4 Geology and Physiography

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Abstract

The Nepal Himalayas lies in the central part of the Himalayan arc. The range is a product of the collision between Indian and Eurasian plates in the Miocene period (50 M yr) and is bounded by Indus Tsangpo Suture Zone (ITSZ) to the north and the Ganga basin to the south. The coupling effect of earthquake reoccurrences and strong Asian monsoon has resulted in a steep slope, rugged mountains, deep valleys, intermontane basins, and flat land. Geologically it is divided into five tectonic zones separated by major tectonic discontinuities running parallel to the Himalayan chain. These tectonic zones from south to north are the Indo-Gangetic Plain, the Siwaliks, the Lesser Himalayas, the Higher Himalayas, and the Tibetan-Tethys zone. These zones are formed with different types of rocks including sedimentary, igneous, and metamorphic distributed throughout the Nepal Himalayas, which explains the depositional environmental and evolutionary history of the whole Himalayas range. In addition, the Nepal Himalayas is divided into five physiographic regions based on climatic and geomorphic conditions (Tarai, Siwaliks, Hills, Middle Mountain, and High Mountain). These physiographic regions are attributed to different types of soil, climate, and land use and are mostly characterized based on elevation. The variation on these physiographic zones depends on the micro-climate controlled by peaks and valleys. This chapter discusses the geologic and physiographic classification of the Nepal Himalayas in brief.

Keywords

Climate • Indo-Gangatic Plain • Nepal Himalaya • Physiography • Tectonics

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4.1 Evolution of the Nepal Himalayas

The 2400 km Himalayan arc extends from Nanga Parbat (8138 m) in the west to Namche Barwa (7756 m) in the east with a 230 to 350 km width (LeFort 1996). The Himalayan orogenic belt is a product of the collision between the Indian and the Eurasian plates during the late Eocene to Oligocene period (Valdiya 1984). The Indian plate is subducting with different velocities from ∼ 0.2 to 28 mm yr^{-1} beneath the Eurasian plate and mountains still being formed (Jade et al. 2017). The collision resulted in numerous tectonic faults and highly deformed rocks that are responsible for triggering numerous earthquakes of varying scales, making the Himalayas a seismically active zone (Bilham et al. 2001; Kobayashi et al. 2015; Kubo et al. 2016; Mencin et al. 2016; Sapkota et al. 2013). Generally, two main geodynamic processes have controlled the evolution of the Himalayas: 1) accretion and subduction in the Trans-Himalayan and Karakoram Mountains along the Shyok Suture Zone (SSZ) and Indus Tsangpo Zone (ITSZ), and 2) continental collision in the Himalayas (Jain et al. 2012). However, Valdiya (1984) elaborated on this by dividing the evolution process into four stages:

(1) Karakoram phase: Convergence takes place between two continental plates between 145 to 55 M (Cretaceous to Paleocene).
(2) Malla Johar phase: Collision and subduction of the Indian plate beneath the Eurasian plate occur between 55 and 23.8 M yr (Late Eocene to Oligocene).

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(3) Sirmurian phase: Himalayan upheaval with the development of main tectonic features occurs between 23.8 to 5.3 M yr (Miocene to Pontian).
(4) Siwalik phase: The formation of Siwalik in the frontal part of the Himalayas occurs between 5.3 M to 0.01 M yr (late Pliocene to middle Pleistocene).

This process led to the development of different tectonic slices along the principle thrusts, which are stacked one on top of the other, propagating southward and building the architecture of the Himalayas (Molnar 1984). Politically, this tectonic mountain chain consists of several sections of Pakistan, India, Nepal, Bhutan, and China, whereas the region is longitudinally divided into five sections from west to east (Gansser 1964) (Fig. 4.1):

(a) Punjab Himalayas: This section consists of a 550 km long section of the Himalayan chain bounded by the Indus River to the west and the Sutlej River to the east. It includes the Kashmir and Spiti regions.
(b) Kumaon Himalayas: This 320 km long section lies between the Sutlej River to the west and the Mahakali River to the east. It includes the Garhwal Himalayas and parts of southern Tibet.
(c) Nepal Himalayas: This is the central part of the Himalayas consisting of 800 km. It is bounded by the Mahakali River to the west and the Mechi River to the east, covering the entire length of Nepal. This section includes the world's tallest peaks, such as Everest, Kanchanjanga, Lotse, and Annapurna.
(d) Sikkim-Bhutan Himalayas: This section is bounded by the Mechi River to the west and Bhutan to the east and covers Sikkim and Bhutan (400 km).
(e) North-East Frontier Agency (NEFA) Himalayas: This is the easternmost part of the Himalayas, with a length of 400 km extending from the eastern boundary of Bhutan to the Tsangpo-Brahmaputra cross gorges.

