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Regional Geology and Geological Evolution of the Himalaya

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The Himalaya is divided longitudinally into five tectonic zones, known as (from south to north) the Siwalik Zone (or Sub or Outer Himalaya), the Lesser (Lower) Himalaya, the Higher (Great) Himalaya, the Tethys (or Tibetan-Tethys) Himalaya, and the Trans Himalaya. These tectonic zones are separated from each other by major intracrustal thrusts: the Main (or Himalayan) Frontal Thrust (MFT or HFT), the Main Boundary Thrust (MBT), the Main Central Thrust (MCT), the South Tibetan Detachment (STD), and the Indus-Tsangpo Thrust (ITT). The Himalaya originated as a result of the closing of the Tethys ocean and the subsequent continent-continent collision of the Indian and Asian (Karakoram-Tibet block) plates. The Ladakh-Gangdes granitic-volcanic arc of Cretaceous to early Eocene (100 to 40 million years) age resulted from the subduction of oceanic lithosphere of the Indian plate under the Asian continent. The rock assemblages found in the Indus-Tsangpo Suture region today, represent both the Tethys oceanic crust and the subduction zone complex. Prior to the collision, the Mesozoic sequence of the Tethys Himalaya represented the north-facing passive margin of the Indian plate. The collision between India and Asia took place between 55 and 40 million years ago. The collision and continued northward convergence of India produced the main intracrustal thrust faults, accommodating more than 500 km of crustal shortening. Crustal shortening generated metamorphism and leucogranites at the mid-crustal level (15-20 km), with the metamorphic and granitic rocks being brought to the surface along the MCT as Higher Himalaya crystalline. The principal phase of metamorphism, the main phase of activity of the MCT and of northward displacement along the South Tibetan Detachment, took place 18-22 million years ago. The thrusts grow progressively younger as one moves from north to south; the MCT was initiated 22 million years ago, the MBT 10 million years ago, and the MFT around 0.5 million years ago.

Introduction

The Himalayan mountain range extends from east to west in a massive arc for about 2,500 km with a width of 230 to 350 km. The Himalaya is the highest mountain range in the world, containing 10 of the world's 14 peaks over 8,000 masl, and more than 40 peaks over 7,000m. The Himalaya occupies a unique physiographic and geological setting: it lies between the Indian subcontinent with normal crustal thickness (35 km) to the south, and the highest plateau in the world, the Tibetan plateau with a double crustal thickness (70 km), to the north.

The Himalaya originated as a result of continent-continent collision between India and Asia (Dewey and Bird 1970; Powell and Conagan 1973). The collision took place 55-40 million years (Searle et al. 1987; Dewey et al. 1989). Penetration of India under Asia (Karakoram-Tibet) produced crustal shortening and slicing of the northern margin of the Indian continent into slivers along three principal thrusts: the Main Central Thrust (MCT), the Main Boundary Thrust (MBT), and the Main (or Himalayan) Frontal Thrust (MFT or HFT). The continental slivers were stacked one over the other, propagating southward and building the architecture of the Himalaya (Molnar 1984). The load of the crustal stacks flexed the Indian plate to the south giving rise to a foreland depression in which sediments of the Muree/Dharamsala and Siwalik groups, 18 million years old and younger, were deposited in the basin.

One of the striking features of the Himalaya is the extreme altitudinal variation from almost sea level on the Indo-Gangetic plains to an average elevation of 8,000m in the Higher Himalaya, all within a direct distance of less than 150 km. The perennial rivers of the range are fed by more than 5,000 glaciers, meltwater from accumulated snow, and monsoon rain. The combination of these agents with the young topography and altitudinal variation leads to the erosion of a vast amount of rock material, which is deposited from the Indo-Gangetic and Brahmaputra plains to as far away as the Bay of Bengal and Arabian sea, where the deposits form the very large Bengal and Indus fans.

Hillside stability and mass movement, including landslides, are controlled by several factors, including geology, climate, and topography. In the Himalaya geology plays an important role, but the geology is also very diverse as a result of the great variation in the composition of geological materials and the framework while traversing from south to north. The major zones are described below in the section on tectonic zonation. Fault and fracture zones are sites of structural weakness, to understand them and predict their effects we must understand the nature and origin of the Himalayan structures. Geodynamically, the Himalaya is an active tectonic belt, as evidenced by the changing mountain morphology and frequent earthquake activity. The effect of climate also varies across the region. South of the Higher Himalaya, in the region with a monsoon climate, rainfall is the dominant factor; whereas in and to the north of the Higher Himalaya, in the monsoon rain shadow zone, snow and temperature variation are the dominant factors. Topography is another factor showing great variation; both the topography and the drainage pattern of the Siwaliks, for example, are different from those of the Lesser and Higher Himalaya. Thus there is a very complex matrix of geology, climate, topography, hydrology, and seismic activity - each of which can play a vital role in destabilising slopes in different tectonic zones. Thus it is always difficult to assign failure of a hill slope to any one parameter.

