun glacier situated between 4900 and 4700 m a.s.l. and the Barun Pokhari lake. Relics of Upper Pleistocene moraines (UPM), Holocene moraines (HM), modern moraines (MM) as well as Holocene to Sub-recent lacustrine sediments (LS) and outwash fan deposits (OF) have been preserved (see also Figure 8). The oldest conserved glacial sediments of the Barun glacier originated during the Late Glacial Maximum. Rock glaciers (RG, dotted line) and recent landslide deposits (LD, dashed line) are also remarkable.

sediments hinder and retard the establishment of vegetation over large areas. The contact of the sub-recent moraines of the Barun and Chago glaciers at 5450 m a.s.l., covered relatively continuously with scanty grass and moss, is the uppermost locality at which plants occur. Above 5200 m, the zone of alpine shrubs and meadows passes into an extremely cold semi-arid zone with moss and lichen assemblages. Organic landforms include rocky outcrop surfaces and detritus affected by biogenic weathering above the upper boundary of the alpine steppe (at 4950–5100 m a.s.l.), which is irregularly covered with mosses and especially lichens.

In the periglacial zone, mass-wasting processes are intensified and slopes are deeply denuded. Very marked periglacial landforms are rock glaciers (Figures 8 and 12) that have been situated on steep slopes above glacier basins and in zones from which glaciers have retreated but a cold climate still persists (i.e. rock glaciers). Rock glaciers are often tongue-like bodies with a distinctive

