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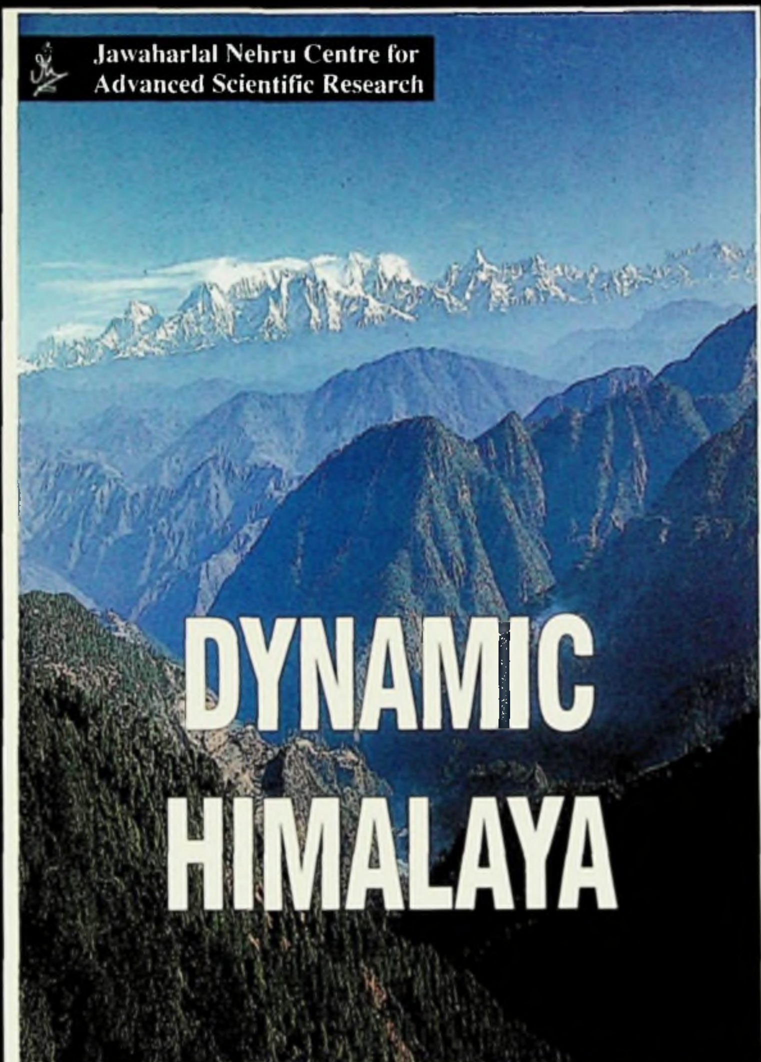

DYNAMIC HIMALAYA

K S VALDIYA

DYNAMIC HIMALAYA

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Foreword

The Jawaharlal Nehru Centre for Advanced Scientific Research was established by the Government of India in 1989 as part of the centenary celebrations of Pandit Jawaharlal Nehru. Located in Bangalore, it functions in close academic collaboration with the Indian Institute of Science.

The Centre functions as an autonomous institution devoted to advanced scientific research. It promotes programmes in chosen frontier areas of science and engineering and supports workshops and symposia in these areas. It also has programmes to encourage young talent.

In addition to the above activities, the Centre has undertaken a programme of publishing high quality Educational Monographs written by leading scientists and engineers in the country. These are short accounts of interesting areas in science and engineering addressed to students at the graduate and postgraduate levels, and the general research community.

This monograph is one of the series being brought out as part of the publication activities of the Centre. The Centre pays due attention to the choice of authors and subjects and style of presentation, to make these monographs attractive, interesting and useful to students as well as teachers. It is our hope that these publications will be received well both within and outside India.

C.N.R. Rao
President

Preface

Even though quite young in age, the Himalaya is disconcertingly complex in its structural design. It has experienced repeated crustal upheavals of great severity, many episodes of hot floods of lava and injection of molten rock material. Deposition of sediments in varied settings proceeded haltingly and differentially over more than sixteen hundred million years, even as life in varied forms appeared in succession and proliferated in bewildering complexity. Crustal movements not only squeezed the rock piles into folds and overlapping sheets but also tore them apart and uprooted them from the original sites of their formation. It is therefore not easy to decipher the history of the evolution of this colossus among the great mountains of the world.

As one who has had the exhilarating opportunity of sustained work spread over more than three decades in the geodynamically crucial and geologically very representative central sector of the Himalayan arc, I have tried to portray a simplified picture of the setting and origin of the Himalaya. In order to achieve a synthesis of disparate investigations and views and attain a broad understanding of the evolutionary history, I have had per force to cut down the maze of bewildering nomenclature that has grown over the years in the technical literature on the subject.

This book has been written primarily for laymen and students who have an understanding of the basics of geology. I have therefore desisted from using geological jargon. Information has been drawn from a large number of works, many of which have been cited. However, my own perceptions of things find free and unabashed projection, but without prejudice to the views of other workers.

I hope this little book will help readers to obtain a clearer understanding of the structure and evolution of the giant edifice of the *Nagādhirāj* — The King of Mountains.

The inspiration to write this book for laymen came from Professor R. *Narasimha, from* whom I derived scintillating stimulus. Professor C.N.R. Rao provided tremendous backing and all facilities. Years ago, Dr. B.P. Radhakrishna wanted me to write a book on the geology of the Himalaya for students of geology. This work thus combines my response to the curiosity of laymen and earth scientists alike.

January 1998 K.S. Valdiya

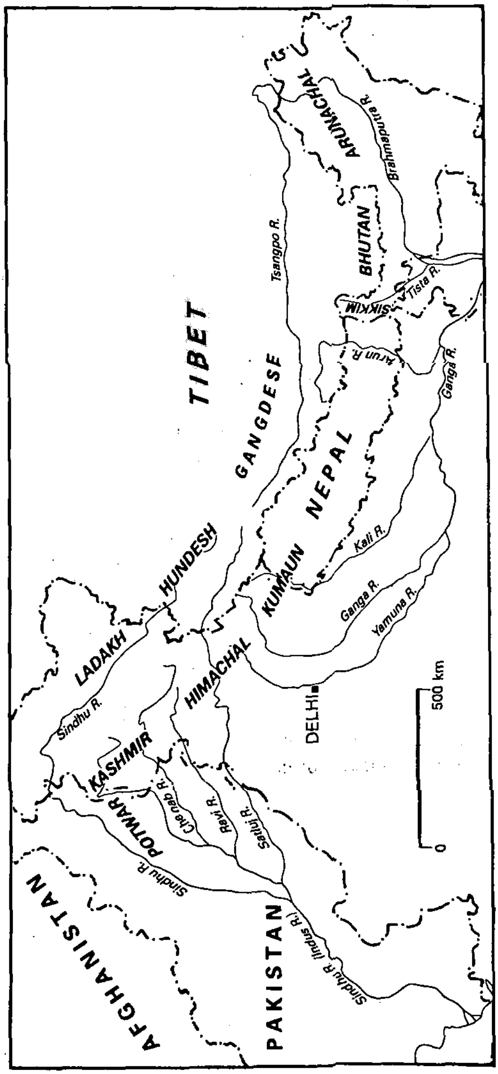

Fig. P1 *Various geographical–geological sectors of the Himalaya.*

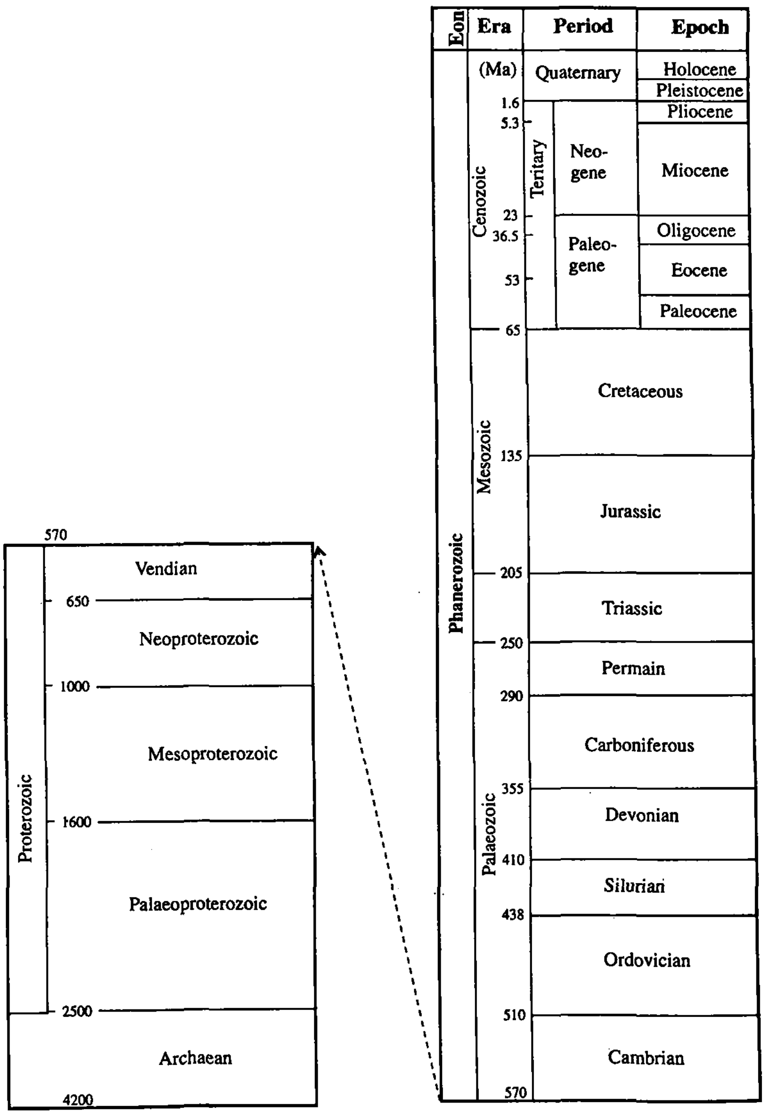

Fig. P2 *Geological time-scale showing divisions of the geological time.*

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This work has really benefited immensely from the critical scrutiny and reviews by Prof. R. Narasimha, Prof. S.K. Shah, Prof. S.B. Bhatia, Prof. Ashok Sahni, Dr. S.P. Jain, Dr. O.N. Bhargava, Dr. V.C. Thakur, Dr. K.K. Sharma, Dr. N.S. Virdi, Dr. A.C. Nanda, Dr. T.N. Bagati, Dr. M.I. Bhat, Dr. V. Raiverman, Prof. B. Parkash, Prof. Ramesh Chander, Prof. S.K. Tandon, Prof. R.C. Fuloria and Dr. S.K. Acharyya.

The Cartography Department of Sangam Books Ltd., in particular Mr. Guru Brahmam and Mr. M.R. Srinivas did an excellent job of redrafting the maps.

Smt. Radha G. Prasad and Smt. K. Pramila very painstakingly typed out the text of the manuscript.

I am profoundly grateful to all these well-wishers and friends.

K.S. Valdiya

1 *Many-Splendoured Mountain*

1.1 'Nagādhirāj'

Dwarfing all other mountains of the world in sheer height, the Himalaya is truly the *Nagādhirāj* — a colossus among the great mountains of the world. The ever-snowy resplendent summits of the Great Himalaya, broken by precipitous scarps (Plate 1A), evoke admiration not unmixed with awe. The astonishingly gentle topography of the Lesser Himalaya with its hurrying streams, whispering woods and smiling fields (Plate 1B) has for millennia attracted unending streams of pilgrims and saints, poets and philosophers, explorers and mountaineers, warriors and fugitives—many of them making it their home. In the enchanting wilderness of the densely forested Siwalik in the southern front live and roam an enormously diverse variety of beasts and birds.

1.2 Restless giant

Very young in age, the rugged Himalaya continues to be seized repeatedly with spells of tectonic restlessness or crustal disturbances. These disturbances indicate accumulating inner tectonic stresses in the crust. The giant body of the mountain quivers in some segments or twitches spasmodically and breaks up violently in other places. These are the manifestations of the tectonic turmoils of growing, for the Himalaya is still growing. Consequently, its framework of structure is recurrently deformed and the landscape reshaped time and again. It is the titanic force of compression resulting from the coming together and eventual collision of the continents of India and Asia that transformed the once enormous pile of layered rocks on the northern margin of the Indian shield into the Himalaya of immense splendour and magnificence.

As the Indian landmass continues to move and press Asia, stresses and strains are building up and accumulating progressively in the fractured frame of the Himalaya. Natural hazards are therefore very common in the mountain domain as well as in the adjacent Indo-Gangetic Plains formed out of the detritus derived from the quivering and growing Himalaya.

1.3 Controller of climate

Guarding the northern border like a mighty sentinel, the Himalaya has not only witnessed the unfolding history of evolution of the Indian civilization, but has also moulded the destiny and lifestyles of its people.

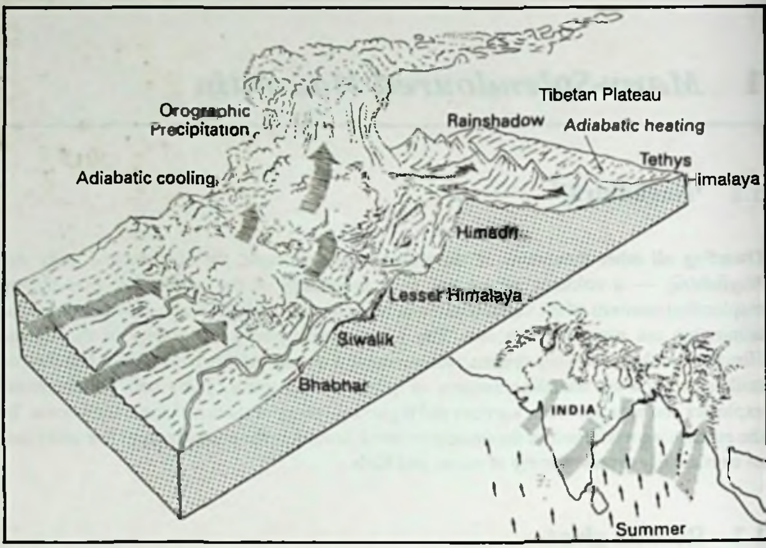


Fig. 1.1 *The Himalaya is the controller of the peculiar monsoon climate in Asia and governs the unique succession of six seasons in India. Arrows indicate the direction of moisture-laden clouds, which rise up as they dash against the mountains (after K.S. Valdiya, 1987).*

The 2400 km long and 250 to 300 km wide mountain barrier, which rises 500 to 8000 m above sea level, vitally affects the atmospheric circulation of the Asian continent including India and controls the climatic conditions here. The Himalaya is responsible for the peculiar monsoon climate of the subcontinent and its unique succession of six seasons — *Vasant, Grishma, Varsha, Sharad, Shishir* and *Hemant* (Fig. 1.1). If there were no Himalayan ranges to wring out moisture from the passing clouds, much of the subcontinent would have been a thirsty, parched and desolate land. The insuperable barriers that stop the clouds from going north are also responsible for the desiccation in Ladakh and Tibet and the development of a hot desert in western India.

The snow-covered ranges have exercised a moderating influence on the temperature and humidity in the land that stretches down to Kanyakumari. Not only that, the Himalaya prevents the ingress of cold wintry winds from Siberia and ensures winters warmer than those would have been in northern India if the Himalaya had not been there.

1.4 Bounty of the Himalaya

The Himalaya confers many gifts on the Indian subcontinent. It is the provider of life-giving water to the subcontinent (Plate 2A). Nearly 1,20,00,000 million cubic metres (m.m^3) of

(A)

(B)

Plate 1(A) Majestic Kedarnath of the Great Himalaya (Himādri) with its facade of awesome scarp nearly 3000 m high. **(B)** Sluggishly and quietly flows the Kosi in its wide and winding course in a mild terrain of the Lesser Himalaya. (Photos by K.S. Valdiya)

(A)

(B)

Plate 2(A) The Himalaya provides a bountiful supply of water to the northern part of the Indian subcontinent. (Photo of the Mandakini in Garhwal by K.S. Valdiya)

(B) Frozen asset—the snow cover (white) in Himachal Himalaya. An Indian remote sensing satellite picture. (Courtesy, Dr. Anshu K. Sinha)

Plate 3 The Himalayan mountain chain is characterized by convex bulges, inward pointing angles and knee-bends at the two extremities.

(A)

(B)

Plate 4(A) Valleys of the Himādri and adjacent belt of the Tethys Himalaya have almost vertical to convex walls and channels. (Photo by K.S. Valdiya of the Dhauli Ganga in Garhwal)
(B) Extraordinarily wide valley of the Sindhu River in Ladakh which flows along the junction of the collided continents of India and mainland Asia. (Photo by M.E. Brookfield)

water flowing down the Himalayan rivers annually (Table 1.1) sustain and nourish the teeming millions of the Indo-Gangetic Plains in which nearly 60% of India's population live in dense concentration. In addition, these waters have the potential of generating 28 million kilowatts of electricity—11,579 kW by the Ganga, 9988 kW by the Sindhu and 6582 kW by the Brahmaputra[173]. Nearly 2,46,600 million m^3 of water from these rivers can be utilized for irrigation—1,85,000 million m^3 of water of the Ganga, 12,300 million m^3 of the Brahmaputra and 49,300 million m^3 of the Sindhu[173] (Table 1.1).

Table 1.1 *Average annual flows and potentials of Himalayan rivers (after Y.K. Murthy, 1981)*

River	Flow ($\times 10^9\ m^3$ / yr)	Irrigation potential ($\times\ 10^9\ m^3$)	Power potential (kW at 60% load factor)
Brahmaputra System	479.30	12.3	9,988
Ganga System	459.84	185.0	11,579
Sindhu System	207.80	49.3	6,582
Total	1147.00	246.6	28,150

This tremendous, almost inexhaustible reserve of life-giving water is replenished directly by rains every year and by the melting of snow and ice occurring at higher altitudes. The average rainfall is 240 cm/yr in the southern front, 150 cm/yr in the populated Lesser Himalaya (in the middle belt where the mountain ranges are 1500 to 2500 m high), 240 to 350 cm/yr in the snow-capped Great Himalayan domain (of rugged ranges 5000 to 8000 m high), and just 10–15 cm/yr in the Tethys domain across the Great Himalaya in the north. The rainfall decreases progressively from east to northwest — from 300 cm/yr at Darjiling, 50 cm/yr at Shimla in Himachal to a mere 10 cm/yr at Leh in Ladakh. The greater proportion of rain water is carried down the valleys in the short period of three months of the rainy season and only a small part (less than 15%) of the rainfall percolates down through the soil and rocks to recharge mountain springs. It is these springs that substantially feed the Himalayan rivers.

The bounty of the Himalaya is also locked in the 1400 km^3 of snow and ice, spread over nearly 33,200 km^2 area in higher altitudes (Plate 2B) above the 4300–5800 m snowline. There are over 15,000 glaciers here. The melting of this frozen asset contributes, on an average, about 58% of the water flowing down the Himalayan rivers — 50 to 70% in the northwestern sector and a little less than 30% in the eastern[19].

How important the role of glaciers is in the water budget of the Himalayan rivers can be judged from the fact that the Gangotri glacier spread over 200 km^2 area is capable of yielding three times the water held in the Govind Sagar behind the Bhakra Dam[333]. The Himalayan snow cover has long been known to affect the monsoon in India.

1.5 Energy from hot springs

There are a large number of springs spewing out heated water and steam in certain belts of deep, long faults. These are inexhaustible sources of thermal energy when tapped. There are

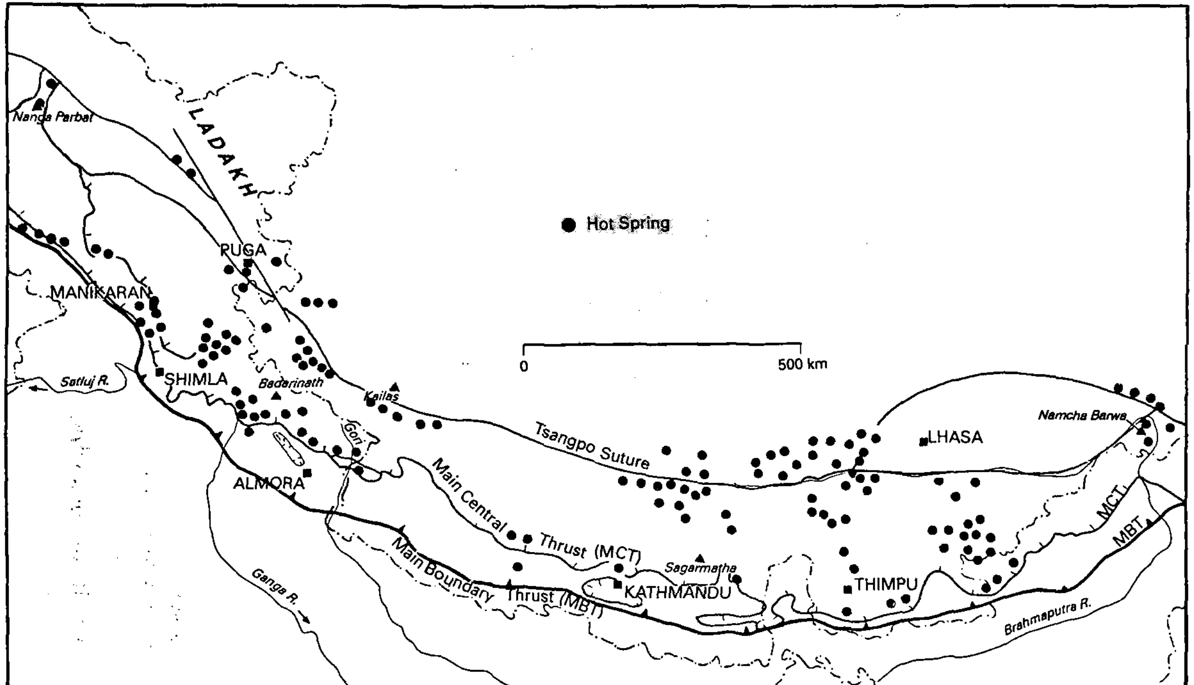


Fig. 1.2 *Hot springs are located in the zones of deep faults that define the tectonic boundary of the Himalayan terranes or subprovinces (based on R. Shanker, 1989, and A. Gansser, 1991).*

34 hot springs in Ladakh, 34 in Himachal Pradesh, 37 in Kumaun, 7 in Sikkim and 11 in Arunachal Pradesh. Figure 1.2 shows the locations of these hot springs in the Himalayan domain.

The hot springs are located in the zones of deep faults that define tectonic boundaries between the Himalayan province and Asia (known as Indus–Tsangpo Suture (I–TS)), between the Great Himalaya and Lesser Himalaya (described as Main Central Thrust (MCT)) and between the Siwalik domain and the Lesser Himalaya (called Main Boundary Thrust (MBT)). According to R. Shanker[(241)] these hot springs have the potential of generating power varying from 130 mW/m^2 to 468 mW/m^2.

The geothermal activity is very strong in the Sindhu Valley in Ladakh where heat-flow is of the order of 300 mW/m^2. Hot springs along the Main Central Thrust, which defines the boundary of the Great Himalaya against the Lesser Himalaya, emit heat at an average rate of 130 ± 30 mW/m^2, while those on the boundary zone between the Siwalik and Lesser Himalaya have an average heat-flow of 41 ± 10 mW/m^2

1.6 Wealth stored in rocks

Although the Himalaya is not blessed with fabulous mineral wealth, deposits of certain minerals are considerable. Reserves of magnesite, dolomite, cement-grade limestone, roofing slate, pavingstone and gypsum are very large and economically very promising. Other minerals like steatite (talc), phosphorite, lignite, rock salt, base metals, etc. are substantial although their mining at present is not economically viable.

There are notable deposits of high-cost but low-volume minerals occurring in various parts of the Himalaya. These deposits can be mined in times of acute need and emergency. Promising deposits of uranium-bearing minerals occur in many places in all four geomorphic terranes — the belts having contrasting structural architecture, rock-formation, different geological history and geomorphic setting.

Figure 1.3 shows the location of deposits of a few important minerals that are found in the Indian part of the Himalaya. Table 1.2 shows the extent of these deposits.

Table 1.2 *Mineral wealth of the Himalaya within the Indian territory (V.C. Thakur, 1976).*

Mineral	Proven reserves in 1980	Mineral	Proven reserves in 1980
Limestone	458 m.t.	Copper–Lead–Zinc	2.2 m.t.
Dolomite	94 m.t.	Steatite–Talc	1.9 m.t.
Magnesite	82.2 m.t.	Fluorite	86,000 t.
Gypsum	66.7 m.t.	Bentonite	40,000 t.
Graphite	26.7 m.t.	Sulphur	2,01,000 t.
Lignite	21.7 m.t.	Barytes	13,200 t.
Phosphorite	18.1 mt.	Antimony	10,588 t.
Bauxite	13.6 m.t.	Borax	5,423 t.
Coal	11.6 m.t.	Uranium minerals	Appreciable
Rock Salt	8.0 m.t.		

Fig. 1.3 *Locations of larger/important deposits of some important minerals in the Indian part of the Himalaya (based on V.C. Thakur, 1976, and Rajendra Singh, 1994).*

1.7 Himalayan forests and their biodiversity

Nearly one-third of the geographic area of the Himalayan province stretching from the Sindhu River in the west to the Brahmaputra Valley in the east, is covered with forests in various states of ecological health. These forests are the most valuable natural assets of the Himalaya. Nearly 30% of the forest species found in the Himalaya are not found anywhere else in the world[261] These include oaks, pines, rhododendrons and numerous lacuraceous species. Nearly 125 plant species are wild relatives of cultivated plant species which would be valuable gene pools for future crop improvements[261].

The Himalayan forests have a tremendous diversity of flora — from the dense evergreen tropical forests of the torrid Bhabhar–Siwalik belts in the south through mixed deciduous trees with grasslands in the middle mountains to the sparse Arctic type vegetation in the frigid northern belt. Several of these trees have great commercial value — the shorea (*saal*) in the tropical lowlands, the pine (*chirpine*) at the lower elevations of the middle mountains and the cedar (*deodar*) and silver firs in the higher elevations. The forests of the Bhabhar–Siwalik terrane are dominated by *saal* (*Shorea robusta*), *khair* (*Acacia catechu*), *sheesham* (*Dalbergia sissoo*), *haldu* (*Adina cordifolia*) and *sain* (*Terminalia tomentosa*), along with infinite varieties of shrubs and grasses. In the lower altitudes of the Lesser Himalaya, the *chirpine* (*Pinus roxburghii*) grows luxuriously on dry slopes with poor conditions of soil, while forests of oaks (*Quercus leucotrichophora, Quercus incana*), rhododendron (*Rhododendron arboreum*), alder (*Alnus nepalensis*), *Schima, Castanopsis* etc., cover moist slopes with good soils. According to S.P. Singh[261], the productivity of this vegetation is quite high — the dry biomass being as much as 20 tonnes per ha per year. Higher altitudes of the Lesser Himalayan mountains have forests characterized by *kharsu* oak (*Quercus semecarpifolia*), *tilonj* (*Quercus dilata*), blue pine (*Pinus wallichii*), *acer*, etc. The Great Himalayan domain is covered with forests dominated by silver fir (*Abies pindrow*) with *bhojpatra* or birch (*Betula utilis*), fir (*Abies spectabilis*), stunted rhododendrons (*Rhododendron companulatum*) and junipers (*Juniperus squamata, Juniperus indica*). Still higher, the forests give way to alpine meadows having infinite varieties of flowering grasses.

The Himalayan forests abound in a wide variety of animals including elephants, tigers and panthers in the Bhabhar–Siwalik domain in the south, and bears in the higher mountains. There are many animals which are uniquely Himalayan, such as *Kankar* (*Muntiacus muntjak vaginalis*), *Ghural* (*Nemorhaedus goral goral*), *Bharal* (*Pseudois nayaur*) in the middle mountains, snow leopards (*Panthera unica*), Himalayan black bear (*Selenarctos tibetanus*), musk deer or *Kastura* (*Moschus moschiferus*), Himalayan tahr (*Hemitragus jemlahius*), etc. in the higher realm[132]. The bird life is fabulously rich — there are 230 species in the Kumaun Himalaya alone.

1.8 The People

Amidst the plenty provided by the bountiful Himalaya live people who belong to three racial groups. West of westcentral Nepal, the entire Lesser Himalaya is inhabited by the people of the Khas stock believed to have migrated, beginning in 1500 BC in several waves, from central Asia. The northern territory beyond the Great Himalaya from Ladakh to Kameng in Arunachal, is the home of the tribes of Tibetan stock of the Mongoloid race. And in the eastern Himalaya live people of Tibeto–Burman stock who migrated here from southeast Asia.

2 *Perspective: Physiographic and Environmental*

2.1 Bulges and bends

The more than 5200 km long mountain chain, bordering the Indian subcontinent, isolates it securely from the rest of Eurasia. Rivers Sindhu (Indus) and Brahmaputra hold the lofty rampart in their sweeping embrace. The arc-shaped mountain is convex southwards and embodies big bulges and inward pointing acute angles — called the re-entrants — of mountain ranges (Plate 3; Fig. 2.1). The bulges are pronounced like festoons in the west in Pakistan, where the tearing of the mountain arc is particularly severe. In the east it is a long convex curve along the Patkai Hills–Arakan Yoma forming the Indo-Myanmarese border ranges. The arc shape, the bulges (Fig. 2.1) and the bends of the Himalayan chain indicate that the northern edge of India suffered very strong deformation.

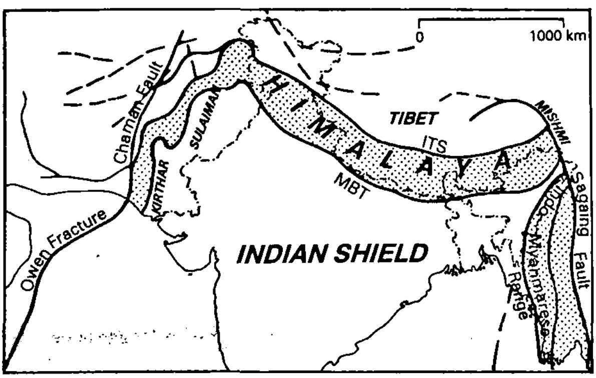


Fig. 2.1 *The mountain front of the Indian subcontinent is characterized by bulges and bends, and delimited by long continental faults along which considerable horizontal movements have taken place*

Most spectacular are the knee-bends in the northwestern and northeastern ends of the *main* Himalaya. In Kashmir the entire mountain system abruptly turns southward from its northwesterly trend, making an acute angle of 40° near Muzaffarabad. Along with the mountain ranges turn the whole pile of rock-formations and the succession of fault planes along which rock masses have moved long distances. This has given rise to what was described by D.N. Wadia[337] as the *syntaxial bend*. The two flanks of the syntaxial bend (Fig. 2.1) are, however, not exactly similar to each other geologically. The structural architecture and stratigraphic succession on the two sides of the bend are quite different. There is yet another syntaxial bend down south—along the Sibi–Quetta axis between the Sulaiman and Kirthar ranges.

In the east, three different mountains having altogether diverse histories of evolution seem to meet along a deep NW–SE trending fault. The NNE trending Indo-Myanmarese range is sharply truncated by the NW–SE striking Lohit–Mishmi ranges, which are indeed the northwestern extension of the Kachin–Shan–Malaysia province of the Asian landmass (Fig. 2.1).

2.2 Continent-tearing faults

The mountain chain is sharply cut at its two extremities by very long and deep faults known as the Chaman and Sagaing Faults, respectively (Fig. 2.1). The faults cut across diverse terranes of different geological generations. The faults delimiting the Himalaya are linked with the much longer and fundamental faults of the Indian Ocean — the Owen Fracture in the Arabian Sea, for example. The oceanic faults originated due to stretching and spreading of the ocean floor. This implies that the movements related to the spreading of the ocean floor are transmitted or relayed through these faults to the Indian subcontinent. This is manifest in the northward movement of the Indian landmass along with its Himalayan front, relative to the Afghanistan block in the west and the southeast Asian landmass embracing parts of China, Thailand, the Shan Plateau of Myanmar and Malaysia to the east (Fig. 2.1).

2.3 Physiographical – geological subdivisions

Considered as a whole, the mountains that border the Indian subcontinent in the northwest, north and northeast constitute a geological province characterized by nearly similar structural architecture, lithological setting and evolutionary history. Within the 300 to 400 km wide expanse of this Himalayan province, four physiographically distinctive and geologically contrasted subprovinces or terranes are recognizable (Fig. 2.2), particularly between the rivers Ravi and Arun. Each of these four terranes has not only its distinctive structural layout and stratigraphy in respect of geographic position and rock sequence, but has also nearly similar physiographic characteristics. The mountain province abruptly rises above the vast flat expanse of the Indo-Gangetic Plains. The foot of the southern frontal ranges has a discontinuous apron of coalescing fans and cones of gravel or detritus dumped by rivers and streams rushing out of the mountains. This fringe of debris is known as *Bhabhar*.

The 250 to 800 m high Siwalik Ranges form the southern front of the Himalaya. These are made up of sediments deposited by the ancient Himalayan rivers in their channels and floodplains in the last 16 to 1½ m.y. The rugged Siwalik ranges are commonly broken by south-facing scarps, while on their steepened northern slopes dash down rushing streams through unending cascades and waterfalls as seen in the central sector. Then there are long flat stretches within the otherwise rugged Siwalik terrane called the 'duns'. The duns represent gravelly deposits in depressions or fillings of now vanished lakes that were formed

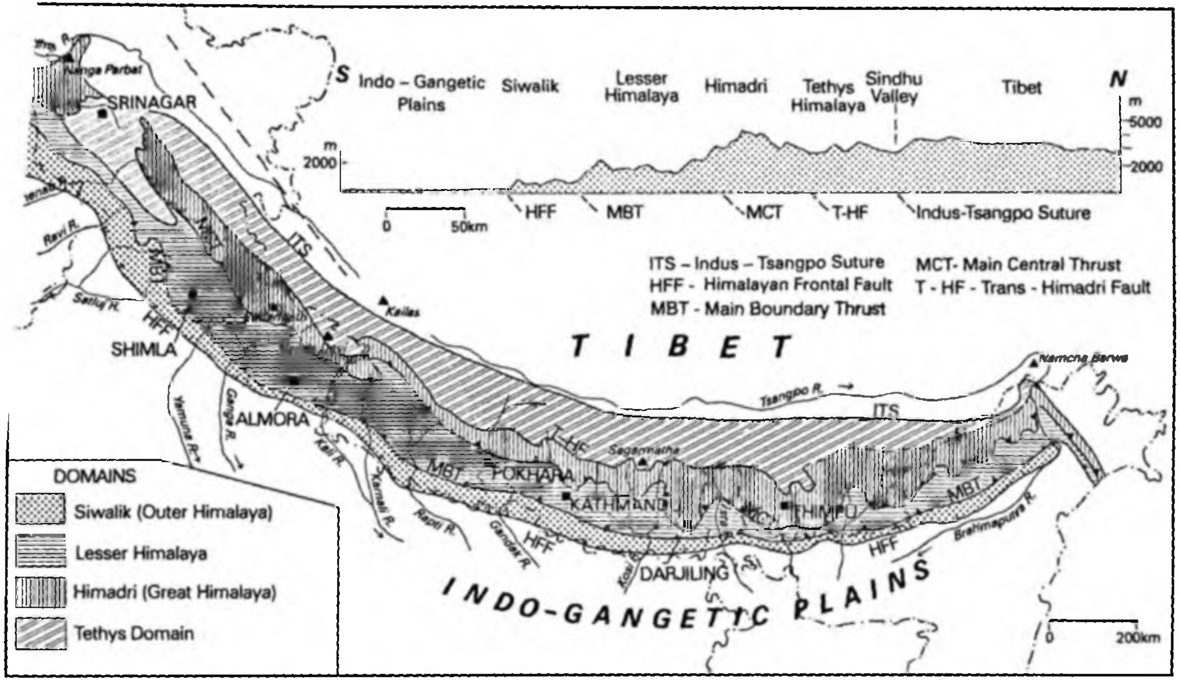


Fig. 2.2 *Physiographically distinctive and geologically contrasted terranes or subprovinces of the Himalaya. In the upper part a simplified profile of the Himalaya along the line marked by two arrows (I–TS = Indus–Tsangpo Suture, MCT = Main Central Thrust, T-HF=Trans–Himādri Fault, MBT = Main Boundary Thrust).*

in the synclinal valleys, owing to ponding of rivers and streams or slackening of current velocity as a result of decrease in gradient following tilting of the ground. Covered densely with forests east of the river Yamuna, the Siwalik is a sparsely populated terrane.

North of the Siwalik rise the formidable ranges of the *Outer Lesser Himalaya* — the Pir Panjal–Dhauladhar–Nag Tibba–Mahabharat ranges which are in general higher than 2500 m. The Pir Panjal in the northwest rises to heights greater than 3500 m. These extremely rugged ranges looking down on the Siwalik are thickly forested. In the central sector (Kumaun and Nepal), north of this lofty rampart stretches the beautifully gentle terrain of the 600 to 2000 m high middle Lesser Himalaya (Plate 1B). The summits of the mountains are rounded, the slopes are gentler; and in the undulating stretches flow streams and rivulets like the Giri, Kosi, Ramganga, etc. in their winding and wide channels. The valleys of rivers like Ravi, Satluj, Yamuna, Ganga, Kali, Karnali, Gandaki, Kosi, Arun, Subansiri, etc. — which are older than the mountains they cross — are characterized by deep gorges and defiles. These have made extremely rugged 'badland' landscapes exhibiting an intricate topography with fine drainage networks and stream dissection. Once the land of Lesser Himalaya was thickly forested, but presently is bereft of the sylvan cover over a greater part. It happens to be the comparatively densely populated terrane of the Himalayan province. This terrane is by and large made up of Precambrian rocks — older than 570 m.y. in age. Sedimentary and volcanic rocks are covered by thick and vast sheets of still older metamorphic and granitic rocks.

Overlooking the Lesser Himalayan terrane, the perennially snow-capped extremely rugged Himādri or Great Himalaya rises to elevations of 3000 m to more than 8000 m. It includes the celebrated peaks of Nanga Parbat (8126 m), Nun Kun (7135 m), Kedarnath (6900 m) (Plate 1A), Badarinath (7138 m)(Plate 14B), Nanda Devi (7817 m), Dhaulagiri (8172 m), Sagarmatha or Everest (8848 m), Kanchanjangha (8598 m) and Namcha Barwa (7756 m) (Fig. 2.1). The southern face of the Himādri is broken by precipitous high scarps. On the steep northern slopes dash down mountain torrents which churn violently through their deep canyons.

