Geoenvironmental Disaster Reduction

Jan Kalvoda
Eva Novotná *Editors*

The Nature of Geomorphological Hazards in the Nepal Himalaya

Springer

Geoenvironmental Disaster Reduction

Series Editors

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2. Combine international expertise and coordinate their efforts in geo-disaster reduction, thereby resulting in an effective international organization which will act as a partner in various projects; and
3. Promote regional and global, multidisciplinary activity on geo-disaster reduction.

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Editors

The Nature of Geomorphological Hazards in the Nepal Himalaya

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Remarkable geomorphic hazards in the Chomolongma Massif are emphasised by varied patterns of mass movements on the crystalline-rocks landforms developed in extremely cold and semi-arid morphoclimatic conditions. View of the Mount Everest from the western crest of Nuptse appears the unnamed peak (7205 m a.s.l.) above the Khumbu icefall, Sagarmatha (8847 m) with its southern face, Southern Col (7986 m) and Lhotse (8501 m) raised above the Western Cwm valley of morphostructural and glacial origin. *Photograph by* Jan Kalvoda

Series Editors' Foreword

The following book entitled *The Nature of Geomorphological Hazards in the Nepal Himalaya* (Jan Kalvoda and Eva Novotná, eds.) is published in the framework of the new book series entitled "Geoenvironmental Disasters Reduction", under the umbrella of the International Consortium on Geo-disaster Reduction (ICGdR) and UNESCO Chair on Geoenvironmental Disaster Reduction (the Chair). Over the past few decades, various types of geo-disasters have frequently occurred around the world, triggered by tropical cyclones, landslides, earthquakes, floods, tsunamis and volcanic eruptions. These disasters have caused huge damage to infrastructure, the natural environment, and a great loss of human life and property. As disasters are serious threats to human society, the reduction of geo-disasters has become an urgent and critical issue for the protection of human life and economic development. This is why we decided to create a new book series, to support risk reduction and disaster management.

ICGdR and the Chair plan to publish books that are either regionally or process-oriented and based on basic and/or applied research, which reflect current geo-disaster events and trends worldwide, and those that are based on systematic research in the selected areas, and which will increase the level of research knowledge. The book series is focused on deepening the theoretical basis, and the synthesis of data, which can lead to proper disaster reduction in the future.

The presented book is an example of a regionally focused work, which covers one of the crucial topics from high-mountain regions of Asia, where current geomorphological processes determine environmental changes and hazard processes with a strong influence on human society. Global changes are now investigated from various perspectives worldwide, and in this book, the complex relationships between active orogenic processes and climate changes are considered.

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Preface

The mountains of High Asia are areas with very diverse geomorphological processes whose dynamics and interactions are a constant source of dangerous natural hazards and disastrous events. One of the aims of our research conducted in the Nepal Himalaya was to contribute to the identification, recognition, and discussion of the main issues of regional assessment of hazard processes in the high-mountain environment, considering the potentials and limits of human society. Monitoring current morphogenetic processes in the Himalaya makes it possible to determine the intensity and key drivers of environmental changes and various natural hazards that have been dampening societal development over the long term.

Changes in the mountain landforms are testimony to the nature of their long-term evolution. Let us note as well that the time of researching the Himalaya also offers to dive into the depths of our planet. The walls of the Himalayan peaks enable us to look deeper and much better into the rock structures of the Earth's crust than would the diamond cores of drilling rigs in deep boreholes. Studying these phenomena then leads to recognition of the morphogenetic manifestations of the planetary regularities of natural processes and events. These regularities can be called the spirit and cradle of the Earth's surface, where the destinies of humankind take place, too. By systematical research of (not only) Himalayan structures, their rock and shape details, and thus their palaeogeographical history, we make our way to an inkling of the main features of the laws of nature.

For the current development of society in the high-mountain regions of Asia, research into natural hazards and risks is an important task, which is carried out in collaboration among the geographical, geological, and geophysical disciplines. The comprehensive approaches are essential for forecasting and predicting extreme natural processes and phenomena, which makes it possible to understand the evolution of landforms at different spatial and temporal scales. A substantial part of this research work consists of diagnosing hazardous geomorphological processes and recognising the impacts of regional environmental changes on the evolution of georelief.

Geomorphology is one of the traditional branches of Earth sciences that deal with the palaeogeographic evolution of the natural environment in the Quaternary. During this period of the planet's history, the present landscape structures and types were formed by the synergistic action of orogenetic and climate-morphogenetic processes. Research into the geomorphological record of changes in the natural environment in the late Cenozoic and the intensity of the recent landform processes make it possible to determine the dynamics of the landform evolution. The Earth's surface is a complex dynamic system whose parts were formed in different geological periods and paleogeographic conditions. Therefore, evolutionary geomorphology uses data on sets of landforms of varied genesis and age to reconstruct palaeogeographic conditions.

Geomorphological hazards are part of a larger group of natural hazards, including for instance floods, soil or water quality degradation due to climate change, desertification, wildfires and sudden weather events. Natural hazard studies in the high-mountain regions are also essential for a better understanding of ecosystem protection and the relationship between the environment and human health. The protection of people from natural risks in high mountains requires an understanding of the nature of hazardous phenomena. Research into geomorphic hazards in high-mountain regions could be understood not only as a set of case studies but, first, as a rare opportunity for the preparation of theoretical models and for the understanding of origin of natural disasters. It is also important to estimate the range of the effects of anthropogenous activities on the rate of natural geodynamic processes.

Research work in the high mountains is currently carried out about comprehensive research of the natural environment, using available palaeogeographic knowledge and experimental data, especially in relation to the Quaternary history and to contemporary changes in the landscape of the areas under study. At the same time, the integration of geodetic, geophysical and geological measurements and observations with detailed geomorphological research on landform assemblages gradually take place in selected orogenetically active and climate-exposed areas. Currently, interdisciplinary research teams with a long-term focus on the interpretation, correlation and synthesis of measurements and monitoring of recent geodynamic phenomena are being formed, with the intention to understand the dynamics of changes in the natural environment at local, regional and global scales. Physical-geographical and geomorphological surveys, which are part of these multidisciplinary research and applied projects, contribute substantially to these trends of studying the dynamics of natural systems. An example of the current use of multidisciplinary work is advances in diagnosing natural hazards and risks and predicting catastrophic events and phenomena in the High Asia mountain ranges.