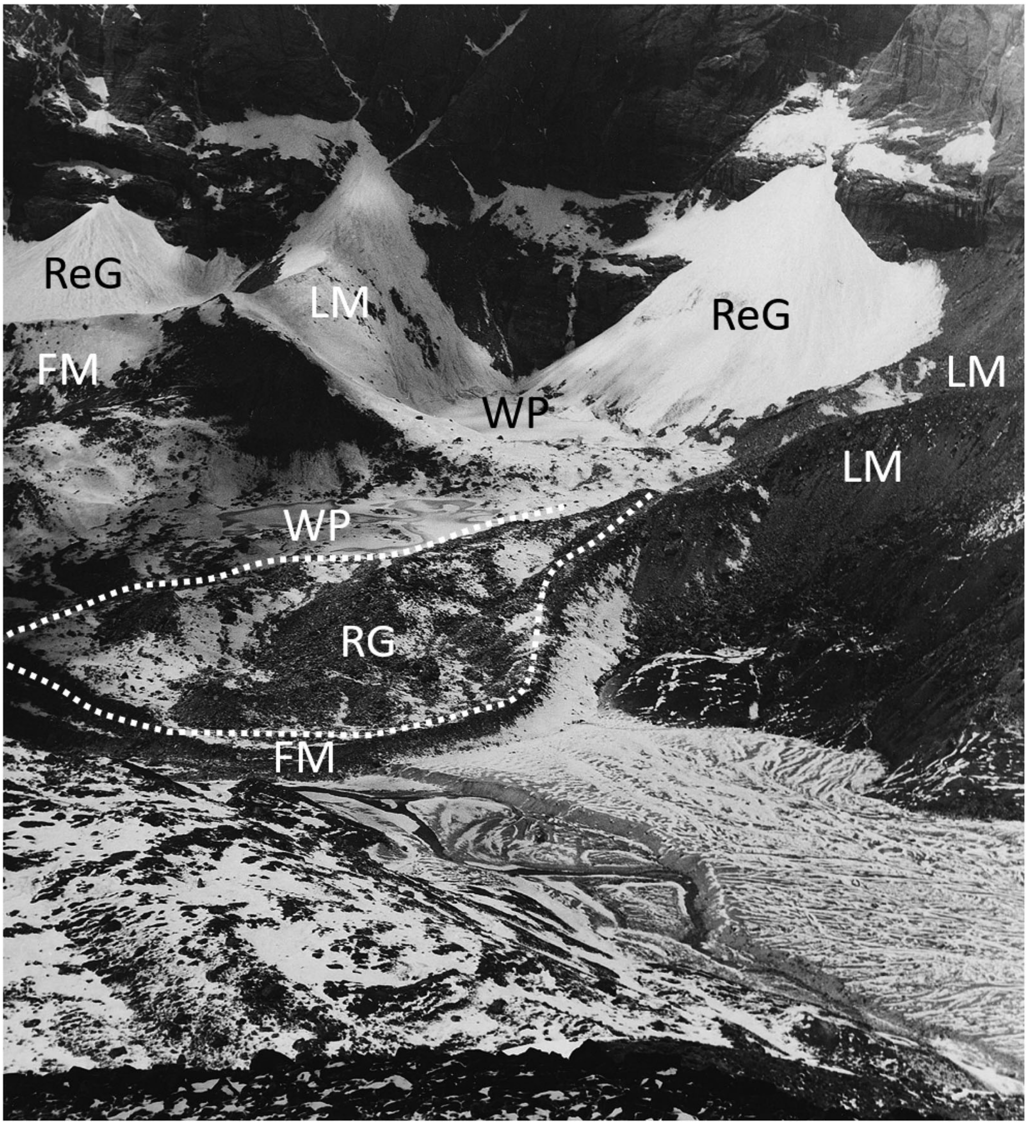

Figure 12. Recent frontal moraine (FM) and lateral moraines (LM) of regenerated glaciers (ReG) and rock glaciers (RG, dotted line) formed below the eastern face of Peak 4 Massif (see also Figure 8). Numerous detritus-covered blocks of dead ice are buried in frontal part of retreating glacirs. These dead ice bodies are being replaced by shallow water ponds (WP). The slow movement of the rock glacier (displayed also in the upper part of Figure 11) which is situated northeast of the Shershon site at 4800–4700 m a.s.l., is due to flowage of ice and creeping by the frost action. The photography was taken in the year 1971.

flowage of rock debris cemented by interstitial ice indicated by wavelike small ridges on its surface. This slow movement reflects flowage of the interstitial ice and creeping by frost action.

The most conspicuous of periglacial landforms are solifluction accumulations on slopes with a thawing layer of permafrost, patterned ground in the form of stone rings, polygonal soils, thufurs, stone debris, talus and rock glaciers. Solifluction processes are conspicuous by the down-slope movement of moisture-saturated slope sediments over substratum material during seasonal periods of surface thaw. Typical for permafrost are polygonal (sub-vertical) cracks initiated in the soil by contraction in the very cold periods. During the thawing period water flows into these cracks and it freezes again in the cold season increasing the size of the ice-filled cracks. Seasonally thawing

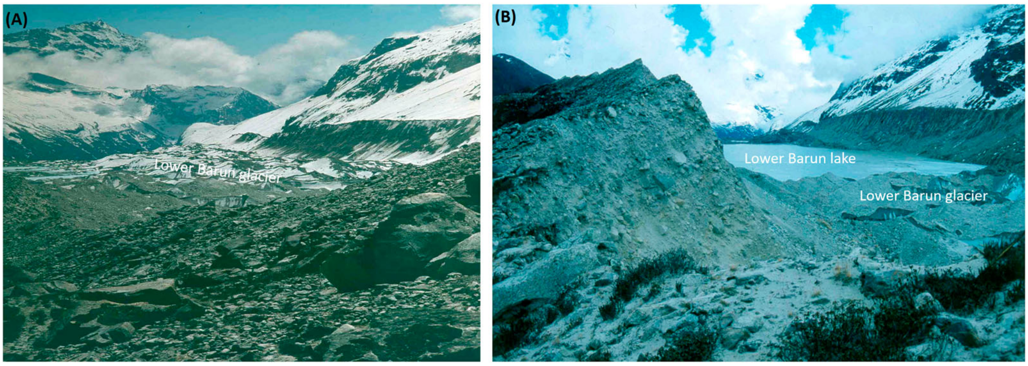

Figure 13. (A) Downstream view on the Lower Barun glacier tongue from near the confluence with the Upper Barun valley at 4550–4450 m a.s.l. Recent lateral and surface moraines are often covered by strongly weathered debris of crystalline rocks. The compound shape of glacier tongue is conspicuously changed and the recent decrease of its volume is accompanied by development of a new lake – the Lower Barun lake. The photography was taken in April 1973. (B) Downstream view on the Lower Barun lake (ca 1.8 km^2, 4500 m a.s.l.) from the left lateral moraine near the confluence with the Upper Barun valley. The lake appeared recently in the frontal part of the Lower Barun glacier tongue, as a result of its recent thinning and retreat. The Lower Barun lake is dammed by a complex of low recessional moraines/rock glacier and deposits of landslides. The photography was taken in May 2002.

surface layers of permafrost are also closely related to grassland or other tundra vegetation. Exposed rock surfaces that have been broken up by frost action are often shaped like hard rocky ridges and towers, or large block fields like a 'sea of rocks' with a thickness of some metres in the form of angular shattered boulders.