Many of the larger Himalayan rivers had established their drainage before local uplift due to crustal movement, and continued to cut their channels deeper and deeper keeping pace with the rate of uplift. These rivers, recognized as antecedent rivers, continued to flow in their original channels despite barriers that rose up. The antecedent rivers have cut awesome deep gorges having vertical to convex valleys walls. Characterized by utterly youthful and forbiddingly rugged topography (Plate 1A), the Himādri terrane is made up of a 10,000 to 20,000 m thick pile of high-grade metamorphic rocks and gneissic granites which are intruded by 40 to 20 m.y. old light-coloured granites. This complex has been described by some workers as the 'Central Crystalline Axis'[(187)] of the Himalayan province.

Beyond the Himādri lies the vast expanse of the *Tethys Himalaya* (Plate 4A). This rugged terrain with its fantastically sculptured landscape is made of sedimentary rocks that range in age from Late Precambrian (> 600 m.y old.) to Cretaceous and Eocene (95–45 m.y. old). Bereft of vegetation on the whole, this desolate domain is a cold desert populated extremely sparsely but only in isolated places in the valleys where clumps of trees have established their precarious footholds.

The Himalayan province ends up against the zone of collision of India with Asia, now occupied by the rivers Sindhu and Tsangpo (Fig. 2.2). This 50 to 60 km wide zone of the junction is characterized by deep faults and a chain of 60 – 48 m.y. old volcanic islands caught inextricably with the mixture of sediments from deep oceanic trenches and sea-floor rocks which were squeezed up when the continents collided. Although now 3600 to 5000 m above sea level, the terrain of the Sindhu and Tsangpo displays a very gentle topography of river floodways (Plate 4B).

North of the Sindhu–Tsangpo valleys, the uplifted plateau of Tibet, belonging to an altogether different landmass of Asia, has been peneplaned — flattened out to undulating plains (Plate 3). The southern front of the Tibetan plateau is made up of 90 to 45 m.y. old granites and granodiorites which make up the Ladakh–Kailas–Gangdese ranges. The granites are associated with 60 – 48 m.y. old volcanic rocks of a volcanic island arc along the periphery. Some of the volcanoes were active until the Quaternary period (younger than 1.6 m.y.).

2.4 Birth and evolution of the 'Nagādhirāj'

At this stage it will be appropriate to discuss briefly how the Himalaya evolved. The history of the conception, birth and growth of the Himalaya begins in the dim lifeless past more than 2000 million years (m.y.) ago. A big sea, embracing what are today the Himalayan province and the Marwar and Vindhya domains, had been in existence. In its shallow basin were laid down pile after pile of sediments washed down by north-flowing rivers of the Peninsular India. This was the start of the very long embryonic development of the Himalaya inside the sea.

The more-than-1000 m.y.-long cycle of basin-filling of the *Purāna* era (from Mid. Proterozoic to the close of Early Cambrian) was broken 525 to 470 m.y. ago by a widespread crustal disturbance which was accompanied by large-scale invasion by molten rocks (granitic magma) and preceded in some centres in the northern belt by volcanic eruptions and explosions. This crustal upheaval put an end to sedimentation in the middle domain known as the Lesser Himalaya and in the whole of Peninsular India. Evidently, the Indian subcontinent was lifted up above the sea water when the crustal movement (Fig. 2.3) convulsed 'Gondwanaland'. However, in the northern belt, known as the Tethyan domain, there was merely an interruption in sedimentation while new areas in the eastern sector came under the sway of the sea for the first time following the palaeogeographic changes this tectonic movement brought about. A rich variety of life prospered and proliferated in the waters of the sea.

India was overtaken by yet another global-scale tectonic upheaval 310 to 280 m.y. ago (Fig. 2.3). The crust in the Himalayan realm was rifted apart along the line stretching from the Pir Panjal in Kashmir to the Siang Hills in eastern Arunachal Pradesh. Through the fissures welled out enormous volumes of lava and many explosive volcanoes deposited fragmental material around their orifices. Sea water rushed in along the narrow sunken belt related to this fissuring of the continent, and glaciers dumped their detritus brought down from the elevated terrain in the south covered with snow and ice.

Sediments continued to pile up, both vigorously and haltingly in the northern domain, even as volcanoes remained active in the northwestern sector and the very northern belt. Meanwhile, the Indian landmass was moving north towards mainland Asia at a very fast rate of 19.5 to 18 cm/yr. The two continents coming closer, the sea floor between the two deepened and sagged, and slipped under Asia about 65–60 m.y. ago. A narrow deep furrow or trench was formed in front of the strained and fractured Tibetan landmass. Volcanoes poured out lavas through these fissures, and an arc of volcanic islands stretching from Kohistan through Kargil and Mansarovar to Shigatse was formed.

Era	Age (m.y.)	Major Events	
Quaternary	0.01	Rapid uplift along active faults	
Tertiary	1.6	Tremendous uplift of Himalaya; Deformation of Siwalik and formation of HFF; Evolution of Indo-Gangetic Basin (~1.7–1.5 m.y.)	Himalayan Orogeny
	5.6	Formation of MBT; Emergence of Siwalik; Beginning of Indo-Gangetic Foreland Basin (~2.5–2.0 m.y.)	
	23	Formation of MCT and T-HF; Widespread emplacement of granite; Evolution of Himādri; Uprooting and overthrusting of Lesser Himalayan nappes; Formation of Siwalik foreland basin (~25 to 20 m.y.)	
	36.5		
	53	Ridging up of Asia-India junction; Establishment of drainages of Sindhu, Ganga and Brahmaputra systems	
	65	Collision and welding of India with Asia; Emplacement and squeezing out of sea floor rocks; Formation of elongate basins north and south of emerging Himalayan province (~65–55 m.y.)	
Mesozoic		Formation of oceanic trench; Development of volcanic island arc in front of Asian landmass	
	135		
	205		
Palaeozoic	250		
	290	**Hercynian diastrophism** Rifting of crust and volcanism in southern belt; Incursion of sea along the rift valley; Widespread glaciation; Interruption of sedimentation in Tethys domain (~310–280 m.y.)	
	355		
	410		
	438		
	510	**Pan-African diastrophism** Cessation of sedimentation in Lesser Himalayan domain; Widespread emplacement of granite; Interruption of sedimentation in Tethys domain (~540–470 m.y.)	
	570		
Proterozoic (Purana)	650		
	1000		
	1600		
	2050	Start of sedimentation with disturbed tectonic condition; Basic volcanism in some centres (Time ?)	

Time span not to scale

HFF = Himalayan Frontal Fault; MBT = Main Boundary Thrust; MCT = Main Central Thrust
T-HF = Trans-Himādri Fault

Fig. 2.3 *Major events in the evolutionary history of the Himalaya.*

About 65 m.y. ago India slammed against mainland Asia along with its island arc of volcanoes. The advancing India had indeed ploughed into the enormous pile of sediments accumulated in the ocean trench or depression and on the sea floor. The Indian landmass was completely welded to mainland Asia by about 55 m.y. ago (Fig. 2.3). The junction of the collided continents occupied by the rivers Sindhu and Tsangpo at present is known as the Indus–Tsangpo Suture (I–TS). The collision of continents initiated the drama of diastrophism which culminated in the emergence of the Himalaya. The leading (northern) edge of India ridged up, and the heavy ultrabasic and basic rocks forming the sea floor and its substratum were squeezed up and implanted in the deep oceanic sediments that lay as tangled masses in the vice-like grip of the collided continents. The zone of junction had become a gentle highland and rivers such as the Sindhu, Satluj, Karnali and Brahmaputra established their drainages. One of the consequences of the collision was free migration into India of mammalian animals from as far as Mongolia and China in mainland Asia.

As the pressure of the northward moving India grew, the belts of the continental junction and the southern periphery of the incipient Himalaya sagged down. The sinking of the ground caused incursion of the sea and initiated a fresh cycle of marine sedimentation 60 to 40 m.y. ago when petroleum-producing marine organisms were particularly vigorous. The climactic phase, the most turbulent tectonic time of the Himalayan revolution, affected the continent 25–20 m.y. ago when the sea — which held sway for more than 1600 m.y. — was forced to recede finally. The metamorphic and granitic rocks forming the basement of the sedimentary pile were split and pushed up southwards along the planes of splitting called the Main Central Thrust (MCT) — to emerge as the Great Himalayan Range or *Himādri* (Figs. 2.3 and 2.4). Deep down where the crust melted because of severe and repeated movements, rock melt of granitic composition was formed. The granitic magma thus generated rose up and froze 25–20 m.y. ago in the framework of the Himādri. The peaks of Leopargial, Kedarnath, Badarinath and Makalu are made up of this granite.

As the pressure of the continental convergence increased, the buckled up mass and wrinkled pile of layered rocks were sheared off their roots and pushed tens to scores of kilometres southwards and thrown upon comparatively younger sedimentary rocks in the domain of the Lesser Himalaya (Fig. 2.4). The townships of Dharmshala, Shimla, Ranikhet, Almora, Kathmandu and Darjiling are located on the uprooted and far-travelled sheets of rocks. A narrow elongate basin had now formed in front of the infant Himalaya. Detritus derived from the brisk erosion of the fast growing Himalaya rapidly filled up this foreland in front of the mountain. Then occurred a very powerful tectonic movement about 2.5 to 2.0 m.y. ago which pushed the Lesser Himalayan rocks over the foreland basin along what is described as the Main Boundary Thrust (MBT), and squeezed its thick riverine sediments into the Siwalik ranges (Figs. 2.3 and 2.4).

Approximately 1.6 m.y. ago the young Himalaya (including its Siwalik front) was seized with an exceptionally severe, very convulsive deformation which lifted up the mountain to tremendous heights, triggered extensive landslides and severe erosion, and broke the Siwalik along its southern front—the Himalayan Frontal Fault (HFF). The basin formed as a result of the subsidence of the foreland has been and is being filled up with the sediments brought by the rivers of the Sindhu, Ganga and Brahmaputra systems. The Indo-Gangetic Plains emerged as a consequence of the filling of this basin in front of the very youthful Himalaya. The rivers of the emergent Himalaya have played, and are still playing a very crucial role in filling these plains.

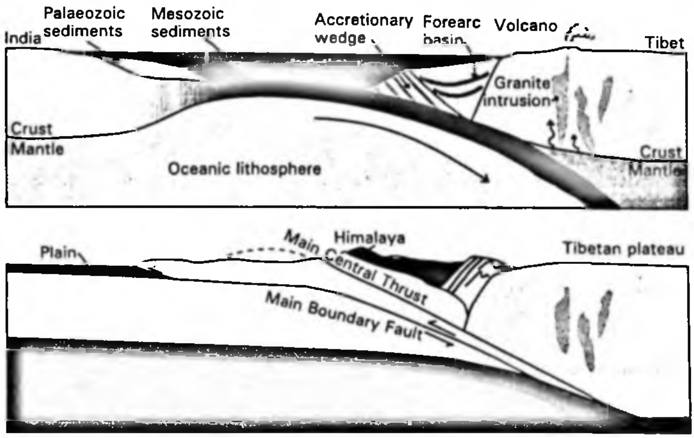


Fig. 2.4 *Evolution of the Himalaya. Peter Molnar's conception in an article 'The structure of mountain ranges', Scientific American, 254(7), 70–79 (1986).*

2.5 Distinctive drainage

The drainage pattern of the Himalayan province is remarkable in that four great rivers originate from one area — the Kailas–Mansarovar tract in Hundesh in southwestern Tibet. The Sindhu flows northwestward, the Satluj takes a southwesterly course, the Karnali (Ghaghara in the plains) descends southwards and the Tsangpo (Brahmaputra in India) goes east. They form a radial drainage pattern (Fig. 2.5) as if originating from a knot or dome (this is discussed in Chapter 6).

The sources of these rivers lie north of the stupendous mountain barrier of the Himalaya. This source area happens to lie in the line of the NNE trending Aravali Range of the Indian shield. It appears that the Aravali exercised control in determining the drainage pattern from the time well before the emergence of the Himalaya (the Himalayan drainage network is shown in Fig. 2.6).

Indeed it is now known that the Himalayan rivers were flowing through their winding, tortuous channels in the land that sloped southwards very gently until the Himalaya emerged as a lofty mountain. The mountain rose but slowly, and the rivers maintaining their original courses, progressively cut their channels deeper and deeper. In this manner evolved the very deep gorges and chasms having practically vertical to even convex valley walls.

Some valley walls have a sheer drop of 3000 to 4000 m (Plate 4A). The rivers rush down their high-gradient channels, characterized by rapids and knick points. In Gilgit in the extreme northwest, the 8125 m high Nanga Parbat looks down the bed of the river Sindhu as it turns southward at 1100 m above the sea level — across a sheer wall 7000 m high! Likewise, the Brahmaputra has cut a 5000 m deep canyon adjacent to the 7750 m high

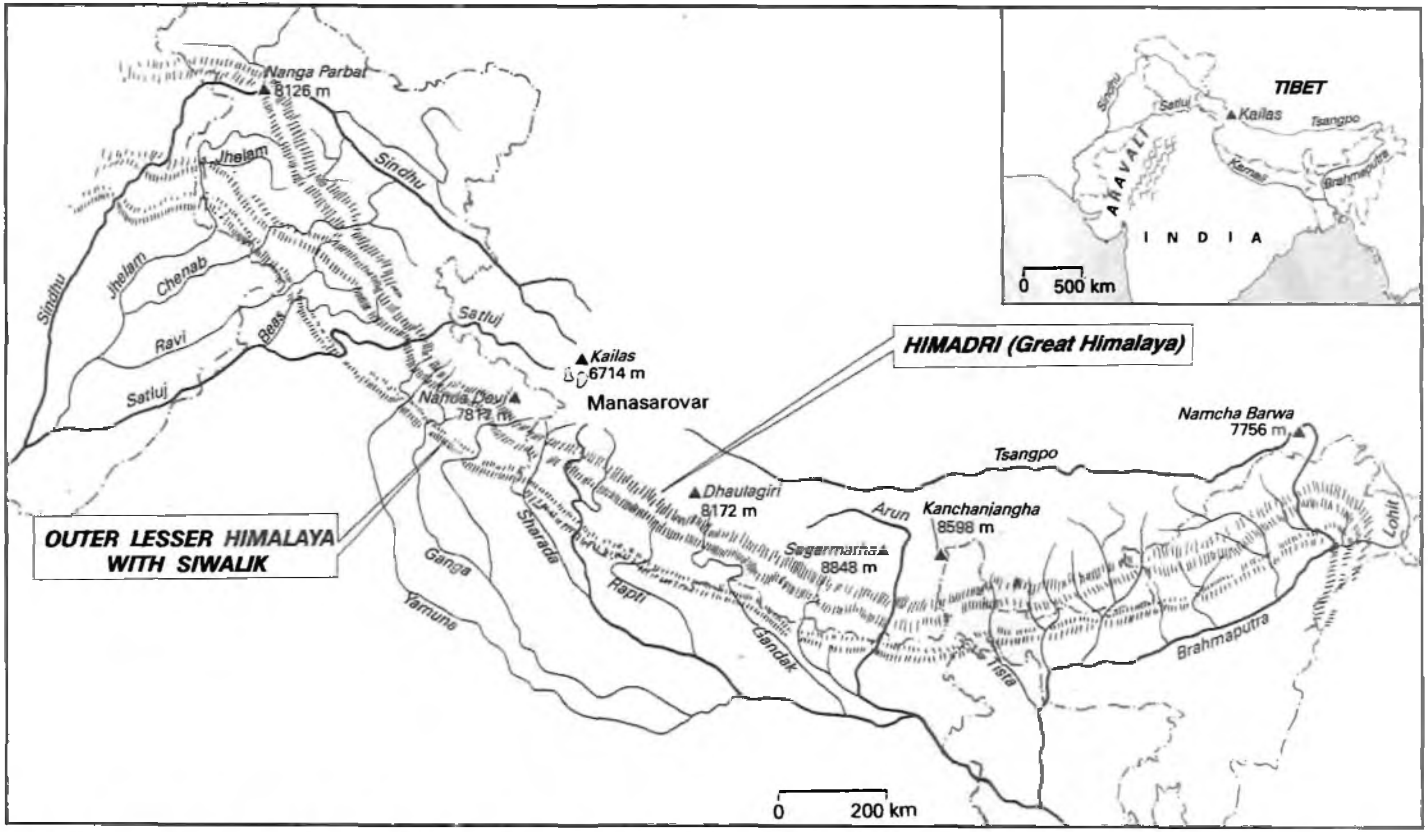


Fig. 2.5 *Rivers Sindhu, Satluj, Karnali (Ghaghara) and Tsangpo (Brahmaputra) all originate from one area — the Kailas–Mansarovar tract lying to the north of the high mountain barrier. The inset brings this out clearly.*

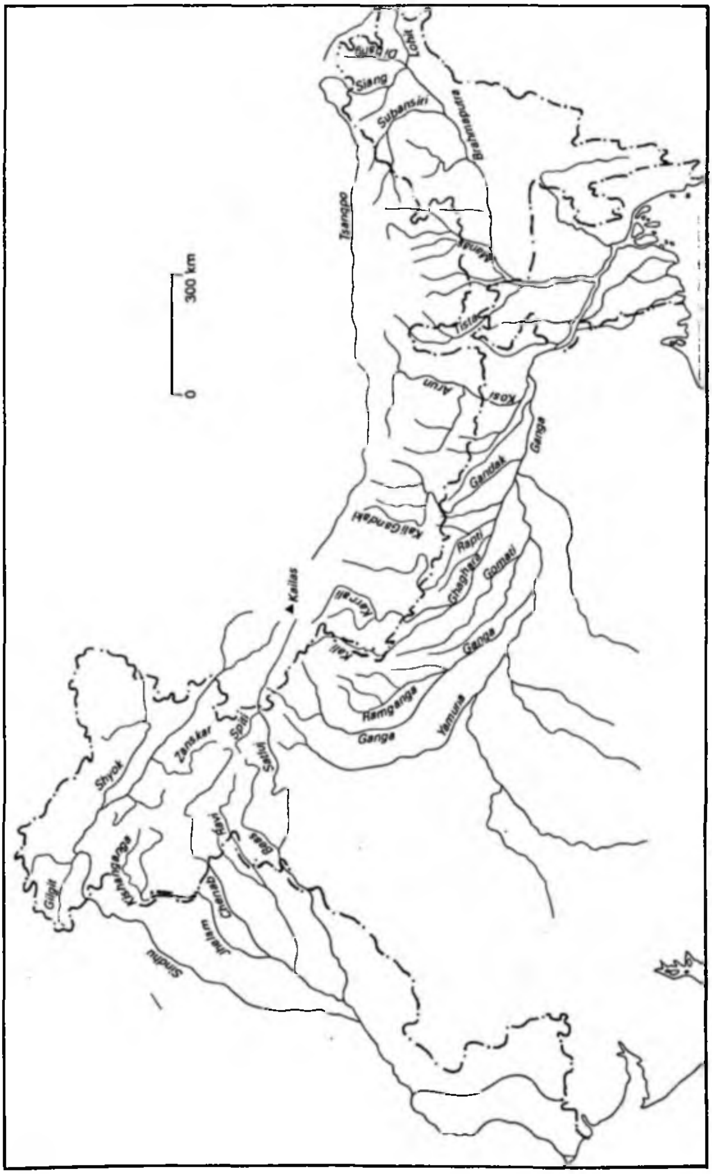


Fig. 2.6 *Drainage network of the Himalayan rivers.*

Namcha Barwa located at the sharp bend of the Tsangpo river. Obviously, well after the establishment of drainage, the rivers cut their channels deeply and incisively, giving rise to a very rugged topography.

Not only these four major rivers, but also the majority of other Himalayan rivers originate north of the Great Himalayan (Himādri) barrier. Their watershed is far north of the line of the highest summits. Originating in the southern slopes of the India–Tibet border ranges, these rivers cut their gorges through the Himādri to reach the plains. As already pointed out, these rivers established their drainage not consequent on the present-day physical features of the country but following the relief of the land as it existed before the Himalaya mountain barrier was formed. These rivers continued to flow in their original channels despite the uplift of the land. In other words, the Himalayan rivers are older than the mountain ranges they cross (Fig. 2.7). They are thus antecedent rivers.

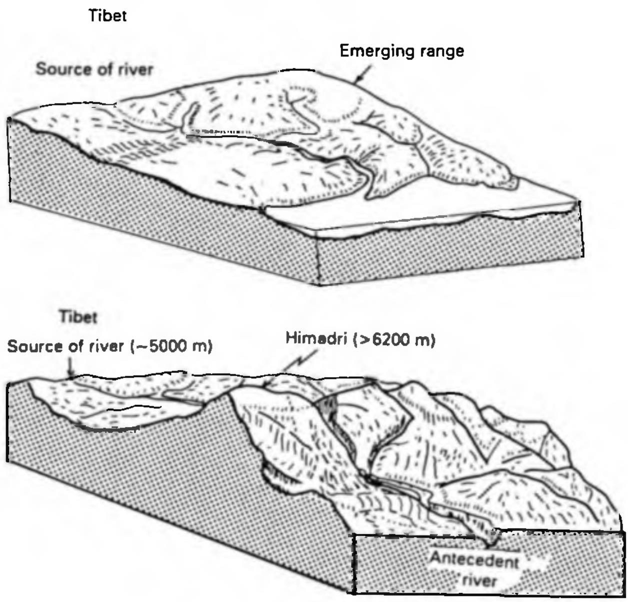


Fig. 2.7 *Himalayan rivers are older than the mountains they cross. They are antecedent rivers. (a) A river has established its drainage on a newly emerged land. (b) As the mountain emerged following uplift of the land, the river keeps its channel open but cutting the bed deeper and deeper.*

2.6 State of natural environment

2.6.1 Earthquake activity

The Himalayan province on the whole is geodynamically very active — it is prone to violent crustal movements causing earthquakes. The snapping and attendant slipping of rocks on

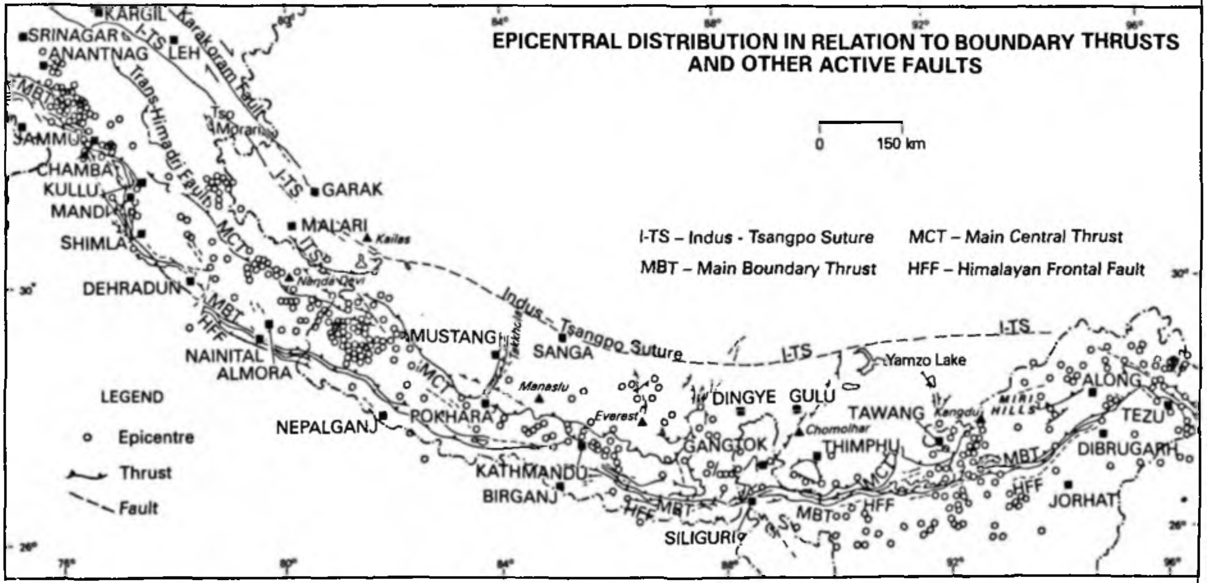


Fig. 2.8 *Distribution of epicentres of earthquakes of magnitude 5 and above in relation to boundary thrusts (prepared with the help of S.V. Chalam at National Geophysical Research Institute, Hyderabad) [I–TS= Indus–Tsangpo Suture, MCT = Main Central Thrust, MBT = Main Boundary Thrust, HFF= Himalayan Frontal Fault].*

faults and thrusts have given rise to earthquakes repeatedly. The magnitude of seismic events has varied from moderate to high. In the last one hundred years, four of them had magnitudes higher than 8 on the Richter Scale. Epicentres generally follow lines parallel to the thrusts or faults defining the boundary of the four physiographic–geological terranes. Figure 2.8 shows the distribution of epicentres of magnitude 5 and above in relation to these boundary thrusts.

There is a clustering of epicentres in the areas cut by tear faults oriented transverse or oblique to the general trend of the mountains. Such clusters are seen in eastern Arunachal, Bhutan, central Nepal, northwestern Nepal and adjoining northeastern Kumaun, southeastern Ladakh and Kashmir (Fig. 2.8).

In the Outer Himalaya, although the frequency of earthquakes is low, their magnitudes have been quite high. As already stated, there were four great earthquakes of magnitudes above 8 — in northern Meghalaya in 1897, in Kangra in 1905, in northern Bihar–southern Nepal in 1934, and in northeastern Arunachal in 1950. These strong-motion earthquakes, in the opinion of V.K. Gaur[(106)], testify to the fact that quite large segments of the mountain front were ruptured in the last hundred years.

The intervening unruptured parts, so far free from the great seismicity, are no doubt under severe stresses as these are being continually strained by the northward pushing Indian shield. These seismic gaps between the segments that have been ruptured by great earthquakes may at any time in future release their accumulated strains by failure, causing earthquakes of high magnitude[(106)(137)]. In other words, the seismic gaps are highly vulnerable to hazards due to rocking or twitching of the mountains.

2.6.2 *Fragile ecosystems*

The southern slopes of all Himalayan ranges are extremely steep with precipitous scarps. Excepting fan-like and cone-shaped accumulation of talus (comprising fragments of all sizes and shapes derived from and lying at the base of cliffs and steep slopes, which were generated by frost action, rockfalls and landslides), the southern slopes are without soil cover and generally without much vegetation. Relentlessly beaten by rains and sun rays, the southern slopes are vulnerable to heavy erosion and degradation of the ecosystems.

Only the debris fans and cones have a vegetation cover which is very sparse. On the other hand, the gentler northern slopes, enjoying abundant rains and shade, are marked by thick mantles of soil and are well-protected by thick forests of deciduous trees, shrubs and grasses. These multistoreyed forests comprising trees, shrubs and grasses provide shelters and sanctuaries to a wide variety of wild life; and simultaneously stimulate recharge of groundwater that is manifest in springs and associated seepages. It is these multitudes of springs and seepages which feed the rivers of the Lesser Himalayan domain and supply nearly 42% (30 to 70%) of the waters of the rivers coming from the snowy peaks of the Himādri.

The snowline is progressively moving higher and the glaciers are receding at an alarmingly fast rate. The shrinking of the snow-cover is due to global warming resulting from atmospheric pollution and/or depletion of the ozone layer.

It is quite evident that the Himalayan ecosystems are in a delicate or fragile condition and therefore very vulnerable to even small disturbances, natural or man-made. Consequently, even minor activities for development precipitate changes which rapidly assume alarming proportions[311]. These changes are manifest in landslides and heavy soil erosion, drying up of springs and desertification of slopes.

2.6.3 Degeneration and loss of vegetal cover

The state of the vegetal ecosystems in the central sector of the Himalaya (Kumaun Himalaya) in a sense illustrates the environmental scenario of the whole of the Himalaya. Here live more than 3.4 million heads of cattle; and only 0.32 to 0.60 ha of grazing land per head is available against the need of at least 2 to 3 ha per head. The grazing pressure on forests is thus 2.5 to 5 times more than the carrying capacity of the forests.

The explosive growth of human population is making an enormous demand on fuel-wood and timber. As a result, the forests in Kumaun have dwindled to less than 28.7% of the ground surface, and only 4.4% of the geographic area is left with forests of trees having more than 60% foliage canopy[258]

Elsewhere in the Lesser Himalaya, the situation is no better. The forest cover left is 18–19% in Himachal and less than 23% in Nepal — considerably less than the 35% in the entire Lesser Himalaya against the optimum of 60%. In other words, more than two-thirds of the Himalayan province is exposed to erosion and thus is vulnerable to environmental degradation.

According to S.L. Shah[247], the total growing stock of forests in Kumaun is 66 million m^3, the out-turn 4.54 million m^3/yr and the annual increment 0.78 million m^3/yr. So, at the net depletion rate of 5.8 percent per year, the growing stock of trees will be almost completely wiped out by AD 2031 and the grass stock by AD 2040[247]. If the present trend of forest exploitation is not reversed, then within half a century the Kumaun Himalaya would become a barren wasteland!

Environmentally, the most compatible and beneficial tree in the Himalaya is the oak, which not only generates abundant litter and protects the soil but also promotes and stimulates recharge of the mountain springs. Reckless and unchecked lopping and felling of oaks and other broad-leaf trees have ravaged the forests, exposing the oaks to infestation by such parasites as *Loranthus* and resultant mortal diseases. The oak of the dominant variety *banj* (*Quercus leucotrichophora*) is failing to regenerate in the degraded forests and is being replaced by the *chir pine* (*Pinus roxburghii*).

The invasion of oak forests by pines has a telling impact on hydrological regimes in the habitats of wildlife and in the above-ground biomass production. In pine forests, springs are scarce and wildlife is non-existent; very little under-tree vegetation (shrubs and grass) grows on the ground surface. Likewise, many degraded forests and deforested slopes have been encroached upon by such pest vegetation as *Lantana camara* and *Euphorbia roylaena*, which do not allow any other vegetation to grow and survive. Even pines have not escaped cruel treatment from avaricious people. Heavy unscientific resin-tapping of pine has resulted in reduced growth and increased susceptibility to attack of beatles, diseases, windstorms and forest fires.

Several species of plants and animals are facing risk of elimination or are endangered because of the destruction or drastic modification of their habitats. About 99 species of Himalayan plants are in danger of extinction. The snow leopard, fishing cat and lynx are among the threatened animals, and the *bharal* (blue sheep), *ghural* (goat-antelope), *hangul*

(Kashmiri stag), *barasinga* (stag) and musk-deer have become very rare. The Himalayan bearded vulture, horned pheasant, mountain quail, monal pheasant etc., are among the endangered birds of the Himalaya.

2.6.4 Erosion and landslides

Slope failures have become a very common phenomena, particularly in the belts cut by active faults (Fig. 2.8). According to J.D. Ives[122], every square kilometre of the Kathmandu–Kakani area in central Nepal is losing 126 km^2 of ground every year through mass-movements at the rate of 1000 m^3/km^2. In southcentral Kumaun the average rate of erosion in the catchment of the Gaula River is 1.73 mm/yr [27]. In the Siwalik Hills in the Hoshiarpur District of Panjab, the extent of seriously eroded land increased from 195 km^2 in 1852 to 2000 km^2 in 1980. In the valley of the Sindhu in the far northwest, the rate of erosion varies from 2 to 12 mm/yr[62].

The Himalayan mountain region is being denuded of its soil cover at the rate of appreciably more than 1.0 mm/yr. In other words, if the entire Himalayan province were to be stretched flat, every year more than a millimetre thick soil cover all over the expanse is being removed by erosion. The rivers are thus carrying very large quantities of debris. The estimated rate of sediment-yield of the rivers of the central sector is 16.43 hectare-metres per 100 square kilometre catchment-area per year[112].

Severe erosion has resulted not only in the piling up of debris in the valleys at the foothills and downstream on the alluvial plain, but also rapid outward growth of deltas at the mouth of rivers in the Bay of Bengal and in the Arabian Sea. The Ganga alone annually carries (at Calcutta) 411 million tonnes (m.t.) of material — 328 m.t. in suspended state and 83 m.t. as dissolved chemical load — implying erosion in the catchment at the rate of 549 $t/km^2/yr$[1]

2.6.5 Reduced discharges of springs and streams

The most alarming development in the populated Lesser Himalaya terrane is the drying up of springs and their becoming seasonal. In a little less than 50% of the villages in southcentral Kumaun, for example, the springs have ceased to yield water during dry season, or have considerably reduced discharges.

The extent of decline in spring discharges in the Gaula catchment in southcentral Kumaun, according to S.K. Bartarya [27][321], is between 25% to 75% in the preceding 15 to 60 years. The Gaula River fed by these springs consequently registered a drop in its discharge (Fig. 2.9) of more than 29.2% between the decades 1951–60 and 1961–70 and about 38.5% between the years 1971 and 1981.

The dismal scenario of the Gaula catchment is representative of the situation discernible throughout the Lesser Himalaya from Jammu to Sikkim. In other words, the Himalayan rivers are carrying considerably less water during drier seasons than they did in the past. The water that flows during the rainy season in the snow-fed rivers like the Karnali is at least 1000 times more than the discharge during the very lean period. In the rivers and streams originating in the Lesser Nepal Himalaya this ratio may be as high as 30,000 or in some cases even 60,000[136]

This too-little-and-too-much water syndrome is a common feature of the desert country[314]

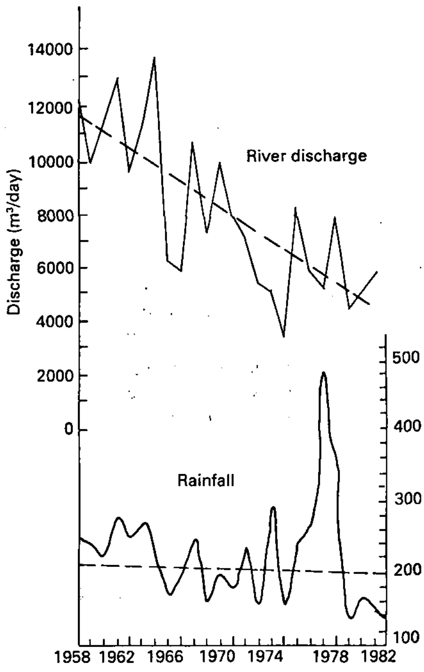


Fig. 2.9 *Alarming reductions in discharge in the Gaula River in southcentral Kumaun. The Gaula joins the Ramganga, a tributary of the Ganga. Note that there is no change in the rainfall in the period of comparison (S.K. Bartarya, 1988; K.S. Valdiya and S.K. Bartarya, 1989).*

3 *Protracted Cycle of Purāna Sedimentation*

3.1 Purāna Sea

The embryonic development of the Himalaya began sometime before the Mesoproterozoic period nearly 2000 m.y. ago when the northern margin of the Indian shield was flooded by sea water. The sea extended far south beyond the limits of the Himalayan province. It encompassed the Vindhya and Aravali domains in central India [143][165][303] and the Marwar platform in western Rajasthan (Fig. 3.1). The sea that encompassed a large part of central India and the Lesser Himalaya has been described as the Great Vindhyan Basin. Represented by its deposits having an aggregate thickness of more than 13000 m, laid down over a long span of time from the Late Palaeoproterozoic (>1600 m.y. ago) through the Vendian (650–570 m.y. ago) to the Early Cambrian periods (until about 525 m.y. ago), this sea may be described as the *Purāna Sea.* This was the period when many parts of the Indian shield in central and southern India were under water — the Chhattisgarh basin in Madhya Pradesh, the Pakhal depression in the Godavari Valley, the Cuddapah basin in southeastern Andhra and the Kaladgi and Bhima depressions in northern Karnataka.

It was not an uninterrupted cycle of sedimentation in the Himalayan basin. Rather, many interludes or pauses accompanied by spurts of volcanic and magmatic activity and submarine slides chronicle the eventful history of the Indian subcontinent of this period. Crustal disturbances caused interruption in sedimentation. These are represented by what are known as unconformities or disconformities. An unconformity is a discontinuity in the succession of rocks. It signifies a gap in the geological record. Towards the middle of the Purāna era about 1600 m.y. ago, life first appeared in the sea. A group of single-celled and many-celled organisms capable of producing oxygen, called *cyanobacteria*, succeeded in establishing a foothold and built reefs and carbonate banks in certain parts of wave-agitated shallow platforms, and formed colonies known as *stromatolites*. Only at the beginning of the Cambrian period (570–550 m.y. ago) did invertebrate creatures make their earliest appearance — first as *Ediacaran metazoans*, which are multicellular animals whose cells are arranged in two layers in the embryonic stage, then as small shelly fauna and later as *Trilobites, Brachiopods, Lamellibranchs*, etc.

