Morphotectonic evidence for chronodynamics of uplift in the East Nepal Himalaya

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1. Introduction

The integration of a geomorphological and geological data from the Makalu–Barun region (Photo 1) and from the adjacent areas (Figs 1 and 2) point to a rapid exhumation of deep crustal rocks during the mature stages of collisional orogeny. Our observations from the years 1971, 1973, 1976 and 2002 suggest a significant feedback between the rate of tectonic exhumation of deep rocks and the intensity of climate-driven morphogenetic processes (Kalvoda, 2003; Kalvoda et al., 2004). High-mountain landform patterns in the relief section between the Mount Everest (8 847 m), Makalu (8 475 m) and the Arun valley (1 350 m) are the result of morphotectonic processes, denudation and erosion efficiency in different paleoclimatic conditions during the Late Cenozoic.

2. Late Quaternary geomorphological processes and landform evolution

The study area is a highly complex and rugged high-mountain landscape (Photo 2), with extreme dissection of relief and an elevation gradient more than 7 000 m with very varied climatic and biogeographical zones. The main features of recent landform changes in the Makalu–Barun region of the East Nepal Himalaya are:

1) *Extraglacial zone:* extensive weathering of rocks in a very cold and semiarid environment, frequent avalanches and rockfalls, rapid wind erosion, stagnation of volume of ice (Photos 3 and 4) and snow masses.
2) *Glacial zone:* recent regression of glaciers and rapid decrease in their volumes, spreading of the periglacial zone to the detriment of lower areas of the extremely cold extraglacial region (Photo 5).
3) *Mountainous terrain from periglacial to subtropical zones:* rapid erosion of rock massifs (driven by tectonic uplift and humidity of summer monsoons) and Quaternary sediments and/or accumulation landforms, very frequent slope movements of various types and magnitude.

The catastrophic course of landscape changes stimulated by human activities can be detected even in strictly protected national parks of the East Nepal Himalaya.

Morphostructural and lithological control of characteristic weathering phenomena is conspicuous (Photo 6). It has variable features in a distinctive vertical climatic zoning of rugged mountain reliefs from the extremely cold extraglacial ridges of the High Himalaya (Photo 7) through the heavily glaciated and periglacial areas (Photo 8) to the warm and seasonally humid Arun valley.

The time correlation of the Lower Barun glacier icefall situated at the end of the narrow hanging valley north of the Chukhung Massif is extraordinary. The shape of