The presence of recent and former lakes of glacial origin on the Barun valley floors (Figures 11 and 12) is indicated by three terraces of lacustrine sediment up to 6 m thick, lying between the fronts of the tongues of the Barun glacier and the Shershon site, surrounded throughout by fossil moraines (Figure 8). The middle of these is the largest, situated at 4850 m a.s.l. between the sub-recent frontal moraines of the Barun glacier and the glacier of the eastern faced of Peak 4. The surface of the moraine is furrowed by melt-water grooves and migrating wind-blown sand at their margins. In exposures rhythmical sedimentation is generally inconspicuous, grain sizes vary from fine sands to coarse gravels; in some places scattered boulders up to 60 cm-diameter of paragneisses and granites occur. Minor relicts of lacustrine terraces lie on the banks of the Barun Pokhari lakes at two levels above the water level; the higher of the terraces corresponds to the level of the filled lake before the collapse of the morainic dam.

Permanent lakes in the Barun glacier valley are of glacial origin. They are elliptical in shape and occur in the foreland or at the flank of the lower parts of the glacier tongues of one valley and further hanging glaciers at altitudes of 4880–5500 m (Figure 8). The lakes are dammed by up to 20 m high morainic walls resulting from sub-recent to modern glacial oscillations. Their depth reaches a maximum during the period of glacier melting, but does not exceed several metres. The Barun Pokhari lake lies in front of the terminus of the Barun glacier tongue (Figure 11). The other small lakes occur at the foot of the eastern face of Peak 4, below the south-western Makalu face at 5350 m a.s.l. and below the large nunatak in the Chago valley. Seasonal ponds (supraglacial lakes) resulting from glacier meltwater on the surface of valley glaciers are numerous. These ponds occur on practically all the glacier tongues below the snowline (e.g. the lowermost parts of the Lower Barun and the Upper Barun glaciers; Figure 8).

A network of subglacial streams originates directly by ice melting and from the lakelets on the glacier tongues. The small river flows through the erosion-cut morainic dam from the southern margin of the Barun Pokhari lake and near Shershon, is joined by streams from the glaciers of the eastern face of Peak 4 and from the valley west of Peak 3. Flow regime of the stream is totally subject to the melting of snow and ice masses during the spring period and to the direct increase in precipitation during the oceanic summer monsoon.

