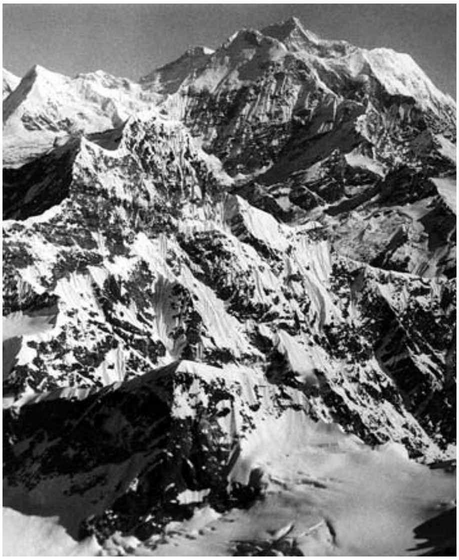
# The Dynamics of Geomorphic Evolution in the Makalu Barun Area of the Nepal Himalaya

Jan Kalvoda



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# 1. Introduction

## 1.1 Morphogenesis of the East Nepal Himalaya – a challenge and its topics

The landform evolution of the Himalayan mountain ranges is an instructive example of the extreme dynamics of geological and geomorphic processes in active orogenic zones of the earth's crust. A historical-genetic analysis of a set of landforms, relief features and Quaternary mountain sediments testifies to the integrity of orogenic and morphoclimatic processes in the forming of the present-day relief of the mountain ranges and also to the specific characters of the disintegration of the near-surface parts of their uplifted mountain massifs. The type, intensity and course of an orogeny in space and time are not only reflected in the structural geological and lithological records, but also in the record of the relief.

The Himalayan branch of the High Asian mountain ranges (*Fig. 1*) can be presented by several aspects of its Cenozoic development: (1) orogenic manifestations of the collision of the Indian and Asian continental plates, (2) the extent of the relief changes during the Quaternary, (3) the origin and morphostratigraphy of glaciation, (4) the high intensity of recent relief-building processes as a cause of extreme geomorphic hazards. In the present book concerning the Makalu Barun area in the East Nepal Himalaya (*Fig. 2*) the challenge of determining the landform evolution as the geomorphic record of active orogeny is integrated with a) analyses of landscape patterns and recent climate-morphogenetic processes, and b) evaluations of exhumation and erosion of rocks related to morphotectonic processes during the late Cenozoic Era (*Photograph 1*).

The Himalaya is regarded as the most perfectly developed continent-continent collision orogen with conspicuous geomorphic features of the active lithospheric plate tectonics (Molnar and Tapponier 1977; Gansser 1983; Valdiya 1998; Burbank 2005). Research on the geological structure and the landforms 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 (*Figs. 3* and *4*). 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. The endeavour to understand the causes and course of collisional orogeny, documented by its structural record (*Fig. 5*) as well as by the specific features and successions of the Himalayan landform evolution, provides a typical example of this complex approach.

The relief record is of particular significance in the Quaternary stage of the collisional orogeny where under suitable conditions the near-surface morphology of the geological structure can be studied in the present-day relief. Experimental measurements of the earth's surface movements in the Himalaya and their geodynamic interpretation (e.g. Bilham et al. 1997; Larson et al. 2000; Chen et al. 2002, 2010; Avouac 2003; Bilham 2004; Jouanne et al. 2004; Jordan and Watts 2005) are the prime source of information on recent geomorphic processes of endogenous, exogenous and anthropogenic origin. Most attention is focused on the interpretation of geological structure, geophysical and geodetic measurements with emphasis being placed especially on the complex of measuring methods which produce maximum precision. In the interpretations of present-day tectonic activity, the results of repeated instrumental measurement (e.g. of seismicity, heat flow, gravity fields, relief changes, etc.) have a different character from the explorations of landform evolution. The geomorphological identification of recent orogenic processes is based not only on field or laboratory considerations of the present-day state of landform patterns, but especially on the determination of morphogenetic processes acting over longer palaeogeographical periods (Seeber and Gornitz 1983; Iswata 1987; Kalvoda 1992; Bishop 2007). Substantial data are available on tectonic inclination and related deformation of river terraces or moraines, as well as on the development of fault slopes, intense downward and backward erosion, the morphological consequences of earthquakes and detection of rapid slope movements.