The Himalayas is bounded by the Indus Tsangpo suture zone (ITSZ) to the north and the Ganga foreland basin to the south. The northern boundary of the ITSZ is generally exposed by a topographic depression along the Indus and Tsangpo rivers, which flow in opposite directions (Heim and Gansser 1939). Geologically, the Himalayan chain is broadly

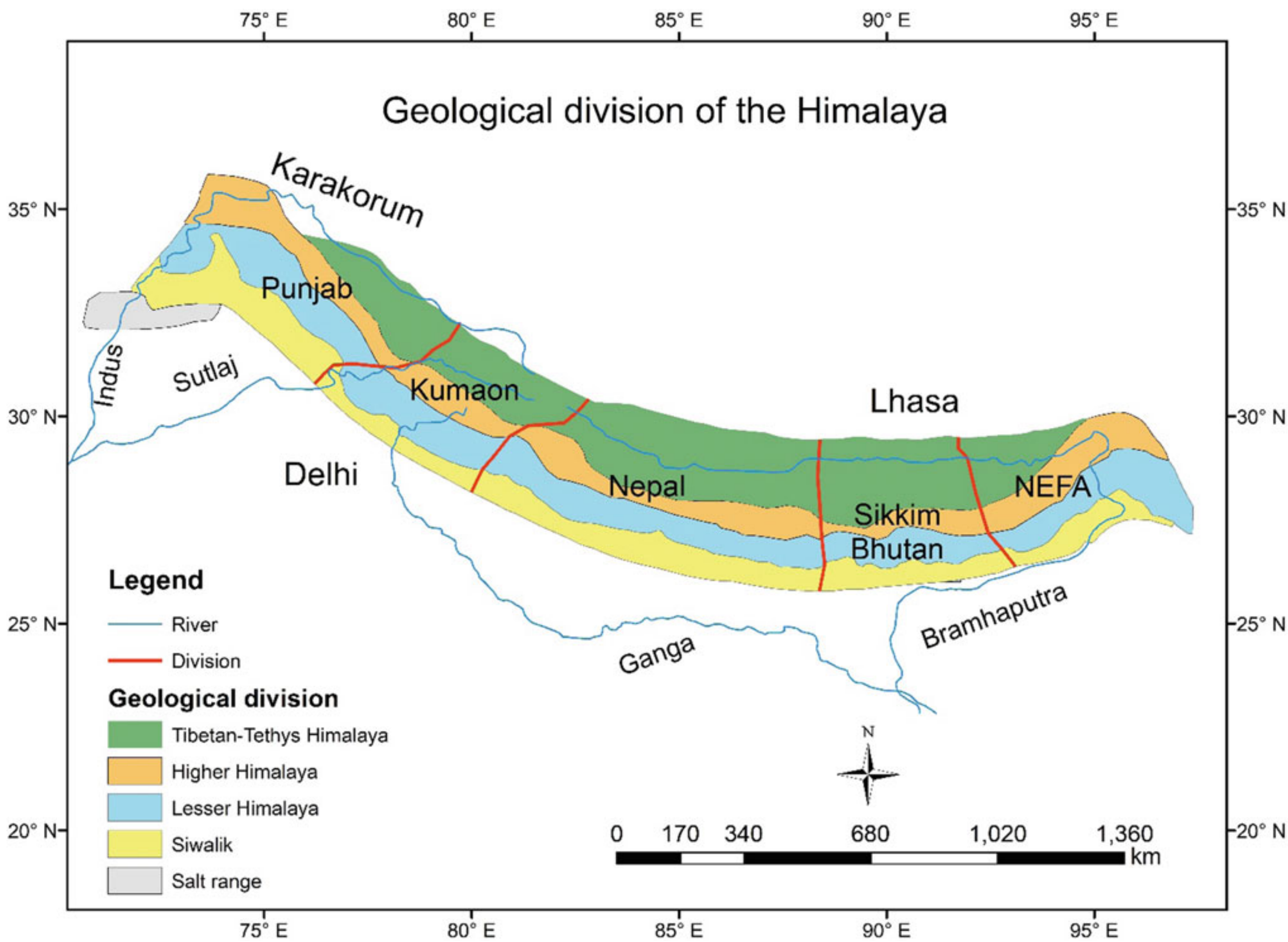

Fig. 4.1 Geological longitudinal subdivision of the Himalayas from west to east (Redrawn after Gansser 1964)

divided into five tectonic units, namely the Indo-Gangetic plain, the Siwalik, the Lesser Himalayas, the Higher Himalayas, and the Tibetan-Tethys Himalayas (Fig. 4.1).