Tectonic Zonation

According to Gansser's (1974) widely-accepted classification, the Himalaya can be divided longitudinally into five tectonic zones on the basis of geological evolution. The tectonic zones correspond broadly with the physiographic and climatic zones. From south to north, the tectonic zones are the Siwaliks (also known as the Outer or Sub Himalaya), the Lesser (Lower) Himalaya, the Higher (Great) Himalaya, the Tethys (Tibetan) Himalaya, and the Trans Himalaya (Figures 1.1 and 1.2). The northern edge of the Indo-Gangetic Plain, or Terai, is sometimes included as the southernmost zone of the Himalaya. The Trans Himalaya is further subdivided into the Indus-Tsangpo Suture and the Lhasa-Karakoram block. These tectonic zones are separated from each other by the principal Himalayan thrust faults (Thakur 1981, 1992). The southernmost fault, the Main (or Himalayan) Frontal Thrust (HFT) separates the Siwaliks from the alluvial plains (the northern edge of the Indo-Gangetic Plain). The Main Boundary Thrust (MBT) separates the Lesser Himalaya from the Siwaliks. The Main Central Thrust (MCT) lifts the middle-level crustal rocks of the Higher Himalaya over those of the Lesser Himalaya. The South Tibetan Detachment (STD) marks the boundary between the Higher Himalaya and the overlying fossiliferous sequence of the Tethys Himalaya along a low angle normal fault. The Indus-Tsangpo Thrust (ITT) separates the rocks of the Indus-Tsangpo Suture in the Trans Himalaya from the Tethys Himalaya. These zones are described in more detail below.

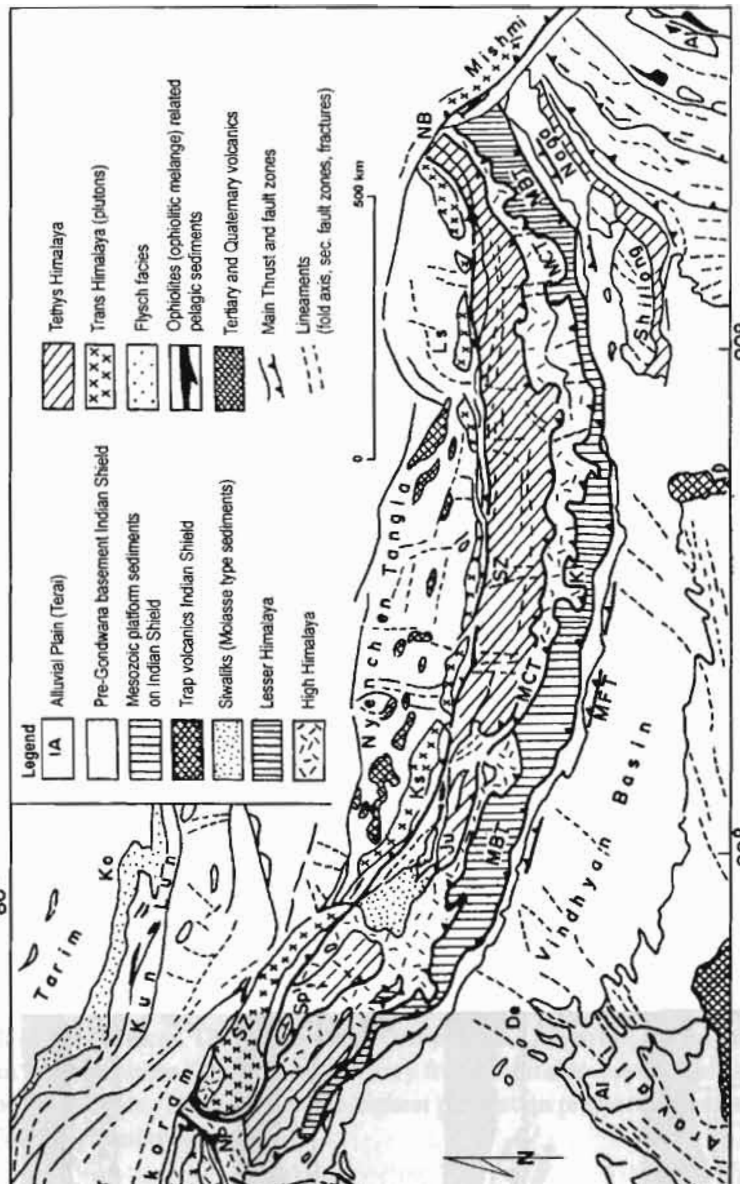

Figure 1.1: Tectonic zonation of the Himalaya (after Gansser 1974)

