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*Jan Kalvoda**

DYNAMICS OF LANDFORM EVOLUTION IN THE MAKALU – BARUN REGION, NEPAL HIMALAYA

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The results of geomorphological analysis of landform patterns in the Makalu – Barun region of the Nepal Himalaya related to morphotectonic features of relief-building processes are presented. High-mountain landforms in the relief section between Mount Everest (8 848 m), Makalu (8 475 m) and the Arun valley (1 350 m) are the result of morphotectonic processes, as well as of denudation and erosional efficiency in different paleoclimatic conditions during the late Cenozoic. Observations in the East Nepal Himalaya also suggest significant feedbacks between the rate of tectonic exhumation of deep crystalline rocks and the intensity of climate-morphogenetic processes. It is suggested that the very high rate of valley incisions also stimulates isostatic compensation, which is one of the factors influencing the uplift of the East Nepal Himalaya during the Quaternary. Extreme exhumation of deep crystalline rocks in the Himalaya during the late Cenozoic is the result of morphotectonic processes, as well as the effective tuning of paleogeographical changes to the extension of the main climate-morphogenetic zones.

Keywords: landscape evolution, active orogeny, glacial and periglacial processes, Nepal Himalaya

INTRODUCTION

Research on the present-day landforms and the main features of climate-morphogenetic processes and phenomena in the Makalu – Barun region of the

* Department of Physical Geography and Geoecology, Faculty of Science, Charles University in Prague, Albertov 6, 128 43 Prague 2, Czech Republic, kalvoda@natur.cuni.cz

East Nepal Himalaya gives evidence for the evolution of the extremely dissected high-mountain relief during the late Cenozoic. This aspect of the Himalayan geomorphology can contribute to the knowledge of a long-term integration of climate-driven morphogenetic and active tectonic processes in dynamically evolving mountainous regions of collision orogeny. The Himalaya occurs in the collision zone of the Indian and Asian plates where the orogenic processes are very active (Iswata 1987, Kalvoda 1988 and 1992, Fielding 1996 and others). The geomorphological record of orogeny provides valuable evidence of the development of mountain ranges. Among them the Himalaya, corresponding to the geodynamic model of the lithospheric plate tectonics, is regarded as the most perfectly developed collision orogene of our planet. Studies of the geological structure and of the landforms of Himalaya produce important facts concerning the extreme intensity of the geodynamic processes which, especially during the Quaternary, remodelled these mountains to their present-day shape.

The Makalu – Barun region is situated between the Khumbu Himal (Mount Everest 8 848 m a.s.l.) and the Arun valley (1 350 m) in the morphotectonically conspicuous zone of the High Himalaya nappes (Bordet 1961, Jaroš and Kalvoda 1978a and 1978b). Observations of landform patterns of peculiar relief types in the Makalu – Barun region (Fig. 1) suggest extremely high rates of denudation, sediment transfer and deposition. The vertical hierarchy of variable high-mountain reliefs is striking, and ranges from the extremely cold arȩte ridges of the Makalu Massif (8 475 m, Fig. 2), through the heavily glaciated and periglacial areas, to the seasonally cold/warm humid Lower Barun and Arun valleys. Distinctive vertical climatic zoning also influences variable features of morphostructural and lithological control of characteristic weathering phenomena.

Geomorphological analysis of landform patterns in the Chomolongma and Makalu Massifs and the Barun Khola valley regions has been undertaken by Kalvoda (1978, 1979a, 1979b, 1982, 1984a and 1992). The largely glaciated part of the East Nepal Himalaya is an area exceeding 400 km^2 comprising complicated systems of hanging, slope and valley glaciers (Fig. 3) which flow from the extremely high crests. The faces and slopes of the peaks form a natural section across the sequence of rocks and the Great Himalayan landscape, extending from the south-eastern part of the Chomolongma Massif to the confluence of the Barun Khola and Arun rivers. The relief section between the Chomolongma Massif and the wider surroundings of the Barun Khola valley is formed by a varied set of alpine-type landforms with conspicuous tectonic dissection. On the 1:50 000 scale geomorphological maps of the Khumbu and Barun glacier regions (Kalvoda 1978, 1979b and 1992), endogenous and exogenous landforms were indicated, together with the main glacial and hydrological features of the landscape. The observation of landforms provides evidence of very dynamic landscape evolution and indicates the extraordinary features of natural hazards in the East Nepal Himalaya. Other topics examined during geographical research in the Makalu – Barun region have been the dynamics of glaciers and, especially, Quaternary glacial history. These studies are also connected with the late Quaternary sedimentary record of geomorphological processes and very high erosion rates in the East Nepal Himalaya.

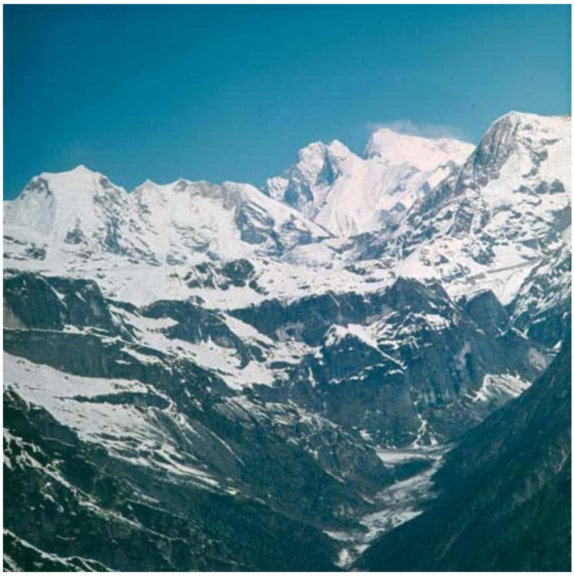

Fig. 1. Morphotectonic differentiation of the High Himalayan relief between the Chomolongma Massif and the middle part of the Barun Khola valley

To the left, on the horizon, is Peak 4 (6 720 m), Nuptse (7 879 m), Lhotse (8 501 m), Lhotse Shar (8 383 m) and Sagarmatha (Mount Everest, 8 847 m). The Barun Khola valley is incised at ca 3 000 - 4 000 m a.s.l. into actinolite paragneisses and granulites of the High Himalayan crystalline nappe. Fig. 1 - 16 by J. Kalvoda.