4.2 Geology of the Nepal Himalayas

The Nepal Himalayas lies in the central part of the Himalayan arc covering one-third of the entire Himalayas. The Nepal Himalayas, bounded by latitudes 26°2’ and 30°27’ N and longitudes 80°11’ E and 88°27’ E, can be divided into five tectonic zones from south to north based on geological evolution (Table 4.1 and Fig. 4.2). These tectonic joints are separated by faults and thrusts and characterized by their tectonics, structure, and evolutionary history, which are briefly described below.

4.2.1 Indo-Gangetic Plain

The Indo-Gangetic plain lies in the frontal part of the Himalayas with an elevation ranging from 100 to 200 m asl deposited by the tributaries of the Ganga River. This tectonic zone was created beginning in the Pleistocene and continues through recent alluvial deposits (Fig. 4.3a) of approximately 1500 m thickness that already show a significant proportion of stress accumulation and form thrust and thrust-propagated folds beneath the sediments (Bashyal 1998; Mugnier et al. 1999; Upreti 1999). This tectonic zone is separated by the Main Frontal Thrust (MFT) from the Siwaliks to the north. Sedimentation began with the shallow marine environment before changing to estuarine-deltaic and finally to fluvial (Pant and Sharma 1993).

4.2.2 Siwaliks

The Siwaliks is also referred to as the sub-Himalaya and is comprised of the southernmost tectonic zone of the Nepal Himalayas bounded by the MFT to the south and the Main Boundary Thrust (MBT) to the north (Fig. 4.2). Many researchers (Auden 1935; Dhital 1995, 2015; Nakayama and Ulak 1999; Sah et al. 1994; Sharma 1977; Tokuoka et al. 1988) have established and presented different classifications for the Siwaliks sequence. Due to the lack of fossil records in the Nepal Himalayas, these classifications can be grouped and correlated into three basic units based on lithostratigraphy. These units are Lower, Middle, and Upper Siwaliks, and age ranges from the Middle Miocene to the Pleistocene (Gautam and Rösler 1999). In general, the entire Siwalik represents a coarsening upward sequence whereas individual units have fining upward sequence. The thickness of the Siwaliks changes significantly from western to eastern Nepal, with thick sequences in the Karnali section and decreasing as one moves east. The Lower Siwalik is composed of the alternation of fine-grained variegated mudstone and siltstone with some layers of fine sandstone. The domination of sandstone increases in the Middle Siwalik with increasing grain size represented by a wide concentration of black-colored biotite and light-colored quartz and feldspar minerals. The Upper Siwalik is well exposed at the foot of the Lesser Himalayas and consists of coarse-grained sediments with few siltstone and

Table 4.1 Geological subdivision and their key features of Nepal Himalayas

SN	Geological sub-division	Major rocks and minerals	Key geologic features	Age
1	Indo-Gangetic plain	Alluvial deposits consisting of gravel, sand, silt, and clay originating from the Himalayas	Alluvial deposits with thrust and thrust-propagated folds beneath the sediment. Shallow marine environment changed to estuarine-deltaic and now to fluvial earth materials	Pleistocene to recent
2	Siwaliks	Mudstone, Siltstone, Sandstone, Conglomerate	Anticline and syncline folds, fault/thrust	Middle Miocene to Pleistocene
3	Lesser Himalayas	quartzite, limestone, slate, siltstone, schist, gneiss, marble, amphibolite, Nepheline syenite, granites	Nappe/Clippe, Tectonic window, Mabharat Synclinorium, Fold/Thrust	Precambrian to Eocene
4	Higher Himalayas	Schist, Gneiss, Marble, Leucogranite	Folds/Thrust, High-grade metamorphism	Proterozoic to Miocene
5	Tibetan-Tethys zone	Sandstone, Limetone, Quartzite, shale	Folds/Thrust, Fossiliferous layers	Cambrian to Eocene