Physical-geographical explorations of the High Asia mountains are a part of research activities performed by geomorphological teams of the Faculty of Science at the Charles University in Prague. Main research themes are focused on dynamic and evolutional geomorphology, landform development in the Quaternary, geodynamic and geomorphic aspects of the theory of orogenesis and regional physical geography. In this respect, we especially examined variable phenomena of morphotectonic activity, slope movements and related rapid geomorphic processes during the late Quaternary landform evolution of the Bohemian Massif, Western Carpathians and Alps, as well as in the Balkans, Asia Minor, Tian Shan, Pamirs, Karakoram and the Himalaya. During these explorations, field documentation, experimental data and their interpretation were obtained as a contribution to themes concerning (1) morphostratigraphy of glacial, periglacial and fluvial geomorphic phenomena focused on the palaeoenvironmental changes in the Quaternary; (2) multiform integrity of orogenic and climate-morphogenetic processes during the late Cenozoic; (3) geodynamic aspects of measurements of the Earth's surface movements; and (4) natural hazards, risks and disasters. Our modest effort is associated with long-term international cooperation, which is also indicated by varied contents of the presented book concerning the nature of the Nepal Himalaya.

This book provides a flavour of the large range of studies that have been undertaken to aid in the understanding of geomorphological hazards in the Nepal Himalaya. In accordance with the diversity of the natural environment of the Himalaya, the authors were given maximum freedom in choosing the concept and structure of individual chapters. The relevant thematic blocks are focused both on the Nepalese Himalayas as a whole and on specific topics in selected areas of Nepal. This freedom in the systemic concept of the entire publication corresponds to the methodological, terrain and interpretive diversity of the authors' approach to the unique high-mountain nature and at the same time to the creative solution to the issue of geomorphological hazards in the Himalaya.

The introduction to the book (Chap. 1) presents the diverse natural environments of Nepal. Furthermore, there are also descriptions of the methodological advances in the research of the high-altitude environment of Nepal and their global trends. The next chapter (Chap. 2) is devoted to the collisional orogenesis of the Nepal Himalaya and findings on the evolution of its landforms in the Quaternary, including the geomorphological record of active orogeny and the extraordinary effects of climate-morphogenetic processes. Chapter 3 provides an overview of the historical cartographic representation of the Himalaya, analysing twenty old maps and presenting their examples with illustrations. Chapter 4 briefly describes and discusses some changes in the perception of natural hazards and disasters by the inhabitants of the Himalaya. The following chapter (Chap. 5) is devoted to an analysis of the main natural hazards, risks and disasters in Nepal through the bibliometric analysis of the WoS database and the specialised natural disaster databases called DesInventar and EM-DSAT.

EIGEN 6C4, the gravity model of the Earth, is used in Chap. 6 to determine the distribution of mass in the near-surface part of the Earth's crust of the Nepal Himalaya, as evidenced by the extent of tectonic uplift and severe erosion. The visualisation and analysis of selected components of the high-mountain landscape through the Earth remote sensing techniques in Chap. 7 enabled the identification of moraine-covered and therefore potentially hazardous glacial lakes for outburst in Nepal. The following four chapters are interdisciplinary case studies concerning former and present-day geomorphic hazards (Chaps. 8 and 9) and an urgent complex of related biogeographical and natural hazards (Chaps. 10 and 11) in the Nepal Himalaya.

Comprehensive methodological Chap. 12 describes and assesses the current state of research on geomorphological hazards in the Nepal Himalaya, including an explanation of the current reactions of the Nepalese government, academic institutions, and international agencies to serious natural hazards. The final part of the book highlights the specific features and complex effects of geomorphological hazards and disasters on the natural environment, as well as the nonlinear properties of the dynamics of natural hazards in the Nepal Himalaya.

Physical geography and geomorphology have now become a prominent focus of research for those concerned with how the Earth system works. Geomorphology exploits valuable records that can be used to enhance the knowledge of Earth surface processes and fundamental linkages between Earth system components. In an effort to assess the effects of environmental change on geomorphic phenomena, increased attention has been given to landform assemblages and landscapes, implying varied spatial and temporal scales. Almost all scales of space and time are necessary to analyse both long-term and rapid geomorphological hazards as well as related natural disasters.

The endeavour of understanding natural hazards in the mountain environments can be recognised by looking at the number of geo-disasters that have affected High-Asian Mountain societies. The nature and magnitude of feedback between orogenetic processes and climate changes in the Himalayan region are now explored in many different contexts of Earth science. Geomorphological hazards in the Nepal Himalaya are considered as essential and complex phenomena of multi-causal origin, operating within the dynamic environment of the coupled natural system and human society.

Prague, Czech Republic
September 2023

Jan Kalvoda
Eva Novotná

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Editors and Contributors

About the Editors

Jan Kalvoda is professor of Physical Geography at Charles University in Prague. During mountaineering and scientific expeditions, he examined Quaternary landform evolution and recent morphogenetic processes in the Himalaya, Karakoram, Pamirs and Tien Shan, as well as in the Asia Minor and Balkans. He published a series of papers and books aimed at (a) georelief development and recent geodynamics in the Bohemian Massif and the Carpathian System, (b) geomorphological record of the Late Cenozoic orogeny in the Asian mountain ranges. The results are a contribution to knowledge of the Alpine-Himalayan orogen and to the geomorphic evidence of the dynamics of the near-surface part of the Earth's crust. His current research activities are focused 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. He is member of the Editorial Board "Geomorphology" (Elsevier) and the Quaternary Palaeoenvironments Group (University of Cambridge, UK).