3.2 Floor of the Purāna Sea

The northward- and northwestward-sloping continental margin of the Indian shield (Fig. 3.2) served as the platform on which was initiated the long cycle of Purāna sedimentation. The

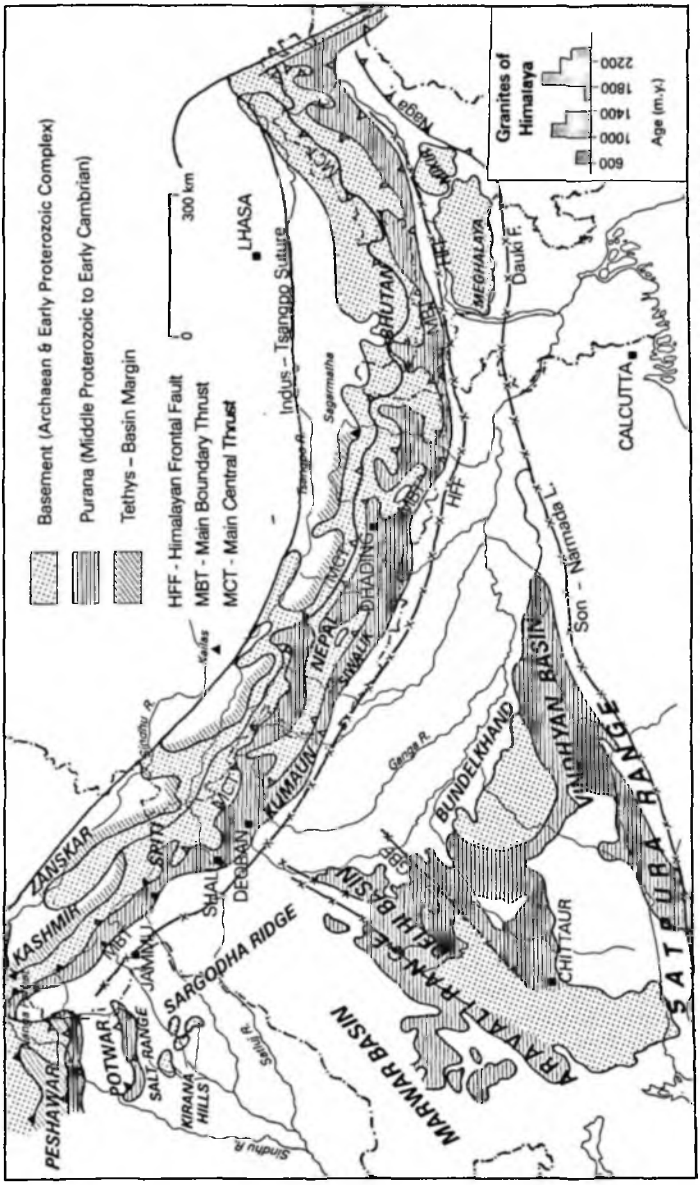


Fig. 3.1 *The Purāna Sea spanning a long period of time from earlier than 2000 m.y. ago to 525 m.y. ago, stretched far beyond the Himalayan province to encompass the domains of Vindhya, Aravali and Marwar.*

Purāna Sea was bordered by the Satpura Hills in the south, and the Aravali Range jutted northeastward through the middle of the basin in the manner of an elongated peninsula. The continental margin was made up of generally low-grade metamorphic rocks, with extensive intrusions of porphyritic granites and porphyries of more than one generation. These metamorphic rocks were originally an assemblage of poorly sorted, locally graded muddy sandstones (greywackes) rhythmically alternating with shales and locally muddy unsorted conglomerates known as the 'flysch'. Described as the *Aravalli* and *Bijawar* groups, these metamorphosed flysch successions, which presently build the Satpura and Aravali Hills, extend northwards under the thick pile of sediments of the Indo-Gangetic Plains, and cover a very large part of the Himalayan province (Fig. 3.1). The Bijawar–Aravali rocks formed the floor of the Great Vindhyan Basin embracing the Vindhya, Aravali, Marwar and Himalayan domains[320]

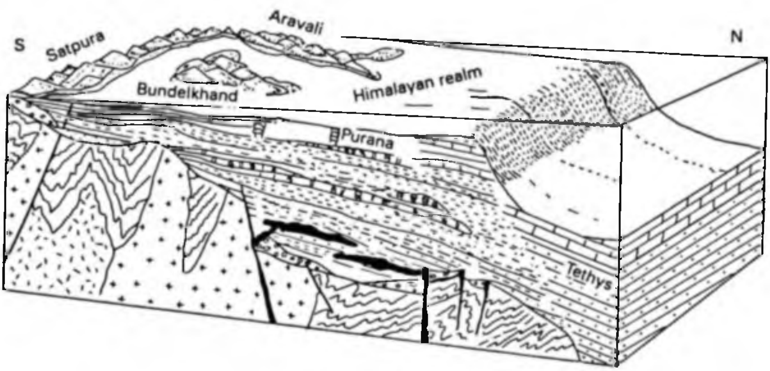


Fig. 3.2 *Sketch illustrating the nature of the Purāna Sea in its central part. This is how the northern landmass must have looked like about 600 m.y. ago.*

In the Lesser Himalayan domain, however, the base of the nearly 13000 m thick Purāna sediments is not exposed anywhere. One can only speculate on the nature of the basement, (which is an undifferentiated complex of rocks) forming the floor of the sea. It is likely to be characterized by extensive occurrences of 1900 ± 100 m.y old porphyritic granite intimately associated with metamorphosed flysch. These rocks presently form thick sheets all over the subprovince covering and concealing large parts of the Purāna sedimentary succession (Fig. 3.3). These must have once formed the floor of the Purāna basin, but later uprooted and dislocated or thrust southwards upon the relatively younger rocks lying to the south. These thick sheets or slabs are called *nappes*. The rock masses of the nappes have moved on predominantly horizontal surfaces due to thrusting or recumbent folding or both (Fig. 3.3). There are three disparate nappes succeeding or resting on the Purāna sedimentary rocks lying underneath. The nappes now occur overlapping partially one another. The uppermost nappe is made up of medium-grade metamorphic rocks comprising micaschists with garnet and 500 ± 25 m.y. old intrusive granodiorite and granite rich in biotite and quartz. These rocks, reconstituted by the rise in temperature and pressure from original sediments to their present form and compositon, were described by G.E. Pilgrim and W.D. West[194] as the *Jutogh* in

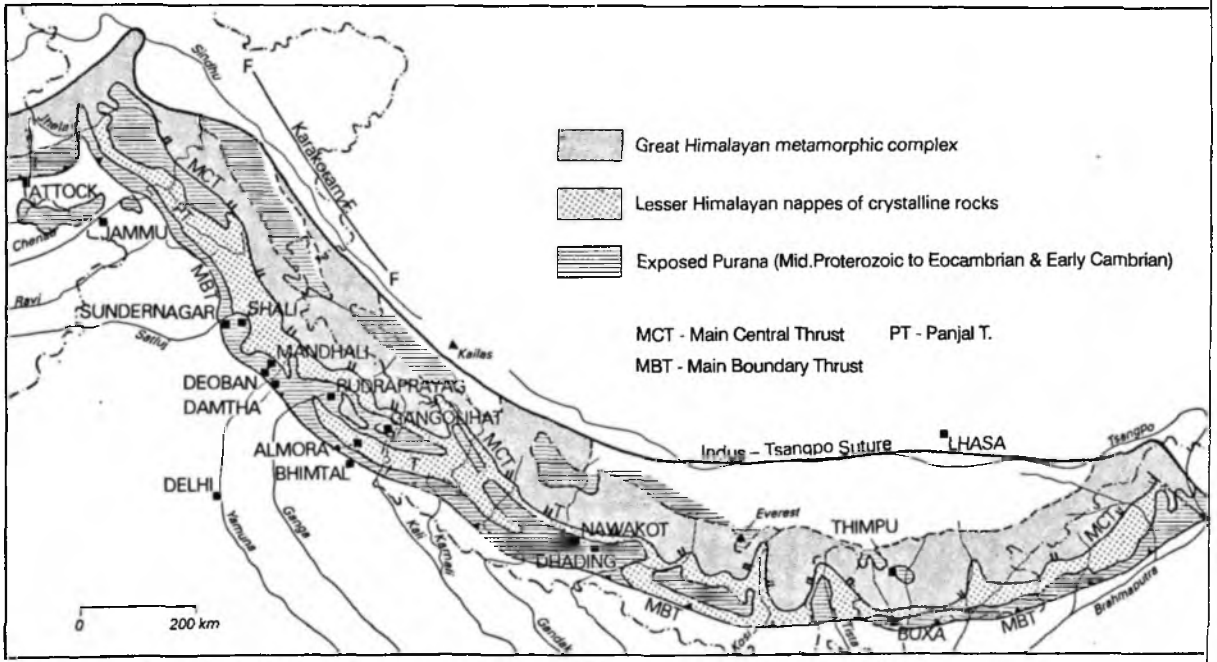


Fig. 3.3 *Sketch map showing Purāna sediments that are visible (exposed) in tectonic windows underneath the sheets (nappes) of basement rocks that once formed the floor of the Purāna Sea. The basement rocks were later uprooted and thrust upon younger sedimentary rocks of the Purāna domain.*

the Chaur–Shimla belt in Himachal Pradesh (Figs. 3.1 and 3.3; Table 3.1). The lower sheet consists of low-grade metamorphic rocks like phyllite, sericitic quartzite, marble and sericite–chlorite schists of the metamorphosed flysch facies. Described as the *Ramgarh* by A. Heim and A. Gansser(116) in Kumaun Himalaya, this extraordinarily vast and thick sheet covers an area many times larger than the Jutogh (Figs. 3.1 and 3.3; Table 3.1). The metamorphosed flysch assemblage is intimately associated with porphyritic granites and porphyries.

The granites are commonly mylonitized, i.e. rendered very dense, streaky and banded as a result of extreme granulation and multiple splitting or shearing during overthrusting of heavy rock masses. V.B. Bhanot, J.R. Trivedi and their associates have determined the age of these granites as 1900 ± 100 m.y. (34) (300) (301). There are also lens-shaped bodies of granite that are 500 ± 25 m.y. old in several areas. In Kumaun as well as in some localities in Himachal, Kashmir and Nepal, the Ramgarh rocks are underlain by extremely thick sheets of sericitic quartzite and quartz–sericite schist associated with lava and volcanic ash (tuff) now converted into amphibolite and chlorite schist. This sedimentary assemblage has been described as the *Berinag* by K.S. Valdiya(302) (309) and it appears to be a part of the Ramgarh Nappe (89). The lava associated with these quartzites is more than 2500 m.y. old(40) (41)

Before the mountain-building tectonic upheaval overtook them quite later, some 45 to 20 million years ago, these metamorphic rocks must probably have lain in this order — Jutogh (bottom) →Ramgarh →Berinag (top) — and formed the floor of the Purana Sea in the Lesser Himalaya, just as the lithologically comparable Bijawar and Aravali groups constituted the floor of the Great Vindhyan Basin (Purana Sea) in central India.

In the very northern part of the Purana province — in the so-called Tethyan domain — the Tethyan sedimentary succession transitionally grades down through mildly metamorphosed sedimentary rocks to very high-grade metamorphic rocks which build the bulk of the Great Himalaya. In many places there is a break, the contact being tectonized. Characterized by minerals like garnet, staurolite, kyanite, sillimanite, etc., these rocks comprise quartz–biotite–muscovite schists and gneisses, and calc–silicate rocks. The high-grade metamorphic rocks are extensively penetrated by younger granites and migmatites, the latter made up of granite intimately admixed layer-by-layer with metamorphic rocks due to squeezing in or injection of molten material. This rock assemblage was designated as the *Vaikrita* by C.L. Greisbach(111) in Kumaun and Himachal (Fig. 3.1; Table 3.1).

3.3 Early sedimentation: Disturbed conditions

No reliable information is available at present to date the beginning of the long cycle of Purāna sedimentation. It commenced under conditions of tectonic disturbance which caused depression of the basin floor and simultaneously raised the land around the depressions in different parts of the Indian landmass(320). There was brisk erosion of the land bordering the basin, namely the Aravali–Satpura highland, and the detritus was dumped briskly on the rapidly subsiding basin floor. Consequently, there was little sifting and sorting of the sediments. The poorly sorted greywackes, muddy sandstones, shales and lenses of unsorted muddy conglomerate (called diamictite) in the basal part of the flysch succession(236) seen throughout the larger part of the Purāna Basin bear testimony to the prevalence of tectonic instability.

Table 3.1 *Precambrian rock formations that formed the floor (basement) of the Purāna Sea in the Himalaya [T = Thrust].*

Domain	Kashmir	Himachal	Kumaun	Nepal	Darjiling	Sikkim–Bhutan	Arunachal
Tethys Himalaya	Zanskar/ Suru Crystallines	Rohtang Gneiss, Vaikrita	Vaikrita	*Tibetan Slab*, Annapurna Gneiss, Himalayan Gneiss, Khumbu/Barun Gneiss	Darjeeling Gneiss	*Thimpu Gneiss*, Chasilakha Gneiss/ Takhtasang Gneiss	Sela
Lesser Himalaya	Salkhala	Jutogh ———T Chail	Almora ————T Chail	Kathmandu ————T Bhimpedi	Paro ——T Daling	Chunthang ————T Shumar/Samchi	Bomdila/Dirang ————T Tenga/Siang

K.S. Valdiya's[306] studies in Himachal and Garhwal demonstrated that parts of the flysch assemblage were deposited by turbidity currents that flowed in the northerly directions from the edges of what could have been the extensions of the Aravali and Satpura mountains (Fig. 3.4). Stimulated by gravity, these currents were laden with suspended sediments derived from the deltas and descended rapidly on underwater slopes to spread horizontally along depressions in the sea floor.

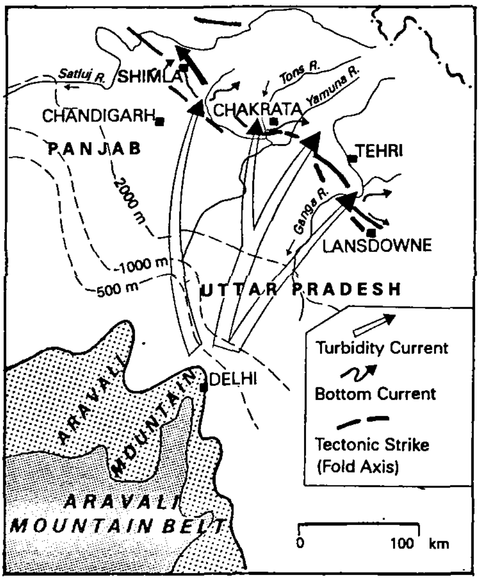


Fig. 3.4 *Tectonic conditions were disturbed at the outset of the Purāna sedimentation and turbidity currents flowed in the northerly direction from the edge of the then Aravali mountain (K.S. Valdiya, 1970).*

There were occasional submarine slides, triggered presumably by tectonic disturbances, giving rise to lenses of unsorted muddy conglomerates or diamictites at various levels in the sedimentary succession[217][309] as seen in the Chakrata area in western Kumaun, in the Baliana Valley in Himachal and at Tanakki in northern Pakistan. A majority of geologists[13][35], however, believe that these diamictites were emplaced by glaciers that descended into the sea. The flysch assemblage has been described as the *Damtha* by J. Rupke[218] and K.S. Valdiya[309] in the Yamuna Valley. These occur in the Shimla Hills in central Himachal, and in the Haimanta area in northeastern Himachal (Figs 3.3 and 3.7; Table 3.2).

In areas where tectonic tranquility prevailed, particularly later in the stage, the pace of sediment deposition became slow. Since lesser volumes of detritus were brought to the sea

Table 3.2 *Purāna formations of the Lesser Himalaya and Greater Vindhyan Basin.*

Age: Period	Age: Time Range (m.y. ago)	Northern Pakistan	Jammu & Kashmir	Himachal Pradesh	Outer Lesser Him. in *Himachal-* Kumaun	Kumaun	Nepal	Sikkim & Bhutan	Arunachal Pradesh	Vindhya	Aravali	Marwar
Early Cambrian	–525–	Jhelam Fm.	Sincha Fm./ Zilant Fm.		Tal		?			Up. Bhander	?	Nagaur Fm. Bilara Fm
Vendian Neo-proterozoic	–570– –650– –1000–	Salt Range Fm. Hariza Fm.	Bhimdasa Fm. Baila Fm . Gamir Fm	Basantpur	Krol	Mandhali	Robang Malekhu Benighat (Up. Nawakot)		Saleri	Lr. Bhander Rewa Kaimur	Bhagwanpura Ls. Up.Ajabgarh	Jodhpur Ss. Malani Rhyolite
Meso-proterozoic	–1600–	Sirban Ls./ Abbotabad Fm.	Great Ls / Jammu Ls.	Shali (I)	Blaini	Deoban (I)	Dhading (Lr. Nawakot)	Buxa (O)	Dedza	Semri	Lr. Ajabgarh with Kushalgarh Ls	
Palaeo-proterozoic	–2500–	Hazara Slate/ Attock Slate	Ramban Fm. (O) Dogra Slates (I) with Sauni Volcanics	Sundernagar (O) with Mandi *Volcanics*	Jaunsar	Damtha	Kuncha (I)	Sinchula-Jainti/ Phuntsholing (O)	Bichom	Basal Vindhyan and Arangi-Patherwa	Alwar	
					Base not seen anywhere					Bijawar	Aravali	Bijawar

(I) = Inner (Northern) belt, (O) = Outer (Southern) belt, Fm. = Formation, Ss. = Sandstone, Ls. = Limestone, Lr. = Lower, Up. = Upper and longer time was available, the sediments were subjected to prolonged and effective sifting and abrasion by waves and currents on the shallow platform. The result was the formation of well-sorted cleaner sands now forming mud-free clean sandstone (called quartzarenite) with but a subordinate amount of shale.

Tidal channels in the coast are represented by shoestring-shaped conglomerates within this quartzarenite succession[309][320]. The best development of this facies is seen in the Jaunsar area in southwestern Garhwal and the Bhimtal area in southcentral Kumaun (Table 3.2).

3.4 Volcanism contemporaneous with sedimentation

The floor of the Purāna Sea was stretched and parted, and through the fissures welled out lava time and again in several places — the Bhimtal belt in Kumaun, the Rudraprayag area in Garhwal, the Rampur belt in Himachal Pradesh and the Sauni area in Jammu (Fig. 3.5). Lava was poured out by volcanoes presumably related to faults and fractures which, in the opinion of M.I. Bhat[7][39], might have developed simultaneously with increasing load of sediments. This is evident from the clean sandstone interbedded with shale and intimately associated and locally intermixed with basaltic lava and tuff (volcanic ash). In the Bhimtal area, fragmental volcanic material (agglomerate) indicating volcanic explosion is also associated with the very shallow-water shore sediments. The outpouring of lava took place, according to M.I. Bhat[40][41], in the early Palaeoproterozoic 2060 to 2500 m.y. ago.

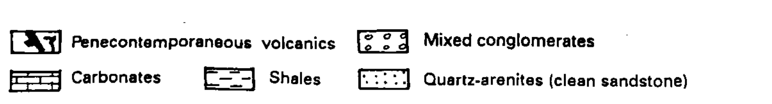


Fig. 3.5 *Volcanism penecontemporaneous with sedimentation in the early period of the Purāna era. There were several centres of volcanic activities.*

3.5 Quiet period of carbonate formation

As tectonic stability prevailed throughout the subcontinent in the period 1200–1000 m.y. ago, there was little influx of eroded detritus from the land. The sea had by now shallowed considerably and the warm waters of the sun-bathed platform provided a conducive environment for chemical and biochemical precipitation of carbonates and for development of reefs by cyanobacteria. The first stirring of life was already manifest in the Damtha times, but prolific growth took place in the later Mesoproterozoic period (1200–1000 m.y. ago) when a wide variety of cyanobacteria-built stromatolites characterized by straight and branching columns of carbonate laminae were formed all through the Purāna Sea. Recognizing a number of crucial forms such as *Kussiella, Baicalia, Minjaria, Masloviella* and *Tungussia* (Plate 5), K.S. Valdiya[(302)(305)(317)] dated the Lesser Himalayan rock formations bearing these forms to be about 1000 – 900 m.y old.

The carbonate rock formations are well-developed in the Gangolihat area in eastern Kumaun, the Deoban massif in western Garhwal (where R.D. Oldham[(183)] had described the succession as *Deoban Limestone*) and in the Shali mountain in Himachal (Table 3.2; Fig. 3.7). A Deoban Limestone cave, which forms a pre-eminent summit north of Jammu, houses the sanctum sanctorum of the famous Vaishnodevi shrine (Fig. 3.6). In the Vindhyan Basin, the succession of semri-carbonates and shales, and in the Aravali column, the upper Ajabgarh–Kushalgarh limestone were deposited during the Deoban time (Table 3.2).

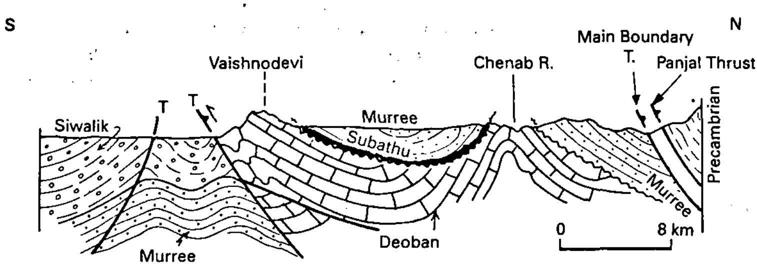


Fig. 3.6 *The celebrated shrine of Vaishnodevi is located in a cave formed in the Deoban Limestone (belonging to 1200 – 1000 m.y. period).*

An outstanding feature of the Deoban deposits is the occurrence of big and small lens-shaped deposits of very coarse crystalline magnesite with associated pockets of soapstone and talc in many areas, particularly in Kumaun. These deposits of magnesite are extensively mined. The magnesite deposits are intimately associated with stromatolitic dolomite. The origin of magnesite has been attributed to replacement of dolomite by magnesia-rich solutions emanating from nearly basic intrusives. However, it is possible that this development took place as a result of replacement of dolomite by $MgCO_3$ during the process of sedimentation under singularly penesaline (i.e. intermediate between normal and hypersaline) conditions that may have developed behind algae-built reef barriers in embayments [(304)]. These barriers inhibited circulation of basin waters. Accumulation of algal debris must have added to the concentration of magnesium and raised the level of pH in the sea water. Magnesium-rich water converted the susceptible framework of algal reefs and biostromes into concordant as well as discordant bodies of magnesite. Significantly, in some places, the branching columns of stromatolites have been moderately phosphatized, the change having been stimulated by algae during the later, almost penultimate, stage of the Deoban times when branching stromatolites were in their heyday of development[(307)]

Sporadic distribution in the form of specks or clusters of grains, pockets and veins of sulphides of copper, lead and zinc in the magnesite and dolomite of the Deoban horizon is seen practically all through the basin. The economic worth of the sulphide deposits is yet unestablished, while the deposits of magnesite and soapstone-talc are commercially mined on an extensive scale.

3.6 Time of transition: Vendian Age

Cyanobacteria-built reefs and domes cluttered the shallow intertidal and supratidal zones of the Purāna platform. These inhibited the flow of currents and movement of waves, particularly in the embayments and gulfs. Consequently, circulation of water was restricted or hampered and the water became deficient in oxygen, while there was excess of hydrogen sulphide. The slowly accumulating sediments got blackened pervasively and were locally impregnated with iron sulphide (pyrite). This horizon of black shales and black limestones with marlites and intraformational conglomerate was described as the *Mandhali* on the Deoban massif in western Garhwal by R.D. Oldham[183] (Table 3.2; Fig. 3.7). Black shale and limestone surrounded the algal reefs characterized by stromatolites identified by K.S. Valdiya[305] and Anshu K. Sinha[264] as *Jurusania, Stratifera, Irregularia, Inzeria*, etc. of the later Neoproterozoic or Vendian Age (650–570 m.y. ago). Towards the upper part of the succession of sediments there are lenses of locally derived breccia and conglomerate made up of debris deposited by submarine slides (which must have become very frequent) or were shed off from fault scarps[144]. The breccia (which comprises broken rock fragments with sharp edges and unworn corners, held together by a matrix of finer sediments) indicates return of tectonic instability precursor to the upheaval that was soon to engulf the whole of the Indian subcontinent.

The calcian limestone of the Mussoorie (UP) and Sataun Hills (southwestern Himachal) is extensively mined for a variety of uses. In the Vindhyan basin the analogues of these Vendian formations are the Kaimur–Rewa and lower part of the Bhander, while in the Aravali domain the contemporary formations are represented by the uppermost Ajabgarh and the Bhagwanpura limestone. In the Marwar platform, the Jodhpur Sandstone — the much used building material — was laid down during this period (Table 3.2).

Soft-bodied (metazoan) creatures of uncertain phyllogenetic affinity described as *Ediacaran* fauna are spotted at a few places in Garhwal and Kumaun. These mark the beginning of a new kind of life. Elsewhere, life is represented by crawling and burrowing creatures and hyolithids and annelids that had appeared on the scene.

3.7 Early Cambrian: Advent of invertebrates

The mixed and varied assemblage of the Vendian sediments of the Krol horizon of the Mussoorie–Sataun Range in southcentral Lesser Himalaya grades imperceptibly into strata containing varied fossils of the Early Cambrian age (570–525 m.y.). This horizon of black shale, siltstone and limestone with prominent beds of phosphorite was described as the *Tal* by J.B. Auden[13]. In the Tethyan terrane in the north, low-grade metamorphic rocks give way to sediments bearing Early Cambrian fossils as seen in the Martoli–Milam section in northern Kumaun, the Parahio Valley in Spiti, the Phe–Karsha section in the Zanskar Range, the Liddar Valley and Kupwara–Hündwara sections in Kashmir, and the Salt Range in northern Pakistan. Among the remarkable and age-indicating fossils found here, mention

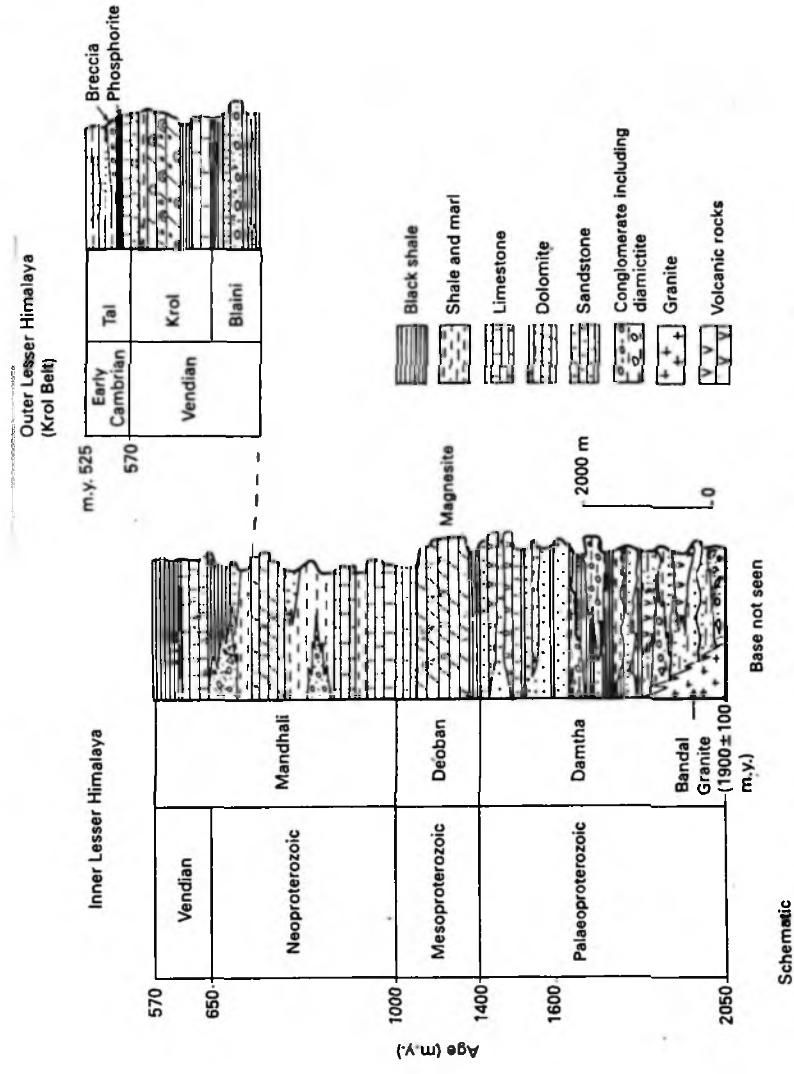


Fig. 3.7 *Lithological column exhibits the order of succession and nature of sediments of the Purāna era.*

may be made of the trilobites *Redlichia* and *Ptychoparia*, and the brachiopods *Lingulella*, *Olenus*, *Neobolus*, etc. (Plate 6).

3.8 Desiccation and salt formation

India was near the equator in the early Cambrian time (570–525 m.y. ago) (Fig. 3.8). Naturally some parts of the shores of the marginal sea experienced desiccation — drying out of the very shallow bodies of water in the coast. Evaporation of water within enclosed embayments and gulfs, owing to development of algal reefs for example, resulted in extraordinary concentration of dissolved salts within the water bodies and resultant precipitation of various salts and gypsum in some places like the Ropri–Mandi tract in Himachal[272], the Sincha–Ramban belt in Jammu[330], the Salt Range in northern Pakistan[108], and the Hanseran (Bilara) area in Marwar[75]. The salts forming the basal Salt Range and Hanseran horizons stretching over a large region formed a little earlier in the Vendian Age, while those of the upper Salt Range and elsewhere, including in the upper Bhander beds of Maihar area in the Vindhyan Basin[165], were formed towards the close of the Early Cambrian Age. Evidently, the desiccation due to aridity was quite widespread. Figure 3.9 shows the salt deposits in the Marwar Basin in Western Rajasthan and the Salt Range in Pakistan that resulted from the spell of desiccation in the Late Vendian and Early Cambrian period.

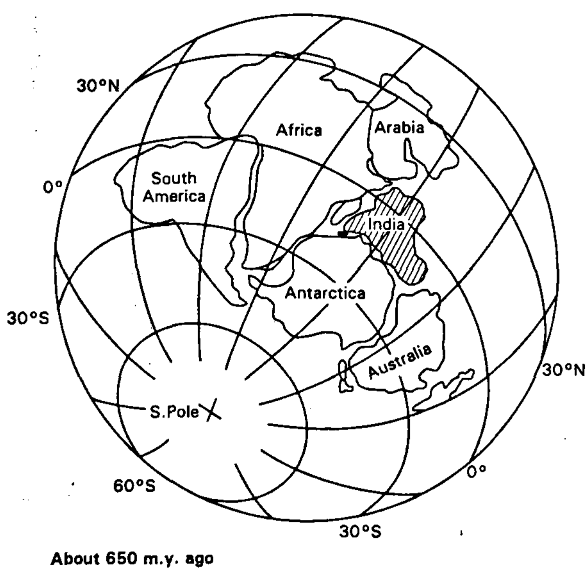


Fig. 3.8 *India was close to the equator in the Early Cambrian time (570–525 m.y.) when quite a part of the subcontinent was overwhelmed by desiccation (after N.S. Virdi, 1990).*

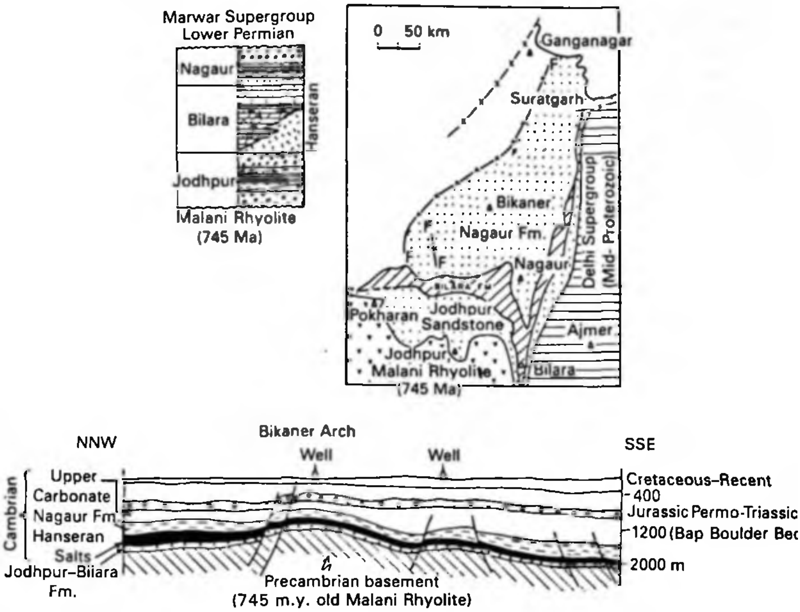


Fig. 3.9 *Salt deposits in the Marwar Basin in western Rajasthan and the Salt Range in Pakistan indicate a spell of desiccation in the Late Vendian and Early Cambrian period 600–550 m.y. ago (based on U. Das Gupta and S.S. Bulgauda, 1994).*

3.9 Phosphatization of sediments

Yet another development of considerable consequence was the phosphatization of sediments in some basins towards the terminal stage of the Purāna sedimentation. Phosphorites occur both in the form of beds with limestones and cherts as well as phosphatized stromatolitic dolomites[(24)]. The phosphorites form a major component of the Tal in the Mussoorie Hills, at Zilant in the Doda district in Jammu–Kashmir, at Sincha in the foothills of the Pir Panjal and in the top horizon of the Abbotabad succession in northern Pakistan. The deposits of phosphorites are mined profitably in the Abbotabad and Mussoorie areas. They are of considerable economic importance as these provide raw materials for phosphatic fertilizers.

3.10 Cessation of sedimentation: End of Purāna era

In the Mandhali Formation, towards its upper part (Table 3.2, Fig. 3.7), accumulation of conglomerate and breccia in the form of lenses and pockets was precursor to the impending tectonic upheaval which eventually terminated the more than 1000 m.y.-long cycle of sedimentation throughout the Purāna Basin encompassing the Lesser Himalaya and the Indian shield. Evidently, the whole of the continent was gradually lifted up above the sea water and became a landmass.

The Tethys terrane in the north experienced the impact of the continental uplift only temporarily. There was merely an interruption of sedimentation for a short but variable period. Obviously, the Indian subcontinent was overtaken by a tectonic upheaval of continental dimensions. This aspect is dealt with in Chapter 4.

4 *From Diastrophism to Diastrophism*

4.1 Retreat of Purāna Sea

Towards the end of the Early Cambrian about 525 m.y. ago, a great tectonic disturbance affected the whole of the Indian subcontinent. The sea, which had held sway for more than a thousand million years, was forced to recede completely from the Peninsular India and Lesser Himalaya; and sedimentation was interrupted in the northern part of the Himalayan province known as the Tethys terrane. The tectonic upheaval was accompanied by extensive invasion of granitic magma, and many parts of the Himalayan province experienced explosive and eruptive volcanism. The sea in the Tethyan domain (Fig. 4.1) was quite shallow on the whole throughout the Palaeozoic era (570–250 m.y. ago) and the sediments laid down were dominantly land-derived detritus in the western part and mainly organo-chemical carbonates in the eastern half. All through this period, land-derived sediments were delivered by rivers that flowed northwards from their watersheds in the distant Indian shield to the south.

Life had established its foothold firmly both in the sea and on land. Indeed the sea was teeming for the first time with a wide variety of invertebrate animals including trilobites, brachiopods, bryozoans, crinoids, corals and lamellibranchs; and on land vascular plants made their first appearance.

4.2 Break in sedimentation: Pan-African diastrophism

The long cycle of Purāna sedimentation came to an end towards the close of the Early Cambrian nearly 525 m.y. ago (Fig. 3.7) throughout the Lesser Himalaya, and *possibly* a little earlier in the Vendian age (650–570 m.y.) in eastern Rajasthan and Madhya Pradesh in the Indian shield. The termination of deposition of sediments practically all over the continent implies that it was a regional diastrophism or crustal movement which heaved up the Indian subcontinent. The diastrophism was contemporaneous with the Pan-African mountain-building movements of Gondwanaland and nearly so with the Cadomian orogeny of Eurasia[320].

This Pan-African diastrophism was quite strong in parts of Zanskar and Hazara where rocks were lifted up, tilted or even folded (Fig. 5.1). According to O.N. Bhargava[38], a northeast trending ridge came into existence in the Spiti region. As a matter of fact, a very large tract of Himachal and Kashmir Himalaya was raised above the sea and rivers became active on the newly emerged land, depositing sediments in their channels and floodplains[20][21][93]. Resting very discordantly on the older part of Late Cambrian marine rocks are pebbly sandstone and conglomerate. (A conglomerate is a coarse-grained rock

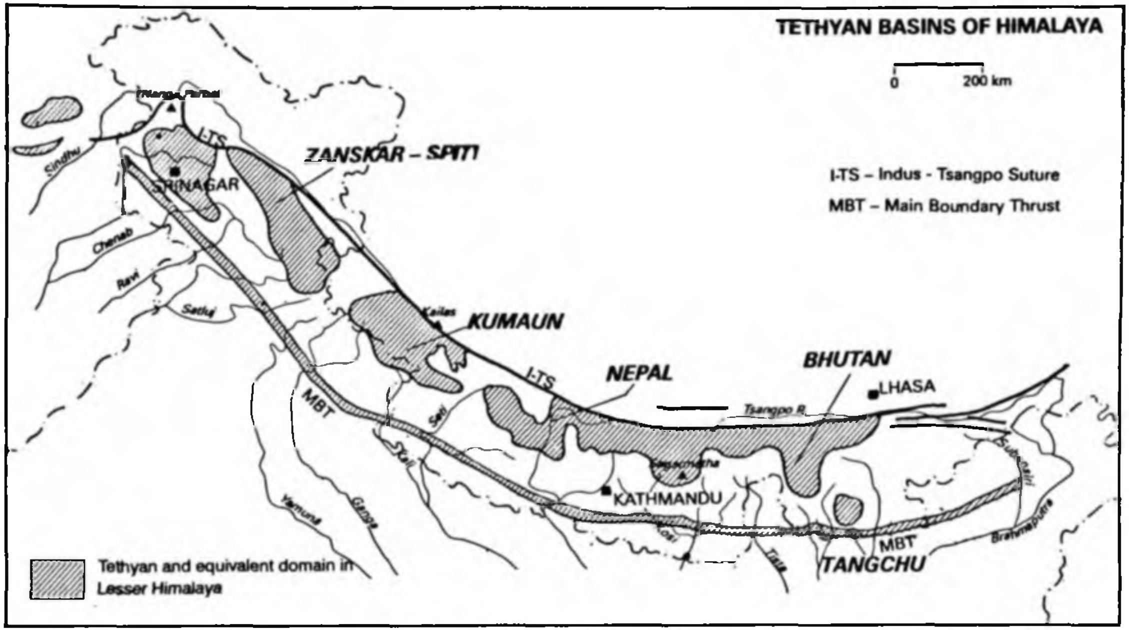


Fig. 4.1 *Extent of the mainly Palaeozoic sea (spanning the period from 525 to nearly 260 m.y.) in the Himalayan province. The Tethys domain is truncated in the north by the deep long fault, the Indus–Tsangpo Suture (I–TS), that marks the junction of the Indian and Asian landmasses.*

composed of rounded to subangular rock fragments larger than 2 mm in size set in the matrix of finer sediments). These were laid down by rivers all over the region in the Middle Ordovician time about 470–455 m.y. ago[243][320]. In the upper reaches of the Kali Gandaki Valley in northwest Nepal, the Chandragiri Hills in central Nepal and in central Bhutan, the earliest recorded fossils in sediments (which rest on the basement rocks) (Fig. 4.2) belong to the 455 to 446 m.y. old Middle Ordovician[50][51][52][69][276][287].

Apparently there are no sediments and fossils of the later Late Cambrian and early Middle Ordovician periods in the Palaeozoic succession of the Himalayan province; and the Middle Ordovician period starts with the deposition of granular or pebbly sediments by streams in a terrestrial (land) setting — quite in contrast to the earlier marine environment.

The radical change in the environment from marine to continental implies tectonic disturbances. It was only towards the Middle Ordovician (455–446 m.y.) that the Himalayan province east of the Kali River (forming the India–Nepal border) was drowned under sea water, although in the western Himalaya sedimentation had been going on since the Precambrian period.

4.3 Widespread granitic activity

Very strong thermal events accompanied the crustal disturbance that caused a pause in the process of basin-filling. This is borne out by the invasion of granitic magma on a large scale throughout the Himalayan province — from Mansehra in northern Pakistan to Manaslu in Nepal and beyond (Fig. 4.3). The older rocks around the hot intrusive bodies of granite were profoundly affected by the release of heat and fluids from the magma and thus wholly transformed or metamorphosed.

The lower-grade metamorphism of the Lesser Himalayan Purāna sediments in Garhwal is possibly related to the invasion of granitic magma and the attendant heating of rocks as evident from Ordovician (486 m.y.) age given by the whole rocks[184]. The climax of this granitic activity occurred 525 to 475 m.y. ago. These porphyritic granites, characterized by high initial strontium isotope ratios, were formed by partial melting of rocks even as there was stretching and thinning of the continental crust[152][154].