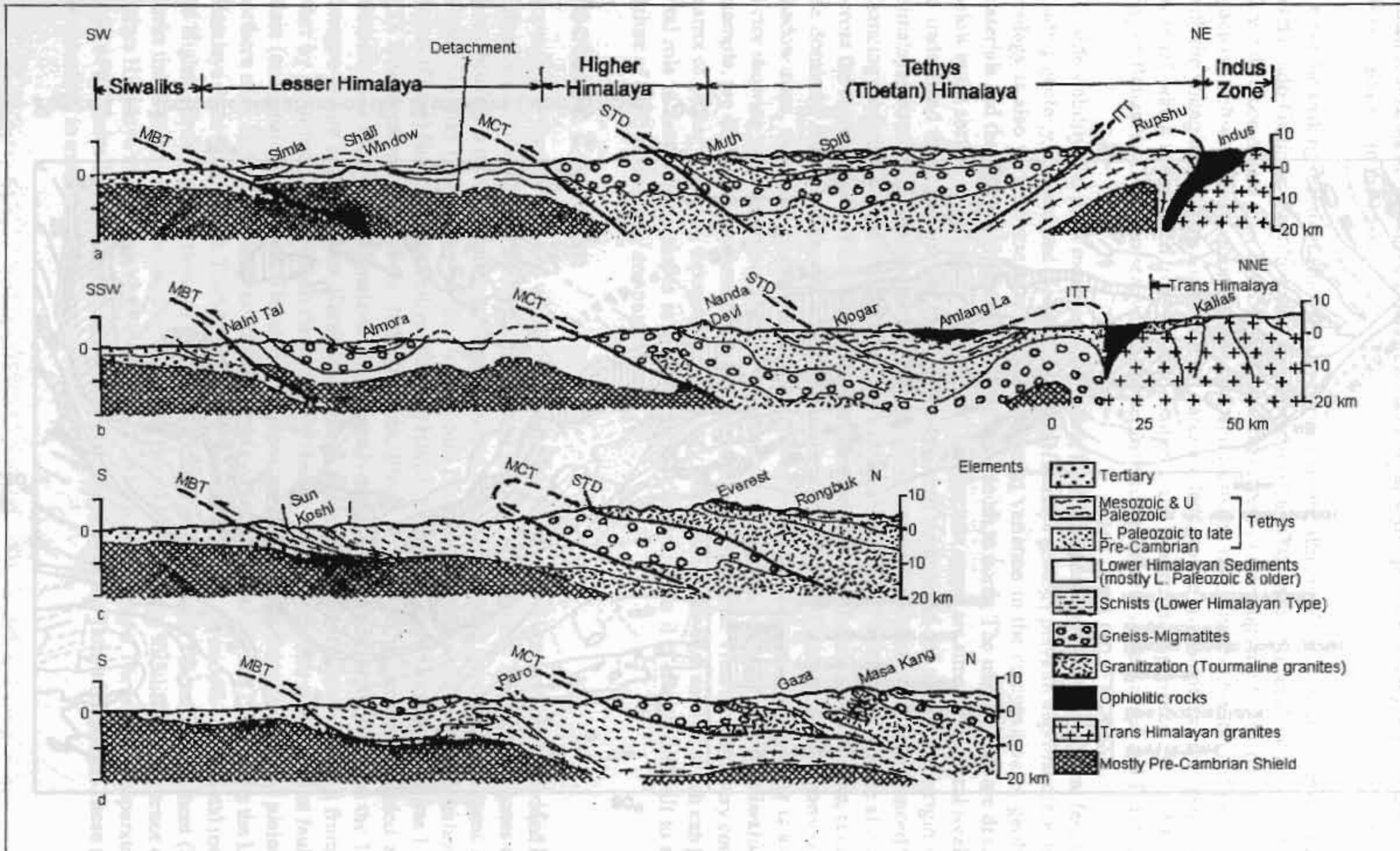

Figure 1.2: Cross-section across the Himalaya: (a) across Western Himalaya, (b) across Kumaun, (c) across Nepal, (d) across Bhutan (after Gansser 1974)

The Siwaliks or Outer Himalayan Zone

The foothill ranges of the Himalaya are called the Siwaliks and comprise the southernmost tectonic zone, which is also called the Outer or Sub Himalayan Zone. The altitude ranges from almost sea level to more than 800m, with an average of 500m. The climate is tropical with a great variation of temperature between summer and winter. Erosion is faster than in other zones of the Himalaya, especially during the monsoon. The Siwaliks consist of an 8,000-10,000m thick pile of sedimentary rocks ranging in age from Paleocene (50 million years ago) to Upper Pleistocene (0.2 million years ago) (Burbank et al. 1997).