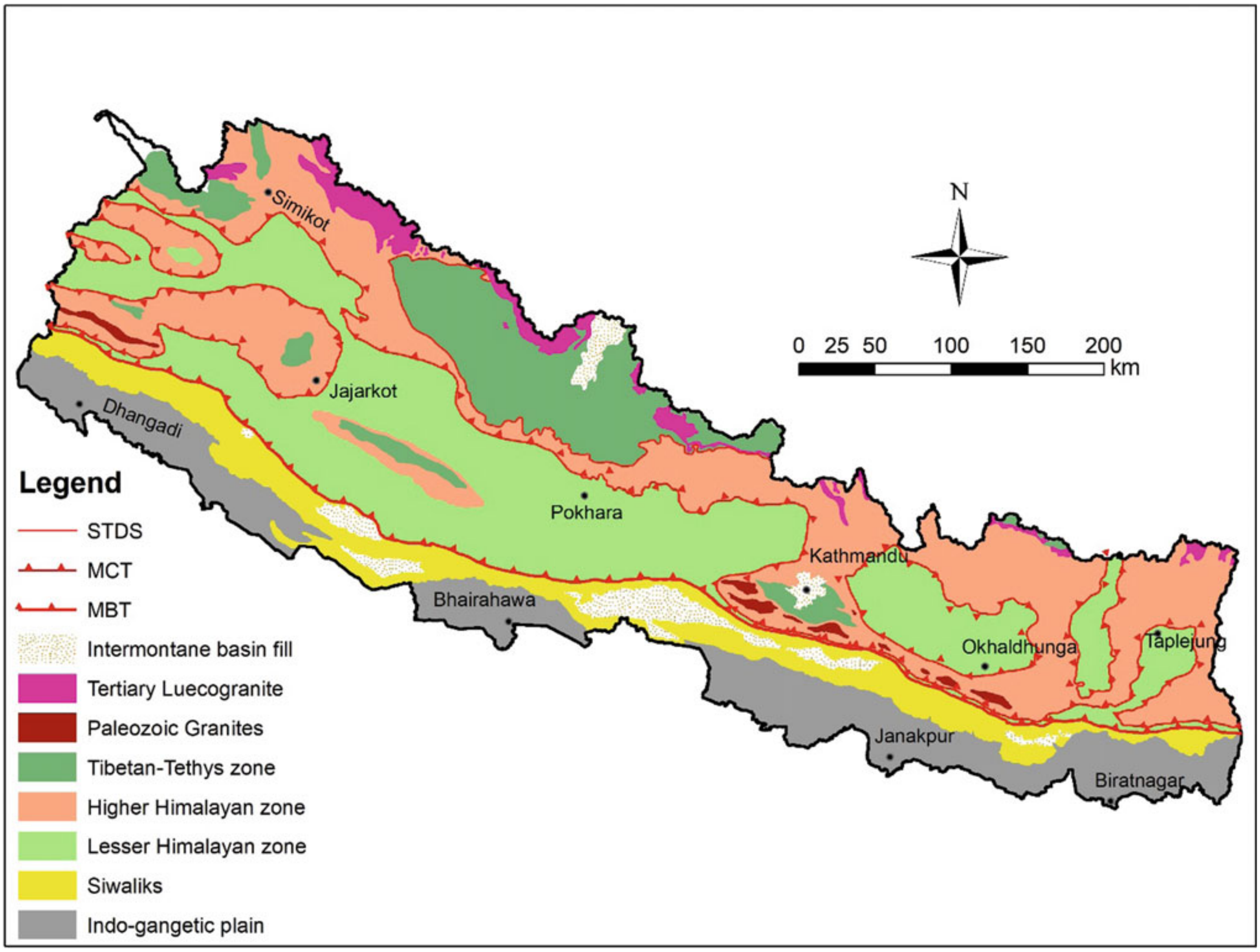

Fig. 4.2 Geological subdivision of the Nepal Himalayas modified from (Amatya and Jnawali 1994). STDS: South Tibetan Detachment System. MCT: Main Central Thrust. MBT: Main Boundary Thrust

mudstone layers (Fig. 4.3b). These sediments were deposited in different depositional environments including meandering, braided, and debris flow (Nakayama and Ulak 1999). The rocks of the Siwaliks are folded and faulted in different directions, resulting in different geological structures.