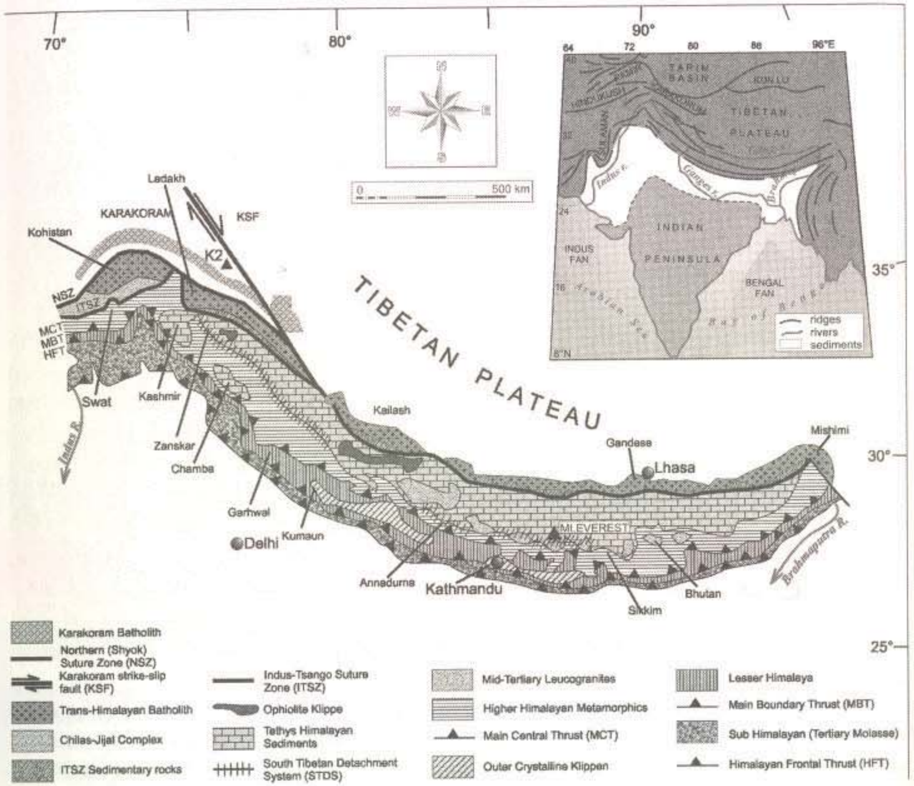

Fig. 1 Geological sketch map of the Himalaya (modified after Lombardo, Rolfo 2000)

the icefall and its crevasses pattern have not changed since the year 1973 (Kalvoda, 2003). On the contrary, the whole lower lying flat tongue of the glacier is not far from extinction in the near future (comp. Photos 9 and 10). The recent decrease of ice masses is also evident from a position of small glacier tongues in the lateral valleys related to their moraines of the Holocene age. However; the shape of the moraines has not changed in the last 30 years and their ridges are only more rounded.

The lower part of the Barun valley is constantly reshaped by huge and frequent slope movements and simultaneous rapid erosion of fluvioglacial and slope sediments (Photo 11) deposited in accumulation landforms of the Late Quaternary age. A large amount of new rockfall accumulations was found in the lower parts of the rock walls in the Makalu–Barun region. Moreover, anthropogenic disturbances 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 an important repository of biological diversity, are currently threatened.

Historical religious texts suggest that pilgrims may have been visiting sacred sites in the main Arun valley since 14th century. Regular seasonal grazing may have commenced in the 17th century (Byers, 1996; Carpenter, Zomer, 1996). Corridors of disturbances related to contemporary indigenous use (tree harvesting, burning, grazing) observed along the trail from Tumlingtar to Sedoa (Photo 12) and impacts on forests (from near-tropical monsoon forest (400–800 m) up to subalpine conifer area with *Abies* and *Juniperus* in cca 4 000 m) appear to be growing in frequency and magnitude.

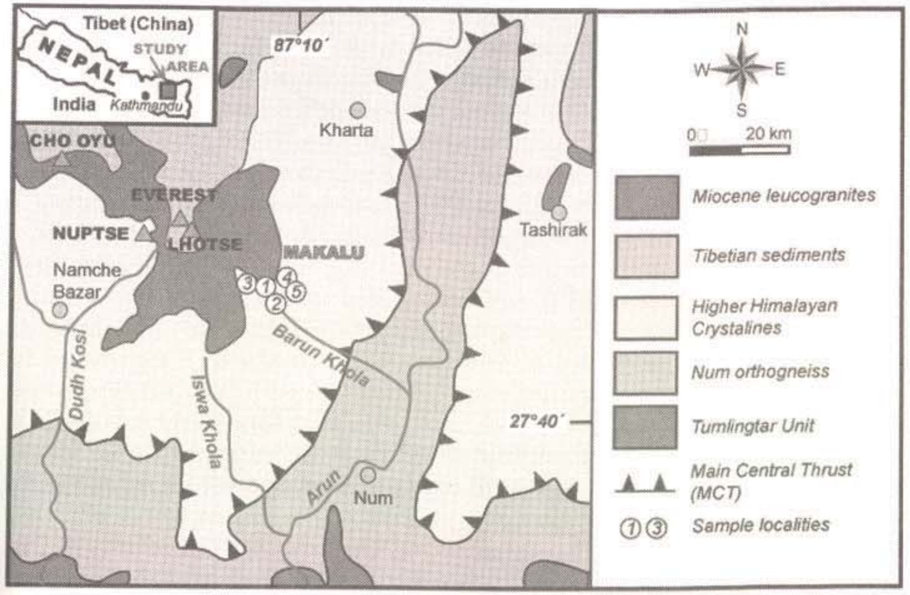

Fig. 2 Geological sketch map and sample locations (numbering of "①" in map is equal to MKFT1 in the text, ②~MKFT2, etc.) of studied area in the East Nepal Himalaya

The geomorphological observations on a decade scale suggest that the 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.