The structure of the book emphasises the principal intentions and themes of our long-term explorations in the Nepal Himalaya. In Chapter 1.2 the geomorphic patterns of the Himalaya in the Makalu Massif – Arun valley section are described. The following treatise in the second chapter deals with landform evolution in the Makalu Barun area (*Photograph 2*), namely in the extreme glacial and glacial areas, subsequently in the periglacial area and eventually in the seasonally cold / warm humid area. The third chapter concerns the dynamics, integrity and

**FIGURE 3** The Himalayan-type relief in Eastern Nepal is characterized by untamed landscape formed prevailingly by long-term orogenic uplifts and glacigenous, nival and cryogenic processes. In the background, behind the high-mountain ranges built of crystalline rocks of the High Himalaya slab, the Makalu Massif (8,475 m) is seen.

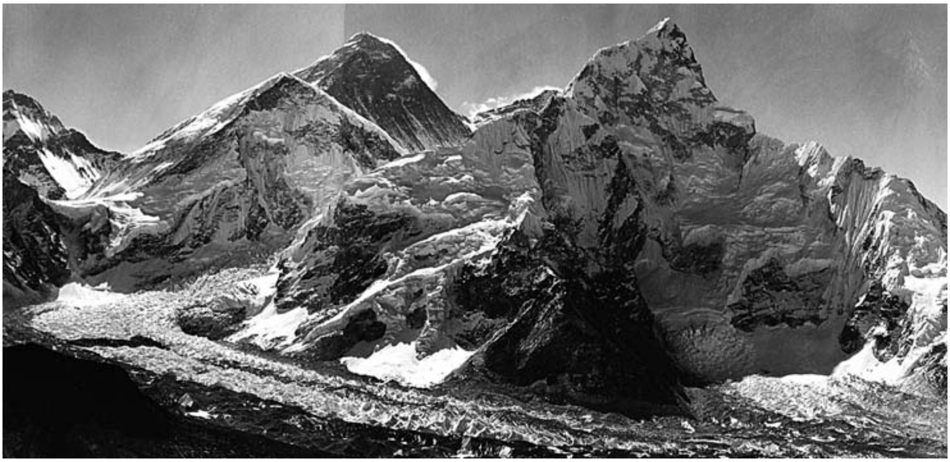

**FIGURE 4** Panoramic view of the Chomolongma Massif from the Pumo Ri crest (from left to right): the Lho La (6,006 m) with hanging-glacier steps, behind it the Changtse (7,550 m), the unnamed peak (7,205 m) above the Khumbu icefall, Sagarmatha (8,847 m), Southern Col (7,986 m), Lhotse (8,501 m) and the western Nuptse face, its foot being at 5,200 m a.s.l. Behind the northeastern Nuptse crest, above the icefall, occurs the Western Cwm valley and in the foreground the Khumbu Glacier is conspicuous.

variety of geomorphic processes, including natural hazards, which effectively operated during the mountain building phases of the East Nepal Himalaya. This chapter also provides a brief correlation related to the other Himalayan belts and their neighbouring High-Asian mountain ranges. This procedure allowed a concise expression of the concluding theses focused on a remarkable Himalayan landform evolution during the late Cenozoic and essential geomorphological consequences of the active continent-continent collisional orogeny continuing simultaneously with specific climate changes in the Nepal Himalaya as a whole.

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. It especially provides information on thrusting, folding and faulting in the near-surface elements of the lithosphere, or uplifting, erosion and denudation of its huge rock assemblages. The Himalaya and the neighbouring High Asian mountain ranges have become not only dynamic regions, which are rapidly evolving in consequence of intensive orogenic and climate-morphogenetic processes, but they also represent natural laboratories where new geodynamic concepts can be tested. For the sake of the Earth Sciences, one finds in the Himalaya, a rich source of data and research topics necessary for the further development of the general theory of orogeny.

## 1.2 Geomorphic patterns of the Himalaya in the Makalu Massif – Arun valley section

The Makalu Barun area is situated between the Khumbu Himal with the Chomolongma Massif (Mount Everest and/or Sagarmatha 8,848 m a.s.l.) and the Arun valley (1,350 m a.s.l.), in the morphotectonically conspicuous zone of the High Himalayan nappes (Bordet 1961; Jaroš and Kalvoda 1978a, b). The vertical hierarchy of variable high-mountain reliefs is striking (*Figs. 6* and *7*), and ranges from the extremely cold arête ridges of the Makalu Massif (8,475 m), through the heavily glaciated and periglacial areas, to the seasonally cold/warm

**FIGURE 6** Group of the Upper Holocene to modern frontal moraines of the Lhotse Nup glacier formed in the Imja valley. Above the strongly weathered paragneisses and migmatite crests of the alpine-type (arête) relief, the 3,000 to 3,200 m high southern faces of the Lhotse (8,501 m) and Lhotse Shar (8,383 m) with granites and pelitic series are exposed.