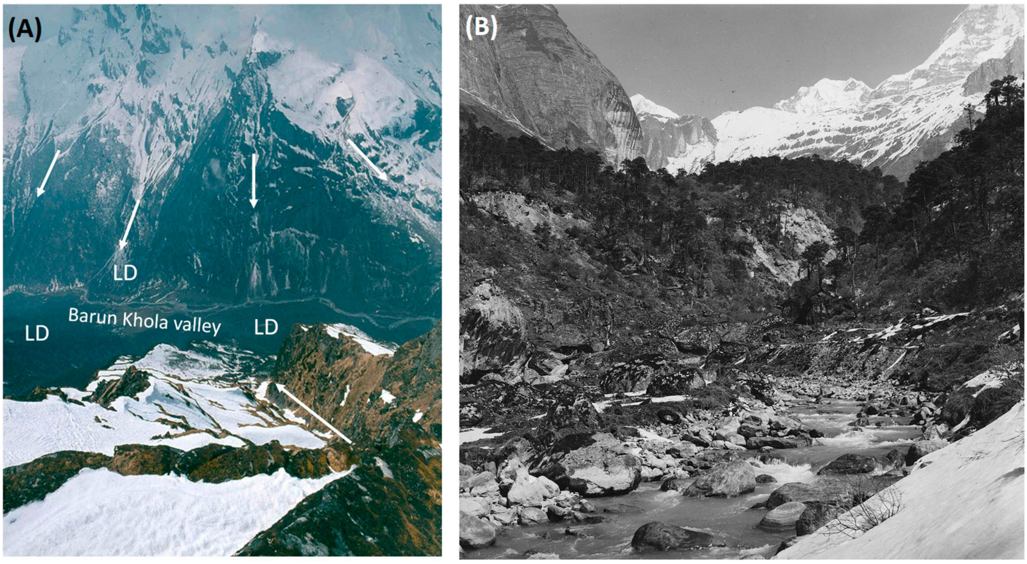

Figure 14. (A) Gullies in the paragneisses of the steeply sloping part of the Barun Khola gorge formed above the Yangle Khalka (4200 m a.s.l.). Collapse slope processes, especially rockslides and landslides, destroyed during the Holocene the older glacial trough of the Barun Khola valley. Main paths of slope movements (arrows) as well as deposition areas (LD) are remarkable. Deposited material in the main valley is permanently transported further downstream by fluvial processes. (B) Recent fluvial erosion reshapes the bottom of the Barun Khola canyon-like valley at 3000–4000 m a.s.l., which is filled of Late Pleistocene to modern accumulation landforms consisted of glacigenous, glacifluvial and slope deposits. Landform patterns of fluvial erosion during occasional flash floods are striking.

In the periglacial area of the Barun Khola valley between the present-day end of the Lower Barun glacier and Yangle Khalka locality (Figure 14) are conspicuous features of rapid nival and fluvial erosion, active exfoliation sculptures on the rock walls and varied slope processes. Especially impressive are products of recent flash floods, landslides and related mass movements.

Seasonally cold/warm humid zone

The Barun Khola canyon-like valley in the area between Tadoza (Figure 1) and Phematan (located on the right bank of Barun Khola valley ca 16 km further downstream from Tadoza; 27°47′N, 87° 08′E; ca 3600 m a.s.l.) sites has a strongly U-shaped form (Figure 14(a and b)). It is primarily of glacial origin with the main stages of its landform evolution during the Middle and Late Pleistocene. The periglacial weathering features of the marginal ridges of the Barun Khola valley disappear even before this valley enters the rocky cliffs of the High Himalayan nappe in the evergreen monsoon mountain forest zone. The Barun Khola valley floor, at up to 2800 m a.s.l., is covered by thick deposits of glaciofluvial and slope sediments cut by vertical erosion from the Phematan locality to as low as the paragneisses and granulites bedrock of the lower part of the High Himalayan nappe.

The following main soil groups have been identified (Smolíková and Kalvoda 1981; Kalvoda 2020): (1) High-mountain soils represented characteristically by humusosilicate Rankers with a sharply-defined skeletal A-horizon. In the immediate foreland of glaciers, Alpine Mul Proto-Rankers dominate, and the formation of humus ceases. (2) Pseudo-gley soils on platforms with an evergreen mountain forest and a silicate-rich substrate. (3) Illimerized soils, particularly Sod Podsols, developed on mixed substrates under an evergreen mountain forest cover, which in moister areas trend towards soils of the Podsol series. In the Barun Khola valley, the biological activity and intensity of chemical weathering decrease with increasing altitude, whereas the influence of mechanical disintegration of the soil framework and cryogenic weathering increase.