Eva Novotná graduated from the Institute of Information Studies and Librarianship at the Faculty of Arts of Charles University in Prague and from the History-Law Department and Pedagogy at the Catholic Theological Faculty of Charles University. She completed her doctoral studies at the Institute of Information Studies of Charles University (2021) with doctoral thesis on the Cartographic Cultural Heritage. She is head of the Library of Geography and director of the Map Collection of the Faculty of Science of Charles University. The historical Map Collection Hall underwent recent reconstruction under her leadership. She is author of a number of research articles, special exhibitions, catalogues and books. She also implemented projects related to the creation of expert databases: the Christian Name Authority Database, the Czech Geographical Bibliography Online, the Digital Map Collections, veduty.cz and the Database of the Digitised Map Collections. Currently, she deals namely with the historical-geographical aspects of ancient cartographic works.

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Introduction

1

Jan Kalvoda, Adam Emmer and Tereza Steklá

Abstract

Specialized topics of this book on geomorphological hazards and related natural phenomena are introduced by a brief description of the diverse environment of the Nepal Himalaya. The physical-geographical features of Nepal are explained through its geological and orographical arrangement and an overview of climatic conditions and hydrological as well as biogeographical phenomena adapted to it. Furthermore, the methodological aspects of the research of the high mountain environment are discussed in relation to the progress in the knowledge of geomorphological hazards in the Nepal Himalaya.

Keyword

The natural environment · Physical geography · Geomorphological hazards · Nepal Himalaya

1.1 The Varied Natural Environment of the Nepal Himalaya

1.1.1 Dynamics of Geomorphic Processes Related to Natural Hazards

The Indian subcontinent is connected to the central part of Asia by the highest mountains of our planet. The dazzling white ridges and peaks of the Himalaya and Karakoram are dissected by canyons and deeply eroded valleys, which hide glacial lobes, numerous lakes and raging rivers heading south to the Indian Ocean. The Himalaya is a 2400 km long and 220–330 km wide mountain range, slightly curved towards the south. Its western and eastern endings are syntaxial bends that follow on major geological structures in the ocean. The Himalaya ends in the west with the ophiolite belt of Quetta, which follows on the Owen fault zone, and in the east with the ophiolite belt of Arakan-Yoma connected to the oceanic ridge of the 90° meridian

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(Gansser 1964; Molnar and Tapponier 1977). The Indo-Gangetic Plain borders the Himalaya to the south. It represents the Holocene evolution stage of the Molasse foredeep (Jaroš 1980; Valdiya 1998) whose older upper Miocene to Pleistocene stage is morpho-structurally distinct in the folded Siwalik molasse as foothills of the massive Himalayan arch. The Indus-Tsangpo ophiolite structure with a rudimentary retroarc molasse is most frequently considered to be the northern boundary of the Himalaya.

A remarkable feature of the present-day research on the Himalaya and its neighbouring regions are the attempts to reach an understanding of the evolution of their environment during the Quaternary. The challenge also remains to determining the landform evolution in the Nepal Himalaya in which the geomorphological record of active continent–continent collisional orogeny is integrated with changes of climate-morphogenetic processes (Kalvoda 1992, 2020). In the Nepal Himalaya, giant ridges alternate with canyon-shaped valleys (Fig. 1.1) and intramountain basins infilled by deposits that can be deciphered to reveal the way landforms have evolved in the recent past under the influence of orogenic and climate-morphogenetic processes. Very high rates of tectonic uplift and seismicity (Iswata 1987; Bilham 2004, 2019), extreme monsoon precipitation promote glacier and river incision, large landslides and related mass movements (Fig. 1.2), a major source of sediment and the potential cause of valley blockage and catastrophic flooding.

The evidence and extent of the present-day orogenic activity (see Chap. 2), 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 dynamics of geomorphic processes in the Nepal Himalaya show that glacial, periglacial, and fluvial processes are very effective at destroying the rock assemblages exhumed and uplifted during the Quaternary stage of the collisional orogeny. The exhumation of the High Himalayan slab was enhanced by the rapidly incising rivers and by focused monsoon precipitation acting on the southern side of the evolving Himalayan belt. 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 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 building in the Nepal Himalaya.

Geomorphological hazard is defined as the probability that a certain phenomenon, reflecting georelief instability, will occur in a certain territory in a given period of time (Panizza 1986). The probability that economic and social consequences of a particular phenomenon reflecting landform instability will exceed a determined threshold is stated as geomorphological risk. The degree of risk present in each area is a function of both the type of hazard and the vulnerability of the area and people. High mountain areas are among the regions where natural disasters with high risk are most frequent. The protection of people from natural risks in high mountain areas requires an understanding of the nature of hazards phenomena. Research into geomorphological hazards in the high mountains can also be viewed as a rare opportunity for the preparation of theoretical models and for understanding the general architecture of the origin of natural disasters (Kalvoda and Rosenfeld 1998). Regarding the defined topics and regional focus of this book, we will first outline the basic features of varied natural environment in the Nepal Himalaya.

1.1.2 Geological and Orographical Division of Nepal

The geological features of Nepal have been created predominantly by the collision of the Indian and Eurasian plates, which has taken

Fig. 1.1 Northern ridges and the main summit of Makalu (8475 m) rising above the Chago Peak (6840 m) with hanging glaciers which stagnate due to extremely cold but semi-arid climatic conditions. *Photograph* by Jan Kalvoda

place since the Cretaceous and has formed the mountain range of Himalaya. Nevertheless, the oldest rocks of the region, which belong to the Lesser Himalayan Gneissic Basement, were stabilised around 2000 Ma years ago as a part of the Bundelkhand craton, i.e. the northern part of Indian shield (Sharma 1998). These Proterozoic sequences later formed a basal part of the rift-related Tethys basin. The subsequent continuous sedimentation on the northern continental margin of the Indian craton created an extensive sedimentary prism (Valdiya 1984), that suffered compression and deformation during the convergence and collision of the Indian and Eurasian plates (Fig. 1.3).