**FIGURE 7** The structural denudational slopes of the tectonic Arun half-window with a monsoonal evergreen mountain forest in the vicinity of the village of Sekaha are reshaped by forest burning, clearing and agricultural terrace fields up to altitudes of 3,200 m. The photograph of landscape patterns was taken in the year 1973. In the background, steep structural slopes of the Main Central Thrust and the High Himalaya ranges are seen.

humid area of lower Barun Khola and Arun valleys (*Fig. 8*). Distinctive vertical climatic zonation also 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 area suggest extremely high rates of denudation, sediment transfer and deposition (*Figs. 9* and *10*).

The nature of the Makalu Barun area has been studied since the middle of the 20th Century and has mainly focused on (a) geology and geophysics (e.g. Bordet and Latreille 1955a, b; Bordet 1961, 1970, 1977; Ishida 1969; Brunel and Hamet 1976; Jaroš and Kalvoda 1976, 1978a, b; Maruo and Kizaki 1981, 1983; Palivcová et al. 1982; Schärer 1984; Schärer 1986; Brunel and Kienast 1986; Lombardo et al. 1988; Hubbard 1989; Hubbard and Harrison 1989; Hubbard et al. 1996;

Yagi and Minaki 1991; Lombardo et al. 1993; Meier and Hiltner 1993; Colombo et al. 1995; Lombardo and Bortolami 1998; Lombardo and Rolfo 2000; Searle et al. 2002, 2006; Visona and Lombardo 2002; Svojtka et al. 2003; Cottle 2007; Cottle et al. 2007, 2009; Groppo et al. 2007, 2010, 2012; Corrie et al. 2010); and (b) geomorphology (Kalvoda 1978, 1979a, b, 1982a, b, c, 1984a, b, 1992, 2004, 2007; Kalvoda and Valenta 1997; Karki and Koirala 1997; Kalvoda et al. 2004; Kuhle 2004, 2005; Wagnon et al. 2013); and c) biology and geoecology