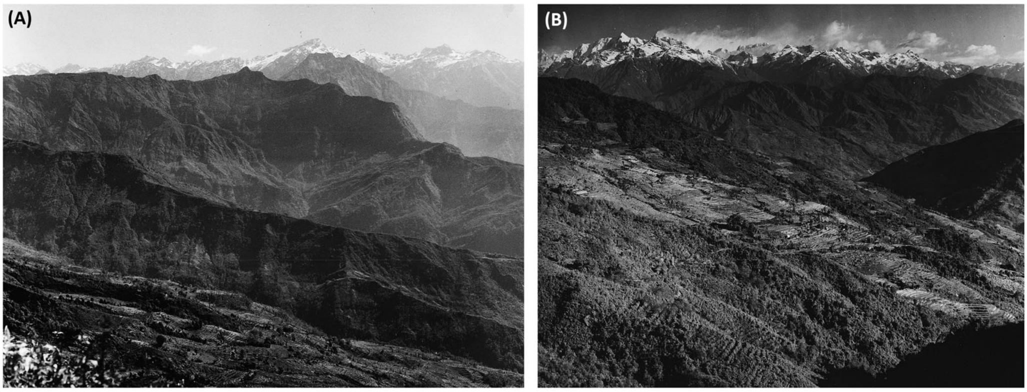

Figure 15. (A) The deforested structural denudational slopes above the Barun Khola and Arun River valleys around the Sedoa village (27°35′N, 87°16′E; ca 3400 m a.s.l.) are affected by strong precipitation and associated erosion processes of soils. (B) The broken slopes of the Arun River valley (originated in a tectonic half-window) with a monsoonal evergreen mountain forest in the vicinity of the village of Sekaha (27°24′N, 87°10′E) are reshaped by forest burning, clearing and agricultural terrace fields up to altitudes of 3200 m. In the background, structural denudational slopes of the Main Central Thrust and the High Himalaya ranges are seen.

The lower part of the Barun Khola valley is constantly being remodelled by huge, frequent slope movements and simultaneous rapid erosion of glacifluvial and slope sediments deposited as accumulation landforms of Holocene age (Figure 14). At altitudes in the range of 1800–3100 m is remarkable a subtropical evergreen mountain mist forest with *Pinus khasya*, *Quercus lamellosa* and other oak species, *Tsuga dumosa* and *Abies densa*. The Barun Khola and Arun canyon-like valleys are areas of frequent natural disasters with high risks involved to all types of human activities (Kalvoda 1984, 2007; Byers 1996; Chhetri et al. 2017). A large number of rockfall accumulations has been found in the lower part of the Barun Khola valley. The erosion and denudation of rock massifs is driven by tectonic activity and the humidity of the summer monsoons (Figure 15(a)).

The Barun Khola river is a subsequent right-bank tributary of the Arun river whose north–south orientation has been preserved throughout the orogenetic uplift of the High Himalaya during the Quaternary (Figure 15(b)). The Nepalese part of the Arun valley, up to the northern margin of the Tumlingtar (27°19′N, 87°12′E; 400 m a.s.l.) intermontane basin in the Lesser Himalaya, has a steep irregular gradient. Incision rates for the Arun River in the High Himalaya are reported to range from 0.5 mm/yr (Das 1968) to 1–8 mm/yr based on ^{14}C dated terrace elevations to 4–8 mm/year based on calibrated numerical models (Lavé and Avouac 2000, 2001). These rates are substantially higher than those for the High Himalaya belt as a whole referred to by Finlayson et al. (2002). For comparison, it can be reminded that Einsele et al. (1996) derived an average denudation rate for the High Himalaya of 1 mm/yr for the past 20 Ma and Vance et al. (2003) reported whole erosion rates of 2.7 ± 0.3 mm/year for High Himalaya drainage basins based on cosmogenic arrays of river sediments.

Discussion

Comparison of geomorphic processes in four morphoclimatic zones

Vertical climatic zonation (Figure 16) influences the variable features of morphostructural and lithological control on the characteristic weathering phenomena present in this region (compare Figures 3, 10 and 14). Landform patterns of peculiar relief types in the Makalu Barun region give evidence of mass wasting and other geomorphic hazards (Kalvoda and Rosenfeld 1998; Kalvoda et al. 2010). We interpreted our observations, characterized remarkable morphoclimatic zones of the Makalu Barun region, and subsequently compared the intensity of selected geomorphic