In the most mountain ranges of the Alpine-Himalayan belt, the structural record of the collision orogeny is superimposed onto an earlier structural record related to oceanic subduction. The collision of continental plates is associated with the origin of the nappe structures within broad compressional zones where horizontal

Fig. 1.2 Blocky accumulations of a giant landslide situated in forests west of the Sedoa village at steep structural slopes of the Main Central Thrust. These blocks of crystalline rocks in diameters up to 4 m are at altitudes of 3600–3000 m in persistent slow movement. *Photograph* by Jan Kalvoda

movements and high local tensions are typical (e.g., Cattin and Avouac 2000; Bollinger et al. 2006). The horizontal movements of rock masses in the collision zone of the earth`s crust are especially significant. They led to the heterogenous wedging-in of the irregularly shaped margins of the frontal parts of the continents or to the sideways displacement of the minor blocks which were derived from local hyper-collision zones.

The collisional orogenetic process occurred in several major phases. The Karakoram phase (the late Cretaceous to Palaeocene) represents a period of continent convergence. The subduction of the lighter Indian plate resulted in the formation of the subduction-island arc complex Sindhu-Tsangpo, which was built by the alkaline volcanics and tectonically modified sediments of the oceanic trench and sea floor (Valdiya 1984). This island arc was integrated into the Eurasian tectonic plate during the following Malla Johar phase (late Eocene to Oligocene), which was characterised by the collision and subduction of tectonic plates. The large-scale folding resulted in the thickening of the Tethyan sequences (Hashimoto et al. 1973; Sharma 1998) and basal metamorphism. The major uplift of the Himalaya associated with the formation of its key geological structure took place during the Silmurian phase (middle Miocene

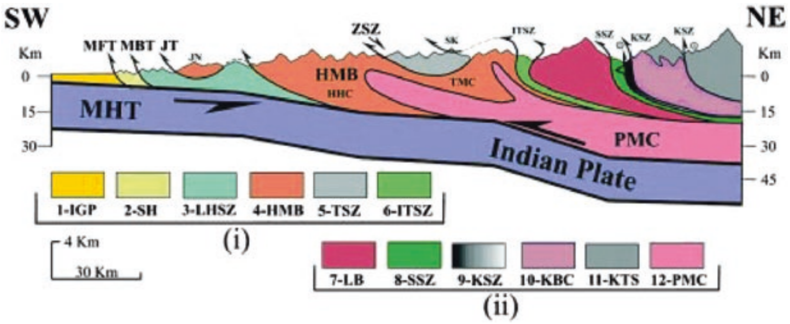

Fig. 1.3 Geological cross-section through the NW Himalaya and Karakoram (after Jain et al. 2012). Himalayan Collision tectonic zone: 1—Indo-Gangetic Plains (IGP), 2—Sub-Himalayan Cenozonic foreland basin (SH), 3—Lesser Himalayan Sedimentary Zone (LHSZ), Himalayan Metamorphic Belt (HMB) including Lesser Himalayan Jutogh Nappe (JN), 4—Higher Himalayan Crystalline (HHC) Belt and Tso Morari Crystallines (TMC), 5—Tethyan Sedimentary Zone (TSZ), Trans-Himalayan tectonic units, 6—Indus Tsangpo Suture Zone (ITSZ) and Spongtang Klippe (SK), 7—Ladakh Batholich Complex (LB), 8—Shyok Suture Zone (SSZ), Asian Plate Margin, 9—Karakoram Shear Zone, 10—Karakoram Batholith Complex (KBC), 11—PaleoMesozoic Karakoram Tethyan sequence, 12—Partially Molten Crust (PMC). Subducting Indian Crust (IC) given in blue colour: MFT—Main Frontal Thrust, MBT—Main Boundary Thrust, MCT—Main Central Thrust, ZSZ—Zanskar Shear Zone, MHT—Main Himalayan Thrust. Vertical exaggerate above 0 km to show topography is used. Partial melt on mid-crust and extension of the Indian Plate beneath Karakoram and further north-east are constrained from magnetotelluric and teleseismic receiver function analysis after Arora et al. (2007) and Caldwell et al. (2009)

to Pontian). During the Siwalik phase (late Pliocene to Pleistocene), the outer ranges of the Lesser Himalaya were uplifted (Valdiya 1984, 2002). The northward movement of the Indian plate, accompanied by the active orogenetic processes, continues up to present at a rate of about 5 cm per year (Bilham et al. 1997; Jouanne et al. 2004).

Geomorphological analysis of landform patterns in the Himalaya to a certain degree provides evidence of the dynamics of exhumation and erosion of rocks during the ongoing collisional orogeny in the late Cenozoic (Fig. 1.4). The tectonic sutures testify to the destruction of a certain area of the continental surface, an increase in the thickness of the earth's crust and a potential uplift (Fig. 1.3). On the contrary, erosion and denudation effectively grind off the mountain ranges and the highlands, and thus reduce the thickness of the earth's crust. During continent–continent collision orogeny the earth's crust change the horizontal dimensions as well as elevation of its near-surface part by loss of volume and by an increase in the vertical thickness. In the subduction zones, part of the disintegrated and molten material is transported back into the asthenosphere (Avouac 2003; Searle and Treolar 2019).

Nepal can be divided into five major tectonic zones, whose lithology and tectonic features largely demonstrate individual stages of the Himalayan evolution (Upreti 1999). Due to the continuing pressure caused by the northward drift of the Indian plate, the major tectonic zones are aligned in the south-to-north direction (compare Fig. 1.5). Generally, morphostructures and seismicity in the Nepal Himalaya are controlled by three master thrusts (Gansser 1964; Bollinger et al. 2006; Naik 2015; UNDRR 2023), namely the Main Central Thrust, the Main Boundary Thrust and the Main Frontal Thrust. They form the low-angled basal detachment zones of the Main Himalayan Thrust. This largest active continental thrust in the world descends to the North accommodating the crustal shortening of India and Eurasia (Hubbard et al. 2016).