Fig 2. The Makalu Massif (8 475 m) is a dividing range between the humid monsoon region to the south and semi-arid areas of the High Himalaya and Tibet Highlands to the north. The northwestern wall of the Makalu Massif consists of the Miocene leucocratic granite body and its injection zones into paragneisses.

Fig. 3. Glaciated relief of the Baruntse Massif (7 220 m) in the western part of the Upper Barun glacier region with retreating glacier tongues and conspicuous Holocene and present-day moraines

The nature of the Makalu – Barun region has been studied since the middle of the 20th century main focused on a) geology and geophysics (e.g. Bordet 1961, Jaroš and Kalvoda 1976, 1978a, 1978b, Palivcová et al. 1982, Schärer 1984, Brunel and Kienast 1986, Hubbard 1989, Hubbard and Harrison 1989, Hubbard et al. 1996, Yagi and Minaki 1991, Lombardo et al. 1993, Visona and Lombardo 2002, Svojtka et al. 2003), b) geomorphology and physical geography (Kalvoda 1978, 1979a, 1979b, 1982, 1984a, 1992 and 2003, Šmolíková and Kalvoda 1981, Kalvoda and Valenta 1997, Kalvoda et al. 2004b), c) biology and geoecology (Daniel et al. 1985, Byers 1996, Carpenter and Zomer 1996, Zomer et al. 2001 and 2002).

The Himalayan branch of the High Asian mountain ranges can be presented by four aspects of its Cenozoic development (Kalvoda 1988 and 1992): 1) orogenic manifestations of the collision of the Indian and Asian continental plates, 2) the extent of the relief changes in the Quaternary, 3) the origin and chronodynamics of glaciation, 4) the dynamics and extremely high intensity of recent and/or present-day relief building processes. In the present study about the Makalu – Barun region in the East Nepal Himalya the challenge of determining the landform development as the geomorphological record of active orogeny is integrated with the investigation of landscape patterns and recent climate-morphogenetic changes of the high-mountain relief.

DYNAMICS OF EROSION AND EXHUMATION OF ROCKS RELATED TO MORPHOTECTONIC PROCESSES

Geomorphological analysis of landform patterns in the Makalu – Barun region of the East Nepal Himalaya related to morphotectonic features of relief-building processes in the late Cenozoic can be used to evaluate of the dynamics of erosion and exhumation of rocks during ongoing collision orogeny. The geologically very short period of time separating the present from the youngest orogenic phase permits formulation of the problem of the Himalayan relief evolution as an exceptional possibility of a direct study of the course of the most dramatic geological events known.

Interpretation of geological structure related to landform patterns from the Makalu – Barun and Mount Everest regions have been published by Jaroš and Kalvoda (1976, 1978a and 1978b) and Kalvoda (1978, 1979a, 1979b, 1982, 1984a and 1984b). Detailed description of the petrography and chemistry of crystalline rocks from the studied area can be found in Palivcová et al. (1982). The relief of the uppermost cliffs of this part of the East Nepal Himalaya represents a thick rock succession comprising three main lithostratigraphic units (Jaroš and Kalvoda 1976, 1978a and 1978b); the Chomolongma group, the Makalu Formation and the Barun group. In the Makalu – Barun region, the Chomolongma group occurs only in the vicinity of the unnamed peak of 7 502 m elevation (Fig. 4). Its lower part consists of pelitic, slightly metamorphosed Palaeozoic rocks.

The Makalu Formation consists of a number of Miocene granite bodies associated with extensive contact injection zones intruded into the lower part of the Chomolongma group and the upper part of the Barun group. The later consists mostly of biotite gneisses, originally of Precambrian age. The complex of sillimanite-, kyanite- and cordierite-bearing gneisses, calc-silicates and amphibolites ("Barun gneisses" described by Bordet 1961 and Lombardo et al. 1993) is intruded by Namche migmatitic orthogneisses (Fig. 5, Brunel and Kienast 1986, Pognante and Benna 1993) and overlain by biotite-sillimanite gneisses ("black gneisses" of the Rongbuk Formation). At lower elevations, below the Shershon site towards the Main Central Thrust, the Barun group consists of an up to 5 000 m thick formation of banded biotite gneisses with garnet, kyanite and sillimanite with interlayered garnetiferous amphibolites, pyroxenite lenses and granulites.

The biotite-sillimanite gneisses in the upper part of the High Himalayan nappe were intruded by tourmaline leucogranites of the Makalu Massif in the late Oligocene and early Miocene (24.4 – 21.7 Ma, Schärer 1984). The bedrock topography on granites is developed especially on the ridges and the rock faces of the Massifs of Peak 4, Baruntse, Chago and Makalu (Fig. 4). Yellowish-white granites form strikingly steep rock faces, often polished by wind and avalanches, occasionally ice-affected, which display extensive desquamation planes. A compact bedrock topography is developed on black paragneisses along the lower parts of the eastern cliffs of Peak 4, below elevation points 5 860 and 6 260 m and in the foreland of the southwestern wall of the Makalu.