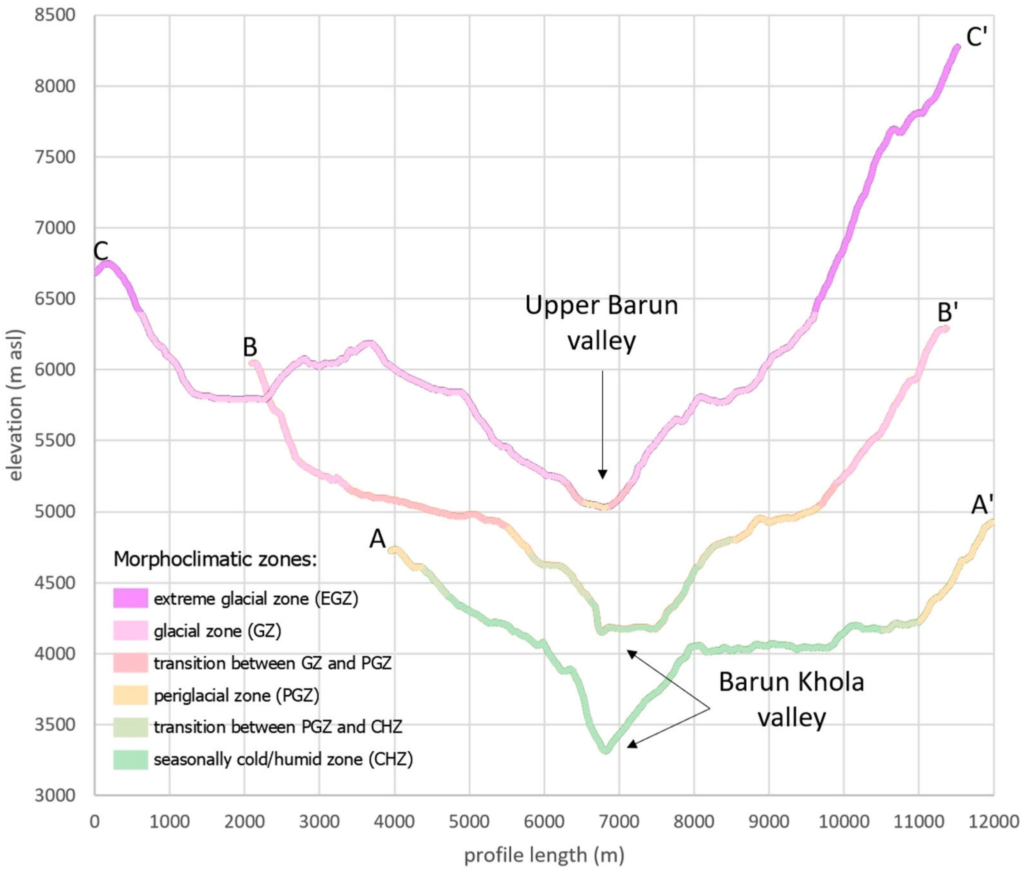

Figure 16. Morphoclimatic zones in the three cross-profiles throughout the study area (for the location of these cross-profiles see Figure 4).

processes in varied climate-morphogenetic conditions (Table 5). In is emphasized the prominent role of periglacial areas in accommodating landslides, GLOFs and periglacial and glacial areas in initiating far-reaching process chains. Some of geomorphic processes included in Table 5 can reach outside defined zones (e.g. ice avalanches can reach periglacial zone) and some may interact (e.g. ice-avalanche -induced GLOF; Byers et al. 2019). Moreover, the importance of extreme glacial area and glacial area for downstream societies lies in the water supply role (Immerzeel et al. 2020), while the vast majority of population, settlements, assets and infrastructure are located in seasonally cold/warm humid zone (Figure 15(a and b). This morphoclimatic zone also represents the hotspot of elements vulnerable to hazardous processes originating in geomorphic zones located further upstream in the mountain range.

Glacial lakes and process chains across morphoclimatic zones

The most striking changes associated with changing climate are anticipated in glacial and periglacial areas. Periglacial areas will expand or move their extent to higher elevations while glacial areas will shrink, resulting in the exposure of new land and formation of new glacial lakes trapped behind moraines or within overdeepenings. The Hindu Kush-Karakoram-Himalaya (HKKH) region experienced a lot of attention in GLOF research during the past few decades (Emmer 2018). Numerous studies addressed GLOFs at various spatial scales, ranging from cross-border studies

Table 5. Main characteristics and substantial incidence of geomorphic hazards in determined morphoclimatic zones of the Makalu Barun region.

	Morphoclimatic zones			
	Extreme glacial zone	Glacial zone	Periglacial zone	Seasonally cold/ warm humid zone
Basic characteristics:				
Approximative elevation (a.s.l.)	Above 6400 m	From 5200 to 6400 m	From 3800 to 5200 m	Below 3800 m
Areal extent*	20.4 km^2	183.0 km^2	63.9 km^2	38.3 km^2
Recent changes of areal extent	Stagnant	Decreasing	Stagnant (possibly decreasing or increasing)**	Increasing
Dominant exogenic geomorphic agents	Ice and cryogenic processes	Ice, snow and glacial processes	Water and regelation and slope processes	Water and slope processes
Rapid mass movements:				
Ice avalanches	++	+++	+	0
Initiation of far-reaching (cascade) geomorphic process chains	0	++	+++	+
GLOFs	0	+	+++	0
Landslides and rockslides	+	++	+++	+++
Human dimension:				
Presence of population and assets exposed to natural hazards	0	0	+	+++
Importance for water supply	+++	+++	++	+