3. Fission-track dating of zircon and apatite

We have studied the low-temperature history of the crystalline units in the upper part of the Barun Valley (Photos 7 and 8) above the Main Central Thrust zone (Fig. 2). Zircon and apatite grains from the biotite-sillimanite paragneiss, migmatitic orthogneiss and glacifluvial sediments from the elevation of 4 600–5 000 m were examined through ^{238}U fission-track analysis. The major exhumation event related to denudation and uplifting processes in the Makalu area was recorded as follows (Fig. 3):

1) The fission-track zircon cooling ages for the migmatitic orthogneiss (sample MKFT4) and paragneiss (sample MKFT5) were 7.1 ± 1.0 Ma and 12.2 ± 1.0 Ma

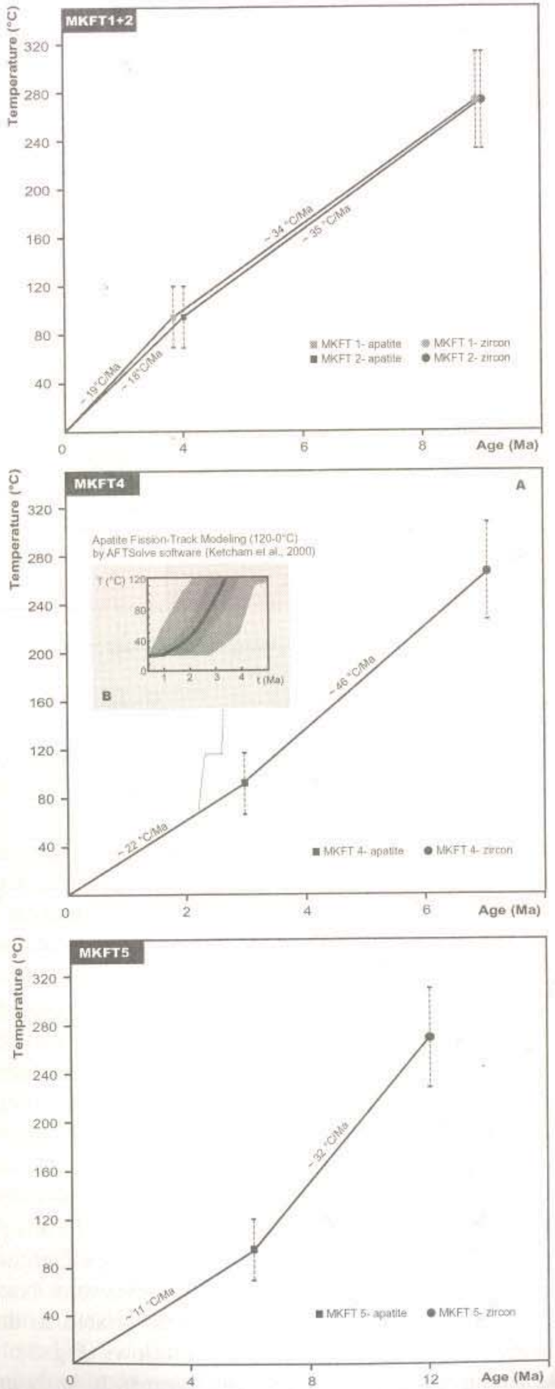

Fig. 3 A closure temperature vs. cooling age plot for the studied Makalu area samples

(1 sigma), respectively, interpreted as resulting from a steady slow cooling through the zircon partial annealing zone (PAZ) between 310–230 °C. The fission-track ages of zircons from the glacifluvial sediments (MKFT1 and 2, 9.0 ± 0.7 Ma and 9.2 ± 1.0 Ma, respectively) represent a mixture of the fission-track cooling ages of rocks exposed in the upper part of the Barun Valley (Svojtka et al., 2003).