4.2.3 Lesser Himalayas

The Lesser Himalayas is bounded by the MBT to the south and the Main Central Thrust (MCT) to the north. This sequence consists of sedimentary rocks, low-grade metamorphic rocks, and granitic intrusion distributed throughout the Nepal Himalayas (Fig. 4.3c). This zone is composed of quartzite, limestone, slate, siltstone, schist, gneiss, marble, amphibolite, Nepheline syenite, and granite, ranging in age from the Precambrian to Eocene (Bordet et al. 1961; Hagen 1969; Kohn et al. 2010; Parrish and Hodges 1996), including the oldest Lesser Himalayan Augen gneiss (1.8 B) in the Kuncha Formation (DeCelles et al. 2000; Le Fort and Rai 1999). There is a clear depositional gap between the Proterozoic rocks and the overlying Paleogene beds, indicting a prolonged history of denudation (Dhital 2015). This sequence has a complex pattern of nappes, klippen, and windows due to thrusting, erosion, and folding (Fig. 4.3). The Okhaldhunga, Arun, and Taplejung windows are well exposed in eastern Nepal, where they are surrounded by the Higher Himalayan thrust sheet (Brunel and adnrieux 1977; Dhital 2015). While it is difficult to classify more than a 15 km pile of the Lesser Himalayas, Valdiya (1964) classified araneceous, calcareous and pelitic units that were later applied throughout the Nepal Himalayas (Sharma 1973).

4.2.4 Higher Himalayas

About 10 to 12 km thick crystalline sequences of the Higher Himalayas consist of high-grade metamorphic rocks. This

Fig. 4.3 Different rock types of the different geological zones of the Nepal Himalayas. **a** Sand and gravel in the Indo-Gangetic Plain at the Karnali River, Kailali; **b** Contact between gravel and sandstone beds in the upper Siwalik, Puntura River, Dadeldhura; **c** Highly fractured quartzite beds of the Lesser Himalayas, Kaligandaki River, Myagdi; **d** Garnetiferous schist of the Higher Himalayas, Kaligangaki Valley, Myagdi; **e** Fold and fault of Tibetan sedimentary rocks, Kaligandaki River, Mustang. *Photos credit* Basant Raj Adhikari

zone is confined by the South Tibetan Detachment System (STDS) with the Tibetan-Tethys sedimentary sequence and the MCT to the south marking the border with the Lesser Himalayas. The first appearance of the MCT is marked by the garnet minerals in the schists, which record the temperature and pressure of the thrust movement during the evolution of the Himalayas (Fig. 4.3d). It consists of Tertiary Leucogranites in the upper portions, whereas high-grade crystalline rocks including various kinds of gneisses, schists, and migmatites extend continuously along the entire length of the Nepal Himalayas (Fig. 4.2). Le Fort (1981) classified these leucogranites into two types of granites: older granites from 500 to 1800 Ma and younger leucogranites from 15 to 20 Ma. Detailed classification of the Higher Himalayan crystalline is extremely difficult because it is located in high altitudes in remote locations. Le Fort (1975) studied the Kali-Gangaki section in detail and classified the Higher Himalayas into three formations: Formation I, II, and III (from bottom to top). Formation I is the lower unit consisting of kyanite-garnet-two mica banded gneiss of politic to arenaceous origin. Quartzite beds are at the base of the Formation II, followed by the alternation of pyroxene and amphibole-bearing calc-gneisses and marbles. Formation III is composed of coarse-grained augen gneiss.

4.2.5 Tibetan-Tethys Zone

The Tibetan-Tethys zone is the northernmost tectonic zone of the Nepal Himalayas, extending to the Eurasian plate and the Indus Tsangpo Suture Zone (ITSZ). It consists of sandstone, limestone, quartzite, and shale with fossiliferous layers ranging in age from the Cambrian to Eocene (Dhital 2015). These rocks are strongly folded and faulted in different places (Fig. 4.3e). A pioneering expedition lead by Tony Hagen (Hagen 1959, 1968) first described the Tethys succession in the Thakkhola region followed by Gerhard Fuchs (Fuchs 1964, 1977) in the Thakkhola and Dolpo sections. Bodenhausen et al. (1964) established the basic stratigraphy of the Tethys zone in the Kali-Gandaki section in their expedition in 1962. This succession is also comparable with the sedimentary units exposed to the west in Kumaon, Spiti, and northwestern Himalayas (Gaetani et al. 1986; Gaetani and Garzanti 1991). This zone is highly fossiliferous, consisting of bicalcarenites, pelletal mudstone/wackestone, oolitic grainstone, bivalves, gastropods, brachiopods, crinoids, belemnites, and rare fish fragments (Bassoullet et al. 1986; Bodenhausen et al. 1964) in the Kali-Gandaki section.