The metamorphism of the High Himalayan nappe in the Makalu and adjacent Mount Everest regions is related to crustal thickening during the collision (T = 550 – 680°C, P = 8 – 10 kbar) followed by decompression and crustal melting at P = 2 – 7 kbar (Brunel and Kienast 1986, Hubbard 1989, Hubbard and Harrison 1989, Lombardo et al. 1993, Pognante and Benna 1993). The thermal peak of metamorphism was close in time to the reported emplacement age

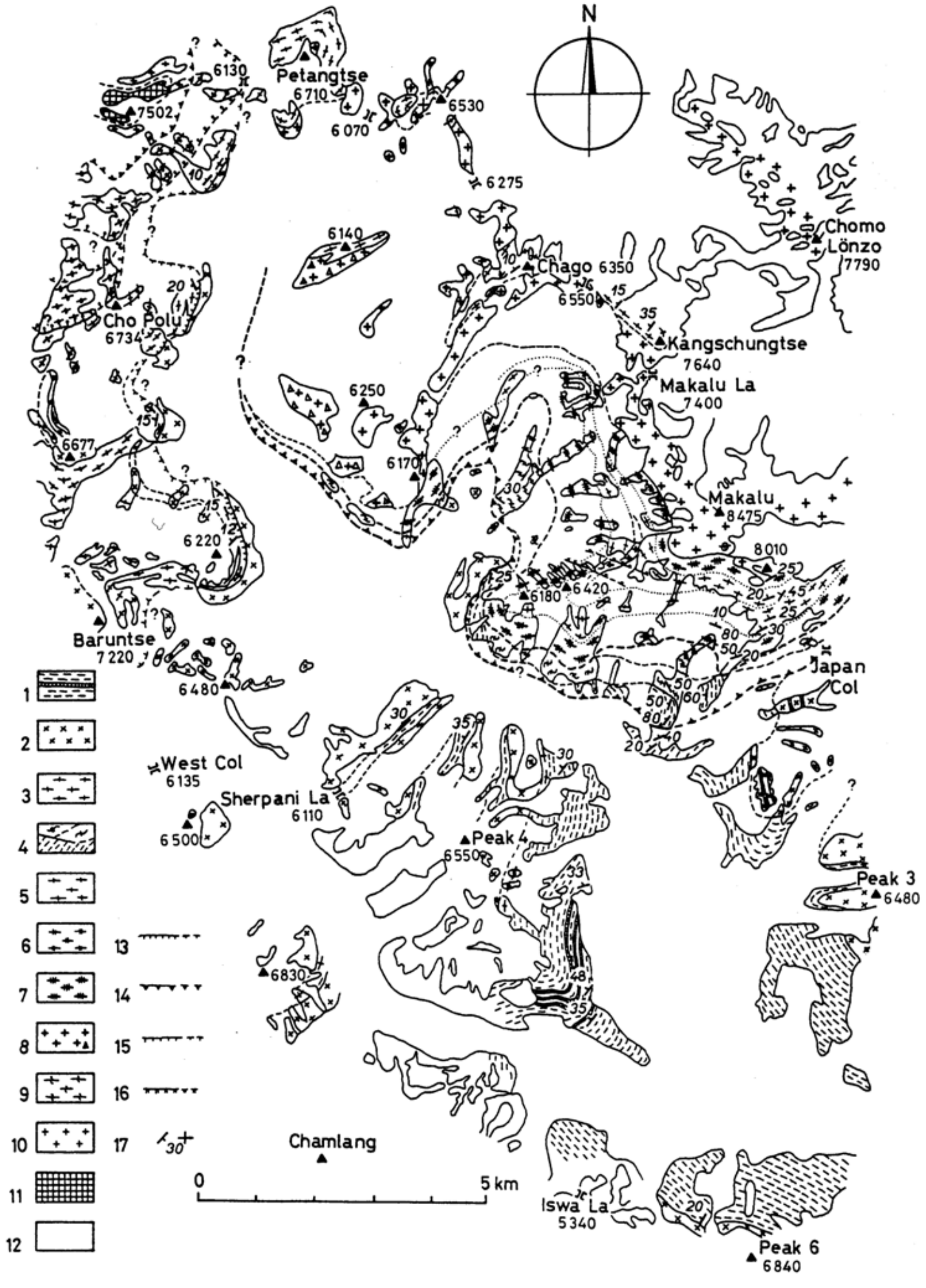

Fig. 4. The uppermost part of the very steep southern walls of the Nuptse (7 879 m) and Lhotse Shar (8 383 m) with evident features of cryogenic and eolian modellation, consisting of leucocratic granites of the Miocene age and their upper injection zones intruded into the biotite gneisses of the Chomolongma group

for the leucogranites (24 – 17 Ma, Searle et al. 1999). It was also suggested that no external heat source was required to explain the formation of leucogranitic magma in the Mount Everest and Makalu Massifs (Visona and Lombardo 2002).