*Areal extent of morphoclimatic zones delimited in Figure 4; the area of two transitional zones is 41.9 km^2.
**Depending on whether areal expansion into formerly glacial zone is equal, larger or smaller than areal loss caused by expansion of seasonally cold/warm humid zone in given period.

evaluating GLOF hazard of hundreds to thousands of lakes over the HKKH region (e.g. Ives et al. 2010; Veh et al. 2020), to regional studies focusing on Nepal Himalaya (e.g. Khanal et al. 2016; Sherpa et al. 2019) and case studies evaluating GLOF hazard of individual lakes (e.g. Lala et al. 2018) or elaborating past GLOF events in detail (e.g. Lamsal et al. 2016).

Yamada (1998) compiled a list of GLOFs which occurred in Nepal and more recently Veh et al. (2019) have updated the inventory and documented unchanged GLOF frequency during the past four decades across the broader KHHK region. However, the frequency of GLOF occurrence on a regional scale is still under debate (Harrison et al. 2018). Importantly, existing GLOF records may suffer from incompleteness, as documented by Veh et al. (2020) and Zheng et al. (2021).

In the Makalu Barun region, only one GLOF is documented to have occurred – the 2017 GLOF from the Langmale Lake reported by Byers et al. (2019), documenting rapid process chain acting across morphoclimatic zones. The triggering ice-avalanche (glacial zone) fell into the Langmale Lake, causing its moraine dam to fail (periglacial zone). Resulting flood rushed through the valley, mobilizing remarkable volumes of entrainment along the stream, far into the seasonally cold/warm humid zone. Despite the pre-outburst size and volume of Langmale Lake was much smaller compared to large moraine-dammed lakes located in the main Himalayan valleys (Byers et al. 2013; Haritashya et al. 2018), this event is among the most considerable recent geomorphic imprints in the valley (Byers et al. 2019). As such, the 2017 Langmale GLOF documents that these processes are among the main drivers of rapid geomorphic changes and fluvial erosion in the region (Vuichard and Zimmermann 1987; Richardson and Reynolds 2000; Cenderelli and Wohl 2003; Cook et al. 2018). Characteristic landforms such as outwash fans located downstream moraine dams may indicate possible GLOF occurrence in the past, e.g. the outwash fan located downstream the dam of Barun Pokhari Lake (Figures 8 and 11). However, a comprehensive analysis of these landforms in the Makalu Barun region and their attribution to specific processes or palaeographical and morphostratigraphical contexts are missing.

Since our first expeditions into the Makalu Barun region during the years 1971 and 1973, we observe a degradation of Lower Barun glacier and the development of the Lower Barun Lake (compare Figures 13a and b). This lake has attracted research attention recently, being considered one of the GLOF-prone lakes in the region (Byers et al. 2013; Haritashya et al. 2018; Sattar et al. 2021), mainly due to its large size and potential for further expansion. These concerns are driven by witnessing the power of recent events originating from even much smaller lakes (Allen et al. 2016; Byers et al. 2019) as well as increasing exposure and possible adverse societal impacts (Schwanghart et al. 2016).

Palaeogeographical context of recent geomorphic processes

The observation of landform patterns provides evidence of very dynamic landscape evolution in the East Nepal Himalaya. The dynamics of geomorphic processes in the climate-morphogenetic zones of the Makalu Barun region are conformed with the generally accepted opinion that glacial, periglacial and fluvial processes in the Nepal Himalaya are very effective at destroying the rock assemblages exhumed and uplifted during the mature morphogenetic phase of the collisional orogeny (Gansser 1983; Kalvoda 1992; Avouac 2003; Fort 2004; Owen 2011; Searle 2013). The orographical pattern between the main Himalayan watershed in Tibet and the southern foreland of the mountain ranges in the East Nepal evolved as the result of Quaternary mountain-building phase integrated with an extreme intensity of the erosion and denudation processes. The key factor of rapid uplift of the Himalaya during the Quaternary, as one of the geodynamic manifestations of the ongoing continent-continent collision, is the long-term interaction between the intensity of tectonic exhumation of deep-crust rocks, and the changeable rates of erosion and denudation which also involve the outward flux of eroded material. Variable and rapid landform evolution of the Himalayan terranes is an essential ground for severe natural hazards and risks.