The Siwaliks are bounded to the south by the Main (or Himalayan) Frontal Thrust (MFT), which separates them from the alluvial plains. To the north, they are separated from the older rock formations of the Lesser Himalaya by a fault called the Main Boundary Thrust (MBT). The Siwalik Zone is further differentiated into the Rawalpindi Group, which includes Paleocene-Lower Eocene-marine and Murree/Dharamsala Group fluvial sequences, and the Siwalik Group (Burbank et al. 1997). The rock formations of the Siwalik Group include thick bedded sandstone, mudstone, and shale in the lower and middle parts, and conglomerate in the upper part. These rocks are of fluvial origin, that is they were deposited by rivers in a situation similar to that of the present day Indo-Gangetic plains (Raiverman et al. 1983). The Siwalik strata have yielded rich assemblages of vertebrate fossils of elephant, hippopotamus, giraffe, horse, bovines, tortoise and many others similar to those of the present day, and of their ancestral fauna (Barry et al. 1982). These fossils were used in earlier times to assign ages to the rock formations. In recent years a more precise method, magnetostratigraphic dating, has been used and has shown the base of the Lower Siwalik to be 18.3 million years old, the Middle Siwalik to be 6 to 8million years old, and the Upper Siwalik to be 5.44 to 0.22 million years old (Johnson et al. 1983; Thakur 1992). Paleoenvironmental reconstruction of the Siwaliks based on plant and vertebrate fossils, rock types, and sedimentary structures, indicates that 15 million years ago the climate was warm and humid with active monsoons, that the area had dense forests inhabited by large mammals, and that it was drained by rivers and contained swamps and lakes.

Lesser Himalayan Zone (LHZ)

The mountain ranges lying between the Siwalik foothills and the Higher Himalaya comprise the Lesser Himalayan Zone (LHZ). This zone is characterised by V-shaped valleys and ridges with several levels of river terraces. The average height varies from 1,500m to 2,000m, with a maximum of up to 3000 m in some places. The climate can vary from tropical to subtropical and subtemperate depending on the altitude. This zone has the highest population pressure and most anthropogenic activities of all the Himalayan Zones.

Geologically the LHZ is bounded by two major intracrustal thrusts, the Main Boundary Thrust (MBT) to the south and the Main Central Thrust (MCT) to the north. The LHZ is structurally very complex; between the MBT and the MCT several thrust sheets lie stacked one over the other and folded and faulted on a large scale (Valdiya 1980). The LHZ has two principal components: a) sedimentaries and low grade metasedimentaries including quartzite, limestone, slate, siltstone, and volcanics; and b) crystalline thrust sheets comprising metamorphic rocks like schist, gneiss, marble, metavolcanic, and granites. The sedimentary and metasedimentary rocks of the LHZ are predominantly PreCambrian, i.e. more than 600 million years old, and are believed to represent a continuation of the rock units of the Indian continent; whereas the crystalline thrust sheets were derived and transported from the Higher Himalaya Zone to override the Lesser Himalayan rocks. The granitic gneisses and granites in the crystalline thrust sheets have been dated as 1,800 and 500 million years old, respectively (Valdiya et al. 1988).

Higher Himalayan Zone (HHZ)

The mountain ranges of the Higher Himalayan Zone (HHZ) appear as a rampart wall when viewed from the south. They constitute the highest uplifts in the Himalaya with an average height of over 6000m. The altitudinal variation is extreme. The Higher Himalaya acts as a great barrier to the South Asian monsoon causing it to precipitate most of its rain to the south; it also prevents the cold northern winds from Tibet and the Karakoram reaching the Indian plains. The climate is temperate alpine with a snowline at 5,500m. There are more than 5,000 glaciers, and large parts are covered by snow during winter. The topography is characterised by deep narrow gorges with narrow valleys and steeply rising mountains

The HHZ is composed of a 15-20 km thick slab of crystalline rocks comprising metamorphics like gneiss, schist, quartzite, marble, and amphibolite, together with granites (Pecher 1989; Hodges et al. 1996). These rocks are of Proterozoic age, 1,800-2,000 million years old, and were buried at mid-crustal level at a depth of 15-20 km. Originally, they constituted the northern part of the Indian continent. The southern boundary of the HHZ is demarcated by the Main Central Thrust (MCT). The MCT forms a broad (1-5 km) shear zone, which has brought the rocks of the HHZ from mid-crustal to their present level. The MCT is a structurally weak zone where there are frequent mass movements. A belt of moderate earthquakes lies close by (Yeats and Lillie 1991; Khatri 1987); some scientists think that this zone is neotectonically active. A pressure-temperature (PT) estimate of the metamorphic rocks of the HHZ indicates that they were buried at a depth of up to 20 km at temperatures ranging from 500 to 700°C and pressure of from 5,000 bar to 12,000 bar[1]. Two types of granites are associated with the metamorphics, older granites from 500 and 1,800 million years ago, and the younger leucogranites from 15 to 20 million years ago (LeFort 1981).

The Tethys Himalayan Zone (THZ)

The Tethys (or Tibetan) Himalaya (THZ) occupies a 30-40 km wide belt north of the Higher Himalaya. This zone has an average altitude of over 3,000m and lies in the rain shadow zone of the Higher Himalaya. It receives scant rainfall (less than 30 cm per year) and the climate is cold arid.