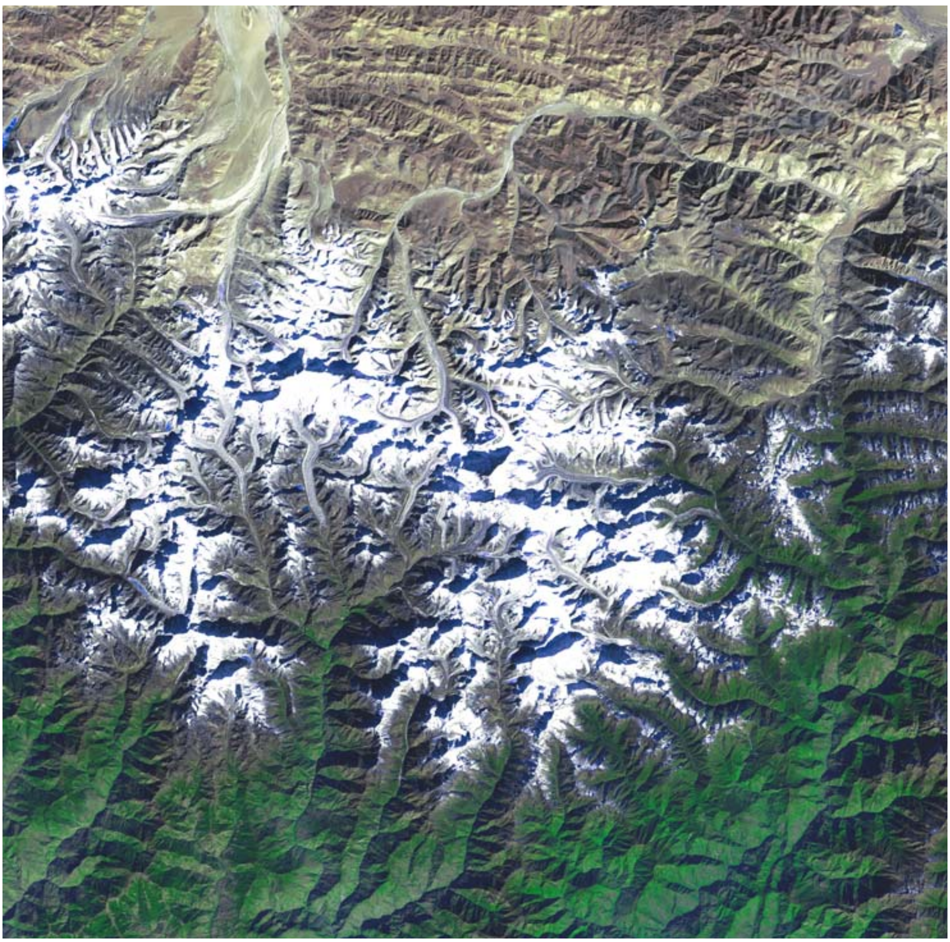

**FIGURE 8** Conspicuous geodiversity and biodiversity of the landscape in the Nepal and Tibetan Himalaya recorded by satellite image on 5$^{th}$ January 2002 by Landsat (2002). The High Himalaya range between the Cho Oyu, Chomolongma and Makalu Massifs (from the west to the east) with extensive glaciation is situated in central part of the image. Tibetan semi-arid landscape in the north and Nepalese humid monsoonal landscape in the south of the High Himalaya are very striking.

# 3. Dynamics and integrity of geomorphic processes in the Nepal Himalaya

## 3.1 Mountain building during the collisional orogeny

Knowledge of the landform evolution in the Makalu Barun area, which is one of the most active areas of the Indian and Asian continental plates collision, can be achieved only in the context of the palaeogeographic history of the Himalayan orogen as a whole. This procedure simultaneously allows integration of the geomorphological research in the East Nepal Himalaya (*Figs. 112* and *107*) to determination of regularities in the integrity and the feed-backs of orogenic and climate-morphogenetic processes during the continent-continent collision. The evidence for timing and progress of this collision of continents comes from ocean-floor magnetic anomalies, paleomagnetic measurements on both continents, biostratigraphy based on faunal correlations and sediment dating and also from a series of geochronological measurements along the Himalayan mountain ranges.

The complex evidence suggests that the active orogeny of the Nepal Himalaya (*Photographs 81* and *82*) represents the youngest stage in the evolution of the Alpine-Himalayan belt which was initiated in the Upper Palaeozoic. After the split of the Pangean continent, when the Palaeo-Tethyan Ocean arose between Eurasia and Gondwana during the Mesozoic, the Neotethyan oceanic basin came into being following the divergence of the lithospheric plates of the Gondwana continent (Gansser 1964, 1983; Hashimoto et al. 1973; Le Fort 1975; Molnar and Tapponier 1977). There then followed the successive closure of the oceanic basins caused by the northward drift of the Gondwanan fragments. The Tibetan plate contributed to the closing of the Palaeotethys during the Upper Triassic. Since the Cretaceous, the Atlantic and the Indian Oceans have come into existence as a result of the splitting of the Laurasian continent. With the opening of these oceans the divergent movements of the Afro-Arabian, Indian and Eurasian plates changed into convergent ones (Valdiya 1998; Zhu et al. 2005, 2013; Bollinger et al. 2006). The peri-Tethyan margins of the continents were activated tectonically, since the convergence of the plates was accompanied by the subduction of the oceanic lithosphere and the closing of the Neotethys.

In the Himalayan region the Neotethys had been opening since the Permo-Triassic for tens of millions of years. During the Upper Cretaceous, the Indian subcontinent, which had split from Gondwana began to move northward, closing the adjacent parts of the Neotethys (Valdiya 1980; Gansser 1983; Jordan and Watts 2005). The subduction stage of the orogeny culminated in the Alpine-Himalayan belt with the infilling of the Tethyan Ocean and the obduction of ophiolite nappes while the ophiolite sutures were forming. These became the structural boundaries of the Himalayan region in the sense that its western and eastern syntaxial bends link up with the Quetta ophiolite suture, the Owen-Murray fault zone and – via the Arakan Yoma ophiolite suture, with the major fault zone at 90° E in the Indian Ocean.