4.4 Volcanic explosions and eruptions

At about the same time when granitic bodies were emplaced and also a little earlier than that, there were volcanic explosions accompanied by eruption of lava in some centres such as at Khewra in the Salt Range, at Kurgiakh in the Zanskar belt, at Hilap in Kinnaur, at Garbyang in Kumaun, the Ganesh Himal in Nepal and the Maneting area in Bhutan. This is evident from the rather sparse occurrence of tuff (compacted volcanic ash) showing layering, bentonitic clay (altered volcanic ash) and lava in the uppermost part of the Purāna succession or in the basal part of the Palaeozoic sequence (Fig. 4.4).

In central Bhutan, volcanic rocks are associated with muddy unsorted conglomerates or diamictites of catastrophic origin[23]. Volcanic explosions appear to have caused landslides and submarine slides in the theatre of these activities.

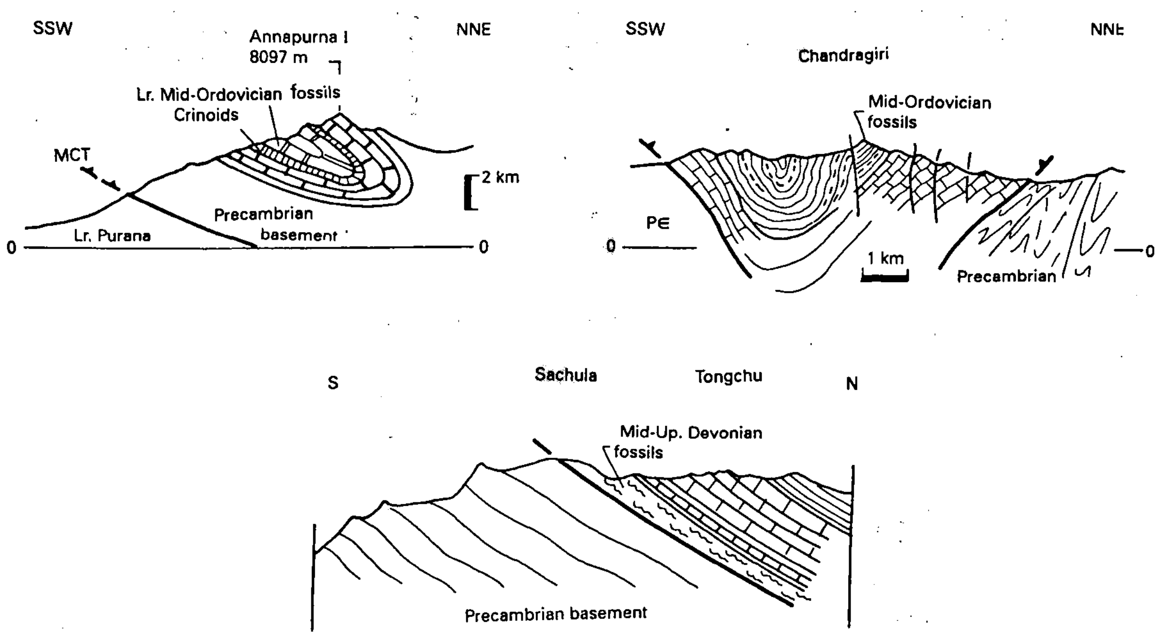


Fig. 4.2 *Earliest recorded fossils in Nepal and Bhutan belong to the Middle Ordovician, implying absence of sedimentation prior to this time due to its uplift above sea-water or an environment not conducive to the preservation of fossils when this was happening everywhere else in the Himalayan province. Based on M. Colchen et al. (1986), J. Stocklin et al. (1977), and B. Termier and A. Gansser (1974).*

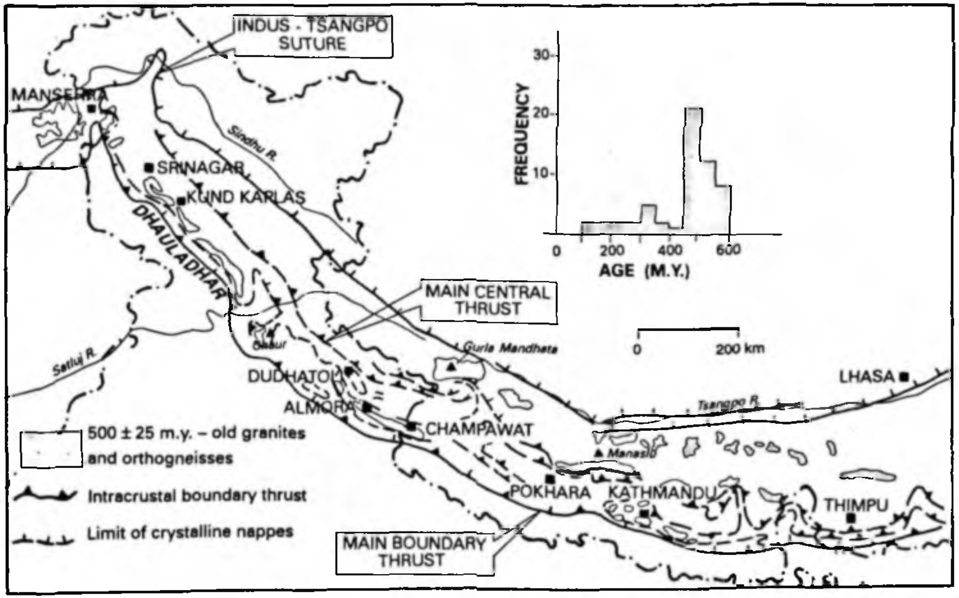


Fig. 4.3 *Pan-African granites occurring all over the Himalaya imply stretching and attendant thinning and differential melting of rocks of the Indian crust some 500 ± 25 m.y. ago.*

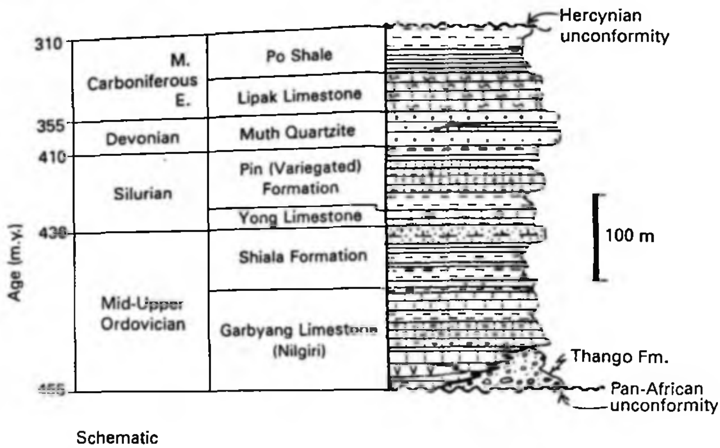


Fig. 4.4 *Column illustrating sedimentary succession of the Palaeozoic Era.*

4.5 Short-lived fluvial regime in the Ordovician

The Middle Ordovician commenced everywhere with the deposition of pebbles, granules and coarse sands by streams and rivers in a terrestrial (land) setting. The fluvial or riverine conglomerate and sandstone rest uncomformably on the older marine strata in the western part of the Himalaya, such as the Thango–Thaple sections in the Zanskar–Spiti belt. Remains of the *Rhaecopteris* plant in these sediments in some places demonstrate that the detritus was derived from the nearby land clothed with vegetations. The fluvial deposition was an interlude of very brief duration. For, very shortly afterwards, the sea-water regained its sway all over the Tethyan terrane (Table 4.1). While greywacke and shale were laid down in the northwestern Himalaya, a thick sequence of dolomitic limestone, dolomite and calcareous shale accumulated in the Garbyang belt in Kumaun and the Dhaulagiri–Nilgiri Range in Nepal during the Middle Ordovician epoch (470–446 m.y. ago). This sediment gave way upwards to a variegated succession of shale and limestone in the Silurian (438–410 m.y. ago), when life forms including algae, bryozoans, brachiopods and crinoids, became prolific and varied (Plate 7).

4.6 Deposition of clean sands on shores

Then came a short epoch of tectonic stability during the Devonian period (410–355 m.y. ago) when the entire stretch of the shore from Tanawal in northern Pakistan through Muth in Spiti to northern Nepal became the site of deposition in very shallow water of very clean sands devoid of any mud. According to T.N. Bagati[20][21], the sediment was swept and sifted

Table 4.1 *Palaeozoic sedimentary formations in the Tethys domain of the Himalaya.*

Age: Period		Age: Time Range (m.y. ago)	Kashmir	Himachal		Kumaun	Nepal	Sikkim	Bhutan
Permian	L	– 250 –	Zewan Fm.	Kuling Shale		Kuling Shale	Thinichu Fm.	Lachi Fm.	Shodung
	M	– 260 –	Panjal Volcanics	Panjal Volcanics					
	E	– 270 –	Agglomeratic Slate	Ganmachidam Congl.					Wachila
		– 290 –							
Carboniferous	L	– 310 –							
	M	– 325 –	Fenestella Shale	Po Shale					
	E		Syringothyris Ls.	Lipak Ls.					Tongchu
Devonian		– 355 –	Muth Qz.	Muth Qz.		Muth Qz.	Tilicho Lake Fm.		
Silurian		– 446 –	Marhaum / Margam Fm.	Takche / Pin		Variegated Silurian	Dark Band Fm.		Nakechu
Ordovician	L	– 438 –		Thango / Thaple		Shiala Fm.	North Face Qz.		
	M	– 446 –							
	E	– 455 –				Garbyang Fm.	Nilgiri Ls.	Everest Ls.	Maneting
		– 510 –						Everest Pelites	
Cambrian	L	– 523 –							
	M		Trahagam Fm.	Parahio/Kurgiakh	Haimanta	Ralam Congl.			
	E	– 525 –	Karikul / Nutunus	Karsha Ls.		Martoli			
		– 570 –	Lolab / Khaiyar Fm.	Kunzamla					

--- = Unconformity, Fm. = Formation, Gr. = Group , Qz. = Quartzite, Congl. = Conglomerate, Ls. = Limestone by vigorous waves and currents giving rise to well-sorted and remarkably clean sands with minor granules and pebbles. They formed elongate offshore ridges called bars-and-shoal complex on the shore. Only small amounts of carbonates accumulated later on over time. Described as the *Muth Quartzite* by H.H. Hayden[115] (after a village in the Pin Valley in Spiti), this cliff-forming quartzite with interbedded fossiliferous limestone is one of the very conspicuous datum lines in the stratigraphic history of the Himalaya.

4.7 Oxygen-deficient reducing environment

In the Early Carboniferous time (355–340 m.y. ago) the shallow shelf in the northern part of the Tethyan domain subsided, and in large parts of the marine basin circulation of currents got inhibited or restricted. Consequently, there was deficiency in dissolved oxygen and excess of hydrogen sulphide generated by decomposing organisms that died in the suffocating or reducing (euxinic) environment. The sediment became black and locally charged with sulphide minerals like pyrite, particularly towards the upper part. These are best seen in the outskirts of the Po village in the Spiti region in Himachal. Indeed, the black sediment is the hallmark of the formations of the Early Carboniferous (355–325 m.y.), described as *Po Shale* (Table 4.1; Fig. 4.4). The older, lower part of the succession is made up of limestone — the *Lipak Limestone* which is abundant in the valley of the Lipak stream. Fossils such as *Productus*, *Syringothyris*, *Linoproductus* and *Fenestella* (Plate 8) are the most prominent and characteristic remains of the Carboniferous formations. The entombment of plant remains such as at Thabo in Spiti and Nishatbagh–Gulabbagh in Kashmir are pointers to the existence of forested landmasses in the vicinity of the sites of deposition.

In the Late Carboniferous there was no deposition of sediments in the Spiti and Kumaun sub-basins. In northwestern Kashmir, the sedimentation had stopped even earlier — just after the Muth time[338]. It appears that tectonic movements had begun lifting the basin above sea level, eventually leading to cessation of sedimentation over a large part of the basin.

4.8 Hercynian diastrophism

While sedimentation stopped, albeit for a limited duration of 30–35 m.y. in the Tethyan domain, the sea returned in the Early Permian time (290–270 m.y.ago) along a narrow elongate depression that was formed owing to sagging and breaking down or rifting of the crust — in what is today the outermost Lesser Himalaya (Fig. 4.1). It may be recalled that the sea had vacated the Lesser Himalaya towards the end of the Early Cambrian about 525 m.y. ago. The sea stretched from the Salt Range in Pakistan through the Pir Panjal, the Chamba–Tandi belt in western Himachal and the Dugadda–Rathwadhab belt in southern Garhwal to eastern Arunachal Pradesh (Figs. 4.1 and 4.5). The incursion of sea water is discernible in the Indian shield as well through Rajhara (Daltonganj) and Manendragarh to Umaria in Bihar–Madhya Pradesh in the east, and through Bap and Badhaura in western Rajasthan. As a matter of fact, quite a few elongated depressions were formed as a result of sinking of the ground between parallel normal faults developed at that time in the Gondwanic

Indian shield along what are today the valleys of the Damodar, Mahanadi, Godavari and Narmada rivers. These rift valleys are related to the diastrophism which gave rise to the Hercynian mountains stretching over long distances in Eurasia.

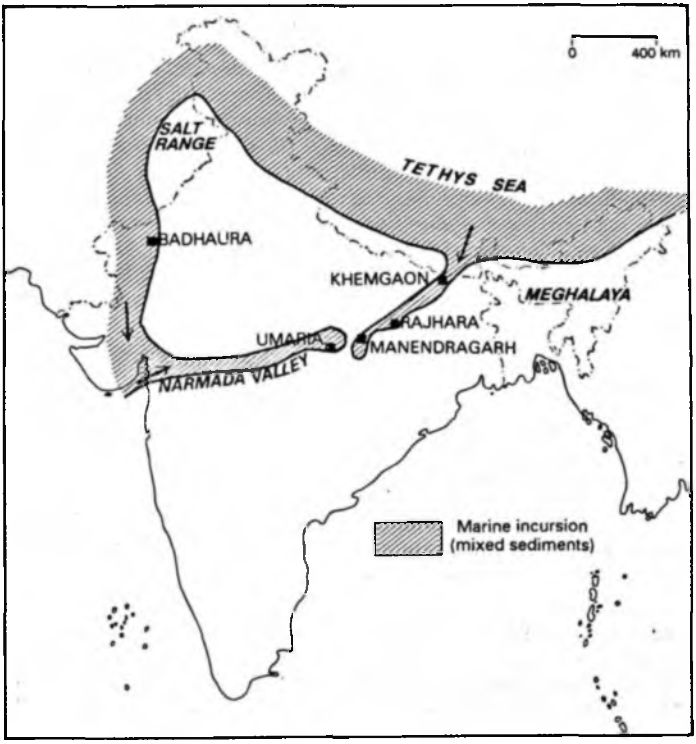


Fig. 4.5 *Marine invasion of the southern belt of the Himalaya took place 290 to 270 m.y. ago possibly through the rift valleys in the Gondwanic Indian shield (S. Chatterjee and N. Hotton, 1986).*

In the Gondwana rift valleys were deposited poorly sorted muddy, unstratified conglomerates or diamictites known as the *Talchir Boulder Beds*. The diamictite is believed to have been dumped by glaciers descending down the valleys in the Gondwana continent that was in the grip of severe refrigeration and thus under cover. In the Lesser Himalayan depression, likewise, large volumes of diamictite along with badly sorted muddy sandstone and mudstone were deposited by the valley glaciers. The boulder conglomerate at Tobra in the Salt Range (Pakistan) as well as at Bap and Badhaura in the Marwar (Rajasthan) contain pieces of very characteristic rhyolite, felsite and granite, presumably transported nearly 600 km all the way from their sources in the Malani and Erinpura areas of the Aravali Range

(Fig. 4.5). Obviously, the glaciers then covering the Aravali extended as far north as the Salt Range. The marine shales associated with the diamictite are characterized by Early Permian *Protoretepora*, *Fenestella*, *Productus*, *Spirifer*, *Marginifera*, etc. (Plate 8) besides the cold-water loving *Eurydesma* and *Deltopecten*, all through the basin from end to end. It seems, the meltwater contributed by the glaciers was responsible for the cooling of the sea water.

Part of the diamictite and greywacke must have been laid down by submarine slides, presumably triggered by earthquakes originating in the faults of the rift valley. A sizeable upper part of the diamictite is made up of fragments of volcanic rocks set in volcanic ash and finer sediments (agglomerate) and compacted or hardened volcanic ash (tuff) — indicating spurts of explosive volcanism along the lines of rifting.

This rift valley in the outer Lesser Himalaya and the ones in the Indian shield were later filled up with sediments brought by rivers and streams of the post-glacial period. These rivers flowed in the northwest to northeast directions, as the studies of S.M. Casshyap and R.C. Tewari(63) in central India in the shield region and of H. Sakai(227) in the Nepal area demonstrate. Evidently, the continental margin of Gondwanic India sloped northwards 290 to 250 m.y. ago, as it did all through the Purāna and Palaeozoic times. The rivers spread sheets of sand, silt and mud on their floodplains, characterized by meandering valleys, crescent-shaped oxbow lakes and swamps. The floodplains were covered with dense forests of *Glossopteris*, *Gangamopteris* (Plate 9) and other plants(325). These Gondwana plants got buried under the sediments and eventually converted into rich seams of coal (so common east of the Arun River in the eastern Himalaya) as well as in the plains of the Damodar, Mahanadi, Godavari and Son–Narmada rivers in the shield.

4.9 Fiery fountains of lava

Explosive volcanoes had become active all along southern Lesser Himalaya 290 to 270 m.y. ago. The lavas must have welled up and flowed out through the deep faults formed due to rifting of the crust as demonstrated by M.I. Bhat(39) and Baud et al.(31)(93). Consequently, a chain of volcanoes must have formed in the southern outer Himalayan belt within the basin (Fig. 4.1). This is testified by deposits comprising volcanic blocks, bombs, lapilli and ashes. As emphasized by S.K. Acharyya(2), the volcanigenic agglomeratic material is intermixed with glacial-formed tillites as well as marine sediments (Fig. 4.6).

The assemblege is appropriately called *Agglomeratic Slate* in the Pir Panjal and Bhaderwah–Chamba belts(338). The accumulation of products of explosive volcanism was nearly synchronous with the eruption of lava of andesitic and basaltic composition — known as *Panjal Volcanics*(338). The volcanic rocks are seen all along the Himalaya (Fig. 4.1) from the Shewa–Shahbazgarha area in northern Pakistan through the Pir Panjal and Zanskar ranges, the Dugadda area in southern Garhwal(164)(309), the Aulis area of the Tansen Hills in Nepal(225)(227) to the southern belt of eastern Himalaya, the last embracing Tindharia, Rangit Valley, Duiri and Igo–Jirdo(2)(3)(82)(126)(129).

The Early Permian (284 ± 1 m.y old) dykes of alkali granite cutting across the sedimentary succession in southeastern Zanskar and adjoining Lahaul(269) and Spiti demonstrate the stretching of the Himalayan crust in the Early Permian time. Some of these volcanic islands were covered with forests of *Gangamopteris*, *Glossopteris*, *Waagenophyllum*, etc. that grew luxuriously in the main Gondwanic Indian shield. In the islands nestled freshwater lakes, in which lived fishes like *Amblypterus* and *Labyrinthodonts.*

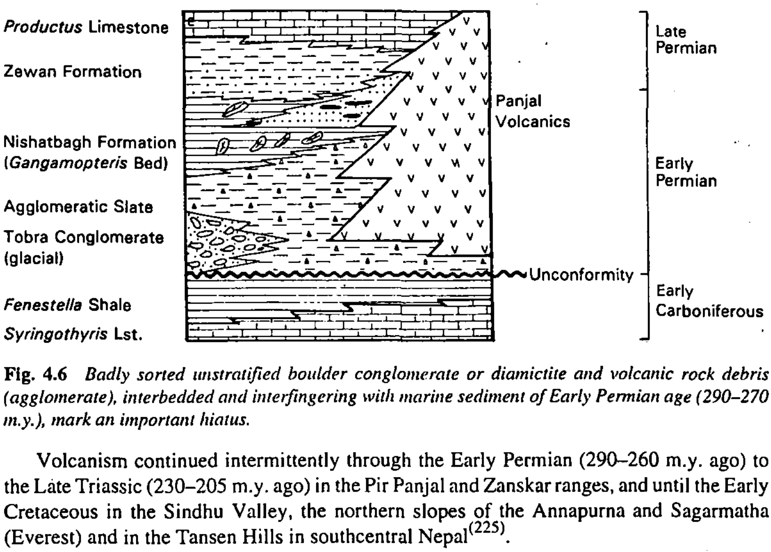


Fig. 4.6 *Badly sorted unstratified boulder conglomerate or diamictite and volcanic rock debris (agglomerate), interbedded and interfingering with marine sediment of Early Permian age (290–270 m.y.), mark an important hiatus.*

Volcanism continued intermittently through the Early Permian (290–260 m.y. ago) to the Late Triassic (230–205 m.y. ago) in the Pir Panjal and Zanskar ranges, and until the Early Cretaceous in the Sindhu Valley, the northern slopes of the Annapurna and Sagarmatha (Everest) and in the Tansen Hills in southcentral Nepal[225].

4.10 Breaking away of the Tibetan microcontinent

The fissuring of the Himalayan province with accompanying volcanism and incursion of the sea along the depression, thus formed implies that the Gondwanic Indian shield was once again overtaken by a powerful crustal movement. This is known as *Hercynian diastrophism.* Indeed the Tibetan landmass in the north — a part of the microcontinent comprising Tibet, Iran and Turkey — broke away as a result of rifting in the later Permian (260–250 m.y. ago).

The separation of Tibet opened up a new sea, called *Neotethys* by A.M.C. Sengor[239], between India and Tibet (Fig. 4.7). This seaway was linked with the Mediterranean Tethys Ocean of Europe that stretched upto Portugal. Significant elements of the fossils found in the Permian sediments of Kashmir[256] also occur among the flora in southern Tibet implying that in the Late Permian Tibet was a part of the Indian subcontinent. Sedimentation continued, albeit with minor interruptions, in the Himalayan basin.

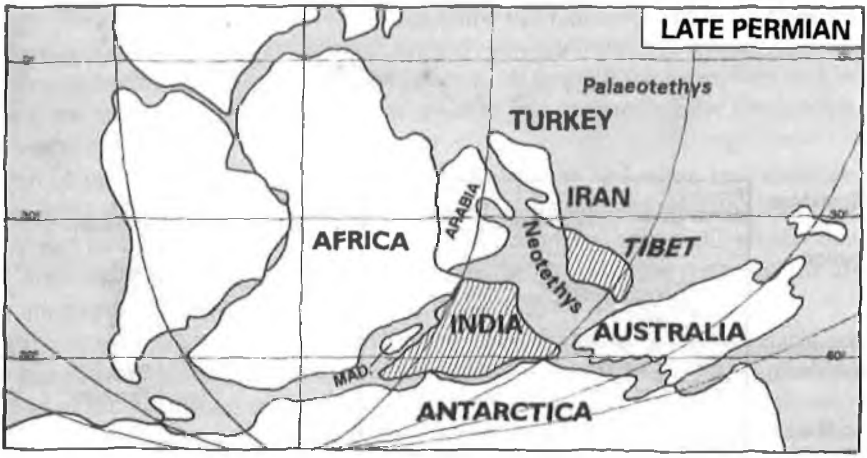
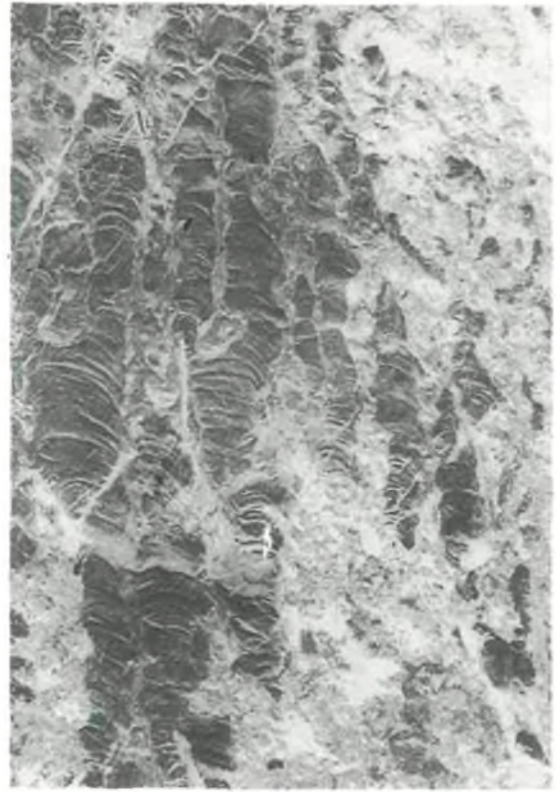


Fig. 4.7 *Opening up of the Neotethys between India and Tibet when the microcontinent of Tibet broke away and got separated in the Later Permian time 260–250 m.y. ago (figure based on A.M.C. Sengor, 1984).*

(A)



(B)

Plate 5 1000 to 900 m.y. old stromatolites built by algae-bacteria that lived in very shallow warm water. (**A**) *Baicalia* and (**B**) *Minjaria*. (Photos by K.S. Valdiya)

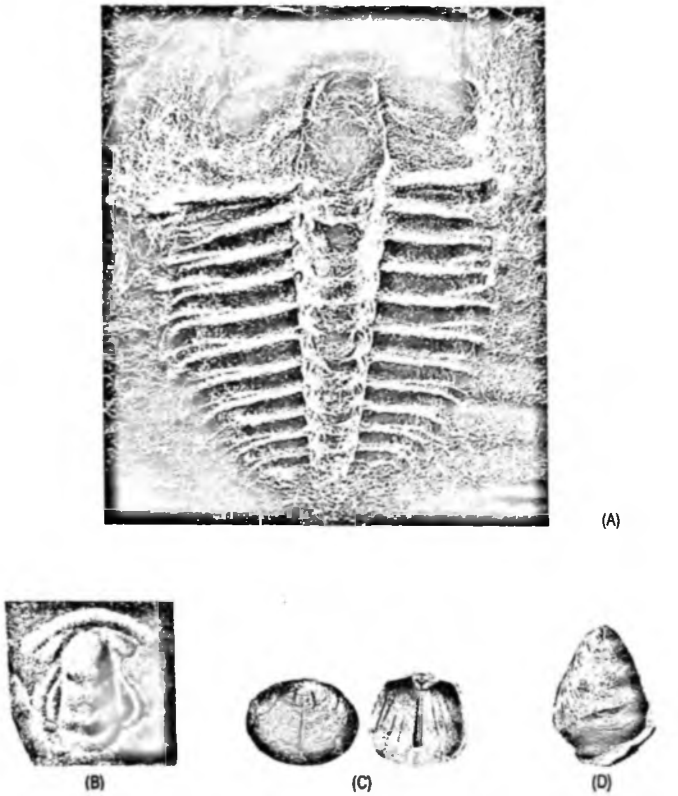


Plate 6 Some important fossils of the Cambrian time: (**A**) *Ptychoparia*—a 525–520 m.y. old trilobite fossil found in the Pin Valley, Spiti Basin, Himachal. (Photo by S.K. Parcha (1995), *Annual Report of the Wadia Institute of Himalayan Geology,* Dehradun.(**B**) *Redlichia* (**C**) *Neobolus* (**D**) *Lingulella*. (Photos from E.H. Pascoe (1959), *A Manual of Geology of India and Burma*, Vol II, Govt. of India Press, Calcutta, pg. 1343)

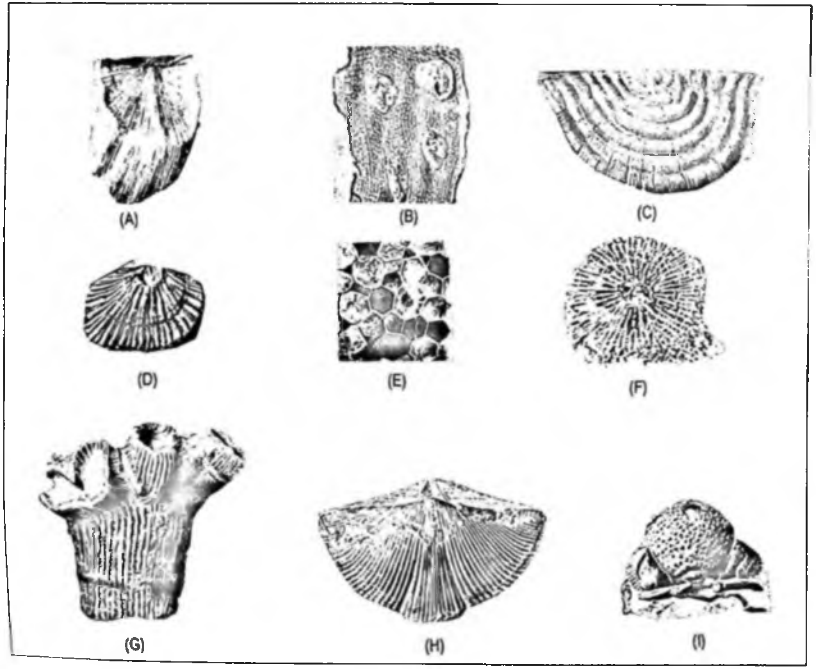


Plate 7 Some well-known fossils indicating Ordovician (A, B, C), Silurian (D, E, F) and Devonian (G, H, I) periods. (A) *Rafinesquina* (B) *Graptodictya* (C) *Leptaena* (D) *Orthis* (E) *Favosites* (F) *Calostylis* (G) *Cyathophyllum* (H) *Spirifer* (I) *Phacops*. (Photos from E.H. Pascoe (1959), *A Manual of Geology of India and Burma*, Vol II, Govt. of India Press, Calcutta, pg. 1343)

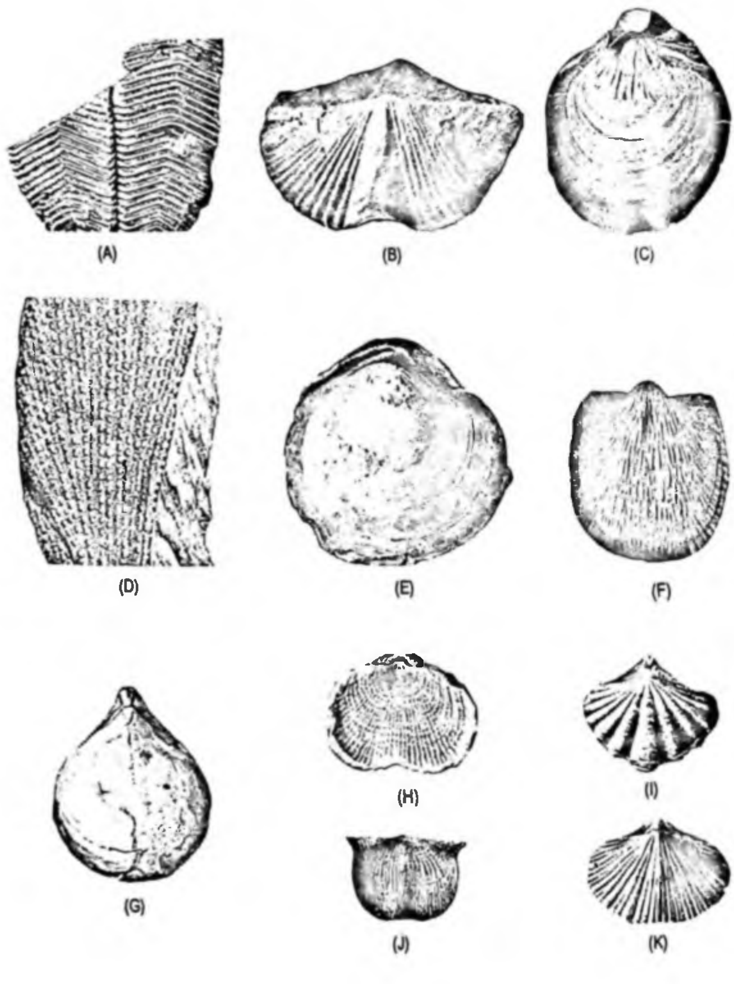


Plate 8 Prominent characteristic fossils of the Palaeozoic era. (**A**) *Conularia* (**B**) *Syringothyris* (**C**) *Dielasma* (**D**) *Protoretepora* (**E**) *Eurydesma* (**F**) *Productus* (**G**) *Spirigerella* (**H**) *Productus* (**I**) *Spiriferina* (**J**) *Marginifera* (**K**) *Spirifer*. (Photos from E.H. Pascoe (1959), *A Manual of Geology of India and Burma*, Vol II, Govt. of India Press, Calcutta, pg. 1343)

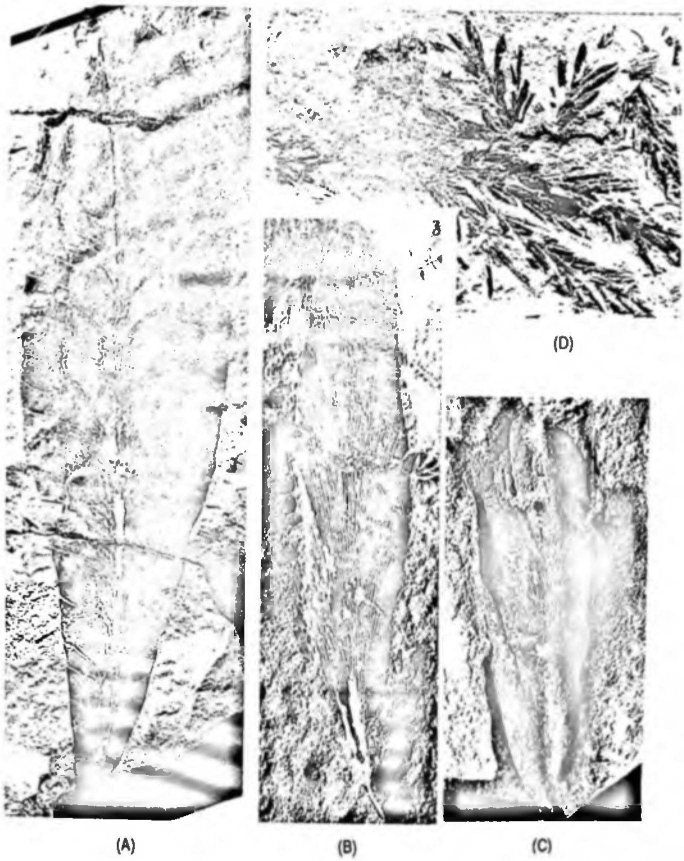


Plate 9 Plant fossils—impressions of leaves—of important plants of the Gondwanaland in the late Palaeozoic time: **(A)** *Glossopteris* **(B)** *Euryphyllum* **(C)** *Gangamopteris* **(D)** *Buriadia*. (Photos by Nilambar Awasthi)

Plate 10 Some crucial fossils of the Triassic (**A–F**), Jurassic (**G, H**), and Cretaceous (**I–M**) periods: (**A**) *Meekoceras* (**B**) *Otoceras* (**C**) *Xenodiscus* (**D**) *Daonella* (**E**) *Ophiceras* (**F**) *Ceratites* (**G**) *Reineckeia* (**H**) *Perisphinctes* (**I**) *Hemiaster* (**J**) *Trigonia* (**K**) *Turrilites* (**L**) *Schloenbachia* (**M**) *Nautilus*. (Photos from E.H. Pascoe (1959), *A Manual of Geology of India and Burma*, Vol. II, Govt. of India Press, Calcutta, pg. 1343)


(A)


(B)

Plate 11 Unique ice stalagmite (**A**) of tremendous beatitude in the holy cave of Amarnath (**B**) is located in the 230 to 205 m.y. old Late Triassic limestone of the Zanskar Range. (Photos by B.L. Dhar)

(A)

(B)

Plate 12(A) *Shaligrams*, a peculiarity of the 200 to 135 m.y. old Jurassic sediments, are concretionary nodules with fossils as the nuclei. (Photo by T.N. Bagati) **(B)** Locality in the northern border of Himalaya where the *Shaligrams* are found.

5 *Era of Growing Tectonic Instability*

5.1 Regional unconformity

The era that followed the Hercynian crustal movements witnessed the splitting away of the Tibetan landmass from India and the linkup of the Himalayan basin with the *Neotethys*. As already stated, the breaking up of the ancient Gondwanaland — comprising what are presently the continents of Antarctica, Australia, India, Africa and South America — was preceded and accompanied by bursts of volcanism through the larger extent of the Himalayan province. An elongate depression had also developed in its southern belt extending from what is at present the Pir Panjal in Kashmir to the Siang Hills in Arunachal Pradesh. The invasion by the sea along the depression in the southern Lesser Himalayan belt was marked by development of thick accumulations of poorly sorted muddy boulder conglomerates or diamictites of diverse origin — partly glacial, partly volcanic and to a small extent due to submarine slides. In some belts, the diamictites rest discordantly on older rocks of variable age (Fig. 5.1). This is a regional unconformity marking the Hercynian diastrophism. It is an important hiatus in the stratigraphic history of the Himalaya. For, it represents a substantial break or gap in the geological record; there is not only interruption in the continuity of deposition, but also a few of the younger rocks are discordantly or unconformably placed. In addition to volcanic activity on a grand scale, the sea water rushed in and flooded long stretches of the Lesser Himalayan and Peninsular Indian landmass. These events were preceded by a halt in sedimentation for variable periods of time in different parts of the sea within the Tethyan domain.

5.2 Sedimentation pattern in the Mesozoic

The post-Hercynian sedimentation commenced with the dumping of conglomerates throughout the Himalayan province by glaciers, due to volcanic explosions and as a result of submarine slides, triggered presumably by earthquakes. However, in the central sector (Kumaun and Nepal) there was no deposition of detritus of any kind during the Late Carboniferous to the Early Permian period[116][245], nearly 300 to 275 m.y. ago!

The climate became warmer after the brief interlude of glaciation and the Late Permian (260–250 m.y. ago) saw laying down of limestone, dolomite and calcareous sandstone together with carbonaceous shale on the shallow shelf in the sun-bathed and well-aerated water (it may be recalled that warm waters promote precipitation of carbonates).The sea was inhabited by such creatures as ***Productus*, *Spirifer*, *Spiriferella*, *Neospirifer*, *Spiriferina*, *Eomarginifera*, *Marginifera*, *Dielasma*, *Streptorhynchus*, *Cyclolobus*** and ***Xenaspis***, and

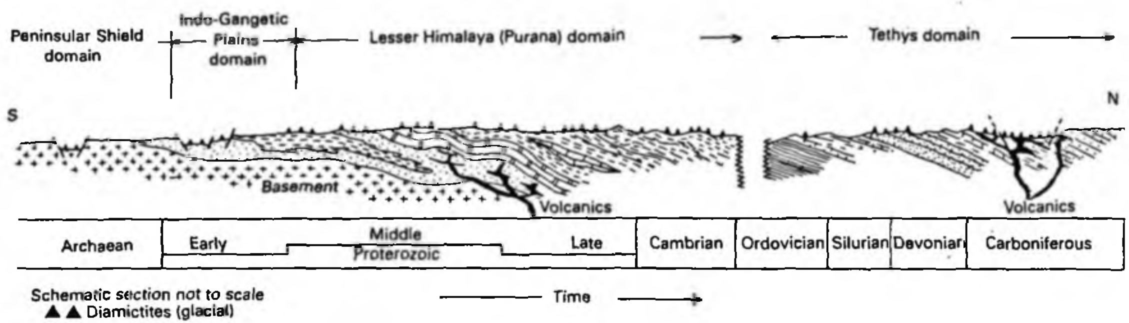


Fig. 5.1 *Hercynian unconformity — a break in the continuity of sequence of sediments — towards the close of the Palaeozoic Era is marked by the break in sedimentation and deposition of boulder conglomerate, glacial tillite and volcanic agglomerate on uplifted and tectonically deformed landmass comprising rock formations of different ages (based on A.K. Jain, 1981).*

such bryozoans as *Protoretepora* and *Acanthocladia* during the Middle and Late Permian time (Plate 9).