The northern areas of mountain ranges in Nepal belong to the Tibetan-Tethys tectonic zone, which is situated between the South Tibetan Detachment Fault System and the Indus-Tsangpo Suture Zone in the northernmost part of Himalaya (Bollinger et al. 2006; Searle and

Fig. 1.4 Selective erosion and denudation of the high-mountain relief originated on the folded Mesozoic sediments north of the Annapurna Massif in the Tibetan Himalaya. *Photograph* by Jan Kalvoda

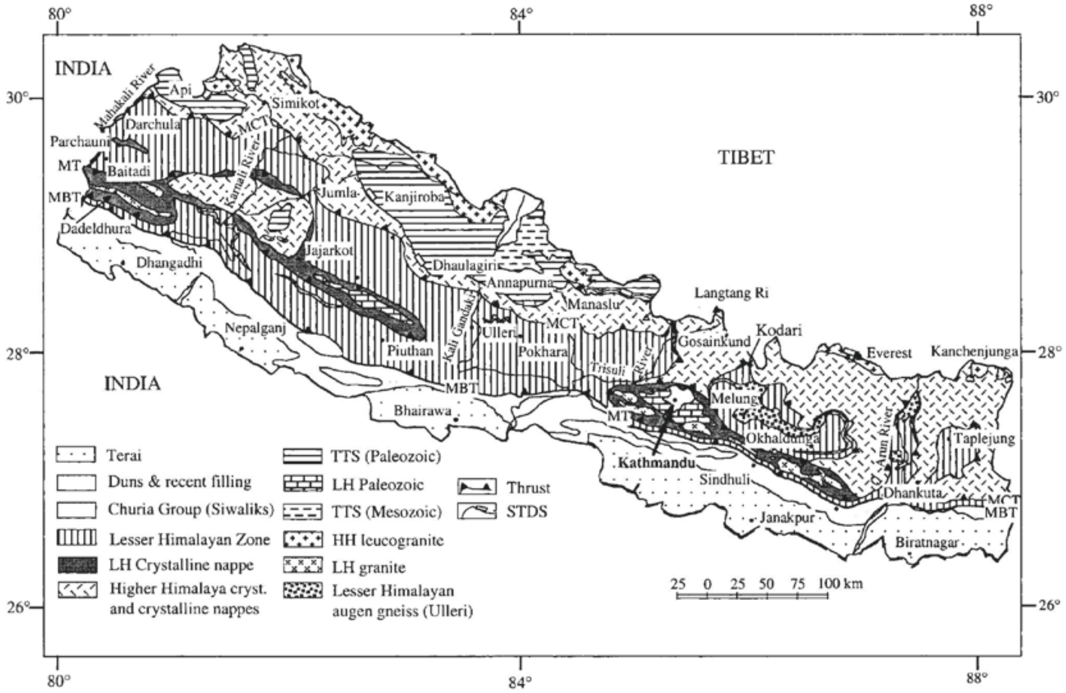

Fig. 1.5 Geological map of Nepal (after Upreti and Le Fort 1999). LH—Lesser Himalaya, HH—Higher Himalaya, TTS—Tibetan-Tethys sediments, MBT—Main Boundary Thrust, MCT—Main Central Thrust, MT—Mahabharat Thrust, STDS—South Tibetan Detachment System

Treolar 2019). The Tibetan-Tethys zone is predominantly built by the thick marine sediments of the Tethys Sea, which were uplifted during the Malla Johar and Silmurian orogenetic phase. According to Colchen et al. (1980), the fossiliferous sequence of the Tethyan Sedimentary Series had been deposited from the Cambrian to the lower Tertiary (Fig. 1.4). This epicontinental to miogeosynclinal sequence is over 10 km thick and includes emplacements of ophiolites and flysh and volcanic and glacial deposits. The occurrence of the Permo-Carboniferous flora correlates the Tibetan-Tethys tectonic zone with the landmass of India and Gondwana (Hashimoto et al. 1973; Stöcklin 1980). The only evidence of metamorphism was identified on the very base of the Tethyan Sedimentary Series, which is in contact with the underlying crystalline rocks of Higher Himalaya.

The Higher Himalayan Zone is situated south of the Tibetan-Tethys sediments zone (Fig. 1.5). It mainly consists of crystalline rocks, such as gneisses, schists and migmatites, which form the core of the Himalayan mountain belt and the bedrock of the Tethyan sediments. The thickness of the Higher Himalayan Crystalline rocks extends to more than 12 km (Ohta and Akiba 1973; Upreti 1999). Radiometric dating of the Higher Himalayan gneisses and granites identified two distinct periods of their origin, i.e. the Precambrian to Cambrian and the Tertiary. It suggests that the Higher Himalayan Zone was built partially by rock assemblages of the Indian shield which were mostly destroyed during the Himalayan orogeny (Stöcklin 1980). During the Tertiary, intervening bodies of leucogranite protruded along the South Tibetan Detachment Fault System. The southern boundary of the Higher Himalaya Zone follows the complicated course of the Main Central Thrust.

The Main Central Thrust is recognised as the fundamental fault of the Indian Plate subduction (compare Chap. 2), and it takes a form of a thick ductile shear zone. According to Harrison et al. (1998), the Main Central Thrust was active especially between 25 and 15 Ma. The major deformation and melting of the Main Central Thrust hanging wall took place around 22 million years ago (Hodges et al. 1996). The sub-horizontal movements along the Main Central Thrust forced the Higher Himalaya rocks more than 100 km over the Lesser Himalaya rock assemblages. The Main Central Thrust was reactivated between 6 and 8 Ma (Harrison et al. 1998).

The Lesser Himalayan Zone is bounded by the Main Central Thrust in the North and the Main Boundary Trust in the south. It features very complicated tectonic and lithological structure. The bedrock is built by the Precambrian metasedimentary sequences, which are separated from the younger formations by the Lesser Himalayan unconformity caused by the Late Panafrican diastrophism (Valdiya 1998). The unconformity is overlain by the Permo-Carboniferous continental facies, which originated on the Gondwana continent. Sakai (1985) classified the following layer of marine sediments as of Early Cretaceous to Eocene age. The capping consists of the fluvial Dumri Formation, which served as the late Oligocene to early Miocene Himalaya foreland. Along the Main Central Thrust, the overriding crystalline nappes of two kinds we identified (Upreti 1999). The root composition of the fist nappe kind (amphibolite to granulite rocks) closely resembles rocks of the Higher Himalayan Zone. Hayashi et al. (1984) assumed that the nappe core represents the basal part of the Tibetan-Tethys sediments. On the other hand, the second kind of nappes consists of the Bhimphedi Group, whose origins are more complicated. Upreti and Le Fort (1999) assumed that the Bhimphedi Group was created between the Precambrian sediments and the Phanerozoic Tethyan sequence.