2) The fission-track apatite cooling ages for migmatitic orthogneiss (sample MKFT4) and biotitic-sillimanite paragneiss (sample MKFT5) were determined as 3.2 ± 0.2 Ma and 6.6 ± 0.6 Ma, and the glacifluvial sediments yielded age 3.7 ± 0.5 Ma and 4.0 ± 0.5 Ma.

The estimate of an average cooling rate (Fig. 3) is based on the ratio of closure temperature to obtained ages. The apatite and zircon fission-track data sugest 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. After the relatively rapid cooling, the cooling rate for the migmatitic orthogneiss (sample MKFT4) and for the paragneiss (sample MKFT5) 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 by AFTSolve software (Ketcham et al., 2000) has shown that the migmatitic ortogneisses (sample MKFT4) cooled from the apatite partial annealing zone (PAZ, 60–120 °C) to 20 °C since ca 3.0 Ma. Since ca. 1 Ma ago temperature has not significantly changed.

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 time, which is caused by their orogenic uplift as well as global or regional changes of climate (Fielding, 1996` Willet et al., 1997) 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 humid (monsoon) periglacial and seasonally warm mountain zones. This phenomenon is in a 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. The paleogeographical consequence of these long-term differences is conspicuously deep penetration of erosion and denudation to rock massifs in regions of steep windward Tibetan-foreland transitions with the influence of humid air masses (Beaumont et al., 2001). The extreme activity of these climate-driven morphogenetic processes also stimulated an isostatic contribution to the uplift.

The apatite fission-track data documenting a rapid decrease of temperature from 120 °C (PAZ) to 20 °C in the gneisses already between 3.0–2.0 Ma suggest the existence of dissected mountain relief at that time which probably developed (in a substantially lower elevation above the sea level) during the Pliocene. The rapid decrease of temperature of the exhumed crystalline rocks can be an evidence for one of the substantial periods of rapid erosion and denudation of the paleorelief of the High Himalayan nappe which were stimulated by the integration of its tectonic uplift with the increasing intensity and range of exogenous geomorphological processes as a consequence of global climatic change.

4. Conclusions

The long-term interaction between the intensity of morphostructural processes, including the extent of the tectonic exhumation of deep-crustal rocks, and the changeable rates of denudation and outward flux of eroded material, is the key factor of chronodynamics of the rapid uplift in the Himalaya. The high intensity of recent denudation and transport of weathered and eroded material correlates with a striking absence of older Quaternary sediments. Climate fluctuations determine the short-term and rapid geomorphic response of the landscape. The dynamics of these climate-morphogenetic processes asserts the long-term denudation rates, which are driven by the active tectonic processes. The effectiveness of weathering and transport of its products increases with the frequency of alternations of glacial, periglacial and fluvial processes during the evolution of the mountain georelief.

Research grants and projects

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Photos 1–12 by Jan Kalvoda

Photo 1 Structural and tectonic differentiation of the High Himalayan relief between the lower part of the Barun glacier valley and the Chomolongma Massif. This part of the Barun valley lying at ca 3 000–4 000 m a.s.l. is incised into actinolite paragneisses and granulites of the High Himalayan crystalline nappe. Note the relics of the Pleistocene structural denudational level and one of the lateral hanging valleys (Kalvoda, 1992). To the left, on the horizon, there are the Massif of 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) and to the right, Peak 3 (6 825 m), the southern peak 8 010 m and the main peak of the Makalu (8 475 m)

Photo 2 Giant sculpture of the Makalu Massif (8 475m) is a dividing range between humid monsoon region and much drier mountains to the north. The northwestern wall of the Makalu consists of the Miocene leucocratic granite body and its injection zones into the Precambrian paragneisses. Leucogranites in the Mount Everest area were dated by Searle et al. (2003) at ca 21 Ma, north of Everest at 14 to 17 Ma, and Makalu leucogranite by Schärer (1984) ca 21–22 Ma