The landmark horizon of *Productus* bearing limestone and shale (Table 5.1 and Fig. 5.2) is developed widely over the stretch from Zaluch–Nilawan in northern Pakistan, through the Zewan Valley in Pir Panjal, the Thinichu Valley in northcentral Nepal, the northern slope of the Sagarmatha in northeastern Nepal and in the Shodung area in Bhutan. However, in the Kuling area in Spiti, there was deposition of sand. Locally, the sea got partially enclosed or barred, and in the oxygen-deficient restricted basins, nodules of phosphate were formed as seen in the Zanskar and Kumaun sections, as also in the Barahkshetra area (Fig. 4.1) in southeastern Nepal[29] in the Lesser Himalaya.

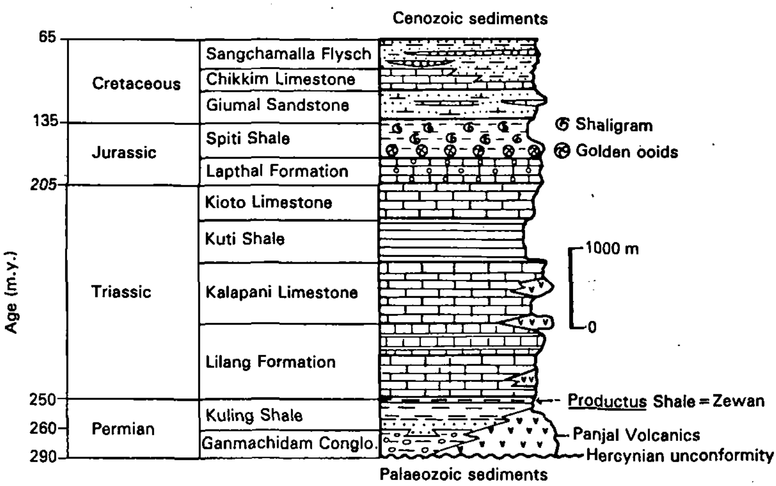


Fig. 5.2 *Lithostratigraphic column illustrating the integrated succession of sedimentary rocks during the Mesozoic era.*

Then something extraordinary happened at the end of the Permian about 250 m.y. ago. Brachiopods, which till that time held a pre-eminent position among the fauna, were suddenly relegated to a very insignificant status by the ammonites while lamellibranchs reasserted themselves strongly. High anomalies of europium (1.9) and cerium (1.4) in the limonitic sediments at the base of the horizon bearing *Otoceras* in the Lalung section of the Spiti Valley[33] demonstrates that some unusual incidents had occurred. The sea retreated from some parts, exposing the land to weathering and formation of red lateritic soil as seen in the Spiti Valley.

The Triassic period (250–205 m.y. ago) was a time of cosmopolitan faunal life, exhibiting great diversity and prolificity[134]. Among the ammonites, *Otoceras*, *Ophiceras*, *Meekoceras*, *Ceratites* and *Tropites* held conspicuous positions (Fig. 5.2 and Plate 10). The Triassic fauna bear a remarkable similarity to their contemporaries in the Alps of the

Table 5.1 *Mesozoic formations in the Tethys domain of the Himalaya.*

Period	Zanskar–Spiti	Kumaun	Western Nepal	Eastern Nepal – Sikkim	Bhutan
Cretaceous	Chikkim Limestone Giumal Sandstone	Sangchamalla Formation Chikkim Limestone Giumal Sandstone	Kagbeni Group	Khampa Group	Chebesa Formation
Jurassic		Spiti Shale Ferruginous Oolite Lapthal Formation	Saligram Formation Ferruginous Beds Lumachelle Formation		Mochu Formation
Triassic	Kioto Limestone Lilang Formation	Kioto Limestone Kuti Shale Kalapani Limestone Chocolate Formation	Jomosom Limestone Thinigaon Formation	TsoLhamo Formation	
Permian	Kuling Shale Ganmachidam Congl.		Thinichu Shale	Lachi Formation	Shodung Formation

Congl. = Conglomerate

Mediterranean province. Obviously, there was free migration of fauna in the Tethys Sea which stretched upto Europe (Fig. 4.7).

The Triassic succession of dominant limestone and dolomite is well developed throughout the Tethyan terrane, typically in the Lilang section of the Spiti region. The holy cave of the Amarnath shrine — with its exquisite ice stalagmite (Plate 11) — is located in the upper part of the succession of the fossiliferous limestone in the Sonmarg and Zanskar ranges of northeastern Kashmir. At the top of the Triassic succession is the *Kioto Limestone* (Fig. 5.2), characterized by *Megalodon, Stephanoceras*, etc., which forms spectacular cliffs in the desolate landscape of the Tethys realm.

In the Jurassic period (205–135 m.y.ago), some more parts of the Indian shield were depressed and flooded by the water of the sea encompassing Marwar, Kachchh and Saurashtra in the west and the southern slope of Meghalaya in the east. Parts of the floor of the Himalayan basin subsided, and characteristic black shale, siltstone and limestone were laid down in the oxygen-deficient reducing environment rich in hydrogen sulphide that developed as a consequence of a combination of factors. The *Spiti Shale* represents this horizon of singularly black shale. One of the most conspicuous features of the Jurassic period is the striking golden and reddish spherical or ovoidal oolites and pisolites in the iron-rich limestones seen practically throughout the vast sea. Resembling fish roes in appearance, these grains are characterized by concentric shells of calcium carbonate. Yet another very arresting peculiarity in the Jurassic succession is the *Shaligram* (Plate 12). Shaligrams (which some people worship as deities) are concretionary balls or nodules with ammonite fossils like *Perisphinctes, Macrocephalites, Cytoceras, Phylloceras, Hoplites*, etc. (Plate 10) forming the nuclei. One other age-indicating fossil is *Belemnites sulcacutus*

5.3 Precursors to impending tectonic revolution

The sea continued to deepen progressively in the northern periphery and by the Early Cretaceous time (less than 135 m.y.ago), the sea floor adjacent to the shelf had sunken considerably to form a trench of sorts. It had started subsiding much earlier — in the Triassic in northern Zanskar, and in the Jurassic in Tibet. In front of this shelf were deposited a thick succession of glauconite-bearing siliceous and calcareous sandstone, siltstone and siliceous shale, typically seen at Giumal in northern Spiti, northern Kumaun and in the Kagbeni area in northcentral Nepal. The *Giumal Sandstone* is suggestive of deep and cold water. The succeeding mudstone with phosphatic nodules and greywacke interbedded with radiolarian chert and siliceous limestone of the Chikkim Hills were laid down in this trench as well as on the adjoining sinking sea floor all along the tract from Ladakh to southeast of Lhasa (Fig. 5.3; Table 5.1). Simultaneously, with the subsidence of the sea floor adjacent to the shelf commenced the eruption of lava which eventually formed volcanic islands in the sea. This is evident also from profuse occurrence of fragments and grains of volcanic rocks, volcanic glass and ash occurring in the sediments of this age.

The flysch assemblage of rhythmic alternation of muddy sandstone, shale and bedded chert (Fig. 5.2) is of regional extent and great thickness in the northern periphery of the Himalayan province stretching from Nindam in the Zanskar Valley, through Chikkim in northern Spiti, Sangchamalla in northern Kumaun and the Kagbeni Valley in northcentral Nepal, to the Kangpa section north of Sagarmatha (Everest). It is characterized by

Belemnites, Hippurites, Cardita, Dentalina, Globotruncana, Orbitolina and a variety of floating organisms as well as bottom-dwelling *Foraminifers, Lamellibranchs and Radiolarians*, indicating Late Cretaceous (83–65 m.y.) Age. Very similar sedimentary assemblage accumulated on the southern slope of the Meghalaya plateau in the east and in the Salt Range–Kirthar–Laki Hills belt in Pakistan (Table 5.1).

Sudden steepening of the slope of the Tethys shelf (Fig. 5.3), resulting from tectonic movements, triggered submarine slides in an environment in which turbidity currents laden with suspended sediments (mostly mud) moving rapidly down the slope under water had started flowing.

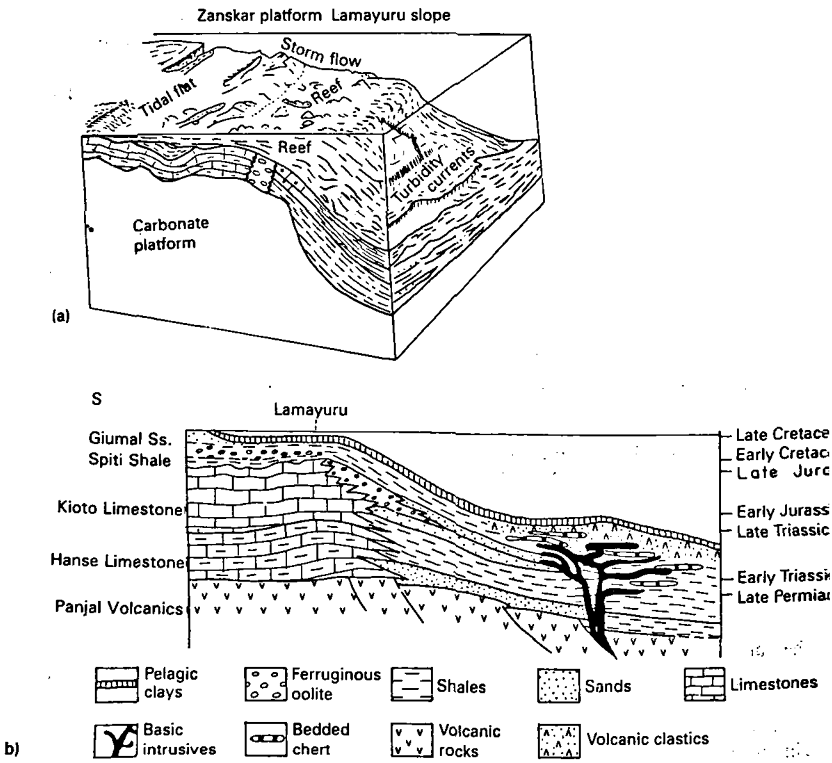
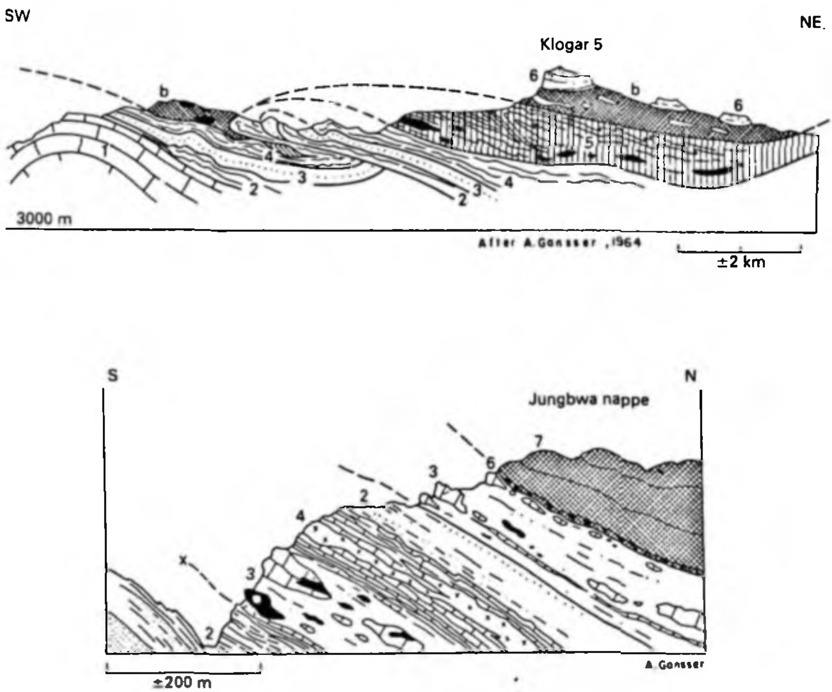


Fig. 5.3 *(a) Nature of the continental slope in the north just before the onset of Himalayan diastrophism (A.K. Sinha and R. Upadhyay, 1994). (b) Sedimentation towards the terminal stage of Tethys time in the Lamayuru section (based on A.H.F. Robertson et al., 1993).*

This is evident in the deep-water muddy and ill-sorted sediments rhythmically alternating with fine pellitic muds of the peripheral belt, which contains a significant proportion of blocks and fragments of older sedimentary and volcanic rocks that were not formed in the site of their present occurrence. These are quite extraneous and quaintly exotic because of the fossils embedded in them.

The fossils found in these assemblages indicate that the sediments belong to the southern continental slope of Tibet (of the Asian plate). A. Von Kraft[334] had described them as 'Exotic Blocks of Malla Johar' (Fig. 5.4), after the area in northern Kumaun on the India–Tibet border. The exotic blocks, in the opinion of S.K. Shah [245][246] and M.E. Brookfield [54][55], must have been carried to the site of deposition (the trench) by submarine slides. This situation of tectonic ferment and resulting instability had developed as early as Late Triassic (210–208 m.y. ago) in the Lamayuru area in Ladakh, close to the tectonic junction of India and Asia (Figs. 4.1 and 5.3).



1. Giumal sst. 2. U.C. flysch (partly pyroclastic) 3. Exotic block (ophiolitic melange)
4. U.C. lst. and basic monzonite 5. Upper pyroclastic flysch zone
6. Ophicalcit zone 7. Harzburgite-lherzolite

Fig. 5.4 *Chaotic assemblage or 'wild flysch' of the Upper Cretaceous (83–65 m.y. old) marks the terminal stage of sedimentation in the Tethys Sea.*

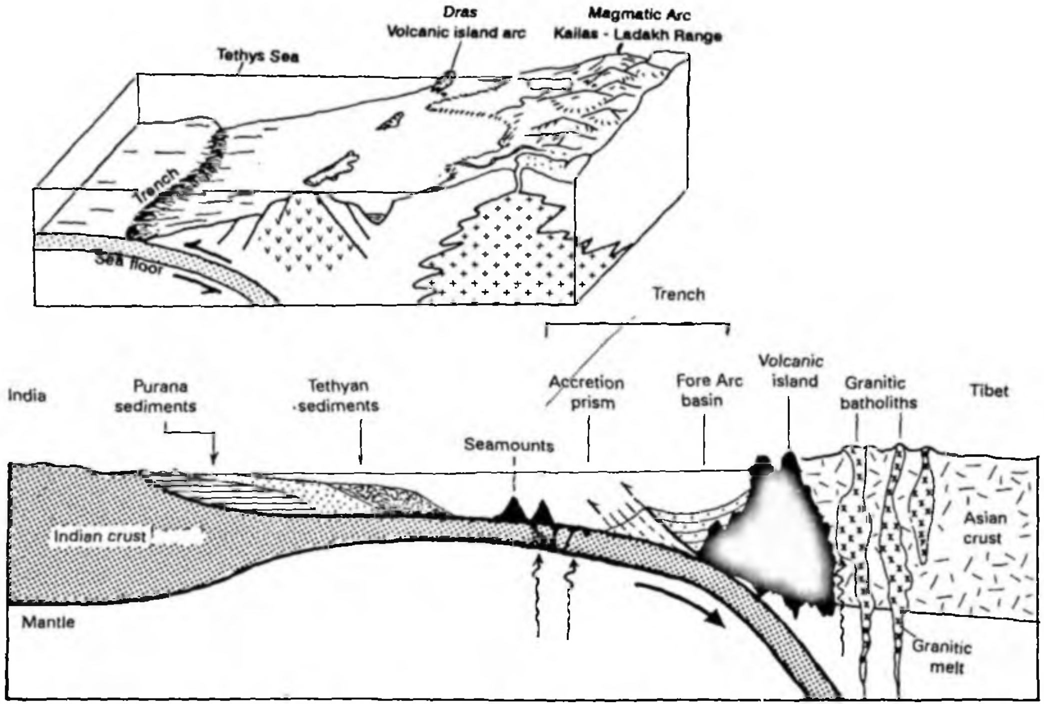


Fig. 5.5 *A narrow elongate depression of the deep sea floor — an oceanic trench-developes in front of the impacted continent as India and Asia approached one another. Upper diagram after E. Garzanti and V.T. Haver, (1988).*

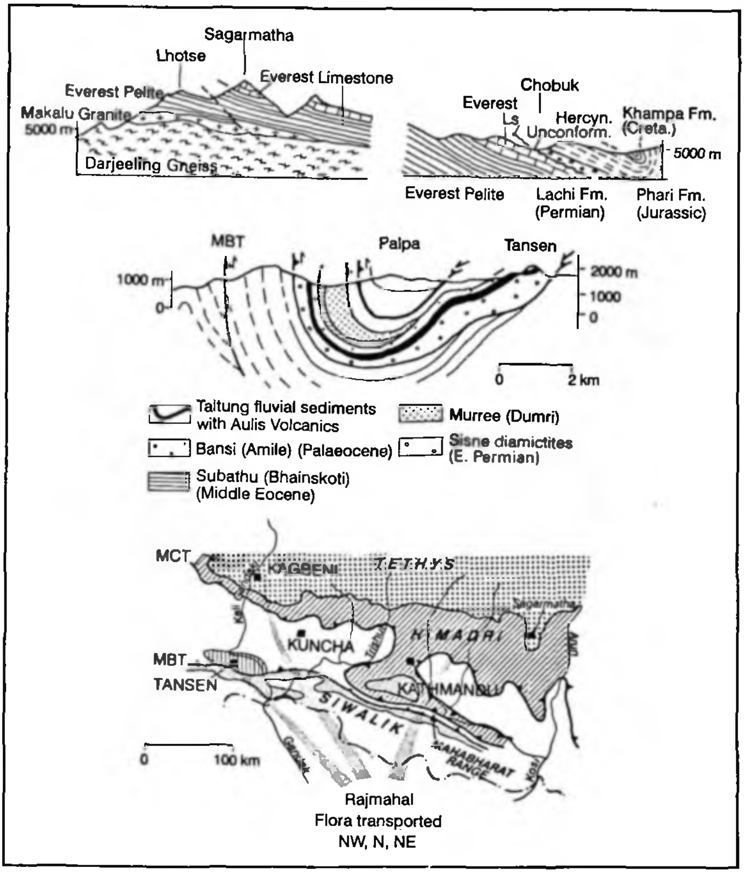


Fig. 5.6 *Late Cretaceous rivers draining the Rajmahal Hills in eastern Bihar in the Gondwanic India flowed northwards and carried plant debris along with loads of sediments and deposited as deltas in the Tethys shore. The sections show the areas where these plant fossils occur — in the southern border of Himalaya and across the Great Himalaya [upper section after L.R. Wager, 1939; lower section and map based on H. Sakai, 1991].*

It would appear that during the Late Cretaceous time, the continents of India and Asia had come very close to one another, and the belt adjacent to the collided continents had sunken into an oceanic trench (Fig. 5.5) — an elongate depression parallel to the trend of the continent of Asia. And in this trench was deposited material derived from both the Indian and mainland Asian landmasses. This explains why there is a mixture of sediments and fauna from the two different domains.

Varied plant fossils have been found in the Umia area in Kachchh and the Taltung tract in southcentral Nepal. H. Sakai[(225) (226)] has shown that the Taltung sediments, in which plant fossils occur, were deposited by rivers that flowed in a northerly direction as shown in Fig. 5.6.

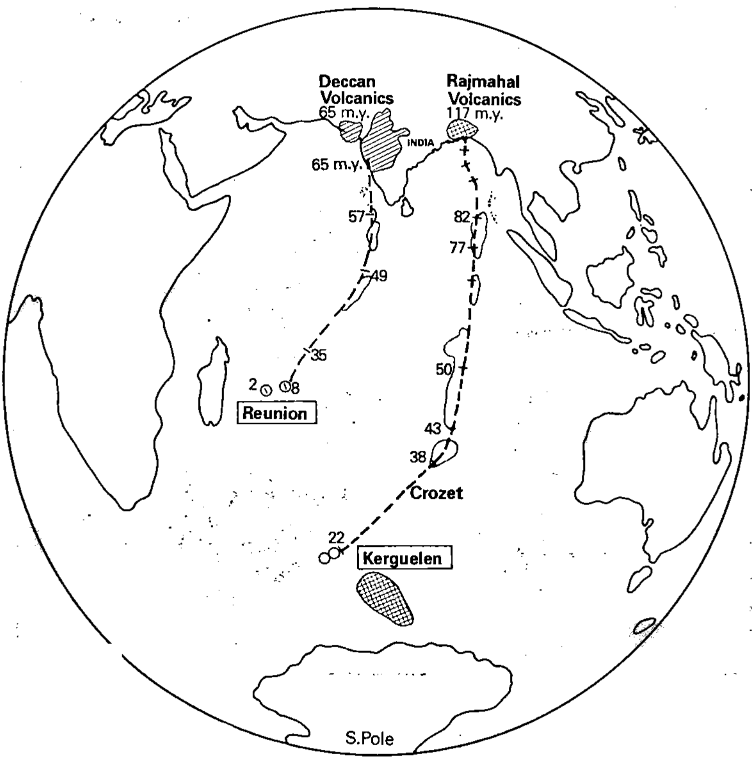


Fig. 5.7 *The Rajmahal–Sylhat tract was engulfed in volcanic activities 117–115 m.y. ago as the Indian plate rode over the fiery fountain called the 'Crozet Hotspot' (after R.A. Duncan and M. Storey, 'Synthesis of Results from Scientific Drilling in the Indian Ocean', Amer. Geophy. Union, Washington, 91–102 (1992)).*

The Taltung plants strongly resemble the Rajmahal flora interbedded with the lava of the Santhal Pargana in eastern Bihar. It seems that these rivers originated in the distant Rajmahal Hills in eastern Bihar in the Indian shield and carried plant debris along with land-derived sediments and deposited not only in the Taltung area but also in the far northern tract in the Kagbeni, Kangpa and Lingshi basins of the Tethys shore. The Late Cretaceous succession in some sectors contains the fossils of such plants as cycads (*Ptilophyllum*), conifers (*Elatocladus, Brachyphyllum*) and ferns (*Cladophlebis*) as found in the Umia area in Kachchh and the Taltung tract in southcentral Nepal. At Kalabagh in the Salt Range, the plant remains have been converted into commercially useful deposits of lignite.

The Rajmahal Hills comprise lava, agglomerate and tuff interbedded with plant-bearing sediments and cover 200,000 km² of the Rajmahal–Sylhat tract in the Bihar–Meghalaya region. The lava erupted 117–115 m.y. ago (Fig. 5.7) when the northward moving Indian plate traversed over a blazing fountain of hot material under the crust called the 'Crozet Hotspot'[73] located in the southern Indian Ocean. The Early Cretaceous volcanics at Aulis in the Taltung tract must have been emplaced a little earlier due to the same phenomenon.

5.4 Chain of volcanic islands

Tiny and large fragments of volcanic rocks occur in the sediments in the deep water on the margin of the Tethys shelf. These indicate that volcanoes had once again become active — this time in the proximity of the depression or trench in front of the Asian continent (Fig. 5.5). About a 5000–8000 m thick assortment of sediments, intermixed with enormous quantities of basaltic to andesitic lava together with volcanogenic fragmental debris (agglomerate) and (ash) tuff, piled up in what are today the valleys of the Sindhu and Tsangpo. The lava is characteristically pillow-like in shape and has a hummocky surface. The pillow-shaped lava formed due to emplacement of molten material in cold water on the ocean floor and in the elongated depression having steep slopes, and at depths of more than 2000 m on the sea floor. There are seamounts too involved in this setting, indicating that by the 101–72 m.y. period volcanism had started in the trench zone[266][267].

A chain of volcanic islands grew up in the north (Figs. 5.5 and 5.8). This chain extended from Chalt–Ultror in Kohistan[278][280] through Astor–Dras in western Ladakh[339], Nindam in central Ladakh[87][270][295] to Shigatse in southern Tibet[100][101][110]. The volcanic arc extended southeastward through the Abor Hills in eastern Arunachal [4][260]. The volcanic activity in the Siang District in Arunachal Pradesh seems to have continued into the Palaeocene–Eocene time (65–50 m.y. ago) until the completion of the welding of the continents which had come together. The islands and seamounts were later caught in and entangled with the sediments of the oceanic trench as the Indian shelf plunged into the relatively weak shell of the earth below the lithosphere. This phenomenon occurred in front of the Asian continent when the two landmasses came together and collided.

5.5 Arc of granitic bodies

The coming closer of the drifting India to the Asian continent had narrowed down the Tethys Sea. Across the much narrowed sea, the strongly impacted southern margin of Tibet developed

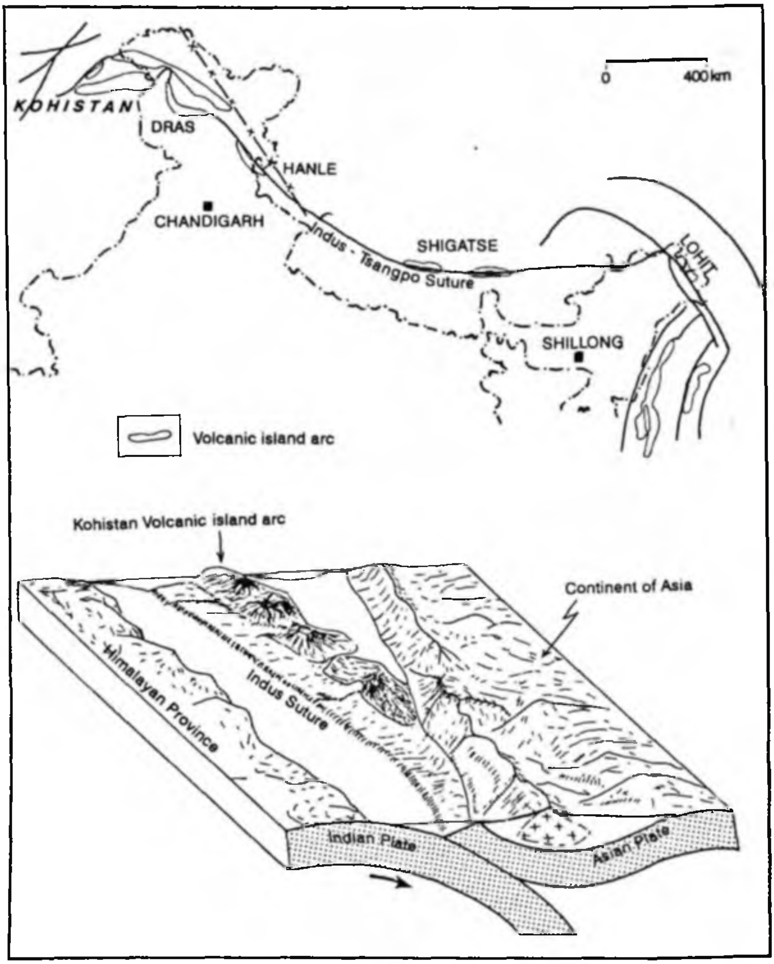


Fig. 5.8 *Chain of volcanic islands and seamounts, now entangled with the sediments of the ocean trench between the converging continents of India and Asia. Diagrams after Garzanti and Haver, 1988, and LeFort, 1988, respectively .*

deep fissures. Through these welled up, in successive spurts, great volumes of granitic magma, giving rise to a belt of discordant intrusions of magma forming huge batholiths, stocks and bosses of granodiorite, granite and aplite. The granitic magma was generated by the melting of crustal rocks at possibly shallow depths[102]. The granitic activity spread over a long period from 110–40 m.y., but the peak occurred about 60–45 m.y. ago.

The 2700 -km long Kohistan–Ladakh–Kailas–Gangdese–Lohit ranges (Fig. 5.8) are built up of composite batholiths of granite and granodiorite. They were formed in the manner the magmatic arc in the Andes mountain in South America had evolved. The Andean magmatic arc is developed in front of the Chile Trench, in which the Pacific floor has subducted — that is, gone down into the interior and is still sliding down (Figs. 5.5 and 5.8). It seems that the intrusion of granite and granodiorite accompanied by eruption of lava in some places represented by the Kohistan–Kailas–Gangdese–Lohit arc (Fig. 5.9) were related to the subduction of the floor of the Tethys Sea beneath the continent of Asia.

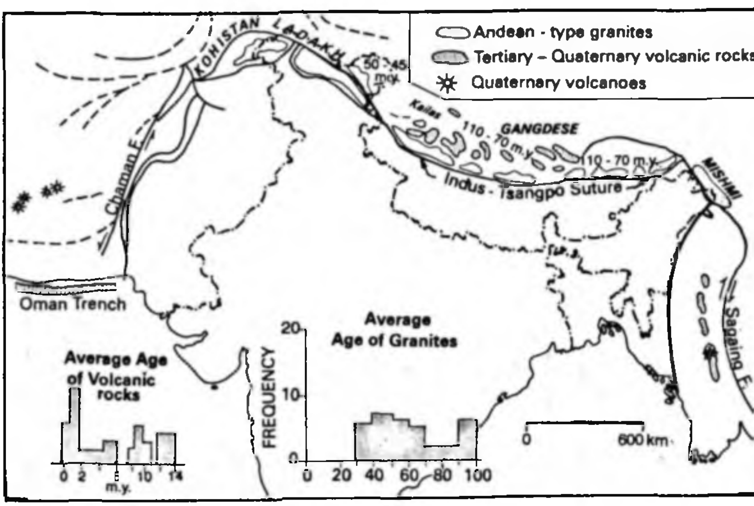


Fig. 5.9 *Magmatic–volcanic arcs along the southern margin of Asia in front of the Himalayan province (based on I. Reuber, 1989 and A. Gansser, 1991).*

6 Collision and Welding of India with Asia

6.1 End of long journey

Breaking away from Africa and later from Madagascar about 88 to 87 m.y. ago, India move northwards. It travelled nearly 7000 km in about 30 to 20 m.y. (Fig. 6.1) before touchir mainland Asia. It rode as a passive passenger on the crustal plate that forms the floor of tl Indian Ocean. The frontal part of the northward moving Indian plate slid under the crust plate of mainland Asia and slowly sank into the Earth's mantle.

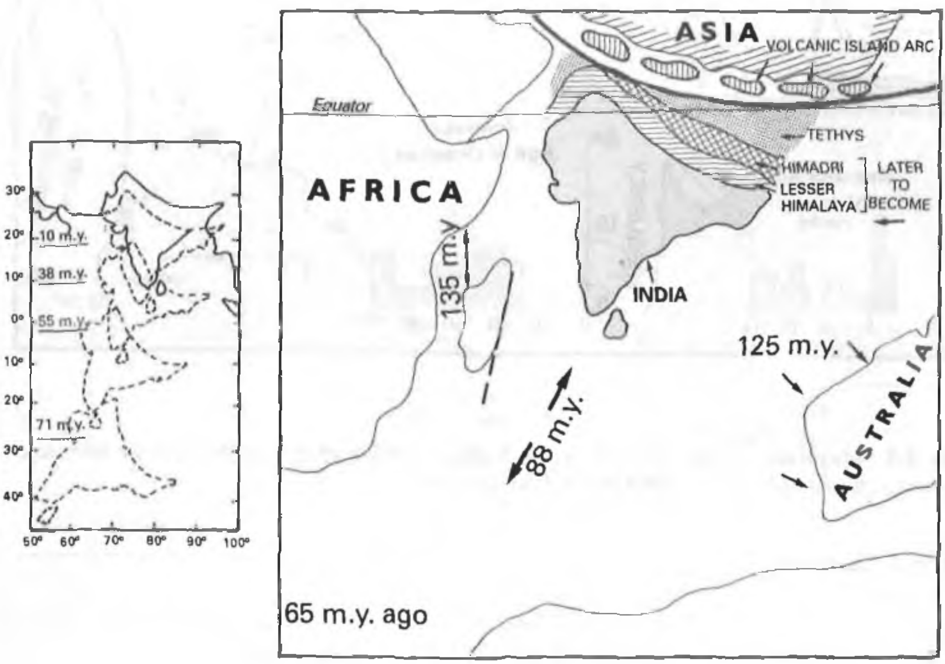


Fig. 6.1 *India touched Asia about 65 to 55 m.y. ago. After the first collision, India rotate anticlockwise. The numerals (in inset) indicate the time in m.y. of separation of landmasses.*

India's northern margin was made up of the great sedimentary pile of the Himalayan province. It touched Asia initially at its northwestern edge around 65 m.y. ago[32][125][139] As India slammed against Asia, stupendous volumes of lava poured out through volcanoes in the central and western regions of the Peninsular India— in what is today southwestern Madhya Pradesh and Maharashtra. The 67 – 62 m.y. old lava and volcanic ash, covering more than a million square kilometre region, constitute what is known as the *Deccan Trap* (Fig. 5.7). The volcanism occurred when the northward-moving Indian plate crossed over a rising column of hot buoyant lava forming a blazing fountain beneath the crust called the 'Reunion Hotspot' [211] in the Indian Ocean. Earlier in the Jurassic–Cretaceous period, another array of volcanoes had simultaneously formed an arc of islands north of the leading edge of the Indian continent. The volcanoes remained active in this zone óff and on throughout the Cenozoic era. Its present extension southeastwards is represented by the volcanic– sedimentary island arcs of Andaman–Niccobar and Indonesia, the latter lined by the deep Java Trench.

The flood of molten material (lava), the rain of hot volcanic ash (tuff) and tiny fragments of volcanic rocks (lapilli) that followed the volcanic eruption must have considerably affected the environment and appreciably modified the landscape of the land. The fire that burnt down the forests might have killed on a large scale much of the wildlife which lived at that time in the humid forests of central India. Volcanoes had poured huge amounts of gases, including carbondioxide, into the atmosphere, thus bringing about global warming. The animals must have suffered greatly as it grew warm and hot. There was probably a wholesale extinction of heavy-footed animals and destruction of luxuriant vegetation. As it collided with the island arc and mainland Asia nearly about the same time, India rotated slightly anticlockwise. The sea between the two continents became progressively narrower. The amalgamated part of India with the Kohistan–Dras volcanic arc collided with and was welded to Asia about 65 m.y. ago[298]

6.2 Welding of India with Asia

India collided with mainland Asia about 65 m.y. ago. The suturing or welding was completed about 55 m.y. ago when, as C.T. Klootwijk [139] has shown, the speed of drifting India suddenly slowed down to 45 mm/yr from the earlier 195–180 mm/yr. The collision of the continents caused faulting down on a multiplicity of deep and steep faults of the frontal part of the Tethys terrane (Fig. 4.1).

Not only that, the Tethys domain was compressed into a series of folds, giving rise to a composite synclinal structure of regional extent comprising a series of anticlines and synclines, which was truncated in the north. Sediments such as greywacke, pelagic clay, radiolarian chert, siliceous limestone, etc. which had been deposited in the trench and the adjoining ocean floor were compressed into tight folds. The tightened folds were split by faults and then thrust up and pushed southwards. Even the pillow-shaped basaltic lava of the sea floor and the underlying swarms of dykes of dolerite, with a still deeper layer of ultrabasic heavy rocks like dunite, peridotite, pyroxinite, gabbro and norite, were squeezed up and implanted within the chaotically deformed mass of sediment. The whole mixed assemblage of diverse rock types — or *melanges* of rocks — were sheared, shattered and uprooted in the zone of welding of the continents (Figs. 6.2 and 6.3). The melanges comprise blocks and fragments of all sizes of rocks, both indigenous and exotic, embedded in fragmental material. These are characterized by lack of internal continuity. This tectonized melange zone has been described as the *Indus–Tsangpo Suture* (I–TS) by A. Gansser[99][100][101][102].

Rivers Sindhu and Tsangpo occupy the highly tectonized zone of the I–TS. Skirting parabolically around the transverse Nanga Parbat–Haramosh massif in northwestern Kashmir, the arc shaped I–TS, described as the *Main Mantle Thrust* by R.A.K. Tahirkheli[277][280][12], forms the southern tectonic boundary of the Kohistan complex. Further west it is linked with the N–S trending Chaman Fault (Figs. 2.1 and 6.2).

In eastern Arunachal, the I–TS (Figs. 6.2 and 7.16) is demarcated by volcanic rocks associated with ultrabasic rocks and serpentinized siliceous limestones of the Tuting–Tidding belt[3][4][77][260]. Extending southeastwards into Myanmar, the suture zone is linked with the Sagaing Fault, a transcurrent fault affecting several terranes trending north–south. The NNE-to-SSW trending Patkai–Naga–Arakan ranges of the India–Myanmar border abut against this fault. These ranges are made up of sedimentary succession of Late Cretaceous to Eocene age. The thick pile of these sediments is split into multiple thrust sheets, one overlapping another — obviously due to sliding of the Assam shield beneath the Asian plate embracing the Shan–Tenasserim–Malaysia landmass.