This THZ is characterised by a 10 km (maximum) thick, well-bedded sedimentary sequence made of limestone, marl, shale, quartzite, and sandstone. This sequence is richly fossiliferous and a paradise for fossil hunters (Gaetani and Garzanti 1991; Gardstein et al. 1991). The fossils of bivalves, molluscs, ammonoids, and others have helped scientists to assign ages to the different rock formations and construct biostratigraphic zones in the sequence. The Tethys Himalaya sequence of rocks range in age from Cambrian (500 million years old) to Lower Eocene (60 million years old). The THZ rocks are essentially composed of marine facies deposited in the shelf and slope region of a continental margin of the ancient Tethys sea (Gaetani and Garzanti 1991). A record of the marine life of the past is preserved in the rocks in the form of fossils, which have been extensively studied in Spiti and Malla Johar in India and in Nepal (Hayden1904; Sinha 1989; Gardstein et al. 1991). The Tethys sedimentary sequence overlies the crystalline rocks of the HHZ along a low angle, north dipping normal fault, the South Tibetan Detachment, and is separated from the rocks of the Trans Himalaya Zone to the north by the Indus-Tsangpo Thrust fault (ITT).

Trans Himalayan Zone (TRZ)

The Trans Himalaya Zone (TRZ) lies to the north of the Tethys Himalaya. Monsoon precipitation is very low, with an average annual rainfall of less than 30 cm. The climate is cold and dry. The base level erosion and valley floors lie at a height of 3,000m.

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[1] 1 bar = 10^5 Pa

The TRZ can be further divided into the Indus-Tsangpo Suture (ITS), and the Karakoram-Lhasa block. The Indus and Tsangpo rivers flow in opposite directions, towards west and east respectively, parallel to the mountain range. The Indus-Tsangpo Suture (ITS) represents the collision boundary between the Indian and Asia plates, and it is the site along which the vast Tethys ocean gap was closed (Searle et al. 1987). The ITS is mainly composed of ultramafic rocks (like peridotite and dunite), gabbro, and volcanics representing the oceanic crust of the Tethys ocean (Nicolas et al. 1981). The other components are granites, tonalites, and volcanics of magmatic arc, and sedimentary rocks of fore-arc, oceanic trench, and intramontane basin (Thakur and Misra 1984). These varied lithologies of rocks ranging from sedimentary to plutonic and volcanic have ages of 130 to 40 million years. The different hues in the suture zone rocks result in a dramatic panoramic landscape.

The Karakoram-Lhasa block to the north of the ITS comprises the Karakoram mountains and southern Tibet and belongs to the northern Asia plate. This is a region of high mountains and high plateaus with a minimum elevation of more than 4,000m. Rainfall is scanty and most of the precipitation is in the form of snow. The Karakoram-Lhasa block has three main components, a sedimentary sequence, granite, and metamorphics (Allegre et al. 1984; Searle 1991). The sedimentary sequence comprises limestone, marl, siltstone, sandstone, shale, quartzite, and subordinate volcanics. The rocks of this sequence are fossiliferous with an age ranging from Middle Paleozoic to Cretaceous (250 to 65 million years ago) (Yin et al. 1988; Gaetani et al. 1990; Bagati et al. 1994). The metamorphics predominantly comprise schist, gneiss, and phyllite and constitute a narrow belt underlying the sedimentaries. The granites form large bodies with areas of ten to a hundred sq km. and intrude the sedimentary and metamorphic rock sequences. The granites have been dated as around 95 million and 25 million years old (Scharer et al. 1984 a,b).

Geological Evolution

Approximately 200 million years ago before the Himalayas were formed, India formed part of a southern supercontinent called Gondwanaland. The other members of this assembly were South America, Africa, Australia, and Antarctica together with smaller fragments of Arabia, Madagascar, and New Zealand. The northern large landmass, Laurasia, included North America, Greenland, Europe, and most of Asia. A vast ocean called the Tethys lay between these two continental masses. Between 200 and 130 million years ago, a northern fringe separated from Gondwana into a number of small continental fragments which drifted north and were plastered against the southern margin of Asia, eventually forming Iran, Afghanistan, northern Pakistan and southern Tibet (Smith et al. 1981; Molnar 1986).

Closing of the Tethys Ocean

By 100 million years ago India had separated from the other southern continents; the 3,000-4,000 km wide Tethys ocean lay between India and Asia (which included the Karakoram and Southern Tibet). India continued its northward journey at a rate of some 10-15cm per year; the Tethys ocean gap closed and the Indian ocean opened (Figure 1.3). The closing of the Tethys ocean was accomplished by a downward movement, or subduction, of the oceanic lithosphere of the Indian plate under the southern Tibet and Karakoram part of the Asia plate (Figure 1.4).