The Main Boundary Thrust, which divides the Lesser Himalayan Zone from the Churia Zone, was created during the Cenozoic (10–11 million years ago, Mugnier et al. 1994; Meigs et al. 1995). This system of faults experienced significant movements, which resulted in the trust of the metasedimentary sequences of the Lesser Himalayan Zone over the rocks of Churia Zone. The Main Boundary Thrust is still active, resulting in the uplift of the southern part of the Lesser Himalaya (Upreti 2001; UNDRR 2023). Similarly, the Churia group is trusted over the

Terai alluvium along the Main Frontal Thrust, which is the youngest thrust of the Himalayan orogen.

The Churia Zone is an important archive of the final stages of the Himalayan uplift. Its fluvial and alluvial sediments of Neogene to Quaternary age created one of the world's largest foreland basins (Upreti 1999). According to DeCelles et al. (1998), the Lower Churia Group consists of fine-grained sediments, including mudstone, siltstone, shale, or sandstone. Locally, paleosols were also identified. The Middle Churia Group is characterised by alternating beds of thick sandstone and mudstone, while the Upper Churia Group contains boulder conglomerates with mudstone intercalations. According to the palaeomagnetic research, the Churia Group is 14–2 million years old (DeCelles et al. 1998).

The southernmost part of Nepal belongs to the Terai zone, which represents the northern continuation of the alluvial Indo-Gangetic foreland. The Terai plain consists of alluvial strata, which have been deposited during the Pleistocene and the Holocene (Upreti 1999), and thus represent the recent foreland basin of the Himalaya. The thickness of Terai sediments is very variable, with an average of 1.5 km. Underneath the alluvium lies the Churia Group of the Middle Miocene to Pliocene age, while the bedrock itself consists of the peninsular India rocks, which originated in Gondwana during the Permo-Carboniferous era. The grain size of Terai sediments gradually increases to the north (Valdyia 1988). The southern mountain front of the Churia Range, known as the Bhabhar zone, is covered by the coarse accumulations of alluvial fans.

The predominant zonal trend of the morphostructural features manifests itself in the character of the Nepalese landscape. Upreti (1999, 2001) divided Nepal into several physiographic units characterised by distinct topography, altitude, climate and vegetation. Namely, from south to north, the units are the Terai, the Churia Range, the Dun Valleys, the Mahabharat Range, the Midlands, the Fore Himalaya, the High Himalaya and the Inner- and Trans-Himalayan Valleys (Fig. 1.6).

The Terai unit corresponds the northern edge of the Indo-Gangetic Plain. It extends nearly 800 km along the Indian border with an altitude reaching 100 to 200 m a.s.l. Its width varies between 10 and 50 km (Upreti 2001). As a part of the Himalayan piedmont zone, the Terai unit is characterised by an uneven topography descending to the south. The northern part adjacent to the mountain foot, called the Bhabar zone, mostly consists of gravelly alluvial fans. The fan surface is disrupted by the river incision, creating river terraces and high cliffs. The intensity of river incision diminishes to the south (Shukla and Bora 2003), where the flat Terai landscape has formed by the down warping of the basin and migration of river channels (Shrestha and Aryal 2011). The Terai unit is characterised by low drainage density and sub-parallel to radiating drainage pattern. Tectonic displacement of Churia rocks, unpaired river terraces, high cliff lines and nick points in the river channels refer to the continuing orogenetic activity.

The Churia Range (Siwalik) unit is formed by the southern mountain ranges of the Himalaya (Fig. 1.6). It extends along the whole length of Nepal with an altitude ranging between 200 to 1000 m a.s.l. and locally, the elevation reaches up to 1300 m a.s.l. (Upreti 2001). The Indo-Gangetic Plain is separated from the inner Sub-Himalaya by the Front Churia Ranges, which represent an active fold-and-thrust belt. Interaction between several propagating fault segments of the Main Frontal Thrust created a series of folds, which are topographically manifested as linear to curvilinear strike parallel ranges (Divyadarshini and Singh 2019). The north-dipping beds creating hogback and cuesta structures with the south-facing steep escarpment, which rises from the Terai Plain (Upreti 2001; Dhital 2015), build its arcs. Further north, the Inner Churia Ranges developed along the Main Dun Thrust. The immature relief of the Churia Range suffers a high erosional regime caused by the intense chemical weathering, mass movements and fluvial erosion (Hurtrez and Lucazeau 1999; Upreti 2001). As a result, the rugged relief of the Churia Range consists of hills, deep gorges, cliffs, active gullies, alluvial fans, and talus cones.