4.3 Physiographic Subdivision of the Nepal Himalayas

The Nepal Himalayas extends 800 km from east to west. Nepal occupies 147, 516 km^2 and consists of more than 80% mountains and hills. The altitude varies from 64 m asl (Kechanakal, Jhapa) to 8888.86 m asl (the top of the world, Mount Everest) within an aerial distance of about 150 km (Dhital 2015). The Nepal Himalayas has a steep slope, rugged mountains, deep valleys, intermontane basins, and flat land. It is divided into five major physiographic regions: Tarai (below 200 m asl), Siwalik (100 to 2000 m asl), Hill (200 to 3500 m asl), Middle Mountain (700 to 4100 m asl), and High Mountain (1800 to 8888 m asl) on the basis of elevation and climate (Fig. 4.4) (LRMP 1986).

4.3.1 Tarai

This is the southernmost region of the Nepal Himalayas and the northern edge of the Indo-Gangetic plain lying at an altitude of 64 to 200 m. It consists of Pleistocene to Holocene sediments generated from the Himalayas (Fig. 4.5a). These sediments are deposited by major river systems in the Nepal Himalayas, with the sediment size varying from north to south, with large boulders present in the northern side of the Tarai and the grain size decreasing gradually down to clay on the southern side.

The Tarai region is generally divided into three zones: the Bhabar zone, the Middle Tarai and the Lower Tarai. The Bhabar zone lies in the foothills of the Himalayas (Siwaliks) and consists of poorly sorted boulders, cobbles, sand, and silt derived from the Siwaliks and older rocks. The Middle Tarai has a gentle slope (1 to 5%) and consists of mostly sandy and silty soils formed by braided alluvial deposits. The Lower Tarai is the southernmost part of the Tarai, which consists of pebbles, fine silt, and clays. The climate is subtropical and rainfall occurs mostly in June and July (monsoon season). The winter temperature is not severe and the minimum recorded temperature is around freezing. Erosion is generally low, though gulley erosion can be seen in some areas.

Some elongated valleys lie between the Mahabharat and Siwalik ranges representing Inner Tarai. These valleys, namely Udayapur, Chitwan, Dang, Deukhuri, and Surkhet, lie from east to west, and were formed due to continuous erosion from rivers originating from the Mahabharat Lekh and Siwalik.

4.3.2 Siwaliks

The Siwaliks lies in the frontal part of the Himalayas and is locally known as the Churia Hills in Nepal. It extends from east to west parallel to the Himalayan arc, and many dun valleys lie between the Siwaliks and the Hills. The altitude varies from 100 to 2000 m. This region consists of sedimentary rocks and generally has a fragile landscape (Fig. 4.5b). Rainwater significantly affects the soft and loose soil so that debris flow hazards are common in this region. The region is about 20 km wide near the Mahakali River and less than 1 km wide near the Mechi River.