The best present day example of subduction is that of the Pacific oceanic plate beneath the Japan and Aleutian islands, a process manifested in the generation of island arc volcanoes. The large sized granite bodies, exposed as a result of erosion in the Peruvian Andes and Western Cordillera of the USA, were produced as a result of subduction of the Pacific oceanic plate underneath the western continental coast of North and South America.

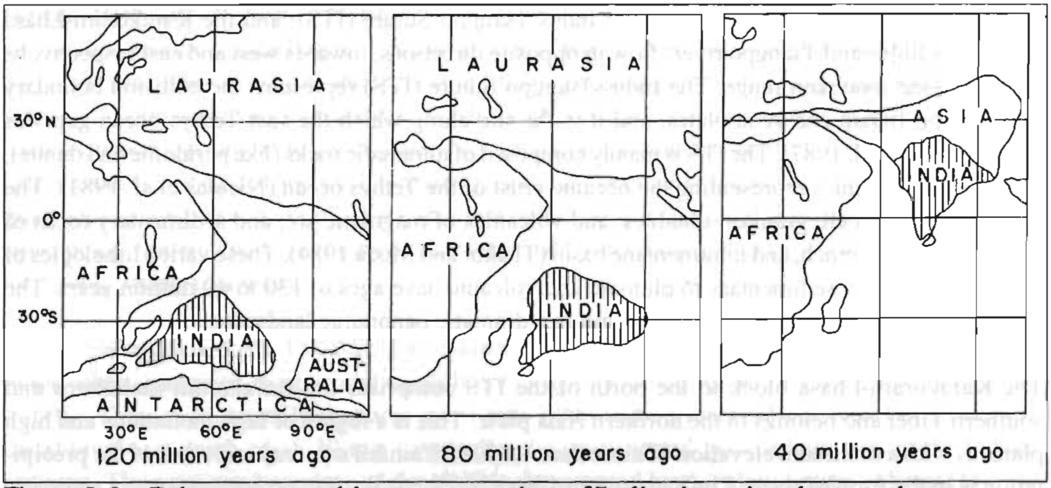

Figure 1.3: Palaeogreographic reconstruction of India vis-a-vis other southern continents 120 million years ago. Separation of India and its northward movement in closing the Tethys ocean through subduction process 80 million years ago. Collision of Indian continent against Asia (Tibet-Karakoram) and formation of Himalaya and high plateau of Tibet 40 million years ago (Smith et al 1981, Molnar 1986)