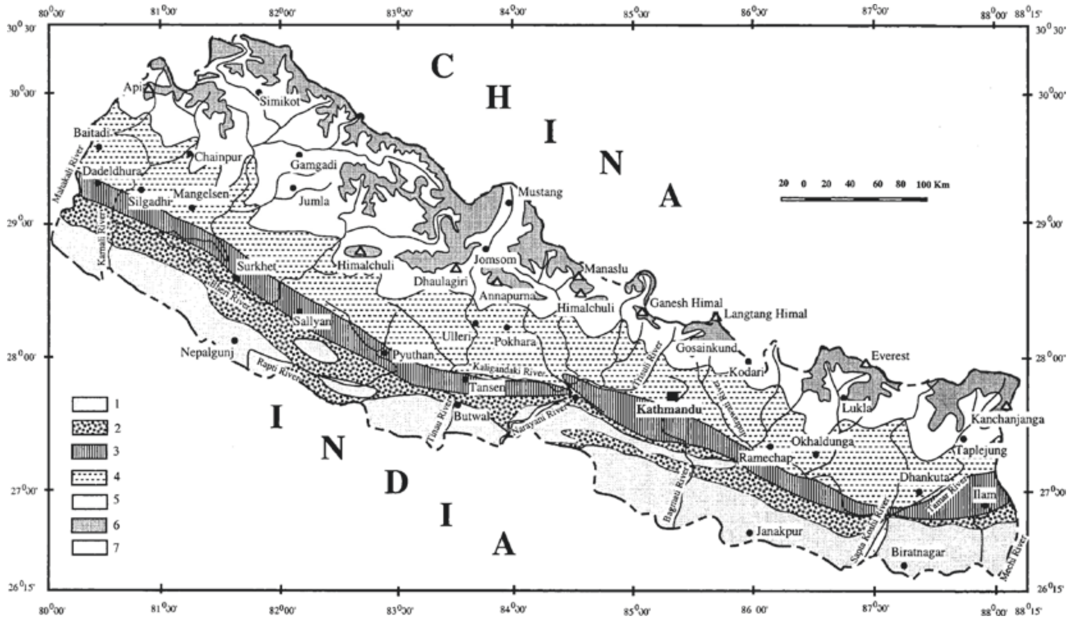

Fig. 1.6 Physiographic subdivisions of Nepal (Upreti 1999, 2001). Key: 1—Terai (Northern Gangetic Plain) and Dune Valleys (100–200 m a.s.l.), 2—Churia Range (Siwalik equivalent) (200–700 m a.s.l.), 3—Mahabharat Range (1000–2500 m a.s.l.), 4—Lesser Himalaya (Midlands) (300–2000 m a.s.l.), 5—Fore Himalaya (2000–4500 m a.s.l.), 6—Higher Himalaya (>4000 m a.s.l.), 7—Inner Valleys (2500–4000 m a.s.l.)

In central and western Nepal, the broad asymmetric arcs of the Churia range are divided by the intermontane basins, called Dun Valleys. According to Mugnier et al. (1999), the Dun Valleys are piggyback basins formed due to the thrust transportation in the Himalayan foreland. The elevation of the Dun Valleys varies between 150 and 500 m a.s.l. These wide valleys are filled by the unconsolidated Quaternary deposit which take the form of alluvial fans, terraces and recent alluvium (Kimura 1999). The amount of basin sedimentation positively correlates with the thickness of a thrust sheet (Mugnier et al. 1999). The westward extent of the Dun valleys is limited by the tectonic lineament of the West Dang Transfer zone (Kimura 1999; Upreti 1999, 2001).

To the north, the Mahabharat Range is separated from the Churia Range by the Main Boundary Thrust. Its elevation rises to 3000 m a.s.l., but most of the area lies under the 2000 m a.s.l. Deep antecedent valleys of the Karnali and Gandaki Rivers divide the Mahabharat Range into three units. The east and the west parts are built with crystalline rocks and form synformally folded crests (Dhital 2015). The central part consists of sedimentary and low-grade metamorphosed layers. In addition to the Karnali and Gandaki Rivers, the Mahabharat Range is crossed by only a few other big rivers, such as the Kosi and Mahakali Rivers. Their antecedent valleys take the form of deep and narrow gorges. Other rivers originating in the Midlands or the Fore Himalaya were forced to change their original direction by tectonic activity and took a course parallel to the Mahabharat Range. The landscape of the Mahabharat Range is very rugged, forming sharp crests and the southern slopes are steeper than the northern ones (Upreti 1999, 2001; Dhital 2015).

The largest physiographic unit of Nepal, called the Midlands, belongs to the Lesser Himalayan synclinorium. It is situated between the Mahabharat Range and the Fore Himalaya. Its mature landscape is formed by intermontane basins (Fig. 1.7) and wide river valleys situated down to 200 m a.s.l. and mountains reaching up to 2000 m a.s.l. (Upreti 2001; Dhital 2015). Extensive weathering of the Midlands rock in the

Fig. 1.7 Rapid erosion strikes the Upper Pleistocene fluvial and lacustrine sediments in the Tumlingtar intermountain basin at altitude of *ca* 800 m. The broken surface of these deposits is covered by earthy Rotlehm soils originated in the mild monsoon climate with summer temperatures over 20 °C. *Photograph* by Jan Kalvoda

subtropical environment caused the formation of fertile red soils, which cover the foothills, ridges and convex slopes (Dhital 2015). The river network is based predominantly on morphotectonic features. According to Hagen (1969), the main Midlands rivers are longitudinally or transversely aligned and follow the fold cores.

The Fore Himalaya represents a transitional zone between the Midlands and the High Himalaya (Upreti 2001). Its elevation varies between 2000 and 5000 m a.s.l. For most of its length, the Fore Himalaya forms a narrow 20–30 km wide zone, which widens up to 150 km in western Nepal along the Karnali River and the Solu-Khumbu area in east Nepal. The broken relief of the Fore Himalaya is built predominantly by the crystalline thrust sheets dissected by narrow river valleys (Dhital 2015). The highest peaks of the Fore Himalaya are permanently covered by snow, while the tree line is found around 4000 m a.s.l.

Nepalese landscapes situated above 4000 m a.s.l. belongs to the High Himalaya (Fig. 1.8). This physiographic unit is in northern Nepal and lies predominantly above the permanent snow line. Eight of the Higher Himalayan summits rise above 8000 m a.s.l., including Mount Everest. The High Himalaya consists of several mountain ranges following three main directions, i.e. E–W, NW–SE and NE–SW. These ranges are dissected by the downcutting trans-Himalayan rivers, which form deep antecedent

Fig. 1.8 High-mountain landscape with remarkable vertical arrangement of glacial and periglacial climate-morphogenetic zones developed above the Dudh Kosi valley east and northeast of the arête ridges (from the left to the right) Kongde Ri (6187 m), Teng Kangpoche (6500 m), Panayo Tupa (6696 m) and Pigpherago Shar (6718 m) which are built of crystalline rocks of the High Himalaya. *Photograph* by Jan Kalvoda

valleys (Shrestha and Aryal 2011; Upreti 2001). These thousands of meters deep gorges are usually situated close to the summit precipices (Wager 1937). The High-Himalayan landscape is shaped by glacial, periglacial, fluvial and aeolian processes. The arête relief includes numerous rock slopes (Fig. 1.9), cirques and hanging valleys. Remarkable history of glaciation in the Nepal Himalaya during the Quaternary belongs to fundamental topics of geomorphological and environmental research in the High Asia mountains (compare e.g., Duncan et al. 1998; Fort 2004; Owen 2004, 2011).