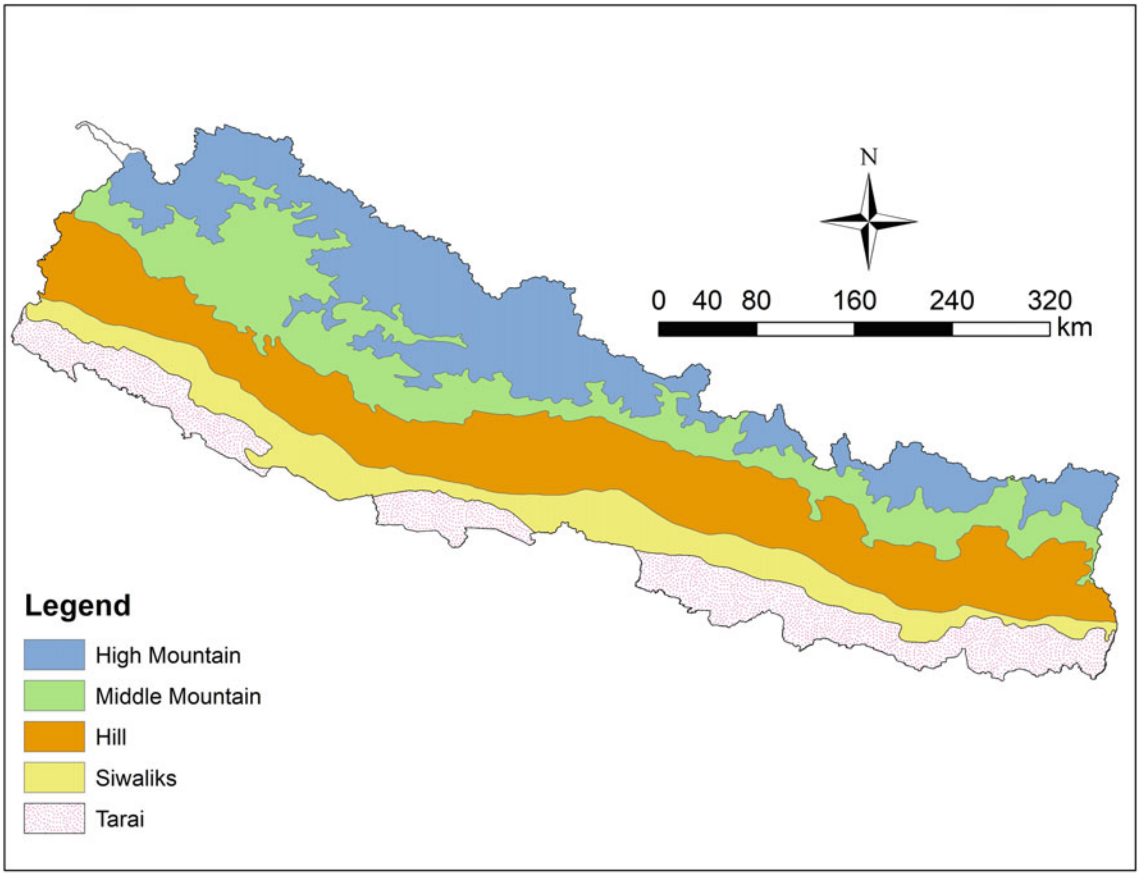

Fig. 4.4 Physiographic map of Nepal. Modified after LRMP (1986)

4.3.3 Hills

The Hills region is located south of the Middle Mountain region and north of the Siwaliks; however, there is no clear boundary between the other two regions. The altitude varies from 200 to 3500 m and extends east to west parallel to the Himalayas. This region consists mostly of agricultural land because of high weathering and erosion rates coupled with rainfall. The extensive erosion in some places has exposed mostly underlying rocks of metamorphic origin. The Hill region consists of Lesser and Higher Himalayan rocks, though some hills are covered by forest, bushes, and grasslands, with some landslides (Fig. 4.5c). This region is dissected by different major river systems in the Nepal Himalayas, resulting in different intermontane valleys (i.e., Pokhara, Kathmandu, and Dhankuta).

4.3.4 Middle Mountain

This region consists of a steep and fragile landscape ranging in altitude from 700 to 4100 m asl (Fig. 4.5d). This region is dissected by two major antecedent rivers (Koshi and Karnali) and is comprised of mostly Higher Himalayan rocks covered by snow in the winter. People have been practicing agriculture on the gentle slopes because the micro-climate is suitable for wheat, maize, millet, and other cash crops. Generally, the climate is warm-temperate, though the micro-climate varies from east to west due to different geomorphology and land use.

4.3.5 High Mountain

The High Mountain region lies in the northern part of the Nepal Himalayas. The altitude ranges from 1800 to 8848.86 m asl and consists of steep slopes with narrow valleys. These high peaks are covered by snow year-round, though some steep slopes at low altitudes are forested (Fig. 4.5e) (Table 4.2). Most of .the valleys at high altitudes consist of glaciers from which all the perennial rivers originate. This region is made up mainly of metamorphic rocks and some sedimentary rocks of the Tibetan-Tethys zone. This region acts as a barrier for Indian monsoons and is responsible for high amounts of rainfall in the southern slope but prevents air moisture from entering the Tibetan Plateau.

Fig. 4.5 Physiographic landforms of different regions. **a** Flat alluvial land of Tarai, Ratu River, Mahottarai; **b** Fragile landscape of the Siwaliks, Kailali; **c** Panoramic view of Hills in the Nepal Himalayas (looking south from the Dolkha); **d** Steep mountains in the Middle Mountain region, Kalikot; **e** Snowcapped mountains in the High Himalayas region, Pokhara. *Photos credit* Basant Raj Adhikari

The climate is cool temperate below zero for more than six months at a time. Agricultural production is mostly concentrated in the valley bottom. The Trans-Himalayan valleys such as the Lo-Manthang, Manang, and Dolpo lie in this region. Many large glaciers and glacial lakes exist in this region and some are potentially in danger of bursting (Veh et al. 2018).