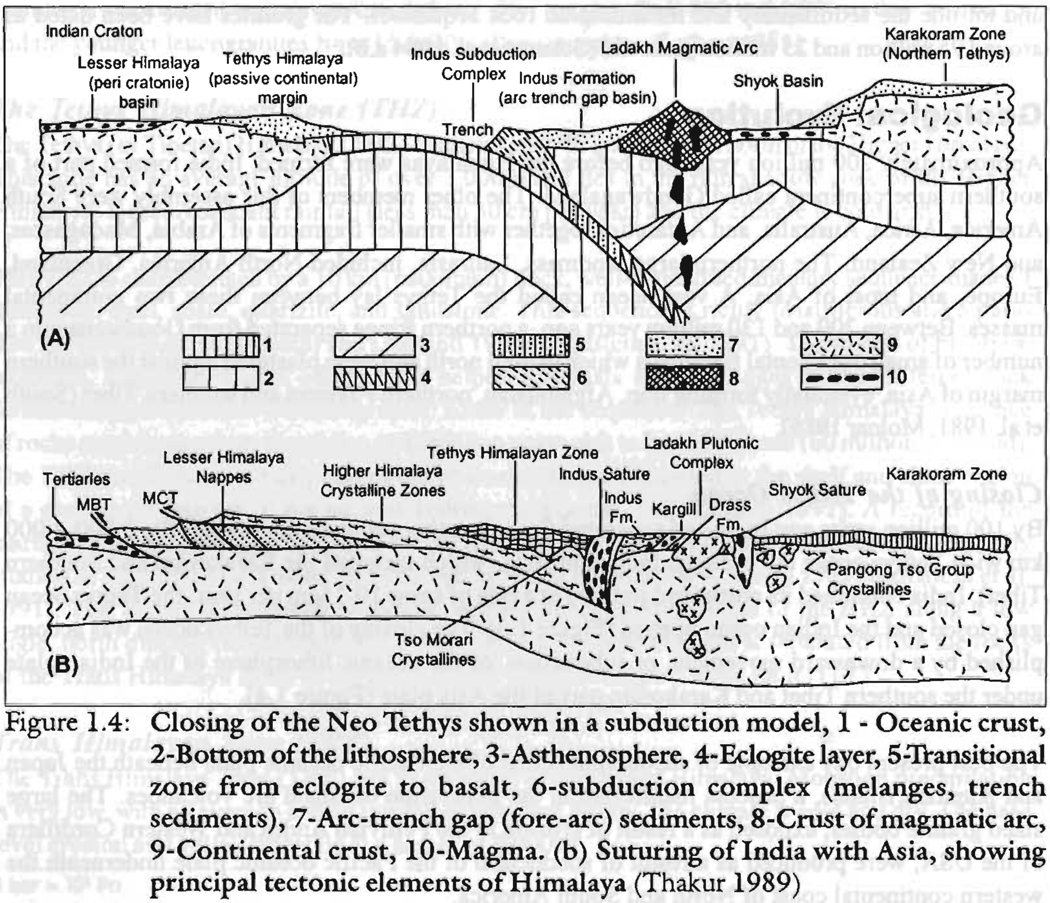

Figure 1.4: Closing of the Neo Tethys shown in a subduction model, 1 - Oceanic crust, 2-Bottom of the lithosphere, 3-Asthenosphere, 4-Eclogite layer, 5-Transitional zone from eclogite to basalt, 6-subduction complex (melanges, trench sediments), 7-Arc-trench gap (fore-arc) sediments, 8-Crust of magmatic arc, 9-Continental crust, 10-Magma. (b) Suturing of India with Asia, showing principal tectonic elements of Himalaya (Thakur 1989)

Geological mapping, geochemical analysis of the rocks, and geochronological dating have proven the existence of island arc volcanoes in Ladakh in India (Robertson and Degnan 1994), Kohistan in Pakistan (Asif Khan et al. 1993), and around Lhasa in southern Tibet (Allegre et al. 1984). These volcanics have ages ranging from 130 to 40 million years, the time of subduction of the Indian oceanic plate. Large granite bodies, hundreds of kilometres long, and associated igneous rocks occupy a belt extending from Deosai in Pakistan through Ladakh in India to the Gangdese mountains in southern Tibet. These granite bodies, 100 to 40 million years old, were generated as a result of subduction of the Indian oceanic plate under the Karakoram and southern Tibet (Honegger et al. 1982; Ahmad et al. 1998). Other evidence of the subduction process is provided by the ophiolitic melanges (scrapped-off oceanic crust rocks like serpentinite mixed with deep sea sediments) and very high pressure (> 8 kb) blue schist rocks recorded along the entire length of the Indus-Tsangpo Suture zone (Jan 1990). The remainder of the Tethys oceanic crust rocks, called ophiolite, are exposed as dismembered fragments along the suture zone both in Ladakh (Thakur and Misra 1984) and in southern Tibet (Nicolas et al. 1981). Thus the Indus-Tsangpo suture zone exposes rock assemblages that are typical products of the geological processes involved in the closing of the Tethys ocean by northward subduction of the Indian plate beneath Asia (Searle et al. 1987).

Continent-Continent Collision

By 55 million years ago, the Tethys ocean gap was completely closed, the oceanic lithosphere of the Indian plate lay beneath the Asian continent, and the continental lithosphere of the Indian plate was juxtaposed against the Asian continent. (The Indian plate has two types of lithosphere: continental, rich in silicates which have have a lower density, and oceanic, rich in Fe and Mg minerals which have a higher density).

Around 50 million years ago the Indian continent was completely lodged against the Asian continent resulting in collision tectonics (Coward et al. 1986). By that time the last remains of the marine condition of the Tethys had disappeared. As the continental crust of India could not sink to the great depths needed (>100 km) to be consumed (unlike oceanic crust), resistance developed against the northward movement of India. The rate of northward movement of India decreased from 15 cm to 5 cm per year. This decrease in rate and disappearance of marine condition are interpreted as representing the time of collision between the continents of India and Asia. After collision, as a result of the ongoing northward convergence of India against Asia (Tibet), the Indian crust thickened, producing metamorphism and transforming the deep-seated rocks of the Higher Himalayan Zone at temperatures ranging from 500 to 700°C and at pressures of 5 kb to 12 kb (Pecher 1989). Around 20-23 million years ago, the northern margin of the Indian continent was sliced at mid-crustal level (~15-20 km) along the fault called the Main Central Thrust (MCT). The rock sequences above the MCT were detached and moved south up to 100 km overriding the rock formations that now constitute the Lesser Himalayan zone (Figures 1.4 and 1.5). The MCT (Hubbard and Harrison 1989) originated at a depth of 15-20 km some 20-23 million years ago and brought the deep-seated rocks, metamorphics, and granites upward to be exposed to erosion as rocks of the Higher Himalaya. This upward thrust movement and erosion initiated the uplift of the Higher Himalaya.