Fig. 5. The extraglacial semiarid climate-morphogenetic zone to the north of the Peak 4 Massif (6 720 m), which consists of crystalline rocks of the High Himalaya, displays conspicuous landform patterns of intensive glacigenic, nival, cryogenous and eolian processes

The peak of metamorphism in the studied region is constrained between 42 – 28 Ma (Lombardo et al. 1993, Pognante and Benna 1993). This time span corresponds well with the evidence reported from the Mount Everest region (36 – 28 Ma, Simpson et al. 2000) for the timing of prograde metamorphism. Given the age of crustal melting constrained by the U-Pb systematics in zircons extracted from the Makalu leucogranites (24.4 – 21.7 Ma, Schärer 1984), there is only a short period of time remaining between the peak of metamorphism and the emplacement of leucogranites into the black gneisses of the Rongbuk Formation. This time delay can be explained by thermal re-equilibration of the crust before the onset of the large-scale crustal melting.

The presence of kyanite in the mineral assemblage of the Barun gneisses and its breakdown to sillimanite are indicative of decompression that started before or shortly after the rocks reached temperatures close to the biotite dehydration melting (Svojtka et al. 2003). The succession of metamorphic reactions is typical for collision orogens where burial of rocks and an increase in pressure precedes the heating, followed by decompression and exhumation of rocks towards the surface (Simpson et al. 2000, Beaumont et al. 2001). The total amount of denudation at present-day rugged high-mountain relief of the Himalaya can be estimated at approximately 6 000 m per 1 Ma (Hubbard et al. 1996, Searle et al.

2003). The integration of a geomorphological and geological evidence from the Makalu – Barun region and from the adjacent areas point to a rapid exhumation of deep crustal rocks during the mature stage of collisional orogeny.

The major exhumation events related to denudation and uplifting processes in the Makalu area were recorded by Svojtka et al. (2003) and Kalvoda et al. (2004a and 2004b). The low-temperature thermochronometry of the crystalline units in the upper part of the Barun Valley above the Main Central Thrust zone was studied at 4 600 - 5 000 m elevation. Zircon and apatite grains from the biotite-sillimanite paragneiss, migmatitic orthogneiss and glacifluvial sediments were analysed. The fission-track zircon cooling ages for the migmatitic orthogneiss and paragneiss were 7.1 ± 1.0 Ma and 12.2 ± 1.0 Ma, respectively, interpreted as resulting from a steady slow cooling through the zircon partial annealing zone between 310 - 230°C. Fission-track ages of zircons from glacifluvial sediments (9.0 ± 0.7 Ma and 9.2 ± 1.0 Ma) represent a mixture of the fission-track cooling ages of rocks exposed in the upper part of the Barun Valley (Svojtka et al. 2003). Cooling ages for migmatitic orthogneiss and biotitic-sillimanite paragneiss were determined as 3.2 ± 0.2 Ma and 6.6 ± 0.6 Ma, and the glacifluvial sediments yielded an age of 3.7 ± 0.5 Ma and 4.0 ± 0.5 Ma.

The apatite and zircon fission-track data suggest that the exhumation / denudation processes are characterized by initially high cooling rates of ~ 46°C/Ma (7.1 Ma – 3.2 Ma) for the migmatitic orthogneiss and ~ 32°C/Ma (12.2 Ma – 6.6 Ma) for the paragneiss (Svojtka et al. 2003). The cooling rate for the migmatitic orthogneiss and the paragneiss from the Pliocene/late Miocene to the present time decreased to ~ 22°C/Ma and ~ 11°C/Ma, respectively. Modelling of the thermal evolution of apatites has shown that the migmatitic orthogneisses cooled from the apatite partial annealing zone (60 - 120°C) to 20°C since ca 3.0 Ma. The temperature has not significantly changed since approximately 1 Ma ago (Svojtka et al. 2003, Kalvoda et al. 2004a and 2004b).

The apatite fission-track data documenting a rapid decrease of temperature from 120°C to 20°C in the gneisses between 3.0 – 2.0 Ma suggest the existence of dissected mountain relief at that time which probably developed at a substantially lower elevation during the Pliocene (Svojtka et al. 2003, Kalvoda et al. 2004a and 2004b). The rapid decrease of temperature of the exhumed crystalline rocks is perhaps evidence for an episode of rapid erosion and denudation of the paleorelief of the High Himalayan nappe. The results of fission-track dating of zircon and apatite in the Makalu – Barun region gave evidence for continuous denudation of the near-surface part of High Himalayan rocks from the Neogene to the present day, which is caused by their orogenic uplift, as well as global or regional changes of climate.

GEOMORPHOLOGICAL SURVEY OF LANDFORM PATTERNS

The exogenous erosional landforms can be divided into two groups of structural denudational levels with alpine-type relief. The lower surface occupies the roof part of the Barun nappe at 4 900 - 5 200 m a.s.l., the second one occurs in the upper parts of the Makalu Massif and in the present-day relief it is situated 1 000 - 1 200 m higher than the first. The Makalu (Fig. 2) is a huge peak, partly isolated tectonically, as are the Baruntse and the unnamed peak of 7 502 m elevation. Peak 4 is an extensively glaciated mass sharply bounded by rock faces. The summits of other peaks are either the terminations of lateral crests or the eroded relicts of connecting ridges between the main mountain massifs (Fig. 6.). The denudational slopes dipping up to 48^{o}, mostly covered with a 20 - 120 cm thick stratum of blocky and sandy-gravelly detritus, extend over large areas, especially between the confluence of the Chago and Barun glaciers and the ridge of elevation point 6 140 m, below the peak of the 6 090 m elevation, and in the surroundings of the southwestern peak of 6 260 m elevation.