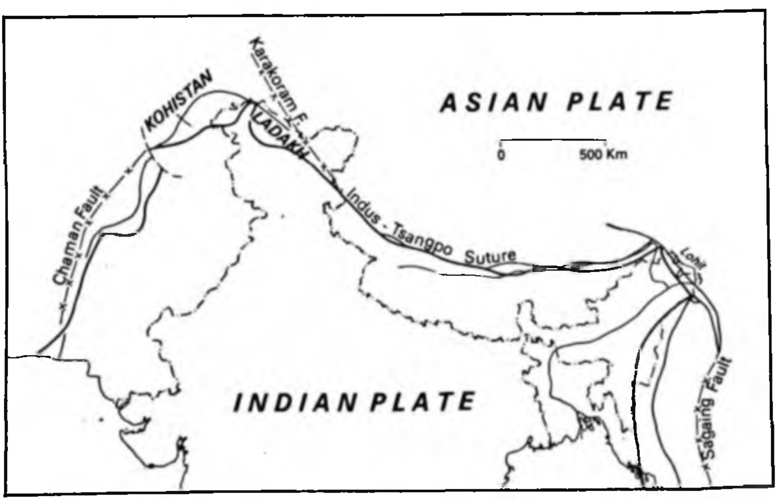


Fig. 6.2 *The Indus–Tsangpo Suture marks the junction of India and Asia — the zone of welding of the two continents (based on A Gansser, 1991).*

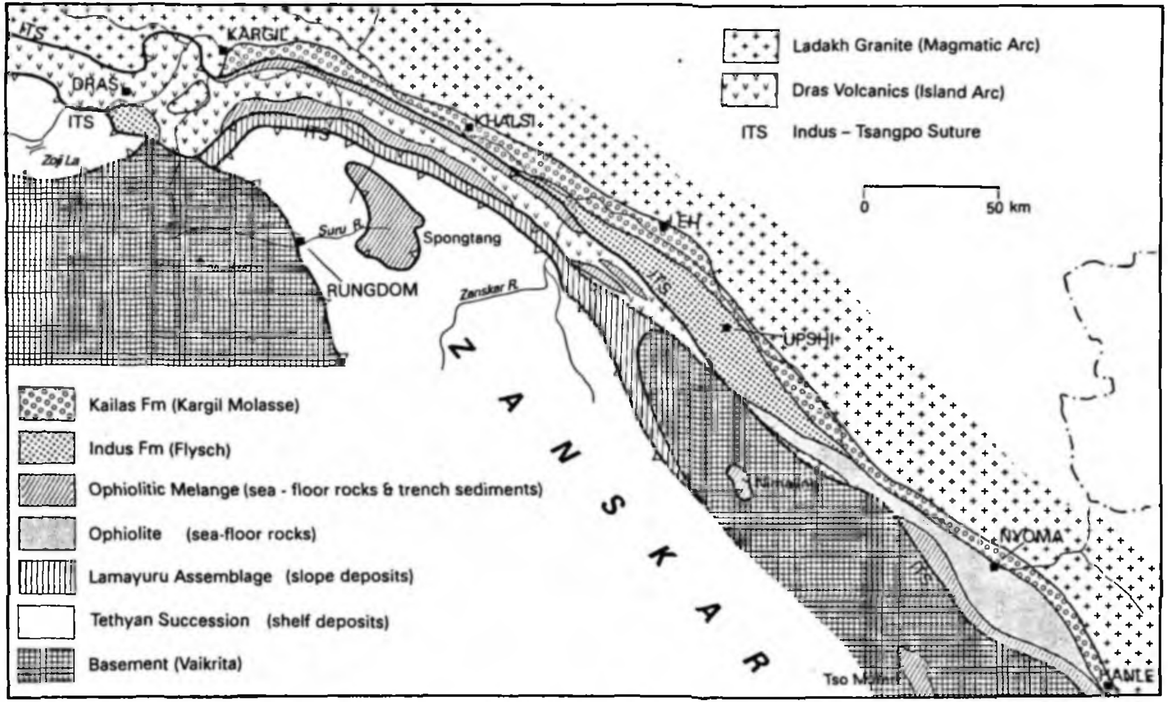


Fig. 6.3 *Northwestern segment of the Indus–Tsangpo Suture (I–TS), which marks the junction of India and Asia or the zone of welding of the two continents (after N.S. Virdi, 1987).*

All along the length of Myanmar from the coast in the south to Lohit in Arunachal Pradesh, ophiolitic bodies occupy a deep thrust fault zone. The ophiolites consist of basic and ultrabasic rocks that were emplaced on the ocean floor or in the oceanic trench at the early stage of crustal upheaval. The Indo–Myanmarese ranges, extending into the Andaman island arc–Java Trench complex (Fig. 7.16), represent the I–TS zone in the east[(4)(238)].

In the west the I–TS is linked with the transcurrent Chaman Fault. East of this fault, the so-called Axial Zone[(15)] — comprising tightly folded Cretaceous sediments, pillow lava, and large bodies of ophiolites in the Bela, Muslimbagh, Zhob and Waziristan areas — represents the I–TS zone.

As the Indian landmass slammed against Asia, it pushed and squeezed the great piles of sediment lying in front of it, tearing and dismembering the pile at its extremities. The two transcurrent Chaman and Sagaing faults denote this tearing of the landmass (Figs. 2.1 and 6.2). The 900-km long Chaman Fault is linked with the Owen Fracture in the Arabian Sea[(150)]. It separates the Laki–Kirthar–Sulaiman ranges of the Himalayan province from the Afghanistan block of the Asian continent. The Indian block has moved nearly 300 km northwards in the last 30 m.y. along the Chaman Fault. Likewise, along the Sagaing Fault, the Myanmar block has moved 300 to 500 km with respect to the Asian landmass to the east[(344)].

6.3 Squeezing out of ocean floor

The collision of the continents was so severe that the entire assemblage of sediments of the deep trench and the adjoining sea floor, together with the rocks of the ocean floor and the heavy subcrust, were chaotically folded and split into a stack of mutually overlapping or imbricate slices (Figs. 6.4 and 6.5). These were then squeezed up from the depth and thrown out on the surface of the land. The phenomenon is called obduction. As a consequence, some parts of the ocean crust and fragments of subcrustal layer were placed upon and pushed over the leading edge of the Indian continent (Fig. 6.4).

The highly deformed and uprooted assemblages of basic and ultrabasic rocks emplaced on the ocean-floor and trench in the early stage of diastrophism are collectively known as *ophiolites*. These ophiolites are chaotically admixed with the sediments giving rise to *ophiolitic melanges*. Ophiolites and ophiolitic melanges are seen all along the I–TS and its southwards extension (Fig. 6.2) — from Mingora in the Afghan frontier through Chilas and Jijal in Kohistan, Zildat and Shergol in Ladakh, Darchen in the Kailas–Mansarovar region, Shigatse in southern Tibet to Tuting–Tidding in eastern Arunchal Pradesh (Figs. 6.2, 6.3 and 5.8).

Pressures as strong as 11 to 9 kilobar (kb) under rather low temperatures of sea-water (420 to 350°C) converted the ophiolites in many places into *blue schists* — comprising minerals like glaucophane, jaedite, lawsonite with or without prehnite, phengite, etc.[(87,121,197,198, 248,328)]. The blue schists indicate the very severe compression to which these rocks were subjected to when caught between the vice-like grip of the collided continents. They also suggest downward movement of the rocks to great depths along the subduction zone.

In many sectors, so severe was the impact that the ophiolites and ophiolitic melanges were squeezed out and pushed or thrust 30–80 km away from their roots. As discrete sheets or nappes, these squeezed out masses lie piled up one over another (Fig. 6.4 and Plate 13A).

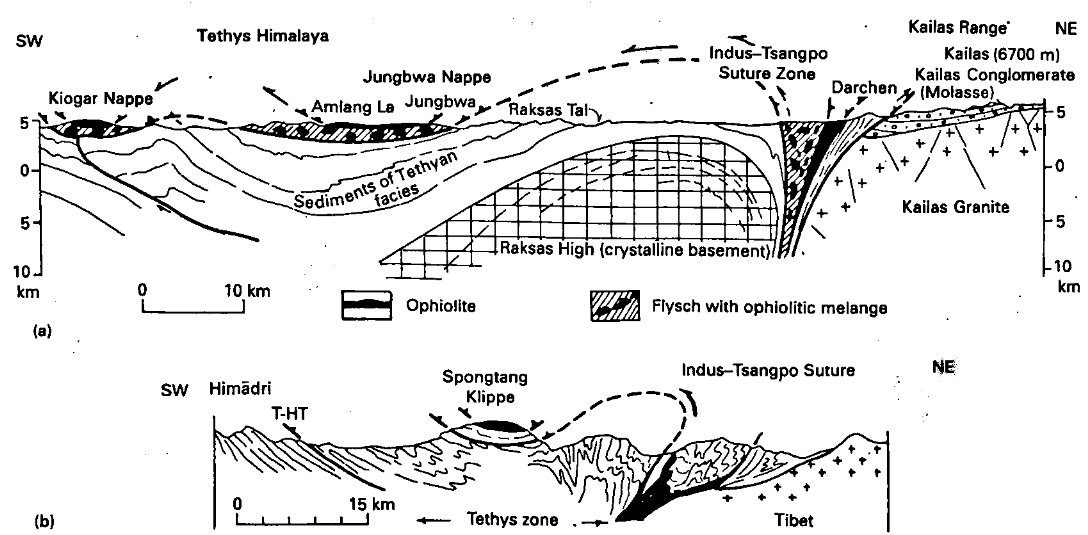


Fig. 6.4 *Squeezed out (obducted) and considerably displaced ocean-floor materials (ophiolites and ophiolitic melanges) resting as odd or exotic blocks and pieces of sheets in an alien setting [(a) after A. Gansser (1964); (b) after A.K. Sinha and R. Upadhyay (1994)].*

The sliding of the thick slabs of these rocks must have been aided by gravity. For, the edge of the colliding continent (India) had heaved up, steepening the slopes and triggering gravity gliding. Remnants of such displaced or far-travelled sheets are seen 30 km away at Dargai (Fig. 6.6) in Kohistan[278,280], 34 km south of the I–TS in the Spongtang area in Ladakh (Plate 13A), and 80 km of the I–TS suture in the Malla Johar belt (Fig. 6.4(a)) in northern Kumaun. These are indeed exotic blocks resting in alien surroundings as A. von Kraft[334] had appropriately described them in Malla Johar in northern Kumaun.

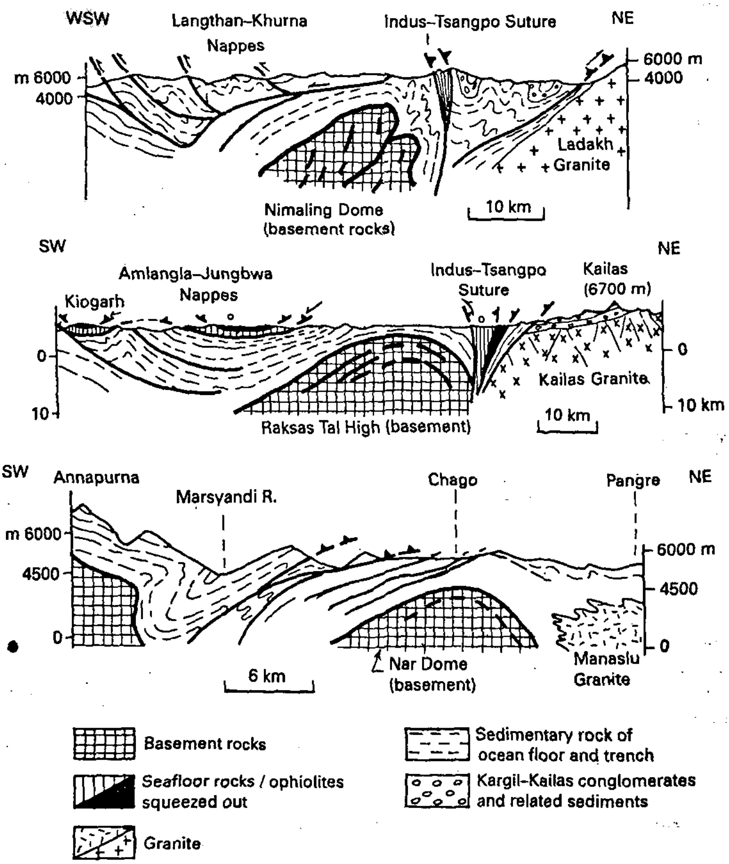


Fig. 6.5 *Doming or warping up of the leading edge of India after the collision with Asia (section after A. Baud (1992), A. Gansser (1964) and P. Bordet et al. (1975), respectively).*

6.4 Warping up of the leading edge of India

Even after the welding of India with Asia — which was completed nearly 55 m.y. ago — India continued to push northwards, at the rate of approximately 50 mm/yr. Most earth scientists believe that the northern part of the Indian plate plunged and slid under the Asian plate. However, the present author is of the opinion that there being no scope for further northward movement, India's northern edge simply bent down and plunged partially into the asthenosphere. The Indian mass being about 20% less dense than the underlying mantle and therefore comparatively buoyant, there was resistance to its sliding under Asia. Consequently, India's leading edge buckled up into a domal upwarp (Fig. 6.5) all along the collision zone[(313)(315)]. The upwarp is discernible between Nimaling in Ladakh, through Gurla Mandhata in the Kailas–Mansarovar region, to Lhagoi–Kangri–Kangmar belt northeast of Sagarmatha. The warping up of the crust uncovered or exhumed even the Precambrian basement with its 500 ± 25 m.y. old granite immediately south of the I–TS. Analysis of seismic anisotropy shows no sign of the Indian lithosphere north of the I–TS[(118)].

In Kohistan (Fig. 6.6), the development was somewhat different. Slices of the broken crust popped up. In the north, the structures are bent northwards above the thick zone of ductile decoupling of the I–TS, while in the southeast these are quite upright[(71)]. Even the huge batholithic body of granite was deformed and thrust or propelled southwards on the shear planes related to the I–TS.

6.5 Deformation and metamorphism

Shortly after the collison, the rocks were deformed and metamorphosed in the northern belt. In the Swat–Nayan region in northern Pakistan, light coloured granites were emplaced in the Early Eocene[(348)] 53–40 m.y. ago. In the Kohistan–Nanga Parbat region, the temperature rose to 500°C in the Middle Eocene[(298)(299)] 40–35 m.y. ago. Across the Nanga Parbat massif, the Zanskar rocks were deformed and metamorphosed about 45 to 35 m.y. ago as indicated by hornblende[(127)(268)]. Analysis of a large number of dates of minerals indicates that the main event of metamorphism took place in the interval 17 to 20 m.y. ago.

6.6 Water-divide and initial drainage development

As a result of the warping up and uplift of the northern belt of the I–TS zone, an elevated land or ridge came into existence. The Kailas–Mansarovar region formed the knot of this elevated land. Rivers established their drainage in the radial direction[(102)]. The Sindhu flowed northwestwards, the Satluj went southwest, the Karnali took the southerly course, and the Tsangpo flowed eastwards (Fig. 2.5).

The Mount Kailas knot lies roughly in the line of the Aravali Range. It appears that the Aravali orogen had exercised control in the establishment of the drainage of the Himalayan rivers ever since the emergence of the Himalaya — quite before the high ranges developed. The rivers continued to flow in their pristine channels they had carved out at the outset.

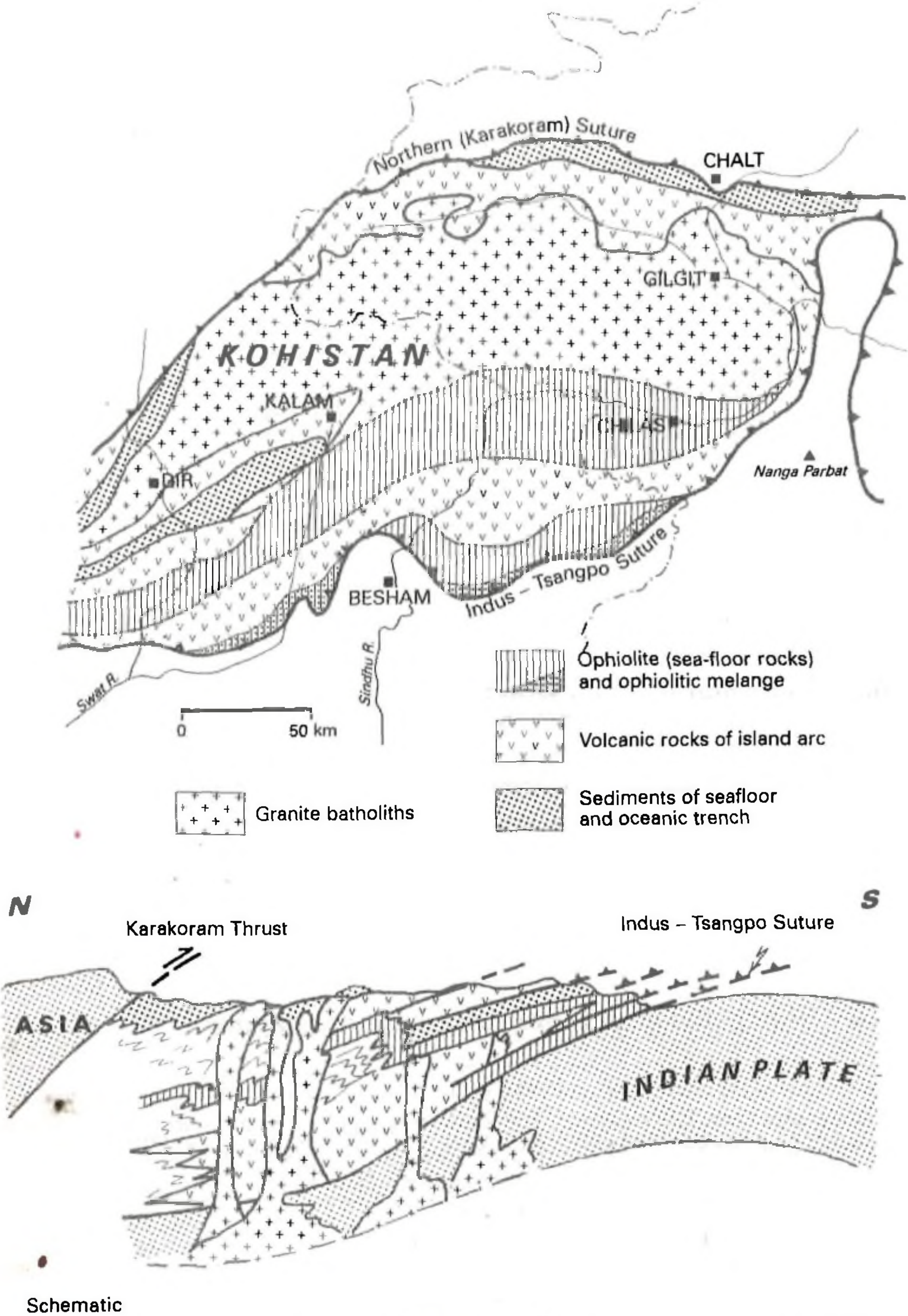


Fig. 6.6 *Tectonic architecture and mode of development of the Kohistan complex in northwestern Himalaya (map after M. Asif Khan et al., 1993, and section after J.R. Bard, 1983).*

6.7 Sagging of Indus–Tsangpo Suture zone

Even as the leading (northern) edge of the Indian plate bulged up, the zone of the India–Asia suture sagged down. This happened in the Late Eocene (34–30 m.y. ago). Perhaps the zone had started subsiding as early as the Late Palaeocene (59–53 m.y. ago). A 2000 km long and 60–100 km wide depression was formed along what are today the valleys of the Sindhu and Tsangpo rivers (Plate 13B). This depression may be described as the *Sindhu Basin*.

There already was, possibly, a remnant of the Tethys Sea well before the suture zone sank to create the depression. In this depression were deposited a varied assemblage of sediments comprising alternation of deep-sea very fine clays, calcareous–siliceous oozes, calcareous–siliceous limestones and greywackes, described as *Indus Flysch*[55,159,251,288,291,294]. The flysch comprises, among other things, limestone containing Middle Eocene (40–34 m.y.) foraminifers that lived in marine environments. The flysch passes upwards into a stupendous succession of molasse — an assemblage of ungraded softer conglomerate, arkose, sandstone, siltstone and mud deposited in the channels, flood-plains and deltas. These rivers were precursors to the Sindhu, Satluj and Tsangpo.

6.8 Foreland basin south of Himalaya

Another depression formed almost synchronously — or perhaps a little earlier — on the southern side of the emerging Himalaya, along what is known as the Outer Himalaya (Fig. 6.7). This

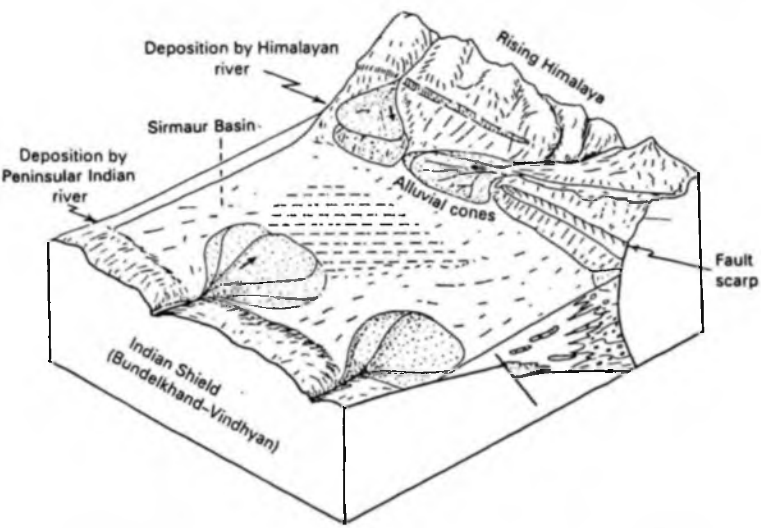


Fig. 6.7 *Development of the Sirmaur Basin in the outer Himalayan belt was a consequence of sagging down of the Indian crust and resultant marine incursion along the foreland depression.*

foreland basin may be described as the *Sirmaur Basin*, named after the Sirmaur District in southeastern Himachal Pradesh. It was formed as a consequence of the warping of the northern edge of the Indian shield south of the Himalayan province. The sagging down of the frontal belt towards the close of the Cretaceous and early Palaeocene (65–59 m.y. ago) caused invasion by marine waters. The sea stretched in the north from southern Lhasa in Tibet through the Sindhu Valley to Ladakh, and in the south from Ranikot belt in Sindh (Pakistan) and covered the Palana area in western Rajasthan, the Kakara area in the Gambhar Valley in Himachal, the Singtali–Bansi belt in Garhwal, the Amile area in the Tansen Hills in southcentral Nepal and the Jaintia Hills in Meghalaya (Table 6.1; Fig. 6.8). Like the Sindhu Basin, it became a site of vigorous marine sedimentation. The basin, understandably, was quite shallow and the shores were agitated by waves and currents as borne out by spherical ovoidal oolites-pisolites characterized by concentric layering of carbonates and by current-formed structures. In the warm waters flourished algae of a wide variety along with bryozoans and foraminifers[(44)(45)].

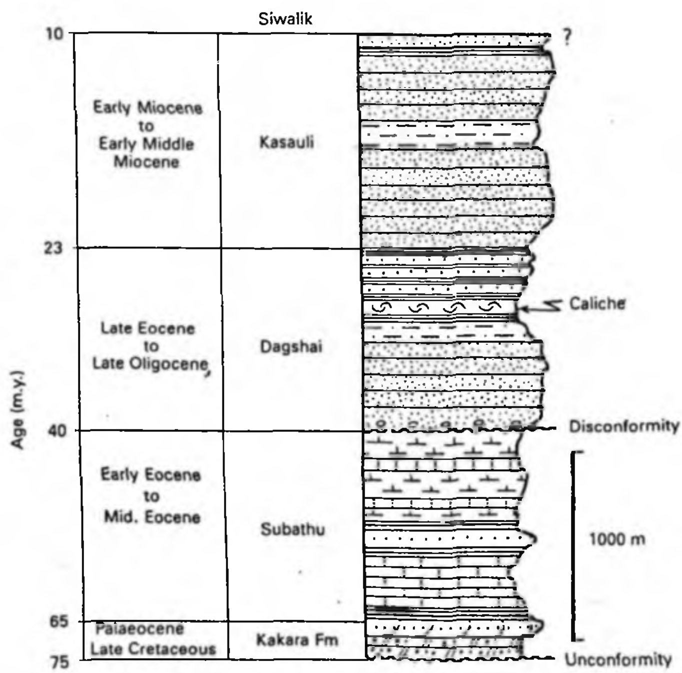


Fig. 6.8 *Lithological column illustrating the order and nature of Palaeogene succession of formations.*

In the Early and Middle Eocene epochs, a much larger area came under the sway of the sea. It spread into the interior of the Lesser Himalaya such as the Poonch–Rajauri belt in Jammu, the Shali area in Himachal, the Phart–Satpuli belt in Garhwal, and the middle reaches

Table 6.1 *Palaeogene formations of the sub-Himalayan belt and Sindhu–Tsangpo valleys.*

Age: Epoch	Age: Time Range (m.y. ago)	Sindh–Salt Range	Potwar–Jammu	Himachal–Kumaun	Nepal	Arunachal Pradesh	Assam–Indo-Myanmar Range		Upper Sindhu Valley	Myanmar
Early Miocene	–16.2– – 23 –	Gaj	Murree	Kasauli	Dumri		Surma	Bokabil Bhuban		
Oligocene	–30.5–	Nari		Dagshai			Barail	Renji	Kailas Congl. (Kargil)	Pegu
Eocene L	– 34 –	Kirthar	Chharat Ls.	Subathu	Bhainskoti	Yinkiong		Jenam • Laisong		
Eocene M	– 39 –									
Eocene E		Laki	Hill Ls.				Jaintia / Disang	Kopili	Indus Fm.	Yaw Podaung
Palaeocene	– 53 –	Ranikot		Bansi–Kakara	Amile	Abor		Sylhet		Tabyin
	– 65 –							Lakadong (Langpar) Therria		Laungshe Paunggyi

- - - - = Unconformity, Congl. = Conglomerate, Ls. = Limestone, Fm. = Formation of the Kali Gandaki in west Nepal. The sea embraced a vast tract (Table 6.1; Fig. 6.8) stretching from the Ranikot–Kirthar ranges in Sindh, through the Jaisalmer–Bikaner region in western Rajasthan, the Salt Range and Hazara region in northern Pakistan, the Jammu–Subathu belt in the Kashmir–Himachal sector, the Bhainskoti area in Nepal, the Yinkiong–Dalbuing area in eastern Arunachal and the Kopili area in Assam to the Jaintia Hills in Meghalaya.

6.9 Formation of a landbridge and faunal migration

About 60 to 55 m.y. ago, a large variety of vertebrate animals such as artiodactyls (even-toed animals), turtles, crocodiles and fishes suddenly made a dramatic appearance in great abundance — in the Kalakot area in Jammu(205)(220), the Kirthar Hills(193) in Pakistan and the Irrawady Valley in Myanmar. Ashok Sahni(219) has shown that the first appearance of the mammals, which bore strong similarity with those of Asia, indicates that India had docked with Asia and a landbridge had been formed. This initiated waves of migration of vertebrate animals from the Asian landmass. The mammals must have come from distant Mongolia, China, Siberia and central Asia, for the fauna bear remarkable similarities and strong affinities. Not only did the mammals come, but also came frogs — which are highly allergic to saline sea waters — and hopped their way through the land corridor and reached as far south as the Deccan, where their remains are found buried in lake deposits trapped between lava flows(125)(219).

6.10 Drastic reversal of drainage

An epochal development took place in the early Palaeogene period 63 to 40 m.y. ago. All through the long history of the Himalaya (since about 2000 m.y. ago) streams and rivers draining the Indian shield flowed northwards (and westward in the Pakistan sector). This is quite evident from the pattern of dispersal of sediments and the current marks in them. Abruptly there was a reversal of drainage — the rivers started flowing southwards (Fig. 6.7) in the main Himalayan province(273) and eastwards in the Pakistan region(342). Obviously the rivers began draining and eroding a highland that had just emerged. By the Eocene time (53–40 m.y.) not only had the Indian continent collided with Asia, but also *an orogen called Himalaya* had emerged and began rising higher and higher.

6.11 Deposits of fossil fuels

The Early Palaeogene age was also the time when extensive deposits of coal and lignite were formed from the burial of plant material in such places as Palana in western Rajasthan, Kalakot in Jammu, Mikir Hills in Assam and the southern flank of Meghalaya plateau (Table 6.1). At the Jwalamukhi temple in southern Himachal Pradesh, methane gas has been coming out uninterruptedly from time immemorial. It appears that there were then thick forests in this region. Vegetable debris derived from the forests accumulated under deep lakes, estuaries and river valleys, and were later covered with sand and mud. Increase in pressure and temperature subsequently converted the vegetable debris into coal — on an average 3 m of debris forming 30 cm of coal seam. The process of transformation into coal involved passing through the stages of peat (unconsolidated plant debris) and lignite (partly consolidated, converted and banded vegetable matter).

Made up of olive green and grey or black shales (with subordinate siltstone and sandstone) and prominent beds of shelly or foraminiferal limestone (bearing fossils such as *Assilina* and *Nummulites*), the Subathu formation and its contemporary formations are sources of petroleum oil and gas. These fuels originated under peculiar conditions that prevailed at that time in the sea in which these sediments were laid down. Oil and gas were produced from organic matter under tectonically quiet conditions in environments deficient in or devoid of oxygen. Bacteria active in the upper 30 to 40 cm depth of sediments must have broken down the detritus of plants and animals and the debris of floating forms (such as algae, fungi, diatoms, foraminifers, radiolaria, etc.) and converted them chemically through different stages like fats, aminoacids, lignins and lipids to finally oil and gas. Some floating forms produce oil as part of their biological activities and thus contain oil in their bodies. Sponges and jellyfish also participate in the formation of petroleum. Some clays and metallic elements act as catalytic agents, and the rise of temperature (upto 80–100°C) and pressure accelerates the transformation of organic matter into oil and gas. The oils and gases migrated upwards and were trapped in younger sediments. It is these younger sediments (Table 6.1) trapping petroleum which have been and still are targets of intensive exploration.

6.12 Final retreat of sea and the beginning of fluvial sedimentation

The sea withdrew finally from both the north and the south of the Himalayan province, that is from the Sirmaur and Sindhu basins. Understandably, the whole of the Himalayan province was elevated and subjected to strong deformation. This happened towards the Late Eocene (34 to 30 m.y. ago). Erosion in the emergent and rising mountain domains was considerably accelerated and heavily loaded rivers and streams brought down large volumes of sediments to the Sindhu and Sirmaur basins. As deltas advanced, the sea retreated.

The floodplains of the meandering rivers extended from the Nari and Gaj areas in Sind, through the Marwar platform in western Rajasthan, the Murree Hills in northern Pakistan and Jammu, the Dharmashala, Dagshai and Kasauli ranges in Himachal, the Dumri Hills in southcentral Nepal to the Surma Valley and Barail Hills in Assam (Table 6.1).

Layers of conglomerate at the base of the Murree succession in the Kohat–Potwar belt indicate the end of marine sedimentation and the beginning of detritus deposition in an altogether different setting — of land. It was in the floodplains of the meandering rivers that purple, maroon and red sandstone, shale and mudstone were deposited in the early (Dagshai) stage of fluvial sedimentation (Fig. 6.8) as pointed out by V. Raiverman[199][201]. Later in the upper (Kasauli) part, preponderently grey lithic sandstone (i.e., sandstone containing tiny fragment or grains of older rocks) with subordinate mudstone were laid down principally in channels of rivers and streams flowing southwest and southeast as demonstrated by V.K. Srivastava and S.M. Casshyap[273], and Y. Najman et al[174]. By the time the Kasauli sediments were being laid down in the foreland basin, the basement of the Himalayan province, made up of metamorphic rocks had been uncovered (exhumed) and exposed to denudation as borne out by the presence of tiny fragments of metamorphic rocks and heavy minerals in the Murree sandstones[(66)(95)(174)]. In the earlier (Dagshai) time, semi-arid conditions prevailed on the floodplains as evident from the presence of caliche in the sediments. However, by the Kasauli time, a warmer humid climate had returned and the floodplains were covered with such plants as the palm *Sabal major*. The plants indicate that it was Late Oligocene to Early Miocene (27–16 m.y.ago) when this happened. In Assam the area from where the Barail sediments (Table 6.1) were scraped must have been covered with thick forests, which eventually contributed to the formation of large deposits of coal and lignite, now occurring within the upper Barail succession.

In the dense forests of the Murree time in Sindh lived and flourished communities of tapiroids, artiodactyls, primitive carnivores, crocodiles, turtles and fishes[(220)], and mammals such as *Antracotherium*, *Brachyodus* and *Teleaoceras*. In the marshy woods of the valleys of Barail, Surma and Irrawaddy rivers roamed the predecessors of our rhinos and other animals like *Rhinoceros sivalensis*, *Paraceratherium*, *Dinotherium*[(341)], etc.

Succeeding the marine Indus Flysch in the Sindhu Valley (Fig. 6.3) and covering a vast stretch of the river valley from Kargil in the west through Hemis in southeastern Ladakh through the Kailas areas in Hundesh to the Liuqu belt in southern Tibet, there is a great thickness (nearly 2000 m) of conglomerate — pebbly arkose (felspathic sandstone) with subordinate shale[(98,100,101,102,116)]. M.E. Brookfield and C.P. Andrews-Speed[(55)] have shown that the sediments were deposited in channels and floodplains of the rivers that alternately meandered and flowed as braided systems in their nearly 30 km wide floodplain. The conglomerate of this molasse facies rests on the floor of the Ladakh–Kailas granite (Figs. 6.3 and 6.9) and together with arkosic, pebbly sandstones it forms an imposing succession of what A. Gansser in 1939 described as *Kailas Conglomerate*. The formation is discernible on the scarps of Mount Kailas — the holiest of the holy mountains in the world (Plate 14A). These sediments were derived largely from the fast uprising Ladakh–Kailas–Gangdese ranges of the Asian continent (Fig. 6.9).

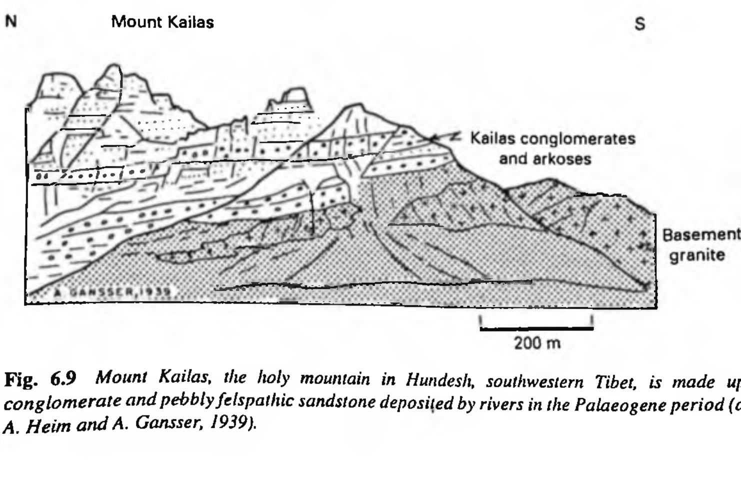


Fig. 6.9 *Mount Kailas, the holy mountain in Hundesh, southwestern Tibet, is made up of conglomerate and pebbly felspathic sandstone deposited by rivers in the Palaeogene period (after A. Heim and A. Gansser, 1939).*

The equivalent of the Sindhu Basin in Pakistan is the 200 km-long Katawas Basin of the Oligocene–Miocene molasses overlying the Axial Zone and extending west upto the Chaman Fault. In the east in Myanmar, the Irrawady River occupies the analogue of the Sindhu Basin.

The shale within the upper part of the Kailas formation in the Liyan area (southeast of Leh in Ladakh) reveals entombed remains of palms like *Sabal major*, *Livistona* and *Trachyacarpus*, together with rosewood *Prunus* and charophytes of the Late Oligocene Age (27–23 m.y.). These plants indicate that the climate at that time was warm and moist and that the altitude of the Sindhu–Tsangpo valley could not have been higher than 2100 m[148]. Remains of such vertebrates as goats, deers, rodents, python-like snakes, small-sized vegetarian mammals (discovered by A.C. Nanda and associates) and of swamp-loving rhino[176,289] in the Sindhu Valley in Ladakh — recalling very similar creatures that lived in the Bugti Hills in Sindh — indicate that these animals were able to migrate freely through the Himalayan province in the Oligocene time. In other words, the Himalayan province was still without high mountains some 27–23 m.y. ago.

7 *Turbulent Times: Birth of the 'King of Mountains'*

7.1 Renewal of crustal movements

India continued to press hard and push very strongly against the landmass of mainland Asia. Tectonic movements were revived as a result of sudden relaxation of the strain that had built up due to the convergence of the two continents. Consequently, the Himalayan province was overtaken by a severe convulsion of tectonic movements. These were accompanied by wide-spread invasion of granitic magma and attendant metamorphism leading to reconstitution of rocks under elevated temperature and pressure in the presence of chemically active fluids. The totality of the phenomena entailing folding, faulting and thrusting accompanied by metamorphism and intrusion of granites that gave rise to the building of the mighty Himalaya is known as the *Himalayan Orogeny* and the tectonic province thus formed is called the Himalayan Orogen.

The anticlinal dome-shaped crustal upwarp adjacent to the India–Asia suture (junction) was strongly squeezed and elevated. Sudden uplift called into play the forces of gravity, which induced gliding of piles of ophiolites and ophiolitic melanges down the steepened slopes of the upwarp (Figs. 7.1, 6.4 and 6.5). The thick pile of sediments of the larger sea were compressed and folded into a large synclinal structure comprising a series of folds; and the folds were overturned and some of them toppled over southwards. Many of the tightened folds were split by faults along their axial planes and were later displaced or thrust southwards as much as 30 to 80 km (Fig. 7.1).

7.2 Breaking up of crust

Continuing convergence of continents caused progressive increase in the compression of Himalayan rocks. Resistance due to buoyancy of lighter rocks like sediments and granites would not allow the northern edge of the crust to sink and slide under Asia. The Indian crust, therefore, not only buckled but also broke up (Figs. 7.1, 7.2 and 7.13) along what was to become the Main Central Thrust (MCT), first recognized by A. Heim and A. Gansser[116] near Dharchula, Munsiari and Joshimath in Kumaun. The broken up crustal blocks moved up and southward along this deep fault all along its more than 2400 km length (Figs. 6.2, 7.13 and 7.14) from near Nanga Parbat in the northwest to south of Namcha Barwa in the east. Even the basement rocks comprising porphyritic granites and metamorphic rocks were pushed up and exhumed or uncovered. Eventually emerged the Great Himalaya or Himādri delimited in the south by the MCT.

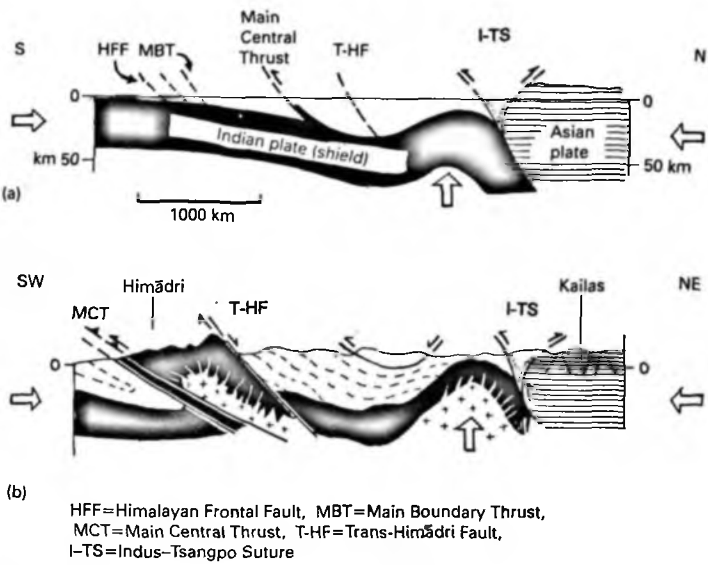


Fig. 7.1 *A bouyant Indian plate buckled at its front and broke up behind the upwarp along what became the boundary faults.*

Inclined 30° to 45° northwards, the MCT is indeed a wide zone of extremely severe deformation characterized by mutually overlapping masses of rocks piled up one upon another like the tiles of a roof. Due to repeated deformations these rocks were sheared, shattered and crushed or mylonitized — granulated and pulverized or milled — giving rise to dense rocks called mylonites. The deformation in the wide MCT zone took place along many planes of gliding and sliding, and was accompanied by metamorphism.