4.4 Conclusion

The evolution of the Nepal Himalayas began around 55 Ma ago and plays an important role in the development of different tectonic discontinuities, which separated different tectonic subdivisions of the Nepal Himalayas. These tectonic

Table 4.2 Physiographic zones of Nepal and their key features (LRMP, 1986)

SN	Physiographic zones	Elevation (m asl)	Area/coverage km^2	Geological/climate/notable feature
1	Tarai	64 to 200	20,220 (14%)	Indo-Gangetic plain, alluvial deposits, subtropical, fertile land
2	Siwaliks	100 to 2000	18,782 (13%)	Siwalik, sedimentary rocks, dissected by rivers, fragile landscape, concentration of settlements
3	Hills	200 to 3500	430,792 (29%)	Lesser and Higher Himalayas, sedimentary, igneous and metamorphic rocks, large-scale folds/thrusts, subtropical
4	Middle Mountains	700 to 4100	29,804 (20%)	Higher Himalayas, steep and fragile landscape, mostly metamorphic rocks, subtropical
5	High Himalayas	1800 to 8848	35,283 (24%)	Higher Himalayas and Tibetan-Tethys Himalayas, metamorphic and sedimentary rocks, steep valleys

zones have different rock types and evolutionary histories. The grade of metamorphism increases from frontal land to hinterland. These tectonic zones coupled with climate and altitude have strong significance on the physiographic division of the Nepal Himalayas. These physiographic divisions have different micro-climates, which control local land use patterns and people's livelihoods.

4.5 Glossary

Ganga Basin: A foreland basin of the Himalayas formed by the Ganga River. It extends from the border between the Ganga and Indus basins and the Aravali mountains to the west, the Brahmaputra basin to the east, and the Vindhyas and Chota Nagpur plateau to the south.

Himalayan arc: The entirety of the Himalayas is 2400 km long and is arc shaped. It extends from the Naga-Parbat (west) syntaxis to the Namcha-Barwa (east) syntaxis.

Indian plate: The Indian plate is one of the major tectonic plates in the earth's crust bordered by the Australian plate, the Arabian plate, and the Eurasian plate. The Indian plate includes most of South Asia and some parts of the Indian Ocean.

Eurasian plate: The Eurasain plate consists of most of Europe and Asia. It shares a boundary with the Indian Plate, the Arabian Plate, and the American Plate.

Lithostratigraphy: An element of stratigraphy that deals with the description and nomenclature of rock based on its lithology and stratigraphic relations. The lithographic classification is based on lithological properties and relations.

Indus Tsango Suture zone (ITSZ): This suture zone is the northern margin of the Himalayas that separates the Tibetan-Tethys zone from the Eurasian Plate. It is the result of a collision between the Indian Plate and the Eurasian Plate. This zone runs parallel with the Indus and Tsangpo rivers. Ophiollite rock is widespread here, showing the remnants of the back-arc basin.

South Tibetan Deatachment System (STDS): A major fault in the Nepal Himalayas, which separates the Higher Himalayas and Tibetan-Tethys zones. This is a low-angle normal fault sequence based on the assumption applied in wedge extrusion and channel flow models. The STDS is well exposed in the Kaligandaki, Manage, and Upper Dolpo sections of the Nepal Himalayas.

Main Central Thrust (MCT): A prominent thrust zone in the Nepal Himalayas, which separates the Lesser Himalayas and Higher Himalayas. The MCT may have been active between 25 and 15 Ma and active until 6 to 8 Ma. The thickness of the MCT is higher in western Nepal compared to eastern Nepal.

Main Boundary Thrust: This thrust separates the Lesser Himalayas and the Siwaliks. It is well exposed throughout the Nepal Himalayas and marked by a pressure ridge. Global Positioning System measurements show that it is still active, creating numerous landslides.

Main Frontal Thrust: This thrust separates the Indo-Gangetic plain from the Siwaliks and extends throughout the Himalayas. It can be identified in the field by non-foliated breccia, fault gouge, and brittle deformation microstructure within the host rock. However, it is very difficult to trace this fault on the surface. It uplifts the Himalayan topographic front.

Intermontaine basin: This basin developed within the mountain landscape during the formation or growing of the mountains. It is generally filled with alluvial deposits transported from the surrounding mountain slopes. Some examples in the Nepal Himalayas include Dang, Deukhuri, Pokhara, Kathmandu, Hetauda, Gaighat, Chitwan, Marin Khola, Puntura Khola and Sindhuli.

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