Fig. 6. The extraglacial semiarid climate-morphogenetic zone to the north of the Peak 4 Massif (6 720 m), which consists of crystalline rocks of the High Himalaya, displays conspicuous landform patterns of intensive glacigenic, nival, cryogenous and eolian processes

During the Quaternary, the width, position and thickness of glaciers and the abrasive action of their ice masses in the Makalu – Barun region were influenced – in addition to the effect of climatic agents – also by morphotectonic activity (Kalvoda 1979a and 1979b) with developing extreme dissection of individual mountain massifs (Fig. 7). The largest areas of glaciation were concentrated in the upper parts of the uppermost morphotectonic units (Figs. 8 and 9). For example, the upper end of the Barun glacier valley cuts into the main ridge of the Great Himalaya between the Chomolongma and Makalu Massifs. This glaciated area passes with a wide transfluence of ice masses into the Kangshung valley to the east of Mount Everest, where the front of the Chomolongma relief nappe is clearly visible.

The nunataks here may be divided into two types: 1) massive rocky crests, the heights of which exceed the maximum thicknesses of the fossil glaciers (ridges with debris eluvium in the environs of the 6 140 m elevation point, and those in the Chago valley) and 2) steep exposed relics of pinnacles between slope and hanging glaciers, e.g. northwest of the 7 057 m elevation point peak, in the lower parts of the northwestern and southwestern cliffs of the Makalu and west of the 6 825 m elevation point. The glacial polish on the groups of roches moutonées, exposed after the retreat of the ice masses 1.5 km from the northern peak of elevation point 6 250 m in the vicinity of the 6 540 m peak below the northwestern face of the Makalu and above the Barun Pokhari lake towards the Japanese Col, provide evidence of the considerable extent of the earlier stages of glaciation.

Fig. 7. Alpine-type relief of the crystalline complexes of the High Himalaya in the Hunku glacier area with conspicuous morphostructural features and tectonic differentiation of partial mountain massifs

Key: 1 – crests of the upper part of the Makalu relief nappe, 2 – rock relief of the upper part of the Barun glacier area, 3 – frontal part of a morphostructural slice with massive biotite gneisses in the Barun relief nappe, 4 – structural denudational slopes with active talus cones and Holocene moraines in the tectonic disturbance zone running through the Hunku valley, 5 – steep rocky slopes on black gneisses of the Barun nappe in the northwestern part of the Chamlang Massif, 6 – Hunku lake (4 400 m a.s.l.) dammed by the Late Holocene moraine of a slope glacier, 7 – lower part of the Hunku glacier tongue.

Intensive glacigenic, nival and cryogenous destruction of the mountain slopes (Fig. 10) is indicated by Holocene and fresh tension gashes in scree slopes, which may be hundreds of metres long, or by the sharp lines of mostly glaciated crests. Simple gravitational landforms include active talus fans developed at the foot of huge rock faces, as well as talus fans of great areal extent, and accumulation piles resulting from rockfalls and landslides which are conspicuous due to the chaotic piling of their boulders. A cover of sliding detritus, mostly consisting of boulders, is formed on slopes. The lateral moraines of glaciers are frequently overlain by accumulations of slope debris ranging in size from coarse sand to boulders.

Fig. 8. Steep crests surrounding a relatively broad depositional basin of glaciers between Lhotse (8 501 m) and Baruntse (7 220 m) suggest that the main exogenic processes are rapid wind erosion and polishing of the rock surface, dry ice and firn fields and sharp cryogenic weathering of crystalline rocks resulting in frequent rockfalls and avalanches

Fig. 9. The Lhotse Nup glaciers area with evident vertical climate-morphogenetic zoning and conspicuous morphostructural patterns of the alpine-type relief situated north of the Amai Dablang Massif. Dejection planes of rockfalls on extremely steep walls of crests of crystalline rocks of the High Himalaya are displayed as well as Upper Pleistocene to Subrecent moraines, glacifluvial and lacustrine sediments. These accumulation landforms are situated below slope glaciers and icefalls at the bottom of an earlier broad glacial valley.

Fig. 10. The Lower Barun glacier with a system of icefalls has conspicuously decreased in volume in the last three decades, which is also accompanied by the origin of large landslides and by formation of a new lake dammed by low recessional moraines

The oldest accumulation landforms are represented by fossil moraines of the Barun glacier. The moraines of the Dusa type, which date from the time of the maximum extent of the glaciers in the Upper Pleistocene (Kalvoda 1978 and 1984a), only have been preserved between the foot of the eastern rock faces of the peak of elevation point 6 380 m in the Peak 4 Massif and the Barun Pokhari lake, as well as north of the Shershon site. These moraines adjoin the valley slopes, attaining thicknesses of 120 - 160 m and above Shershon at least 60 - 80 m. Names of moraines are used after equivalent glacial accumulations in the Khumbu Himal region (Fig. 9), cf. Iswata (1976a and 1976b), Kalvoda (1978), Richards et al. (2000). The surface of the moraines of the Dusa type is slightly furrowed due to periglacial processes and is consolidated by alpine steppe vegetation.

Holocene moraines of the Changri type lie at the southern foot of the Makalu Massif. They are the relics of a stage of glacier advance during which ice masses filled the floor of the lower parts of the Barun valley up to above the Shershon site. The Changri-type lateral moraines are flat and 15 - 20 m high and the frontal moraines, up to 30 m thick, have their arched ridges chaotically distributed (Fig. 11). The valley glaciers in the Makalu – Barun region are bounded by the conspicuously asymmetrical walls of the lateral and frontal moraines of the Khumbu glaciation stage. Surfaces of these Neoglacial moraines with relative heights of 12 - 40 m are practically unconsolidated. The moraines consist of coarse sandy unsorted material, with a pronounced predominance of light-coloured granitic material prevailing over dark gneisses and varied coloured migmatites.