Strong stretching and reorientation of structures like folds, fractures and cleavages in the direction of movement on the thrust planes produced what is called 'lineation' in the transverse northerly directions. These are seen pervasively among the rocks of the MCT. The lineations demonstrate that the rocks have moved repeatedly and strongly along multiple planes of dislocation. The MCT was originally an inclined fault which detached the upper crust along a subhorizontal zone. Registering as much as 125 km of thrusting, it has brought the basement rocks from ductile deformation — when the rocks were able to sustain their integrity without breaking up — to the zone of brittle deformation culminating in shearing, shattering and uprooting[(216)].

Beneath the MCT in the Lesser Himalayan terrane, the metamorphic and associated granitic rocks were likewise severely deformed and drastically compressed (as indicated by 80% to 90% flattening of folds of the compacted package[(46)]). The overthrust rocks were simultaneously squeezed out of their original site (roots) and pushed (thrust) several tens of

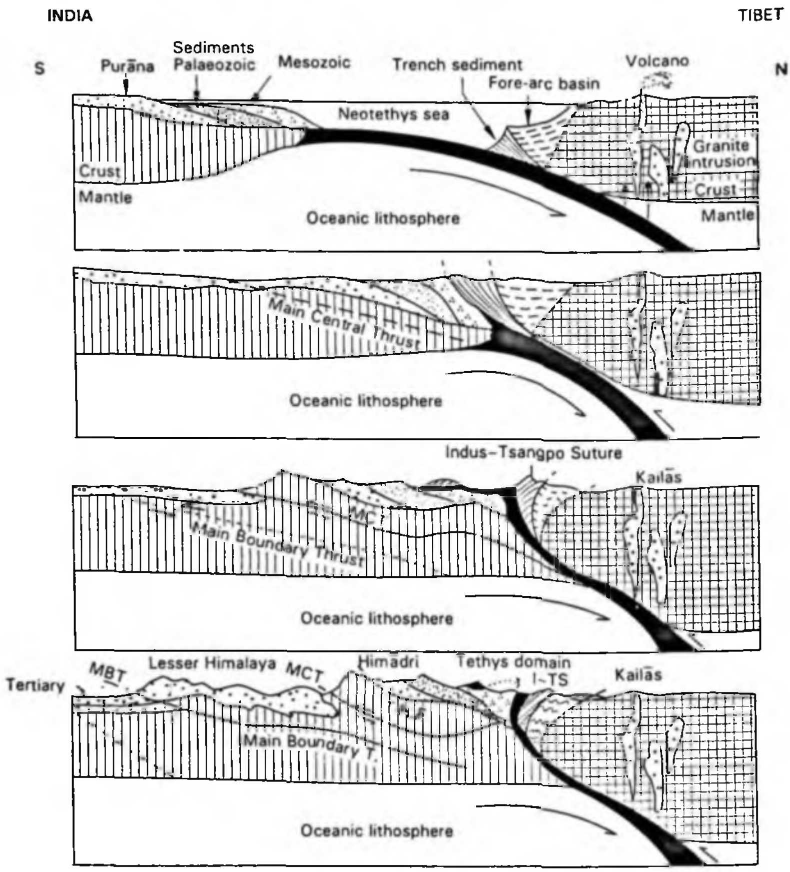


Fig. 7.2 *Successive stages of the evolution of the Himalaya following the coming together of India and mainland Asia. The collision of the continents caused not only compression and folding of the sediments between the two continents, but also breaking up of the Indian crust, giving rise successively to the Main Central Thrust (MCT), Trans-Himādri Fault (T-HF), Main Boundary Thrust (MBT) and Himalayan Frontal Fault (HFF), and the development of the geologically and physiographically distinctive terranes of Tethys, Himādri (Great Himalaya), Lesser Himalaya and Siwalik.*

kilometres southwards as vast sheets or nappes[14,22,50,113,116,228,233,302,309,315]. In the Kohistan region in the northwest (Figs. 6.6 and 7.6), as well as in the Siang District in Arunachal (Figs. 7.5(c) and 7.17), the MCT is a megashear converging towards or ending up against the I–TS [260,278,279]. This implies tremendous compression and attendant deformation at the two extremities of the Himalayan orogen.

7.3 Metamorphism and partial melting of rocks

The metamorphic mineral assemblages of the rocks that build up the Himādri (Great Himalaya) indicate that tectonic movements under the load of 20 to 35 km-thick rock-piles had raised the pressure to the range of 6 to 8 kb (locally upto 12 kb) and the temperature to the range of 600° to 800°C [119][120][149][163][167][191][322]. Under such conditions of high pressure and temperature, some susceptible parts of the metamorphic rocks melted partially and differentially. This phenomenon of partial melting is called anatexis. Minerals like sillimanite, cordierite and garnet, so common in metamorphic rocks, occur profusely in the granites that were formed from the partial melting — anatexis — of these metamorphic rocks. The initial strontium ratios of the anatectic light coloured granites is of the order of 0.743 to 0.787.

The differentially or anatectically molten material penetrated country rocks in the form of large batholiths that discordantly cut through rock successions as smaller bodies like bun-shaped laccoliths, tabular sills (which parallel the bedding planes or foliations) and tabular cross-cutting dykes and veins, and as big bodies like batholiths and stocks (Fig. 7.3). Being highly mobile, it pervasively penetrated layer-by-layer schists and gneisses, giving rise to intricately admixed rocks called migmatites made up of metamorphic horst and intimately permeated light-coloured granite[196]. These occur throughout the Great Himalaya.

The exalted and holy massifs of Badarinath (Plate 14B) and Kedarnath in Garhwal (Plate 1A) are made up of 1.5 to 2.0 km thick slab-like rock bodies called laccoliths (of light-coloured granite) formed in this manner nearly 20–22 m.y. ago. Associated with the vertical feeder dykes of granite—aplite and pegmatite—the Badarinath plutons indicate that there was crustal extension during the emplacement of the granitic bodies [231]. There is also a theory that this granite is a product of heating due to intense shearing on the MCT, following decompression of rocks.

Even the pile of sedimentary rocks resting on the basement of the metamorphic rocks undergoing metamorphism were invaded by the anatectic granite that formed near the top of the Himadri complex (Fig 7.3). The formation of this granite took place 25 to 15 m.y. ago[103,300], the peak activity occurring at about 21 ± 0.5 m.y.[152] ago in the Early Miocene age.

7.4 Detachment of cover sediments from basement

At one stage of the Himalayan tectonic revolution, the movements related to the northward drift of the Indian plate got blocked in the zone of the I–TS, and possibly slowed down on the MCT at the base of the Himādri complex. The blocking and slowing down of movement caused the covering pile of the Tethyan sedimentary rocks to detach from the basement of the hard, competent, unyielding crystalline rocks (Figs. 7.1, 7.4 and 7.13). The whole pile of sedimentary rocks, along with its mildly metamorphosed base (the Salkhala rocks in western Himachal and Kashmir) of the Tethys terrane, was displaced southwards on to the

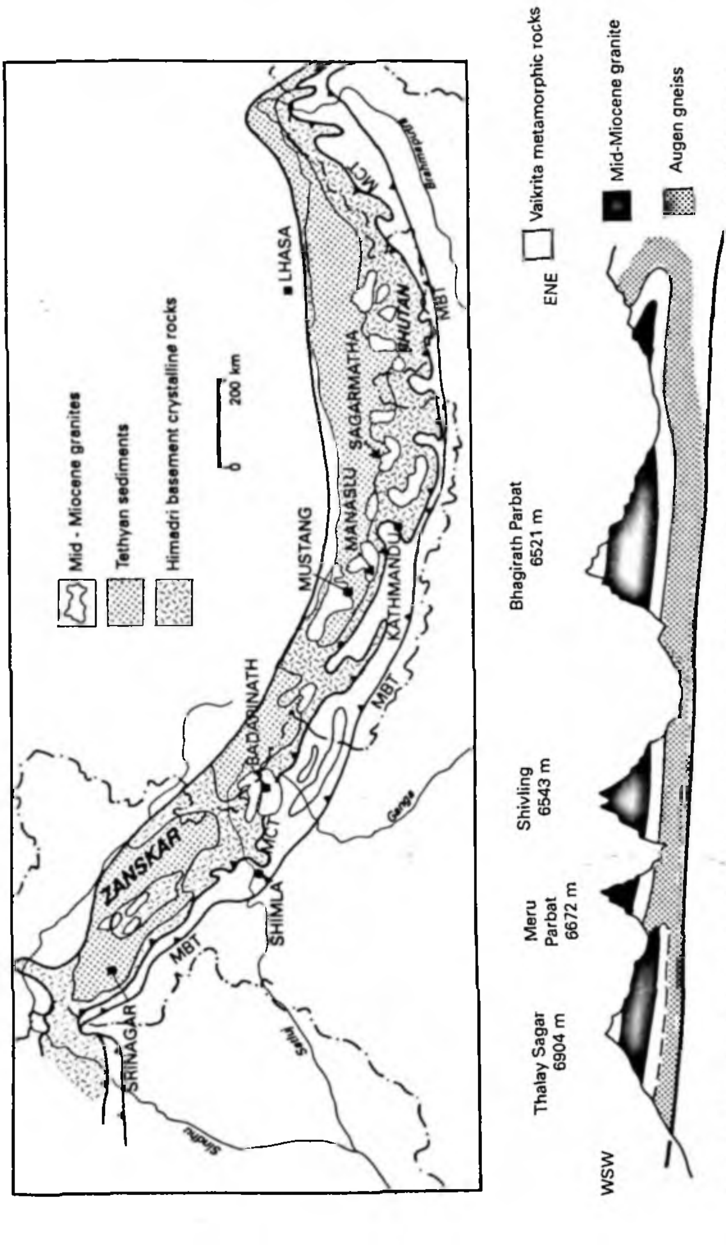
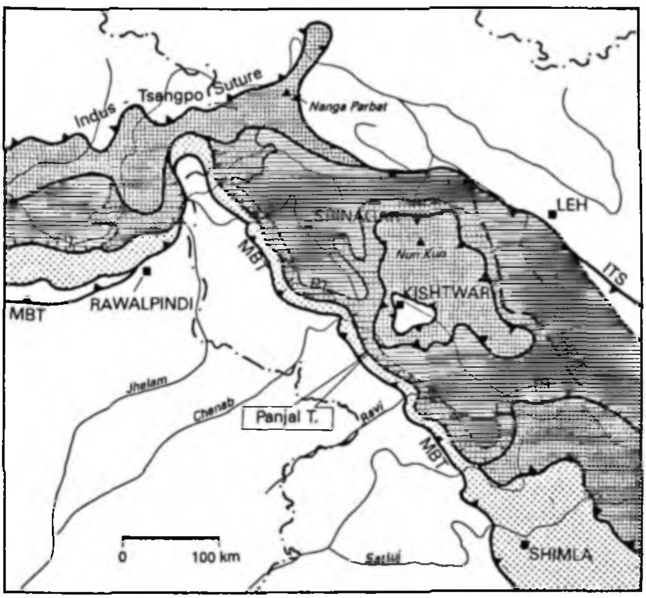


Fig. 7.3 *Distribution in space of the 25 to 15 m.y. old granites formed as a result of partial melting of metamorphic rocks (based on N. Harris and J. Massey, 1994). Section shows peaks of 22-20 m.y. old granites of the Chaukhamba massif (Badarinath) [after M.P. Searle, 1986].*

Purāna sedimentary rocks of the Lesser Himalaya[293] (Fig. 7.4). It is known as the Panjal Thrust in Kashmir. A similar displacement can be seen in the Jaljala and Chandragiri Hills in western and southcentral Nepal. The plane of decoupling, described by K.S. Valdiya[313,315] as *Trans-Himādri Fault* (T-HF) is recognizable over a 1600 km stretch from west of Zanskar[117,235] through Lahaul, Spiti[265,293] and northern Kumaun[313] to northern Nepal, where B.C. Burchfield and L.H. Royden[57] describe it as South Tibet Detachment Thrust.



Precambrian basement (crystalline rocks)

Tethyan sedimentary rocks

Metamorphosed Precambrian Tethyan sedimentary rocks

Purana sedimentary succession

T - HF/T	Trans - Himadri Fault/Thrust
PT	Panjal Thrust
MBT	Main Boundary Thrust
ITS	Indus - Tsangpo Suture

Fig. 7.4 *Uprooted pile of sedimentary rocks of the Tethys terrane rides — as Kashmir Nappe — over the Lesser Himalayan terrane, concealing a considerable part of the Purāna succession (based on V.C. Thakur, 1993).*

In northwestern Himalaya, according to V.C. Thakur[293], splitting of rock succession along the T-HF was accompanied by considerable southward displacement or thrusting of the sedimentary cover rocks as a nappe. As the hard dense basement complex was squeezed upon the MCT, the loaded sedimentary cover got detached from the foundation, slipped and toppled over backwards, thus forming spectacular backfolds all along the stretch of the detachment fault, the T-HF. In addition to slipping, there was lateral movement in the direction of the strike of the T-HF[192] due to the extension. These movements took place in the period 22 to 19 m.y. ago[57], nearly synchronous with the movements on the MCT.

7.5 Development of the Lesser Himalayan domain

The southward thrusting or translation of the basement comprising metamorphic and granitic rocks of the Himādri threw the nearly 7000 m thick pile of the Lesser Himalayan sedimentary rocks into a series of folds. Closer to the MCT, the squeezing and resultant deformation were so strong that the tightened folds were overturned, one toppling over another, and later split by faults along their axial planes. Further compression led to uprooting of the entire folded piles and to their displacement by 80–125 kilometres southwards in the form of gigantic sheets. The uprooted, far-travelled folded piles of deformed rocks are called 'nappes'. The *Ramgarh Nappe* made up of low-grade metamorphic rocks and the *Jutogh Nappe* comprising medium-grade metamorphics are recognized all through the Himalaya from northern Pakistan to eastern Arunachal Pradesh (Table 3.1; Fig. 3.1). In some sectors even the basement made up of metamorhpic rocks and 1800 to 2000 m.y. old porphyritic granites were involved in folding, faulting and uprooting or dislocation southwards (Figs. 7.5 and 7.6).

The southward thrusted, far-travelled sheets of rocks (nappes and their detached pieces called klippen) cover large parts of the Lesser Himalayan terrane of Purāna sediments. The nappes and their klippen are preserved in the cores of the concordantly folded Purāna sedimentary rocks. Through the openings called windows — presumably due to deep erosion or detachment of nappes — the underlying sedimentary rocks are visible (Fig. 3.1).

7.6 Formation of the Main Boundary Thrust

The thick pile of folded rocks of the Lesser Himalaya encountered considerable resistance. It was maximum in the backside of the orogen, or on the southern front. In the southern front the crust broke up in a series of faults all along the entire 2500 km length. Collectively, these thrust faults are known as the Main Boundary Thrust (MBT) — a name first given by H.B. Medlicott[160] to a fault he recognized in southeastern Himachal. Near the surface it is quite steep (>50°) but flattens to less than 20° as we go deeper. It is this regional plane along which the Indian shield — carrying a prism of younger sediments in its frontal part — has been sliding under the Himalaya (Figs. 7.7 and 7.13).

A large number of faults and thrusts developed parallel to or branching off from the MBT. This has converted the southern mountain front into a greatly elevated edifice made up of mutually overlapping slabs of the deformed rock formations. Oblique and transverse faults have wrenched or torn apart this edifice throughout its extent[178][308][315]. These tear faults

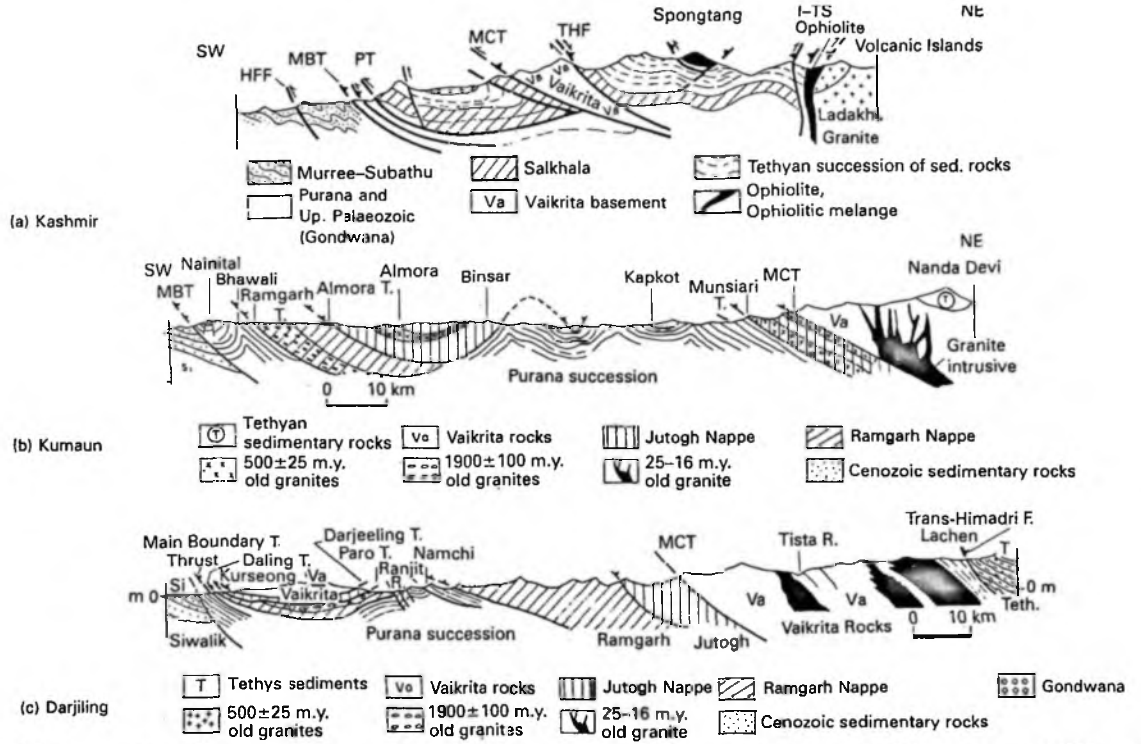


Fig. 7.5 *Structure of the Lesser Himalaya in Kashmir, Kumaun and Darjiling (based on V.C. Thakur (1987), A. Heim and A. Gansser (1939), and S.K. Acharyya (1973), respectively) [HFF= Himalayan Frontal Fault, PT = Panjal Thrust, MCT = Main Central Thrust, T-HF = Trans-Himādri Fault].*

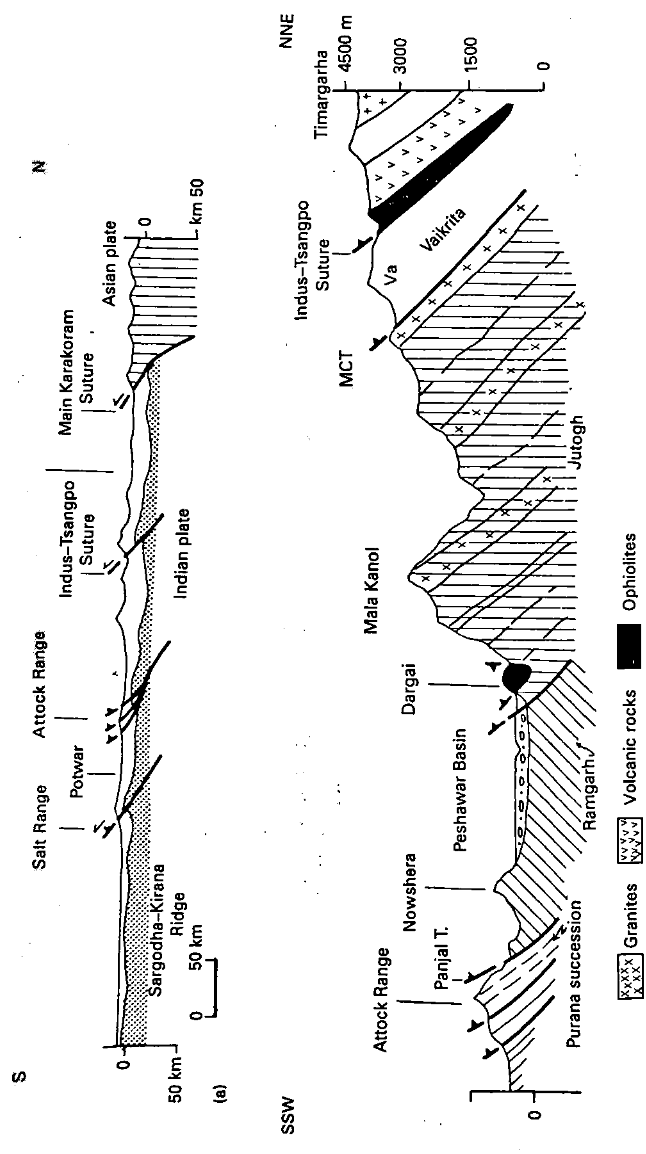


Fig. 7.6 *Structure of the Himalaya in northern Pakistan (based on (a) R.J. Lillie et al. (1987), and (b) R.A.K. Tahirkeheli (1982) [M CT = Main Central Thrust].*

are the consequences of differential horizontal advances of the variably thick and weighty pile of Himalayan rocks.

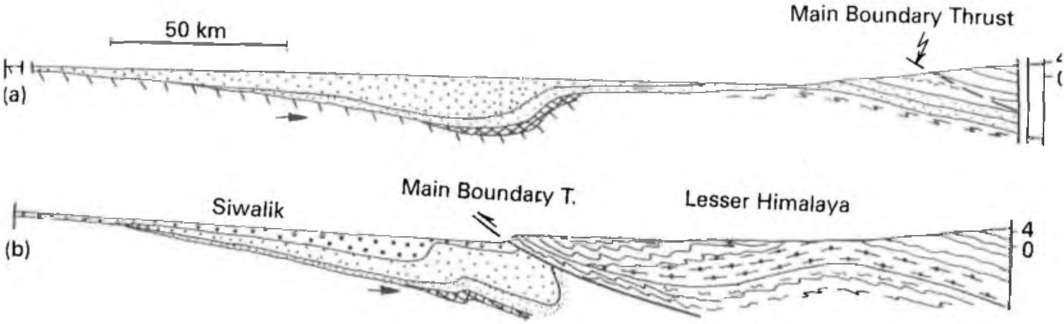


Fig. 7.7 *Formation of the Main Boundary Thrust (MBT) and evolution of the Siwalik Basin in the foreland. (a) The land in front of the rising Himalaya sinks to give rise to a depression (Siwalik Basin) which gets filled up rapidly. (b) As a result of growing compression the Himalayan rock pile is uprooted along what is known as the Main Boundary Thrust, and advances over the compressed, folded Siwalik sediments (based on G. Mascle et al., 1986).*

7.7 Evolution of Siwalik Basin

The Himalayan crust broke between 20 and 18 m.y ago along the MBT and simultaneously sagged immediately south of it (Fig. 7.7). An elongate foreland basin — the second in succession after the Sirmaur Basin of the Palaeogene — was formed about 18.3 m.y. ago(130)(131). It is known as the Siwalik Basin, and remained a great repository of detritus until about 0.22 m.y. ago(208). Sagging or bending down of the land in front of the Himalaya was responsible for the formation of the Siwalik Basin. The total thickness of sediments derived from the fast rising mountains amounts to about 7000 m. Embracing the Manchar succession in Baluchistan and Sindh, the Siwalik group forms the whole of the outermost hill ranges that stretch from Potwar (Pakistan) in the northwest through the Churia Hills in Nepal to the Dafla–Subansiri–Kimin belt in Arunachal Pradesh (Table 7.1), and then through the Namsang–Dihing belt in upper Assam to the Tipam–Dupitila area in Cachar and Tripura further south.

Emptying their abundant load of detritus into the newly formed Siwalik Basin, myriads of Himalayan rivers soon converted it into a vast floodplain (Fig. 7.8). Studies carried out by Rohtash Kumar, S.K. Tandon and A.C. Nanda(145)(146)(282) have shown that the meandering rivers migrated laterally, forming coalescing fans of detritus and built multistoreyed sand complexes with a very small proportion of overbank clay implying that these rivers were very wide and frequently encroached one another's floodplains.

The Siwalik succession comprises alternation of muddy sandstone and maroon mudstone or shale with occasional beds of pebbly conglomerate (in the Lower Siwalik), giving way upwards to dominant coarser sandstone that is characterized by mica and calcareous material

Table 7.1 *Neogene and Quaternary formations of the foothills of the Himalaya.*

<table>
<tr><th colspan="2">Age</th><th rowspan="2">Sindh</th><th colspan="2" rowspan="2">Potwar–Jammu</th><th rowspan="2">Himachal– Kumaun</th><th rowspan="2">Nepal</th><th rowspan="2">Arunachal Pradesh</th><th rowspan="2">Assam</th><th rowspan="2">Myanmar Plains</th></tr>
<tr><th>Epoch</th><th>Temporal Range (m.y. ago)</th></tr>
<tr><td>Early Pleistocene</td><td>–1.6–</td><td rowspan="5">Up. Manchar</td><td colspan="2">Up. Siwalik Boulder Conglomerate</td><td>Up. Siwalik Boulder Conglomerate</td><td>Deorali Boulder Beds</td><td rowspan="3">Kimin</td><td rowspan="3">Dihing</td><td rowspan="5">Irrawady Group</td></tr>
<tr><td rowspan="2">Pliocene</td><td rowspan="2">–5.3–</td><td rowspan="2">Up. Siwalik</td><td>Pinjor</td><td rowspan="2">Up. Siwalik</td><td rowspan="2">Chitwan</td></tr>
<tr><td>Tatrot</td></tr>
<tr><td rowspan="2">Late Miocene</td><td rowspan="2">–11.0–</td><td rowspan="2">Mid. Siwalik</td><td>Dhokpathan</td><td rowspan="2">Mid. Siwalik</td><td rowspan="2">Binaikhola</td><td rowspan="2">Subansiri</td><td>Namsang</td></tr>
<tr><td>Nagri</td><td>Dupitila</td></tr>
<tr><td rowspan="2">Mid. Miocene</td><td rowspan="2">–18.3–</td><td rowspan="2">Lr. Manchar</td><td rowspan="2">Lr. Siwalik</td><td>Chinji</td><td rowspan="2">Lr. Siwalik</td><td rowspan="2">Arungkhola</td><td rowspan="2">Dafla</td><td>Girujan</td><td rowspan="3">Up. Pegu Group</td></tr>
<tr><td>Kamlial</td><td>Tipam</td></tr>
<tr><td>Early Miocene</td><td></td><td>Gaj</td><td colspan="2">Murree</td><td>Kasauli</td><td>Dumri</td><td>—</td><td>Surma</td></tr>
</table>

Up. = Upper, Lr. = Lower, Mid. = Middle

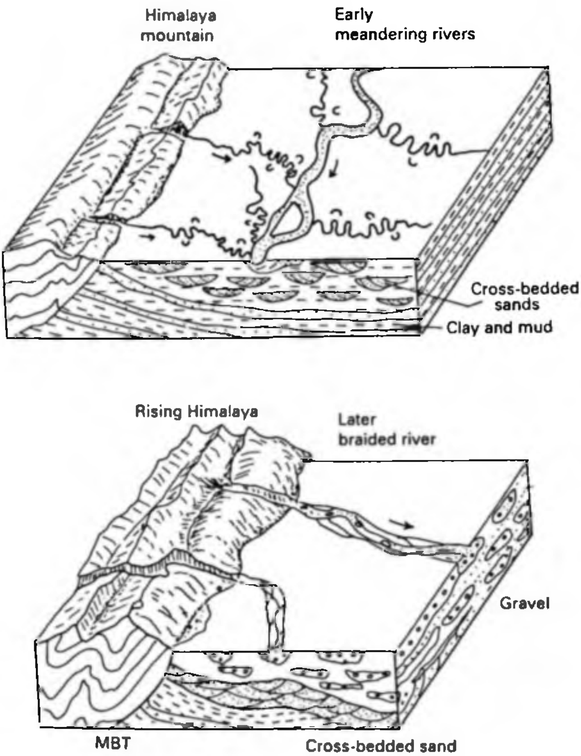


Fig. 7.8 *Deposition by rivers of sediments in their channels and floodplains in the Siwalik period. During relatively quiet (tectonically speaking) time, rivers meandered in their floodplains. Uplift in the Upper Siwalik time was responsible for braiding of these rivers and heavy deposition of very coarse sediments.*

with subordinate grey and brown shale (in the Middle Siwalik). Towards the upper part, sandstone becomes more coarse-grained, pebbly or locally conglomeratic (in the Upper Siwalik) as seen east of Chandigarh in the Pinjor area (Fig. 7.9). Obviously, the meandering rivers of Lower Siwalik time had formed into braided rivers during the Upper Siwalik epoch due to the steepening of the slope of the alluvial plain. This fact implies that towards the Upper Siwalik time (5.1 to 0.22 m.y.), the mountain province and its foreland had started rising up once again. This is further borne out by the very fast rate of sedimentation (300 m/1000 yr) in the Middle Siwalik — which was three times faster than in the Lower Siwalik (as computed by G.D. Johnson et. al.[(131)]).

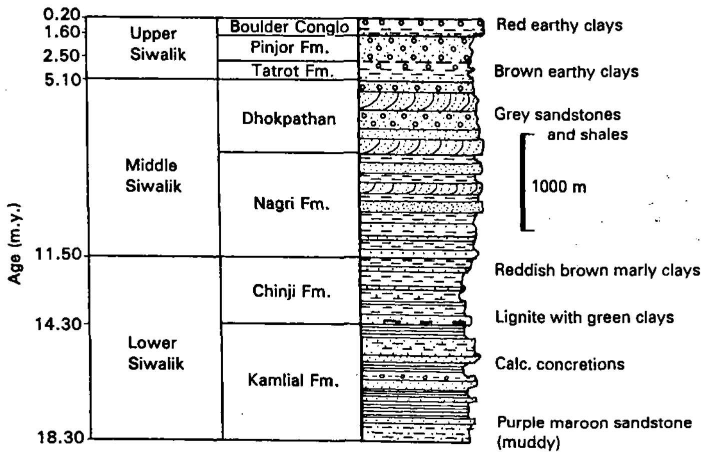


Fig. 7.9 *Lithological succession of the Siwalik Group, illustrating its compositional characteristics and stratigraphic order.*

The excessive delivery of such heavy minerals as kyanite, staurolite, garnet and epidote in the sandstones of the Middle Siwalik — noted by A.T. R. Raju[204] and R.S. Chaudhri[66] — must have been derived from the exhumed metamorphic rocks which once formed the basement. Evidently, by the beginning of the Middle Siwalik time 11.5 to 5.1 m.y. ago, the basement rocks had been thrust over and exposed to erosion in the Himalayan domain as a consequence of strong tectonic movement and the attendant uplift.

The Himalayan Foreland Basin, which includes the Siwalik, possesses according to S.K. Biswas[49] all the major parameters that indicate formation of oil and gas. However, barring the two live oil shows and two gas-bearing horizons at depth in the Jwalamukhi area in Himachal Pradesh, no hydrocarbon field has been discovered so far in the Siwalik. This could probably be due to the absence of impermeable rock beds in this area that could put a seal on the reserves, the poor presence of the hydrocarbon-producing Subathu horizon, or/and the severe tectonic deformation to which the Siwalik has been subjected to. Rethinking on the problem inspires oil finders to continue their search in the Siwalik.

7.8 Contemporary volcanism

While rivers were depositing sediments in their channels and on the floodplains, volcanoes in Afghanistan were active and emitted fire, fume and ash. Wind carried the volcanic dust and ash eastward and shed them on the Siwalik floodplains. The ash falls have since been converted into bentonitic clays. Their ages are between 9.46 ± 0.59 and 1.61 ± 0.10

m.y.[130][208]. A notable increase in volcanic activity about 3 to 1.5 m.y. ago has been noted. Increased volcanic activity in the Middle Miocene time is noticeable in the valley of the Irrawady River in Myanmar and far south in the Andaman Sea. This indicates that the volcanic activity was not confined to Afghanistan alone but was quite widespread.

7.9 Sediment spill beyond the Siwalik Basin

The Himalayan province rose up rapidly in the Late Miocene time (11 to 5 m.y.). Faster rise caused accelerated erosion, and generation of a larger volume of detritus. So excessive was the volume of detritus delivered to the Siwalik Basin that a sizeable proportion of the influx had to be flushed out. Excess sediments thus spilled beyond the foreland basin and flowed down into the Indian Ocean. Huge fans of sediments began to form in front of the deltas — in the Bay of Bengal and the Arabian Sea. The Bengal Fan (Fig. 7.10) had started forming rather earlier — as early as the Early Miocene age — as testified by a 17 m.y. old fan formed by the turbidity currents.

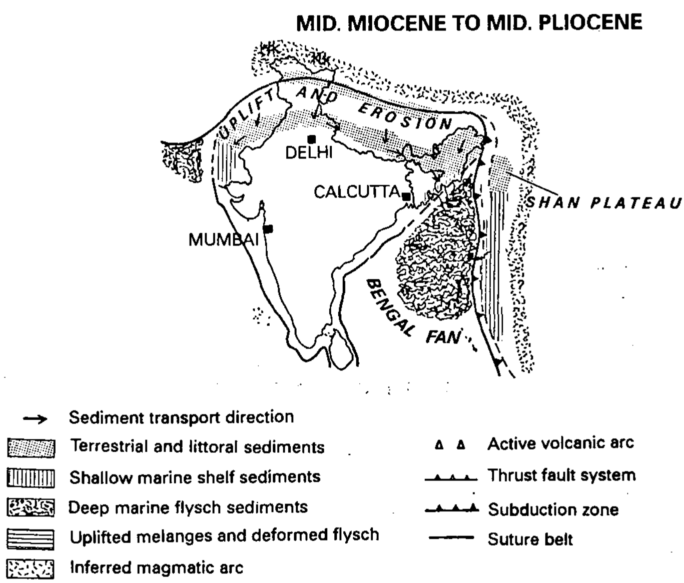


Fig. 7.10 *Sediments that spilled over the Siwalik Basin were deposited in the Indian Ocean in the form of huge fans (after S.A. Graham et al., Geol.Soc.Amer.Bull., Vol. 86, 273–280 (1975)).*

The rate of sediment accumulation in the Indian Ocean varied with the variation in the intensity of tectonic movements in the Himalayan province — the major source of sediments. According to S. Gartner[104], the average rate over the long period between Late Miocene to Lower Pleistocene varied between 20 m/m.y. and 70 m/m.y. There was a nearly five-fold increase in the sediment influx (Fig. 7.11) since about 12 m.y. ago — peaking in the periods 11.5–10.5 m.y. ago, 9–6 m.y. ago, 4–2 m.y. ago and 1–0 m.y. ago [213] — whenever the Himalaya rose up rapidly.

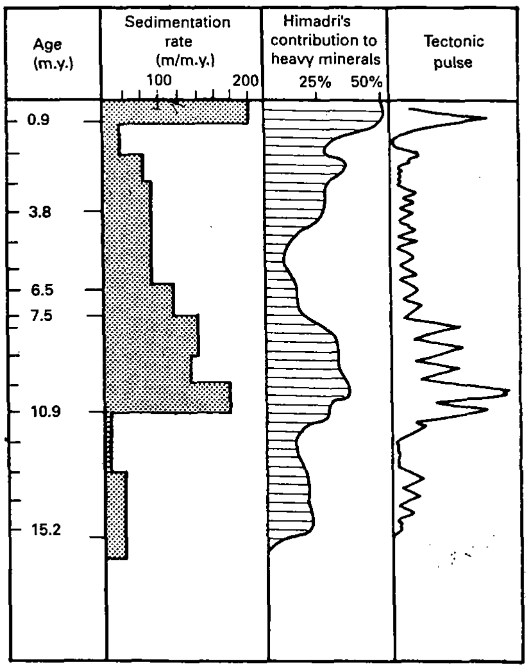


Fig. 7.11 *Maximum sediment influx into the Bay of Bengal occurred in the period 11 to 7 m.y. ago when the Himalaya must have risen up very rapidly (based on K. Ammano and A. Taira, 1992).*

In the initial stage, the influx of sediment to the Bengal Sea was dominated by material derived from the Great Himalaya (Himādri) — 80% of the detritus having been eroded from the high-grade metamorphic rocks that form the Himādri complex[85]. Floods of such heavy minerals as garnet, staurolite, kyanite, etc. in the Bengal Fan sediments (Fig. 7.10) imply their derivation from the Great Himalayan rocks. The Himādri rocks continued to contribute sediments preponderantly throughout the duration of the Later Miocene period

(15.2 to 7.5 m.y. ago). Abrupt floods of calcic amphibole derived from the Himādri terrane about 10.9 m.y. ago imply sudden uplift of the Great Himalaya.

The Lesser Himalayan rocks also became the principal suppliers for a brief duration in early Middle Miocene 17.1 to 15.2 m.y. ago[8]. Significantly, the climactic phase of the uplift and erosion — and thus of sediments influx — was during a brief span of early Late Miocene (10.9 to 7.5 m.y. ago) when the rate of sedimentation in the Bay of Bengal shot up from 20–70 to 200 m/m.y. as computed by S. Gartner[104]. Between 6.8 to 0.8 m.y. ago, not only had the pace of erosion comparatively slowed down, but also the finer sediments were dominated by smecktite and kaolinite clays, which must have been derived from the soil. The presence of soil implies that during much of the Pliocene, tectonic stability promoting thick soil formation prevailed in the Himalayan province.

7.10 Excessive floods of gravels: Events of mass movement

Towards the close of the Pliocene and beginning of the Pleistocene about 1.6 m.y. ago, the entire Siwalik domain from Potwar in northern Pakistan to the Dihing Valley in Assam was overwhelmed by sudden excessive influx of gravel and avalanches of muddy debris from the mountains. The gravelly detritus was derived principally from the outer ranges of the Lesser Himalaya and from the older Siwalik rocks themselves. Understandably, the outer Lesser Himalaya and the Siwalik belts were affected by very strong tectonic movement. These disturbances triggered massive landslides and debris avalanches on the slopes of the destabilized mountains within the Siwalik domain.