Photo 3 The uppermost part of the relatively broad depositional basin of the glaciers near the Chomo Lönzo (7 790 m) with steep rocky slopes and selectively weathered outcrops of the migmatite zone along the crests. Observations of steep rock slopes with cirques and hanging glaciers suggest that the main exogenic processes are rapid wind erosion and polishing of the rock surface, dry ice and firn fields and sharp weathering and exfoliation of crystalline rocks resulting in frequent rockfalls and avalanches

Photo 4 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 Solo Khumbu areas lies between 5 600–5 700 m. Note the features of recent stagnation of the glacier volume

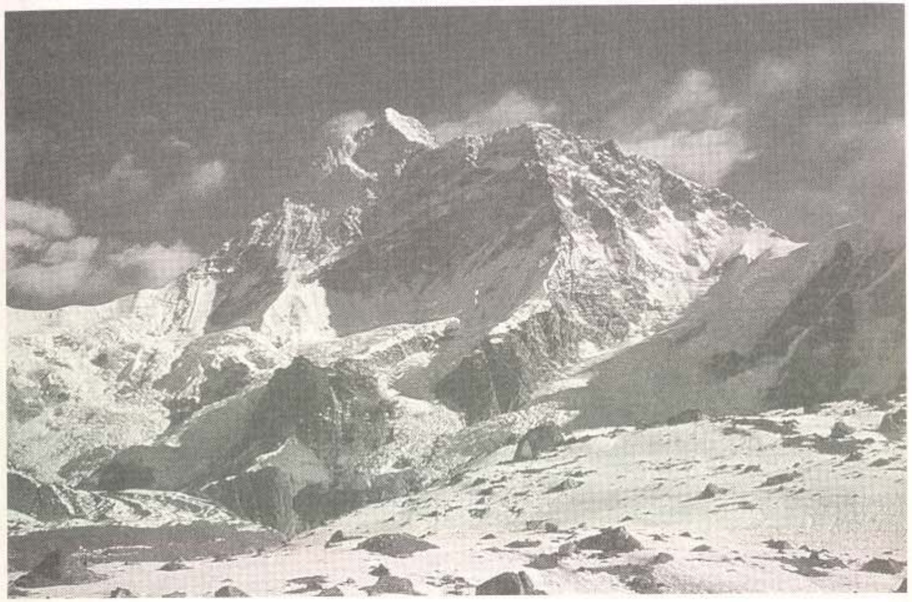
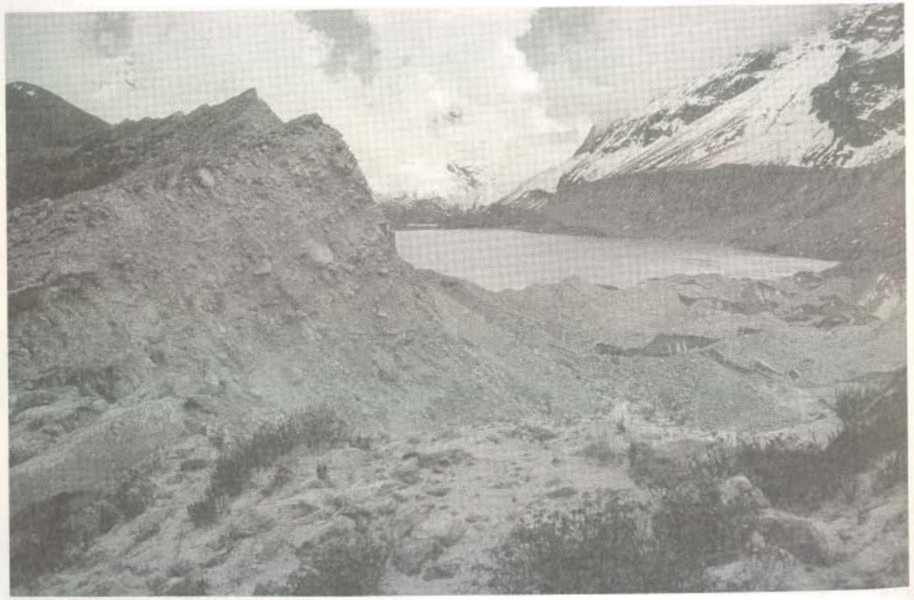


Photo 5 The southwestern side of the Makalu Massif (8 475 m) has its foot at altitudes of 4 900 to 5 000 m. Our observations have shown that conspicuous recent changes in the rock slopes pattern, and, especially, in the volume of ice masses accompanied by a recession of frontal parts of hanging glaciers, are only in the lower part of the walls

Photo 6 Strongly folded injected gneisses and migmatites of a block of debris rimming the nunatak in the middle part of the Chago valley (5 000 m a.s.l.)