Fig. 11. The extensive system of accumulation landforms of glacial, glacifluvial, lacustrine, eolian and slope sediments of the Upper Pleistocene to Recent age originated between the present-day tongue of the Barun glacier (4 800 m a.s.l.) and the Sherson site near the Lower Barun glacier

The moraine of the recent Lingten oscillation has been preserved on the western side of the main Barun glacier tongue, at altitudes of 5 000 - 5 050 m, and in front of the slope glaciers of the western and northern cliffs of Peak 4. The moraine occurs as 5 to 15 metres high, broadly-based ridges, zig-zag or arched in shape, with a chaotic granular texture (Fig. 12). The entire Barun glacier tongue and its lateral ice flows from the valley of the eastern part of the Baruntse Massif and from the Chago valley are covered (from 5 500 m a.s.l. downwards) with an almost continuous surface moraine.

In the foreland of the present-day glaciers a system of glaciofluvial and lacustrine depositional landforms is developed (Fig. 13). The Holocene to Neoglacial terraces and cones of outwashed sediments represent the earlier of two generations of glaciofluvial landforms. The younger Neoglacial to recent glaciofluvial cones lie in the depressions between individual oscillation ridges of moraines. The presence of the present-day and former lakes of glacial origin on valley floors is indicated by terraces of lacustrine sediments up to 6 m thick surrounded throughout by fossil moraines (Fig. 7). Of periglacial landforms, paved and polygonal soils of small areal extent have been found (Kalvoda 1979b, Kalvoda and Smolíková 1981), although always at altitudes of below 5 200 m on fossil moraines.

Fig. 12. Frontal and surface moraines of the valley glacier (4 950 m a.s.l.) to the east of Peak 3 (6 480 m) above the Barun Khola valley display conspicous features of ice-thawing and activity of periglacial processes

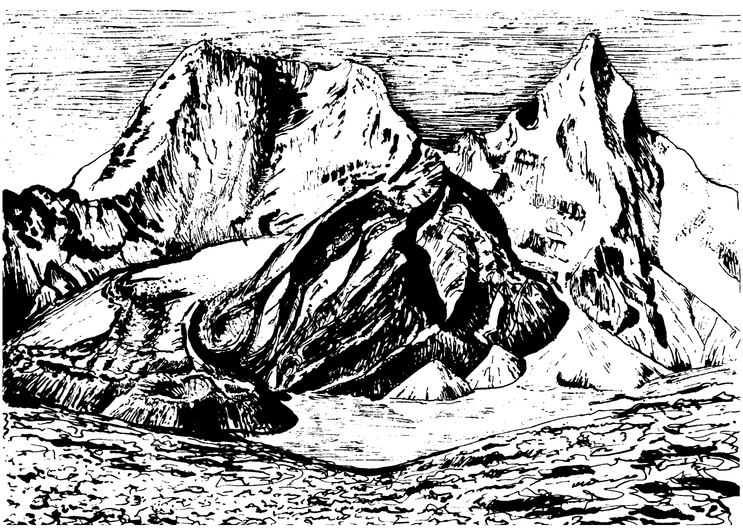

Fig. 13. Lake Tsuro (4 600 m a.s.l.) dammed by an avalanche-type glacier northeast of Taboche (6 542 m) in the Khumbu Himal region

Young aeolian landforms consist of fine sandy to silty accumulations especially originating from unconsolidated morainic, lacustrine and slope sediments (Fig. 11). The terraces, composed of up to 3 m thick wind-blown sand, rest in the lee of fossil morainic ridges on the flanks of the slope-glacier tongue of the eastern face of Peak 4, and to the northwest of the Shershon site. Irregular small active dunes up to 50 cm high border, for example, the bottoms of the depressions between the Neoglacial moraine of the Barun glacier tongue, the environs of the Barun Pokhari lake and its southern foreland. The aeolian sands are strikingly light-coloured, white to yellow, with angular grains and a high proportion of quartz and micas.

From the icefall south of the Peak 4 Massif to the Tadoza site, the valley floor is practically filled with chaotic ridges of fossil oscillation moraines, rockfalls, talus fans and the Lower Barun glacier tongue. In the Barun Khola river valley, glacial and periglacial landforms, which reflect the influence of a former cirque and slope glaciers, occur especially to the east of the Lower Barun glacier. They are located above the Yangle Khalka site and the Arun river canyon-like valley in the foreland of structurally controlled denudational slopes which are developed along the front of the Main Central Thrust. The glacial landforms occur only in the lateral, mostly hanging, valleys and on the crests between them. The periglacial weathering features of the marginal ridges of the Barun Khola valley disappear even before this valley enters the rocky cliffs of the Great Himalayan nappe in the evergreen monsoon mountain forest vegetation zone. The Barun Khola valley floor, up to 2 800 m a.s.l., is covered by thick (up to ten metres) deposits of glaciofluvial and slope sediments (Fig. 14) cut by vertical erosion from the Phematan locality to as low as paragneisses and granulites of the lower part of the Barun nappe.