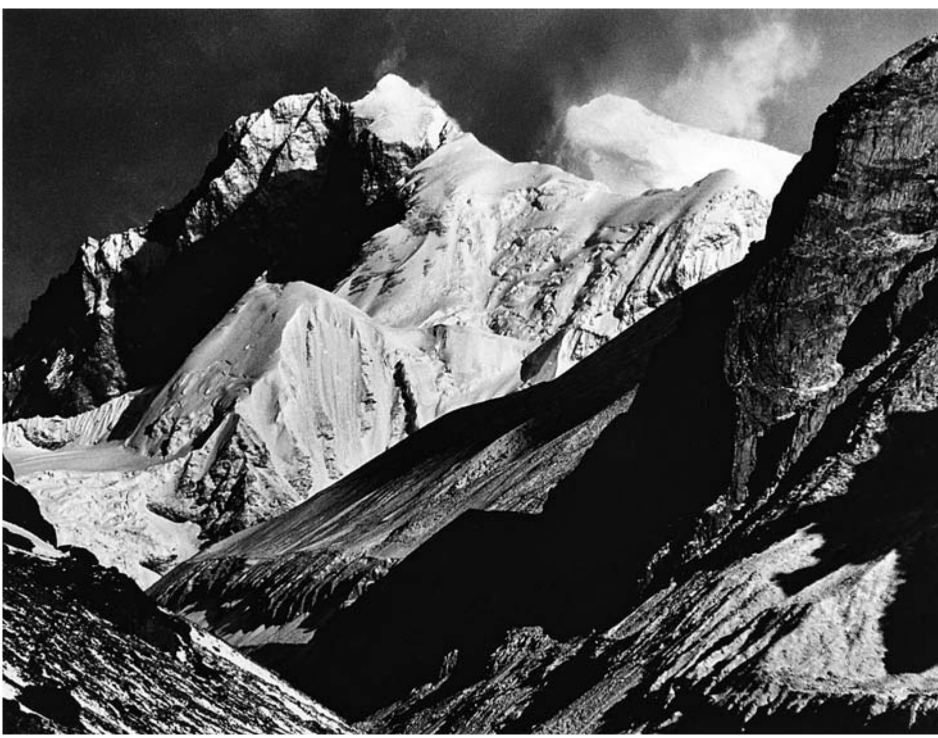

**FIGURE 112** Southeastern front of the Chomolongma Massif near the upper part of the Barun valley. The steep cliffs behind the Cho Polu ice dome (6,734 m) rise up to the Lhotse and Lhotse Shar peaks and pass into the crest of unnamed peaks with heights 7,596 and 7,502 m. Clouds and snow hide the catchment area of the Kangshung glacier situated below the eastern face of the Sagarmatha (8,847 m, compare Figure 16).

In the Karakoram region (*Photograph 83*), submarine volcanism was active from the Lower to the Upper Cretaceous, and Permian to Lower Cretaceous blocks were incorporated into flysch formations (Desio 1974, 1979; Shroder and Bishop 2000). In the south of the Karakoram, the first sedimentation interval had probably already taken place in the Upper Cretaceous. The molasse sedimentation in the southern Himalayan foredeep and in the zone between the southern part of the Tibetan Plateau and the Himalaya, lasted from the Lower Miocene to the Lower Pleistocene.

The northernmost zone of sedimentation of the Himalayan region is formed from the ophiolite zone with pelagic sediments and the flysch of Jurassic to Cretaceous age (*Photograph 84*). This zone represents the Tethyan oceanic basin which had already completely disappeared; the Indus suture is its conspicuous relict. South of this ophiolite zone one finds the sedimentary formation of the Tibetan Himalaya, which contains up to a 6,000 m thickness of Palaeozoic sequences, and Triassic to Eocene limestones, shales and sandstones about 4,000 m in thickness (Bordet 1961; Gansser 1964; Colchen et al. 1986; Clift 2002). The Precambrian basement, exposed by large-scale erosion in the Karakoram (*Photograph 85*), had already formed an elevated area since the Lower Palaeozoic, separating the northern Tethyan oceanic basin from the southern Himalayan basins where sedimentation continued until the Mesozoic. The rock sequences of the Lesser and High Himalaya at that time, therefore, represent the foreland of the Tethyan oceanic basin. During the Eocene and Lower Miocene the sea transgressed the region of the Lesser Himalaya prior to deposition of the Upper Miocene terrestrial molasse of the Siwaliks in the Himalayan foredeep (Hagen 1969; Hashimoto et al. 1973; France-Lanord et al. 1993; Yin 2006).

During the Neogene phase of the Himalayan orogeny, a considerable part of the Neotethyan oceanic basin was destroyed by the subduction of the northern margin of the Indian plate under the Tibetan part of the Asian continent. The scar of the structural suture, represented, for example, between the Himalaya and the Karakoram by the morphostructural pattern of the upper Indus valley, indicates the palaeo-surface of the collision zone between these continental plates. The northern belt of Cretaceous to Eocene, flysch sediments and basic submarine igneous rocks were partly displaced onto the autochthonous foreland of the Transhimalaya (Mu et al. 1973; Gansser 1983; Hodges 2000; Wang et al. 2002). The initial collision of the continental margin is interpreted to have been asynchronous because the base of these molasse sediments in the western part of the Himalayan region is of Upper Cretaceous age, while in the eastern part it is of Upper Oligocene age.