Photo 7 Glacigenous relief of the western part of the Upper Barun glacier region north of the Peak 4 (6 720 m, on the left) with retreating side-glacier tongues and conspicuous Holocene and Subrecent lateral moraines

Photo 8 The upper Barun valley area with a step-like climate-morphogenetic zoning and conspicuous morphostructural patterns of the region. Dejection planes of rockfalls on extremely steep and high walls of crests built by crystalline rocks are displayed as well as fluvioglacial and lacustrine sediments or groups of moraines which can be correlated with equivalent landforms in the Mount Everest region. In the Solo Khumbu area Richards et al. (2000) dated these groups of moraines as results of three advances at 18–25 ka, 10 ka and 1–2 ka



Photos 9 and *10* The main Lower Barun glacier tongue is conspicuously changed and the decrease of its volume is accompanied by formation of a new lake dammed by a not very high recession moraines (*Photo 9* – 1973, *Photo 10* – 2002). These accumulation landforms are situated below slope glaciers and icefalls at the bottom of an earlier broad glacial valley

Photo 11 Observations of landforms in the lower periglacial zones of the Barun region and their recent changes support the concept that denudation and erosion of rock massifs is driven by continuing tectonic uplift. Rates of fluvial and soil erosion in a humid monsoon climate are extremely high especially in canyon--like areas of the valleys

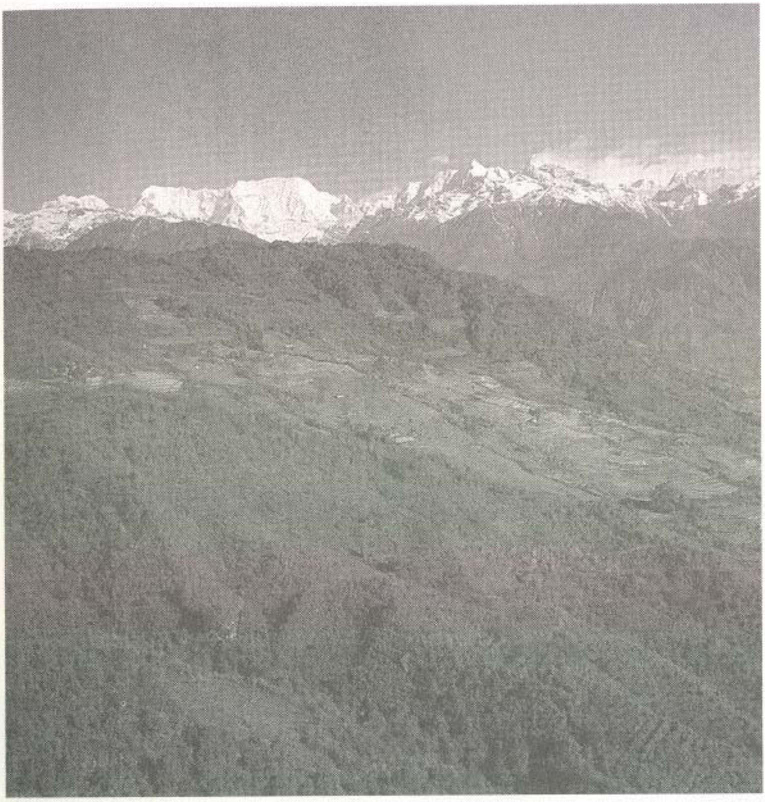


Photo 12 Erosion-denudational slopes of the Lesser Himalaya with a monsoonal evergreen forest, which is being intensively reshaped by burning and clearing. Note the morpho-structural barrier of the Main Central Thrust behind the Arun valley in the southern front of the High Himalaya