Fig. 14. Rates of slope movements and erosion of crystalline rocks as well as glacifluvial sediments of the late Quaternary age deposited in the lower periglacial zone of the Barun Khola valley system are extremely high especially in canyon-like sections of the valleys

The dividing ridges between the Tsang Po and Arun rivers lie 120 km north of the Chomolongma Massif in the Shekar Dzong area, and reach altitudes of 6 500 m. In contrast to the Tibetan Himalayas, the Arun valley is of a very moderate gradient, in the Great Himalayas it suddenly becomes steeper in its deeply incised canyon. At the confluence with the Barun Khola river, the Arun canyon is incised as deep as 1 050 m a.s.l. (Fig. 15), and after a further 12 km, near the village of Num, it is at 850 m a.s.l. The Nepalese part of the Arun valley, up to the northern margin of the Tumlingtar intermontane basin in the Lesser Himalayas, has a steep irregular gradient. The ridges of the Lesser Himalayan relief north of Kumalgaon village distinctly plunge under the frontal parts of the crystalline rocks of the Great Himalayan nappe.

Fig. 15. The extremely dissected high-mountain relief around the antecedent valley of the Arun river in the East Nepal Himalaya is very instructive evidence of the continuing uplift as a consequence of the collision type of orogeny in the late Cenozoic

RECENT CLIMATE-MORPHOGENETIC PROCESSES

The rugged high-mountain landscape of the Makalu – Barun region displays an elevational gradient of over 7 000 m with very varied climatic and biogeographical zones. Recent climate-driven morphogenetic processes in the extremely dissected relief (Fig. 1) can be described in the framework of extraglacial and glacial zones, the periglacial zone and the seasonally cold/warm humid zone.

The extraglacial high-mountain zone with a rock-cut landscape of alpine-type ridges displays a dynamic integration of deep weathering with major glacial and nival morphogenetic processes in a very cold and semi-arid environment (Figs. 3 and 5). Lithological and joint control of relief on crystalline rocks is suppressed in these areas, although its influence is evident on lower lying large slopes and in the periglacial zone. The intensity and duration of temperatures below freezing point led to deep rock disintegration and macrogelivation (Kalvoda and Valenta 1997, Kalvoda 2003). By contrast, shallow freeze-thaw cycles are effective for microgelivation. Avalanches and rockfalls are frequent, and aeolian erosion and stagnation of the volume of ice and snow masses is very conspicuous (Fig. 6). Platforms in the shape of small altiplanos and large glacial valleys serve as an accumulation space for snow and glacier masses of the High Himalayan Range. The present equilibrium-line altitude in the Barun and Khumbu Himal areas lies between 5 600 - 5 700 m.

The southwestern side of the Makalu Massif (8 475 m) has its foot at altitudes of 4 900 to 5 000 m. Observations from the years 1971, 1973, 1976 and 2002 have shown that conspicuous recent changes in the rock slope patterns and, especially, in the volume of ice masses accompanied by a recession of frontal parts of hanging glaciers, are only in the lower parts of the walls. The glacial zone of the Makalu – Barun region displays a recent regression of glaciers and a rapid decrease in their volumes. The spreading of the periglacial zone to the detriment of lower areas of the very cold glacial zone is striking.

The valleys and ridges of the Chomolongma and the Makalu – Barun regions are fully filled with glacier masses at high altitudes above ca 6 000 m a.s.l. (Figs. 8 and 9). Large ice source areas often contrast with very narrow canyon-like lower parts of valleys. A striking phenomenon is the occurrence of the relics of sediments in accumulation landforms of Upper Pleistocene age and younger than 50 000 years (Kalvoda 1984a and 1984b, Iswata 1987, Yagi and Minaki 1991, Richards et al. 2000). The high intensity of recent denudation and transport of weathered and eroded material equates with a striking absence of the older Quaternary sediments.

Accelerated rates of erosion have been observed in the periglacial environment located outside the present glaciers (e.g. Iswata 1976a and 1976b, Kalvoda 1979a and 1979b, Drdoš et al. 1987). The recent rapid retreat of the glaciers is accompanied by a distinctive increasing of the active periglacial zone (Figs. 11 and 12). This increases the volume of transported products of denudation and the level of geomorphological hazards, including frequent rapid events of mass movements (Figs. 10 and 14) triggered by earthquakes, avalanches, flash floods and landslides. Present decreases in the distribution of permafrost has some implication for landscape stability (Kalvoda and Smolíková 1981, Smolíková and Kalvoda 1981), which is mirrored in solifluction, rock-glacier movements (Fig. 13) and sediment release into streams and rivers.

The lower part of the Barun valley is constantly reshaped by huge and frequent slope movements and simultaneous rapid erosion of glaciofluvial and slope sediments deposited in accumulation landforms of the late Quaternary age. Moreover, anthropogenic disturbance in a dynamic environment, including the deforestation in an attempt to increase pasture area, could have a significant role in modifying the Barun and Arun valleys landscapes. Relics of forest vegetation, which are important repository of biological diversity, are currently threatened. The lower part of the Makalu – Barun and Arun river regions are areas of frequent natural disasters with high risks involved in all types of human activities. A large amount of new rockfall accumulations have been found in the lower part of the Barun Khola valley (Figs. 14 and 15), which is part of a subalpine conifer zone with Abies and Juniperus. Rapid erosion of rock massifs is driven by tectonic uplift and the humidity of summer monsoons. Steep erosion-denudational slopes of the Arun river valley, with very frequent slope movements, are covered by a monsoonal evergreen forest, which is being intensively reshaped by burning and clearing (Daniel et al. 1985, Zomer et al. 2001 and 2002). The catastrophic course of landscape changes stimulated by human activities (e.g. Drdoš et al. 1987, Bayers 1996, Carpenter and Zomer 1996) can be detected even in the strictly protected national parks of the East Nepal Himalaya (Fig. 16).