The subduction stage transitioned gradually after the Upper Cretaceous into the stage of collision orogeny, and by the close of the Miocene the margins of the both continental plates underwent intense tectonic deformation (Harrison et al. 1997; Carosi et al. 1998; Catlos et al. 2001; Zeitler et al. 2001). During the oceanic subduction stage of the Himalayan orogeny, erosional denudation of the palaeosurfaces of the continental plates took place, and material produced by the erosion was deposited on both continental margins of the gradually disappearing Neotethyan oceanic basin. The following phase of the Himalayan orogeny had significant geomorphic consequences because as a result of the shallowing of the oceanic basin the primary ridges emerged. During the initial collision contact of the Indian and Asian continents, the oceanic basin between them gradually closed. Its volume was substantially reduced not only tectonically, but also by the extensive sedimentation of clastic fluvial and lacustrine molasses (Bordet 1956, 1970; Valdiya 1980; Einsele et al. 1996; Curray et al. 2003, Yin 2006). A phase of progressive uplift occurred that caused this stage of molasse sedimentation.

The areal extent of the Indian subcontinent, inclusive of the shelf to a depth of almost 2,000 m, is estimated at 5.2 million $km^2$. It is assumed that a further part of the Indian plate of about 2.4 million $km^2$ in area is subducted under the Tibetan Plateau in the Himalayan orogenic zone (Molnar and Wang-Ping 1978; Watts 2001; Searle and Treolar 2019). Seismic investigations in Tibet have shown that the thickness of the earth's crust exceeds 80 km. On the other hand, the spreading process in the Indian Ocean represents an enormous increment in the area of the sea floor and produced pronounced changes to both the types and dissection of the sea-floor topography. The earliest stage in the spreading in the Indian Ocean coincides with the onset of the northward drift of the Indian plate some 130 million years ago, while a further one occurred 80 million years ago, i.e. probably coincident with the first collision contact of the eastern part of the Indian plate with the Asian continent (Molnar and Tapponier 1977; Zeitler 2001; Bollinger et al. 2006). These correlations, as well as that of the interval of relatively slower spreading between the intensive stages 53 and 32 million years ago, that coincides with the high continent–continent collisional activity during the Eocene and Oligocene, indicate a direct relationship between the spreading processes in the Indian Ocean, the movements of the continental plates and the orogenic phases in the Himalayan region.

The data on the spreading in the Indian Ocean indicate that during the Cenozoic the northward drift of India continued for a distance of *ca* 1,500 km. During the collision of the Asian and Indian continental plates, this movement could only be compensated by deformation in their contact zone and in the central areas of the continents (Burchfiel et al. 1992; Hodges 2000; Jiménez-Munt et al. 2008). The convergence was accommodated by: (1) the Oligocene and later orogenic processes on the Indian continental plate, (2) lateral movements of the interior Asian plate for distances of hundreds of kilometres, (3) deviations of movement of the plates from the main trend of their collision, and (4) differential uplift and subsidence of evolving orographic units along the Himalayan orogen

# A photographic atlas of landforms in the Makalu Barun area of the Nepal Himalaya

**PHOTOGRAPH 1** A reflection of sunset rays on the summit granites of the Makalu Massif (8,475 m) and its northwestern face raised above glaciated part of the Chago and Upper Barun valleys.

**PHOTOGRAPH 2** Landform patterns of the High Himalaya evolved between the Chomolongma Massif and the middle part of the Barun Khola valley. The canyon-like valley between *ca* 3,000–4,000 m a.s.l. is incised into paragneisses and granulites. On the horizon, remarkable mountain massifs in the extreme glacial region are conspicuous (from to the left to the right): the Peak 4 (6,720 m), Nuptse (7,879 m), Lhotse (8,501 m), Lhotse Shar (8,383 m), Sagarmatha (8,847 m) and Peak 3 (6,825 m).

**PHOTOGRAPH 3** Crest of the ice-free nunatak in the upper basin of the Barun glacier (*ca* 6,000 m a.s.l.) is situated close to the main ridge of the Himalaya. In the background, icefalls at strongly glaciated eastern walls of the Baruntse Massif (7,200 m) are seen.