Around 10 million years ago, the fault called the Main Boundary Thrust (MBT) developed south of the Lesser Himalaya as a result of continued northward convergence and slowdown of activity along the MCT (Meigs et al. 1995) (Figures 1.4 and 1.5). This thrust detached the top sedimentary layer of the Indian continent (now constituting the Lesser Himalayan Zone) and brought them up to override the younger rocks of the Siwalik (Outer Himalayan) Zone. Finally the Siwalik strata were uplifted as a result of the development of the Main (Himalayan) Frontal Thrust in Upper Pleistocene

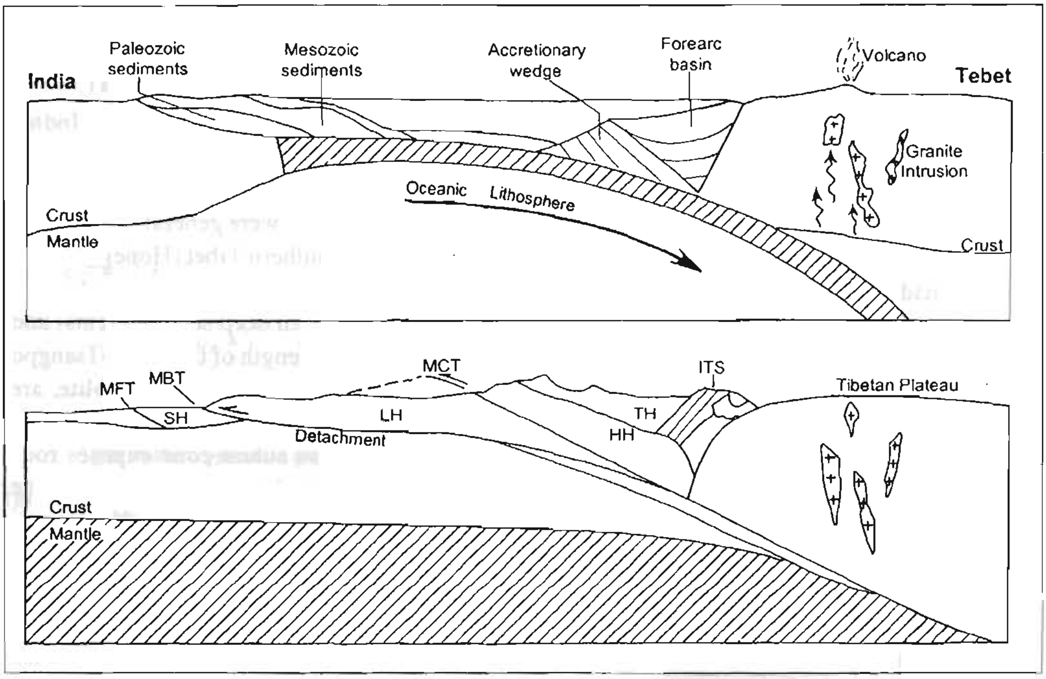

Figure 1.5: **Upper figure: closing of Tethys ocean by subduction of oceanic lithosphre of Indian plate under Tibet (Asia), producing island arc volcanoes, granite intrustions, accretionary wedge and fore-arc basin, some 80 million year ago. Lower figure: continent-continent collision between Indian crust and Tibetan crust at 50 million years ago. Slicing of Indian margin crust along MCT, MBT and MFT and stacking of crustal slabs** (after Molnar 1986, Valdiya 2988)

age (0.5 to 0.2 million years ago), producing a sharp topographic break between the Siwaliks and the alluvial plains (Nakata 1989). Thus the architecture of the Himalaya developed from the stacking up of slivers of the northern margin of India on top of one another (like a pack of cards) over the Indian plate (Molnar 1984). During this process, the crust thickened, and shortening of more than 500 km has been accommodated (Figure 1.5).

The stacking of thrust slabs (slivers) exerted a load on the Indian plate causing flexure (bending) of the plate (Lyon Chen and Molnar 1983). The flexed part of the plate in front of the uplifted Himalaya produced a depression (foredeep), called the foreland basin of the Siwalik and Indus-Ganga. The rocks that were eroded from the uplifted northern tectonic zones of the Himalaya were deposited as the sediments of the Siwalik Group and the Indus-Ganga basin. Dating of the Siwalik Group strata indicates that deposition of sediments started as early as 18 million years ago and has continued to the present. A considerable part of the eroded sediments from the mountains were taken to the sea and deposited to form the Bengal fan and Indus fan. Ocean bed drilling in these fans has yielded rocks at their base with a provenance from Himalayan rocks that are as much as 16 million yearsold.

It The deformation front in the Himalaya appears to have migrated southward. The thrusts grow progressively younger from north to south; the MCT was initiated 22 million years ago, the MBT 10 million years ago, and the MFT around 0.5 million years ago.

For the last 60 million years, the Indian continent has been penetrating deeper and deeper into the rest of Asia (Molnar 1986). In the process it has uplifted the Himalaya and Tibetan plateau. This penetration (convergence) continues to the present, making the Himalaya tectonically and seismically active. This neotectonic activity, together with the climatic factors of rain and temperature variation, and compounded by human intervention, make the Himalaya vulnerable to mass movement and other forms of environmental degradation.

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