The present-day orogenic activity in the Himalaya provides evidence on the manner in which successions of landform evolution are closely associated with the geodynamic processes creating geological structures throughout extensive mountain areas. The geomorphological identification of recent orogenic processes is based especially on the determination of morphogenetic processes acting over longer palaeogeographical periods. Rapid unroofing and exhumation of deeper parts of the rock massifs is also reliant upon vigorous transport agents, such as transgression of glaciers and intensive activity of wind in extreme glacial and glacial zones, or rapid action of water in periglacial and seasonally humid cold/warm zones. The long-term influence of these geomorphic processes on the exhumation of deeper parts of the Earth´s crust and on the dynamics of orogenic activity in the late Cenozoic, including rapid uplifts during the Quaternary, is a fundamental phenomenon of mountain evolution in the Nepal Himalaya.

Conclusions

The vertical hierarchy of variable high-mountain reliefs is striking, and ranges from the extremely cold arête ridges of the Makalu Massif, through the heavily glaciated and periglacial areas, to the seasonally cold/warm humid area of lower Barun Khola and Arun valleys. Distinctive vertical climatic zonation influences the variable features of morphostructural and lithological control on the characteristic weathering phenomena present in this region. Observations of landform patterns of peculiar relief types in the Makalu Barun region suggest extremely high rates of denudation, sediment transfer and deposition. Glacial, nival and periglacial processes, their landforms, influences of cryogenic destruction, and repeated freezing and thawing effects in rocks and their weathered mantle are also an evidence of the range and dynamics of changes in Himalayan landscape during the late Quaternary.

The conspicuous features of recent geomorphic processes in the Makalu Barun region of the Nepal Himalaya are: (1) in the extreme glacial zone: extensive weathering of rocks in a very cold and semi-arid environment, frequent avalanches and rockfalls, rapid wind erosion, stagnation of volume of ice and snow masses; (2) in the glacial zone: retreat and thinning of glaciers and substantial decrease in their volumes, spreading of the periglacial area to the detriment of lower levels of glacial zone; (3) in the periglacial zone: intensive regelation processes and fluvial erosion of rock massifs and Quaternary sediments, frequent slope movements, especially rockfalls and landslides; (4) in the seasonally cold/warm humid area: possible spatial expansion to warming periglacial zone, very frequent slope movements of various types and magnitude and intensive fluvial erosion. We illustrate that these processes are typical but not strictly limited to specific morphoclimatic zones and may interact and act across different morphoclimatic zones as far-reaching process chains, e.g. glacial lake outburst floods.

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Notes on contributors

Jan Kalvoda, is professor of Physical Geography at Charles University in Prague, Czechia. During mountaineering and scientific expeditions, he examined Quaternary landform evolution and recent morphogenetic processes in the Himalayas, Karakoram, Pamirs and Tien Shan, as well in the Asia Minor and Balcans. His current research activities are concentrated on (a) dynamic geomorphology of orogenetically active regions, (b) the Quaternary environment and geodynamics of central Europe and (c) physical-geographical evidence of natural hazards and disasters. Jan Kalvoda is member of the Editorial Board 'Geomorphology' (Elsevier), the Quaternary Palaeoenvironments Group (University of Cambridge, U.K.) and the Union of Czech Mathematicians and Physicists.

Adam Emmer, is physical geographer with background in natural hazard science and high mountain geomorphology. Adam is postdoctoral university assistant in The Mountain Processes and Mountain Hazards group (Cascade) at the Institute of Geography and Regional Science, University of Graz, Austria. He specializes in research on selected aspects of natural hazards in the broader context of ongoing geo-environmental change, especially in mountain areas. More specifically, Adam Emmer integrates field work, analysis of remotely sensed images and documentary data sources for analysing the evolution of glacial lakes and characterizing glacial lake outburst floods and associated processes.

ORCID

Jan Kalvoda http://orcid.org/0000-0002-2789-5495
Adam Emmer http://orcid.org/0000-0002-8268-990X

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