The ranges of the High Himalaya are orographically separated from each other, as well as the Tibetan Marginal Ranges (Fig. 1.10), by the Inner- and Trans-Himalayan Valleys. Inner- Himalayan Valleys (e.g., Langtang valley and Ghunsa valley) are situated south of the Himalayan highest ranges. The Trans-Himalayan Valleys (e.g., Dolpa valley, Mugu valley and Mustang valley) are located to the north. Most valleys are situated in the rain shadow of the Himalayan Mountains, which led to their unique environment (Barnard et al. (2006). During the Quaternary, hyper-concentrated flows and coarse-grained debris flows covered the valley floors with extensive fans and terraces.

The orogenic compression in the Himalayan region has produced a recent tectonic response the effects of which extend far into the central parts of the Asian continent (Kalvoda 1992; Jouanne et al. 2004). In this respect the increased thickness of its earth's crust is of particular importance as well as its widening in the west–east direction and the activity in the

Fig. 1.9 Remarkable rocky slopes of the south-eastern crest of the Peak 6 (6840 m), built by gneisses and amphibolite, represent a lot of dejection planes of rockfalls originated in response to glacial unloading of the Barun Khola valley, intensive frost riving, tectonic uplift and earthquakes. *Photograph* by Jan Kalvoda

Fig. 1.10 Morphostructural arrangement of the high-mountain landscape in the east of the Thakkhola graben developed on Triassic to Jurassic sedimentary formations of the Tibetan Himalaya. *Photograph* by Jan Kalvoda

form of thrusts and movements along faults. For example, the raising of the Hindukush was due to compressive forces, the Pamirs are being thrust northward, while the Tarim block is being pressed toward the north onto the folded structures of the Thyan Shan. Left-lateral movements appear in the Altyn-Takh and Kuen Lun regions, the Karakoram shift to the right strikes northwest-southeast. This suggests that the continental crust of the Tibetan Plateau move eastward.

1.1.3 Climate, Glaciers and Rivers of Nepal

The varied topography of Nepal causes substantial diversity in its climate. The climatic conditions change rapidly according to the latitude, altitude and relative position to the airflow and sun radiation (Pratt-Sitaula 2005; Zurick et al. 2005). Most of these factors are directly connected to the Himalayan mountain ranges, which create unique regional climatic conditions as well as a significant topographical barrier. According to Hannah et al. (2005), the Terai Belt, the Churria Hills and the valley bottoms of the Lower Himalaya belong to the subtropical zone. Slopes of the Lower Himalaya are warm temperate, while their ridges are cool temperate. The High Himalaya belongs to the alpine zone reaching nival climate above the snow line (around 4600–5200 m a.s.l.).

The climate of Nepal is heavily influenced by the seasonal monsoon (Kraus 1967; Uprety et al. 2017), which usually takes place from June to September and causes the highest seasonal amounts of precipitation in the world. The south-easterly monsoon correlates with the movements of the Intertropical Convergence Zone (Nayava 1974, 1975; Shrestha and Aryal 2011). The northward shift of the ITCZ in the summer months creates a depression of pressure over the Bay of Bengal, which moves in the north-westward direction bringing moist oceanic air to the continent. Due to the continuous decrease of air moisture, the amount of monsoon-induced precipitation in Nepal varies from east to west as well as from south to north. Similarly, the amount of precipitation changes depending on the altitude.

Heavy rainfall occurs on the windward side of the Himalaya, where the moist air is forced to ascend and reaches the maximum precipitation zone. In the Nepal Himalaya, the zone is estimated around 2000 m a.s.l. However, íts precise altitude is hard to determine, due to the local climatic variations and a lack of meteorological stations in Nepal (Zurick et al. 2005). The leeward side of the mountain ranges stays in the rain shadow for most of the year (Fig. 1.11). For example, the annual precipitation of the windward southern slopes of the Annapurna Range reaches up to 5000 mm, while the northern slopes receive only 250 mm (Shrestha and Aryal 2011). The palaeogeographical consequence of these long-term climatic differences is the very deep penetration of erosion and denudation of rock massifs and deeply entrenched relief on the steep windward side of evolving Himalayan mountain ranges with the focused influence of humid air masses producing strong precipitations (Lave and Avouac 2001; Hodges et al. 2004; Kalvoda 2020).

The summer monsoon provides 70–85% of the annual precipitation in Nepal, which is 1768 mm (Nayava 1974; Singh 1985; Shrestha et al. 2000). The monsoon reaches the southeastern part of Nepal in June (Fig. 1.12), causing heavy precipitation over the foothills of the Churia Hills (Nayava 1984). The monsoon culminates in July (Fig. 1.13) with the maximum mean monthly precipitation in the areas of the Annapurna and the Langtang Ranges reaching more than 1000 mm (International Centre for Integrated Mountain Development and Chalise 1996). The High Himalaya is drier due to the rain shadow effect.

The intensity of monsoon precipitation also varies during the day. Dhar (1960) observed a rainfall peak in the Kathmandu area (central Nepal) between 11:10 pm and 03:10 am. In the Barakshetra area (south-eastern Nepal), the second maximum of daily precipitation was also identified between 01:10 pm and 02:10 pm. Diurnal precipitation minimum has a similar feature. The first minimum takes place between 08:10 am and 00:10 pm, while the second one usually happens between 07:10 pm and 10:10 pm.