Fig. 16. Stone walls of the seasonal Sherpa village of Dingpocche (4 200 m a.s.l.) south of the Chomolongma Massif are built of blocks of paragneisses, phylites and granites of fluvioglacial and slope accumulations

These walls hinder catastrophic wash and erosion of soil during spring thawing and summer monsoonal precipitations.

Historical religious texts suggest that pilgrims may have visited sacred sites in the main Arun valley since 14th century. Regular seasonal grazing may have begun in the 17th century (Byers 1996, Carpenter and Zomer 1996). Corridors of disturbance related to contemporary indigenous use (tree harvesting, burning, grazing), observed along the trail from Tumlingtar to Sedoa, and impacts on forests (from near-tropical monsoon forest (400 - 800 m) up to subalpine conifer area with *Abies* and *Juniperus* in *ca.* 4 000 m), appear to be growing in frequency and magnitude.

The geomorphological observations on a decadal scale suggest that a frequency and magnitude of recent landform changes in the East Nepal Himalaya are increasing from a very cold and dry extraglacial zone across a large periglacial area up to subtropical landscape with humid climatic conditions. Dynamic changes of landscape pattern are controlled and/or accompanied by rapid endogenic and exogenic geomorphological processes and events, which are an important evidence of the present-day severe natural hazards.

The observed recent landform changes confirm the high intensity of climate-driven morphogenetic processes, especially with very effective erosion and transport of weathered material in the periglacial and seasonally warm humid (monsoon) mountain zones. This is in striking contrast to the relatively small range of denudation and transport of weathered material in the northern cold and semi-arid climatic zones of the Himalaya in Tibet (Fielding 1996). The paleogeographical consequence of these long-term differences is the very deep penetration of erosion and denudation of rock massifs in regions of steep windward Tibetan-foreland transitions with the influence of humid air masses (Beaumont et al. 2001) leading to development of the deeply-entrenched high-mountain reliefs of the Himalaya.

CONCLUSIONS

Research into the development of mountain reliefs in the Asian regions with evidence of active orogeny is intended to gain knowledge of the geodynamically critical zones of the Earth's lithosphere, as well as the physical properties and behaviour of near-surface parts of rock massifs. The dynamics of geomorphological processes in the vertical climate-morphogenetic zones of the Makalu – Barun region in the East Nepal Himalaya shows that glacial and periglacial processes are very effective at destroying the rock massif uplifted during collision orogeny. Rapid unroofing and exhumation of deeper parts of the rock massifs is also reliant upon vigorous transport agencies, such as transgression of glaciers and intensive activity of wind in extraglacial and glacial zones, and/or rapid action of water in periglacial and seasonally humid cold/warm zones. A similar situation has been demonstrated in the Western Himalaya and the Karakoram (Goudie et al. 1984, Kalvoda 1984b, 1990 and 1992, Goudie and Kalvoda 2004). The long-term influence of these geomorphological processes on the exhumation of deeper parts of the Earth's crust, and the dynamics of orogenic uplifts of the East Nepal Himalaya, is evident.

The key factor of the chronodynamics of rapid uplift of the Himalaya during the Quaternary, as one of the geodynamic manifestations of the ongoing collision, is the long-term interaction between the intensity of morphostructural processes, including the extent of the tectonic exhumation of deep-crust rocks, and the changeable rates of denudation which also involve the outward flux of eroded material. The extremely high rate of valley incisions also stimulates isostatic compensation which is one of the factors influencing the uplift of the East Nepal Himalaya throughout the Quaternary. Extreme exhumation of deep crystalline rocks in the Himalaya during the late Cenozoic is the result of morphotectonic processes as well as the effective tuning of paleogeographical changes in the extension of the main climate-morphogenetic zones.

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Jan Kalvoda

DYNAMIKA VÝVOJA POVRCHOVÝCH TVAROV V OBLASTI MAKALU – BARUN, NEPÁLSKYCH HIMALÁJÍ

V práci sú zhrnuté výsledky geomorfologického výskumu oblasti Makalu-Barun v Himalájách východného Nepálu. Veľhorský reliéf v profile medzi Mount Everestom (8 884 m), Makalu (8 475 m) a kaňonovitým údolím rieky Arun (1 350 m) je výsledkom integrácie veľmi intenzívnych morfotektonických procesov, efektívnej denudácie a erózie v meniacich sa paleoklimatických podmienkach mladšieho kenozoika. Geomorfologická analýza reliéfu Himalájí východného Nepálu svedčí o významných spätných väzbách medzi rozsahom tektonickej exhumácie kryštalinických hornín a intenzitou klimato-morfogenetických procesov. Intenzívna glaciálna a periglaciálna modelácia horských masívov, svahové pohyby a erózne prehlbovanie kaňonovitých údolí, spojené s veľmi efektívnym transportom zvetraného materiálu od Indogožanskej nížiny, stimulujú izostatickú kompenzáciu pripovrchovej časti zemskej kôry. Tento geodynamický proces je jedným z faktorov, ktoré determinujú výzdvih Himalájí východného Nepálu v kenozoiku. Extrémna exhumácia pôvodne veľmi hlboko umiestnených kryštalinických hornín je prejavom jednak aktívnych morfotektonických procesov v priebehu kolíznej orogenézy, jednak mnohých paleograficských zmien v rozšírení hlavných klimaticko-morfogenetických zón Himalájí.