According to V. Raiverman[199,201] and Rohtash Kumar and S.K. Tandon[282,283], the collapse and erosion of the uplifted hanging walls of faulted blocks generated sediments of the Upper Siwalik. Stupendous volumes of aggregate of boulders, cobbles and pebbles gave rise to the 2800 to 1800 m thick *Upper Siwalik Boulder Conglomerate* (Fig. 7.9). The conglomerates are intercalated with yellow- brown muds and earthy clays brought down by flooded rivers and debris avalanches. The deposition of debris was very brisk — at a rate varying from 21 to 71 cm/1000 years [208]. The layers of bentonitic clays intercalated with the conglomerates indicate that the cataclysmic events leading to the emplacement of the boulder beds occurred in the period 1.7 m.y. to 1.5 m.y.[59,207,208] ago.

7.11 Structural evolution of Siwalik terrane

The revival of tectonic movement towards the end of the Pliocene age about 1.6 m.y. ago on the MBT and associated faults brought the stupendous pile of the Lesser Himalayan rocks riding over and trampling upon the Siwalik. Deformation in the Siwalik terrane itself gave rise to range after range of hills, many of which were latitudinally cut by strike faults and thrusts (Fig. 7.12). The intensity of deformation was strongest along the MBT zone where the folds were tightened, split along axial planes nd squeezed out. Away from the MBT, the intensity of deformation progressively diminishes.

In the far north, the Sindhu Basin extending from Kargil in the west to Shigatse and beyond in the east, was also subjected to strong compression. The Kailas Conglomerate was folded and thrust upon older rocks as seen in the Ladakh area (Figs. 6.4, 6.9 and Plate 14A).

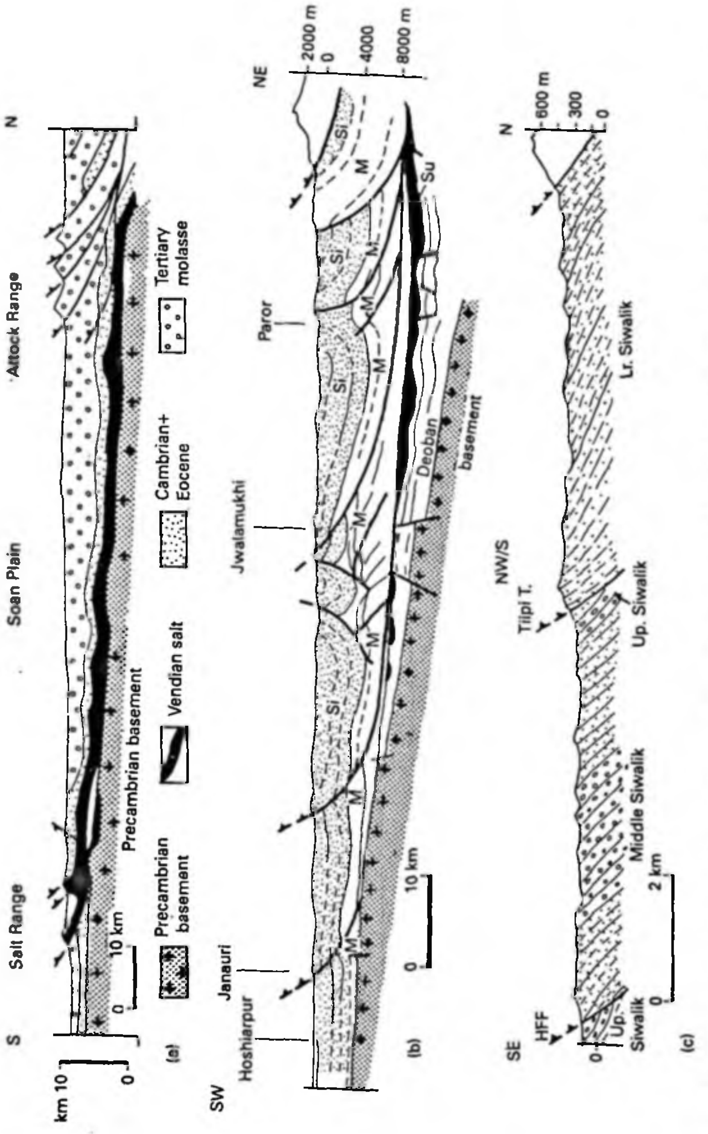


Fig. 7.12 *Structural architecture of the Siwalik terrane. (a) In Pakistan, after R.J. Lillie et al., 1987. (b) In Panjab after V. Raiverman et al., 1993. (c) In Arunachal after C. Karunakaran and A. Ranga Rao (1976) [Si = Siwalik, M = Muree, HFF = Himalayan Frontal Fault].*

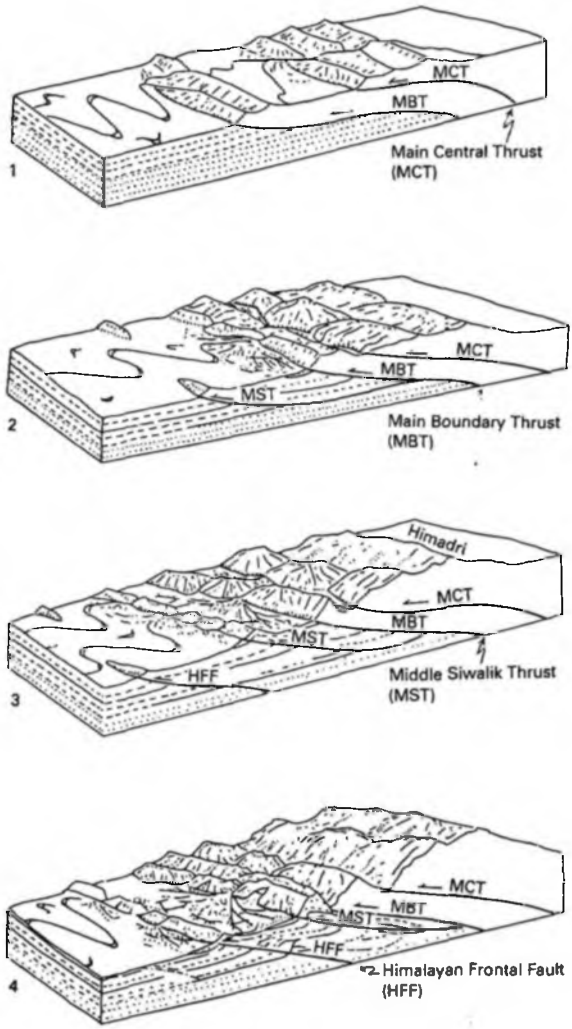


Fig. 7.13 *Evolution over a long period of time of the four major thrusts defining the boundaries of the Himalayan terranes (after T. Tokuoka et al., 1994).*

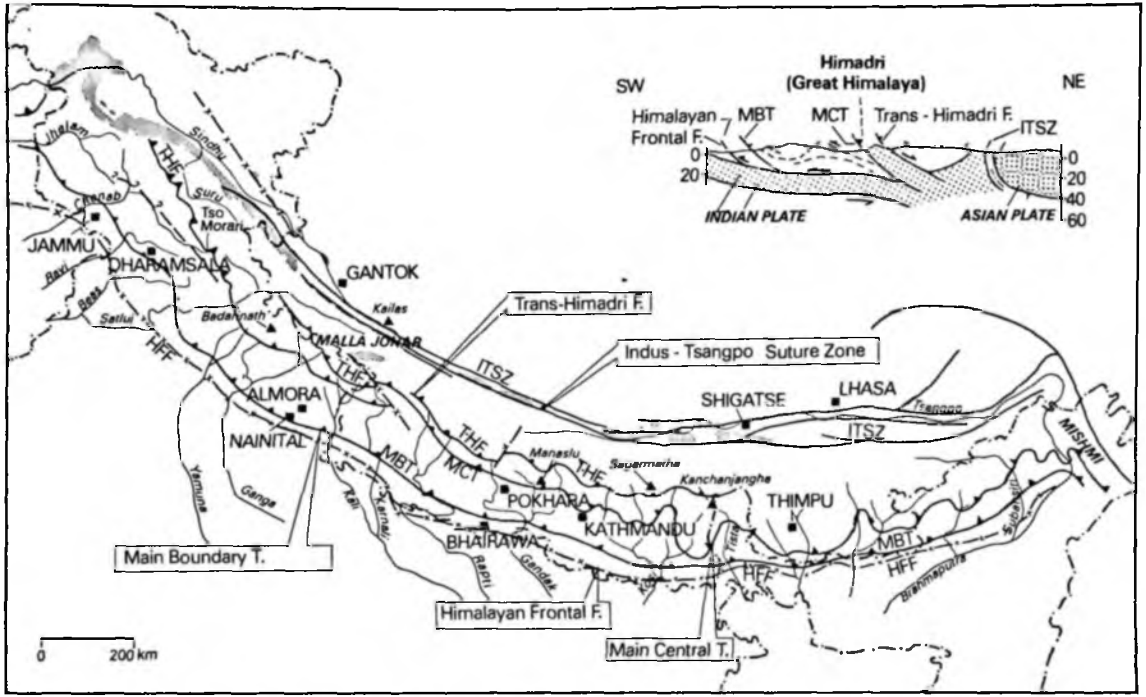


Fig. 7.14 *Extent of the four boundary thrusts of the Himalaya (K.S. Valdiya, 1993).*

7.12 Evolution of syntaxial bends

The collision of India with mainland Asia made a very profound dent on the southern margin of the latter with the projecting parts of the land jutting out boldly into the Himalaya province. In other words, the projecting promontories of the colliding Indian continent (Figs. 6.1, 7.4 and 7.15) stab the Himalaya like the forks of a trident of sorts. The northwestern and northeastern promontories made deeper and stronger penetrations at the two extremities of the Himalayan arc (Figs. 7.15 and 7.17).

Piles of rock formations were pushed, compressed and bent around the projecting land. As the pressure grew, these were displaced on shear faults and thrust planes, culminating in the evolution of what D.N. Wadia[337] called the syntaxial bends which broadly resemble the knee bends (Plate 3 and Figs. 7.15, 7.16 and 7.17).

Fold after fold developed around the projecting promontories. Further pushing resulted in the folds breaking along strike-slip faults along which considerable horizontal movement took place. These faults merged with the long transcurrent north–south trending Chaman Fault in the west and the Sagaing Fault in the east. These transcurrent faults register cumulative northward movements of the Indian block of the order of 300 km or more.

In northwest Himalaya, there are two quite different syntaxial bends, the axes of which make an angle of 90° with one another (Figs. 2.1 and 7.15). Clockwise rotation following the collision of the continents explains the development of this feature. The Nanga Parbat–Haramosh massif parabolically bends the I–TS and has pushed it northeastwards by more than 100 km, causing splaying out and dislocation of the Himalayan thrusts, including the one that separates the basement from the cover of Tethyan sediments giving rise to what D.N. Wadia[337][338] described as the Kashmir Nappe. Consequently, the Tethyan sedimentary succession, uprooted from its basement, advanced considerably southwards to nearly touch the Siwalik domain. In northern Pakistan the Tethyan succession occurs like a nappe upon the Purāna sediments of the Lesser Himalaya (Fig. 7.4).

In the Hazara (southern) syntaxis the whole succession of rock formations with intervening thrust planes bend around acutely, making an angle of 40°. The western flank of the syntaxis behaved differently. There being appreciable amounts of salt in the basal part of the succession, which acted as a lubricant, the rock masses slid, rather glided, smoothly southwards. They advanced as far south as the Salt Range upon the Indian platform without much folding and related deformation (Figs. 7.12(a) and 7.15). In contrast, the Pir Panjal flank, with but little lubricating salt in the rock succession, was severely folded and repeatedly split by faults along the axes of tightened folds.

In the northeastern syntaxis (Fig. 7.17) compressive movements of the continental collision led to northward movement of the Arunachal block and the Myanmar landmass relative to the Lohit–Shan–Thailand and Malaysia block of the Asian plate. The Patkai–Naga–Arakan range links up this syntaxis with the Andaman–Nicobar island arc delimited by an active zone where the Indian Ocean floor is descending under the Malaysian plate (Fig. 7.16).

7.13 Life in the Siwalik times

Under the warm humid tropical conditions that prevailed about 18 to 16 m.y. ago, the floodplains of the Siwalik were clothed with thick rain forests particularly in the early Siwalik

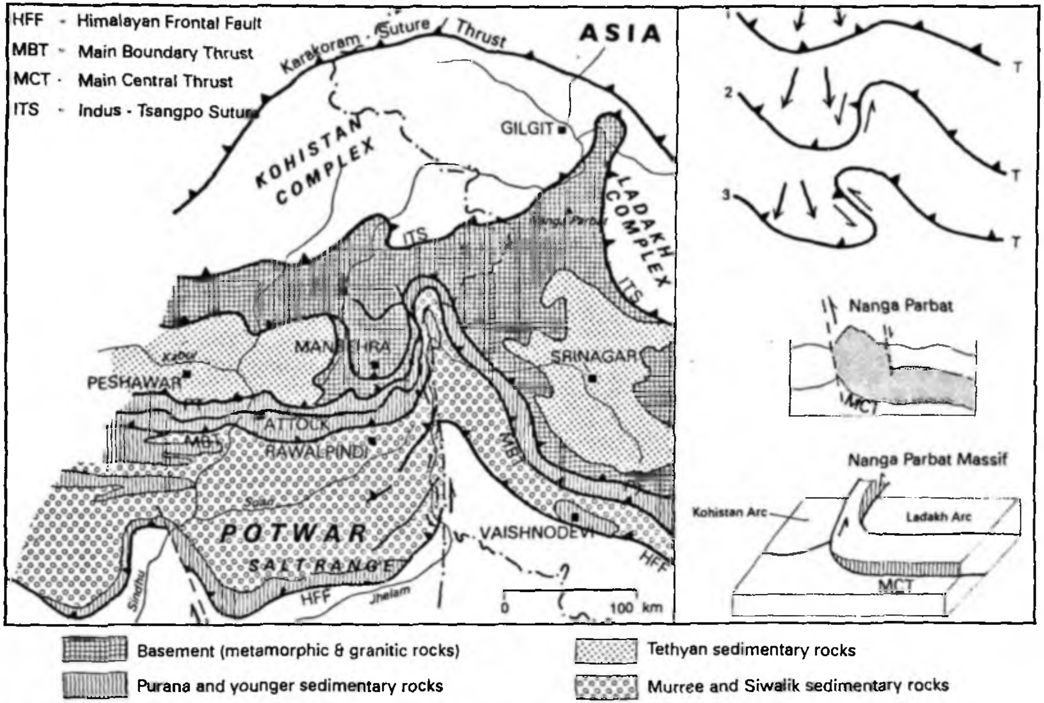


Fig. 7.15 *Nature and origin of the northwestern syntaxial bend (based on R.S. Yeats et al., 1984, and P.J. Treloar et al., 1992). [HFF = Himalayan Frontal Fault; MBT = Main Boundary Thrust; MCT = Main Central Thrust; I–TS = Indus–Tsangpo Suture; PT = Panjal Thrust].*

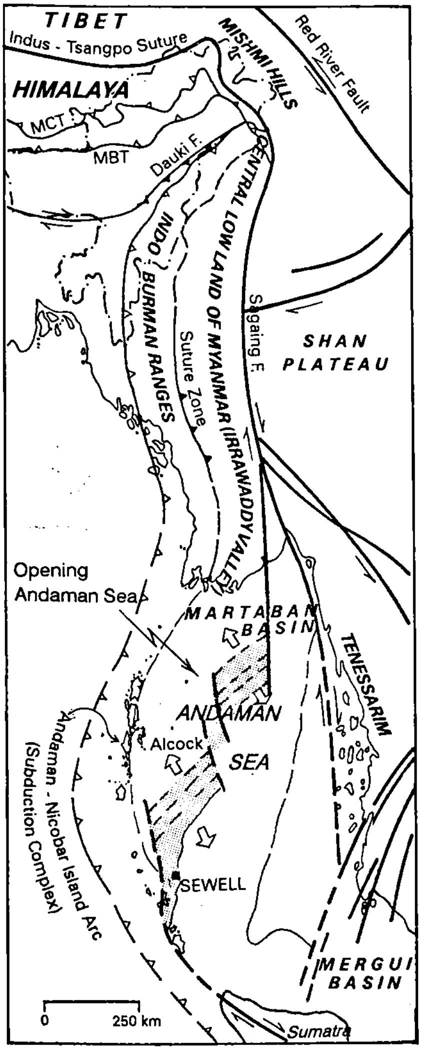


Fig. 7.16 *Tectonic setting of the Indo-Myanmarese Ranges, the Myanmar Plains and the Andaman Sea (based on J.R. Curray et al., 1980). The Indo-Myanmarese Ranges, extending southward into the Andaman Island Arc, form a bisector of sorts in this region of mountain linkage [MCT = Main Central Thrust, MBT = Main Boundary Thrust].*

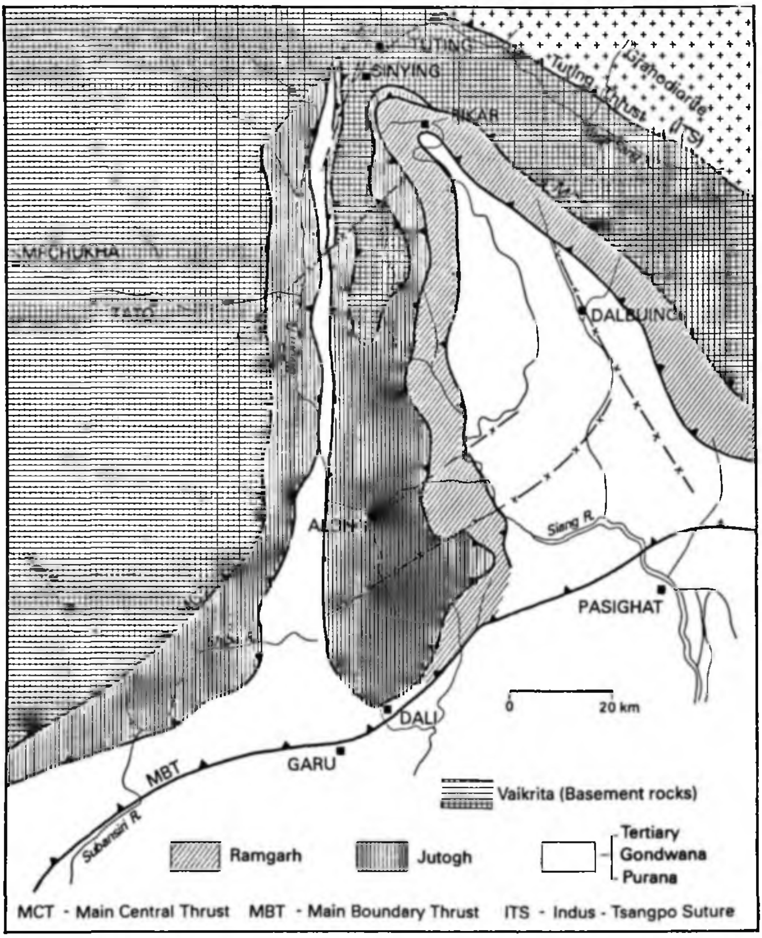


Fig. 7.17 *Eastern syntaxial bend embodies linking up of three tectonic provinces — the Indo-Myanmarese ranges extending into the Andaman Island Arc and forming a bisector of sorts [after Surendra Singh, 1993 and S.K. Acharyya, 1994].*

time. This is evident from plant fossils entombed in sediments deposited by rivers and streams in their floodplains. With abundance of food available from the forests, and water being aplenty in the land of rivers, lakes and swamps (Fig. 7.18), rich and varied life grew and flourished dramatically. In the streams lived reptiles (crocodiles and *Gharials*), and the swamps were populated by rhinos and hippos. In the forests lived animals like the elephant, tiger, buffalo, cow, deer, goat and the tree-climbing primate.

Naturally, herd after herd of quadrupeds came to this land of plenty from different parts of the world including Africa and North America. According to G.E. Pilgrim[193] and Barry et al.[26], pigs (*Suids*) and three-toed horses (*Hipparion*) immigrated to the Siwalik from central Eurasia about 9.5 m.y. ago. The bovid *Selenoportax* came about 7.4 m.y. ago from Africa. The elephant-like proboscid *Stegodon* and the hippopotomus (*Hexaprotodon*) arrived around 5.3 m.y. ago along with *Proamphibos*, the common ancestor of the buffalo and the cow, the langur (*Presbytis*) the carnivore *Dinofelis* and giraffes from central Africa. The elephant (*Elephas*) came from Africa 3.6 m.y. ago (A.C Nanda, personal communication, 1995). The one-toed horse *Equus* came 2.5 m.y. ago all the way from North America via Alaska, almost at the same time when the deer (*Cervus*) arrived from central Asia. The rhinos (*Rhinoceros*), buffaloes (*Bubalus*) and domestic cows (*Bos*) are purely indigenous animals.

The free and large-scale immigration of quadrupeds implies that until the Middle Siwalik about 5 m.y. ago, there were no barriers in the west and the north to stop the movement of animals coming from the west. Even though the Himalaya had emerged and had started rising rapidly, it still was not high enough to prevent the migration of four-footed animals, some of which were bulky in build and heavy in weight. Significantly, the remains of even-toed (artiodactyl) animals like *Hyoboops* found near Kargil in the Sindhu Basin in Ladakh[81] are very similar to those of the Bugti Hills in Baluchistan (A.C. Nanda per. com., 1995). This corroborates the hypothesis of free migration of four-footed animals across the Himalayan province in the Late Oligocene 27–23 m.y. ago. Fossil finds delineate the speculated routes of quadruped movements.

The animals that made the Siwalik domain their home (Plate 15) proliferated and diversified very rapidly and dramatically in the very congenial environment of the floodplains. Indeed, the Siwalik faunal assemblage was three times richer than it is today. Compared to just one species of elephant today, there were nearly 30 species; and there were 15 genera of anthropoid apes in the Siwalik forests[341]*

In the rain-forests of the Lower Siwalik times, pigs (*Listridon*) were abundant in the marshy tracts, along with *Deinotherium*, *Anthracotherium*, the proboscids (elephants) *Trilophodon*, the carnivores *Dissopsalis* and *Vishnufelis*, and the artiodactyls *Conohyus*, *Dicoryphochoerus*, *Dorcabune*. The primates *Sivapithecus* (Plate 16), *Dryopithecus* and *Brahmapithecus* lived on the trees of dense forests dominated by *Dipterocarpus* and *Calophyllum*, while a variety of reptiles including the giant turtle *Colossochelys atlas* (Plate 15C) lived in water bodies.

Then about 11 to 10 m.y. ago, the climate grew drier and pine trees (*Pinus*) secured a foothold; patches of grassland appeared in these forests. The three-toed horse *Hipparion* (Plate 15D) together with giraffes like *Vishnutherium*, proboscid elephants like *Stegodon* (Plate 15A), the hippopotamus *Hexaprotodon* (Plate 15B), the carnivores, the artiodactyls, in addition to rodents and primates (like *Indraloris*) lived and proliferated in the Middle Siwalik terrane[68].

In certain parts of the forests in what is Panjab today, lived the *Macacus* monkey and apes like *Sivapithecus* (Plate 16) and *Sugrivapithecus* which are directly in the line of humans.

By the Upper Siwalik time (5.1 to 1.6 m.y. ago) environmental conditions had changed

* It was Captain P.T. Cautley who in 1832 first discovered the Siwalik fossils in course of digging for the Ganga Canal near a Shiva (Siwa) temple at Haridwar in the Ganga Valley. Hence the name Siwalik to the sedimentary rocks entombing the fossils.

considerably and tropical forests (Fig. 7.18) were largely replaced by savanna-type wide grassy plains clotted sparsely with trees. Grazing and browsing animals became preponderant in the forests dominated by trees like *sain* (*Terminalia*), *am* (*Mangifera*), *kachnar* (*Bauhinia*), *siris* (*Albizzia*) and *khair* (*Acacia*)[16,332]

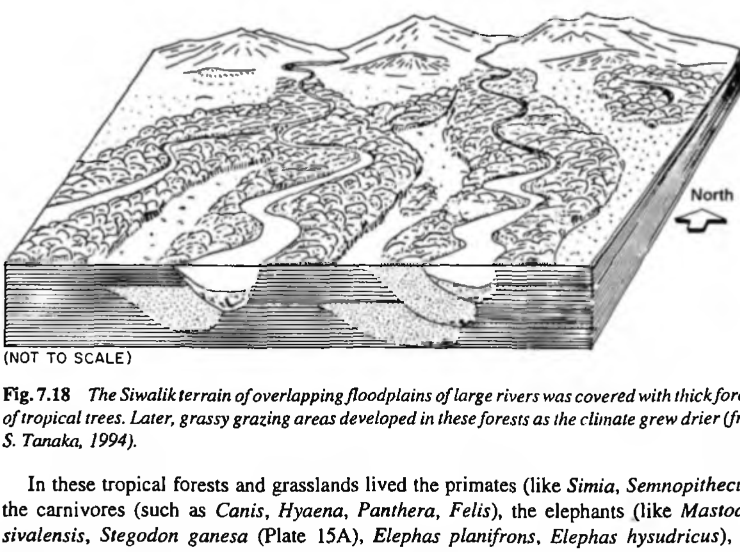


Fig. 7.18 *The Siwalik terrain of overlapping floodplains of large rivers was covered with thick forests of tropical trees. Later, grassy grazing areas developed in these forests as the climate grew drier (from S. Tanaka, 1994).*

In these tropical forests and grasslands lived the primates (like *Simia*, *Semnopithecus*), the carnivores (such as *Canis*, *Hyaena*, *Panthera*, *Felis*), the elephants (like *Mastodon sivalensis*, *Stegodon ganesa* (Plate 15A), *Elephas planifrons*, *Elephas hysudricus*), the ungulates (*Rhinoceros*, *Equus sivalensis*, *Hippopotomus*, *Sus*, *Camelus*), girraffes (*Indratherium*, *Sivatherium*) and other animals like the deer (*Cervus*), buffalo (*Bubalus*), cow (*Bos*) and bison.

Judging from the stone artefacts found in the lower part of the Upper Siwalik sediments in the Saketi Valley, District Sirmaur in Himachal Pradesh, it seems that human-like primates (Plate 16) had by then appeared on the scene[326].

7.14 Intermontane lakes

Well before the Late Pliocene/Early Pleistocene period, when tectonic upheaval engulfed the Himalayan province, certain sectors of it experienced stretching of the terrain in the east–west direction in the northern belt close to the I–TS and in the north–south directions in the middle zone. The Thakkhola graben with its 5 to 2 m.y. old Late Pliocene to Early Pleistocene sediments in the upper reaches of the Kali Gandaki in Nepal[83] was formed when the northern belt suffered east–west extension (Fig. 7.19).

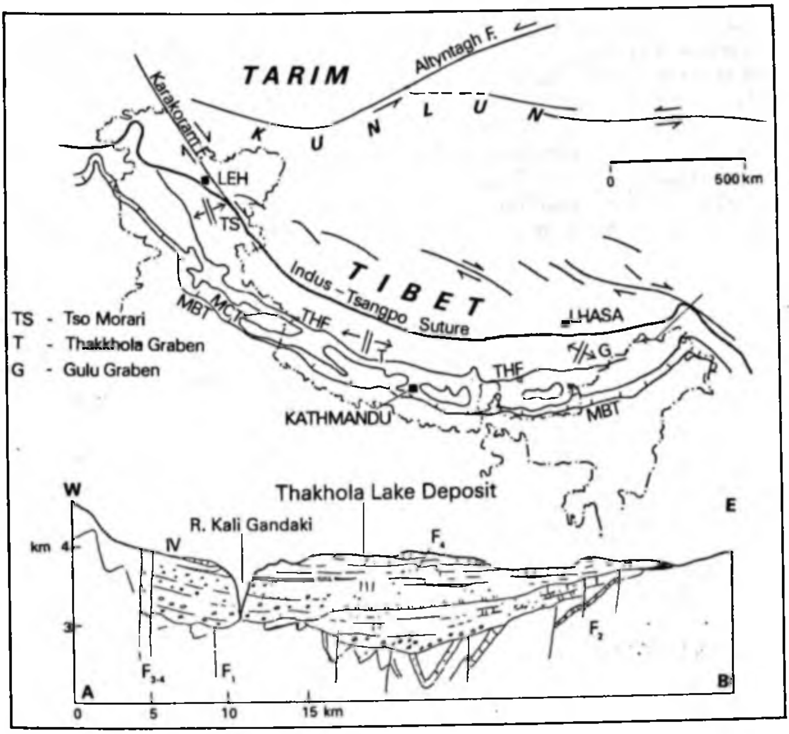


Fig. 7.19 *Thakkhola graben in the northern belt was a product of east–west extension of the Himalayan province (map after D. Gapais et al., 1992, and the section after Monique Fort, 1980).*

In Kashmir, faulting up of the Pir Panjal Range caused ponding of the river Jhelam and the formation of a huge lake — the Karewa Lake. Presently nestling at an elevation of 1700 to 1800 m between the 6100–4500 m high Zanskar Range and the 3500 to 3200 m high Pir Panjal, the Karewa palaeolake is represented by the now shrunken Dal–Wular lakes and 1300 m thick sediments — predominantly mud and silt[5,42,76].

There are several big and small lens-shaped bodies of gravel/conglomerate generated by debris avalanches or landslides[60], and the top has a blanket of 10–25 m thick deposits of wind blown loess[189]. As a result of a similar ponding of the Sindhu River (and its tributaries, the Kabul and the Swat rivers), a huge lake was formed in the Peshawar Basin in northern Pakistan about 2.8 m.y. ago[59]. A more than 300 m thick sedimentary fill forming the Peshawar plains represents this palaeolake.

The Karewa sediments contain, at various levels, remains of heavy and large-sized animals like hippos (*Hexaprotodon*), rhinos (*Rhinoceros*) and elephants (*Elephas hysudricus* and *Archidiskodon planifrons*)[140,141] (Fig 7.20). Such remains along with those of *Stegodon* and *Crocodylus*, are found in the south across the Pir Panjal in the Upper Siwalik of the Jammu region[208] and in the east in the Kathmandu Basin[347]. In central Nepal, when the Bagmati River got impounded due to the uplift of the Mahabharat Range along a fault, a big lake was formed in what is today the Kathmandu Valley. The palaeolake, presently at an elevation of 1300–1500 m, is represented by a thick succession of sediments dating back to 2.8 to 1.0 m.y.[347] (Fig. 7.21).

There is a striking resemblance in the fauna at that time of these three far-separated basins across the presently very high mountains. Doubtless, these bulky animals could move freely

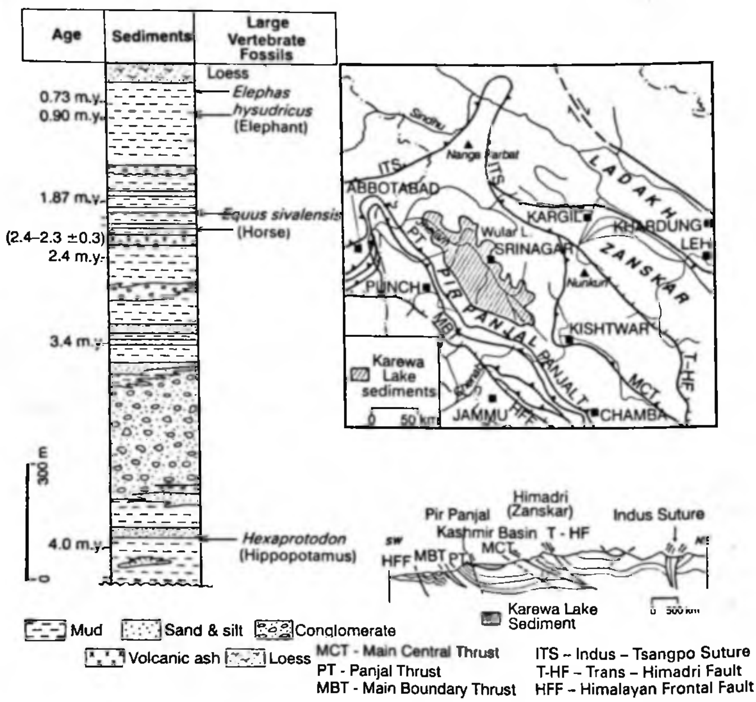


Fig. 7.20 *Tectonic setting, lithology and fossil content of the Karewa Lake (map after V.C. Thakur, 1987, and column after B.S. Kotlia, 1990).*

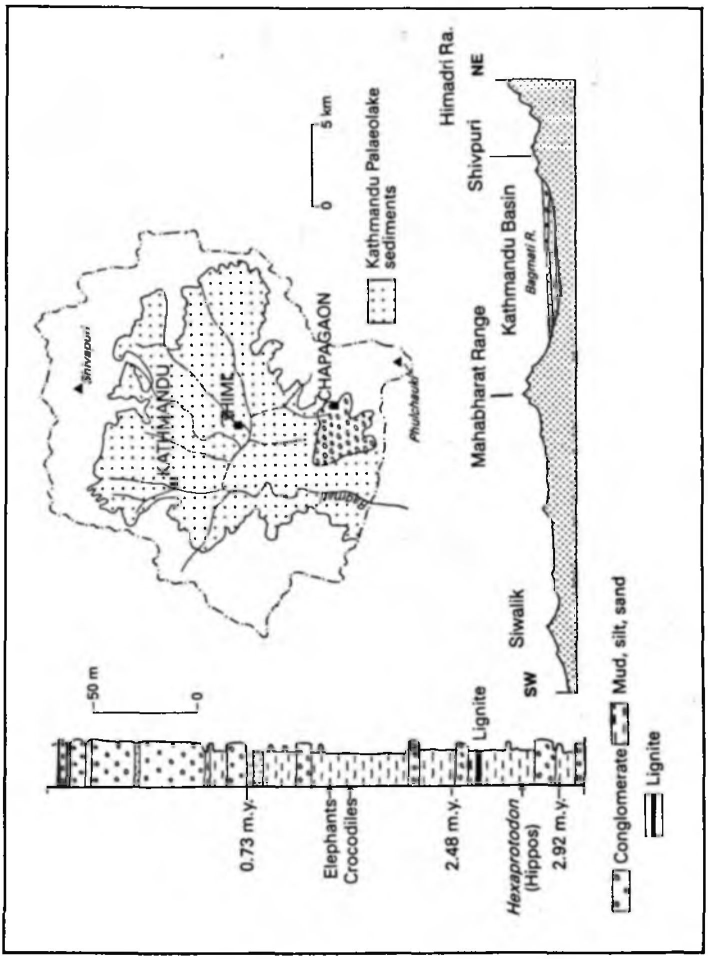


Fig. 7.21 *The Kathmandu palaeolake behind the uplifted Mahabharat Range (map and column after M. Yoshida and P. Gautam, 1988).*

across the terrain at that time when the climate was quite warm and moist (Fig. 7.22). It seems that there were no mountain barriers at that time — 3.8 to 0.40 m.y. ago. Understandably, the terrain must have been gentle, if not flat, and the elevation of the land not more than a few hundred metres above sea level[319]. This then was the scenario of the Lesser Himalaya towards the close of the Tertiary period.

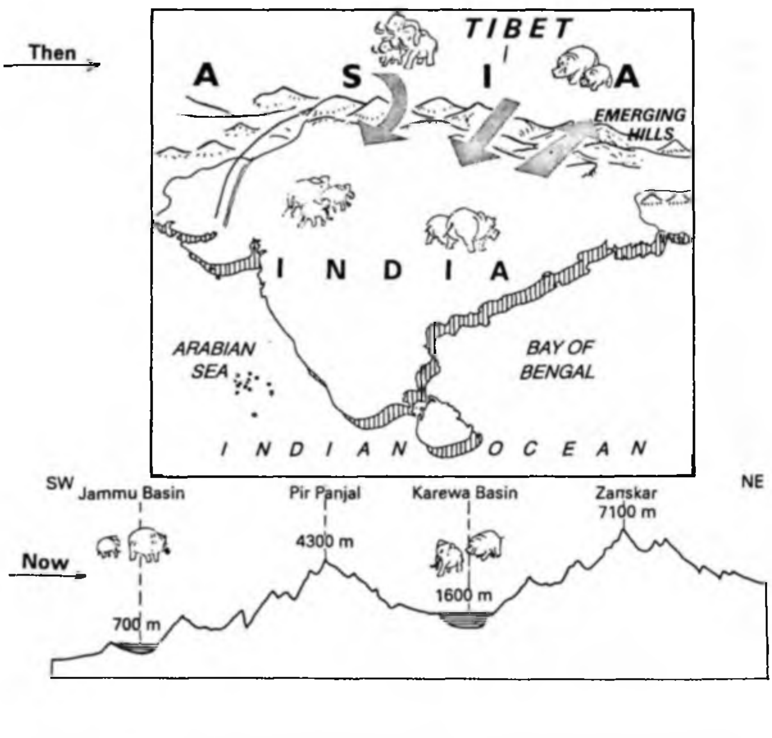


Fig. 7.22 *Hippos and rhinos could not have crossed the high mountains. Perhaps the basins in which they lived were not high enough to prevent their intermigration (map after Raj Chengappa in* ***India Today****, 90–103, March 15, 1993).*

8 *Evolution of the 'Abode of Snows' and Development of Indo-Gangetic Basin*

8.1 Pleistocene landscape

The Himalaya had emerged as an orographic feature stretching from the frontier of Afghanistan to the border of Myanmar. The northern part embracing the Himādri and Tethyan terranes had attained appreciable height, but the Lesser Himalayan belt was not a high mountain — not until the beginning of the Quaternary period 1.6 m.y. ago[(319)]. The Himādri terrane had already become a rugged range, exposed to relentless onslaught of erosion as progressively lower levels of rocks were exposed due to continued exhumation attending uplift. The Lesser Himalaya was a gentle terrain of low relief characterized by undulating landscape of rounded hilltops, gentle slopes and wide valleys of winding or even meandering rivers and streams. Covered with the thick carpet of soil produced by weathering for long periods of time, particularly on the nappes of the Early Precambrian rocks, the Lesser Himalayan terrain then could not have been higher than a few hundred metres above sea level. Tectonic tranquility prevailed on the whole, as borne out by the greatly reduced deposition of sediments in the Indo-Gangetic Basin and in the Bay of Bengal about 8 m.y. ago as clearly brought out by D.W. Burbank et al.[(61)]. Across the Himalaya, the Tibetan land, likewise, was a peneplaned — practically flattened — terrain of low relief having an elevation less than 900 m[(240)]. In this Tibetan land roamed heavy-bodied large animals (like rhinos) in the tropical forests which then flourished there[(102)]. The Siwalik was still a vast floodplain of many braided and a few meandering rivers.

8.2 Tectonic resurrection and geomorphic rejuvenation

At the beginning of the Pleistocene age (1.6 to 1.5 m.y. ago), the southern belt of the Lesser Himalaya heaved up on the reactivated MBT and related subsidiary thrust faults. A formidably rugged mountain rampart stood up looking down on the Siwalik terrane below. Sudden as well as intermittent movements accompanied by catastrophic landslides (and presumably earthquakes also) all along the faulted belts caused environmental havoc, as already stated in the preceding chapter. It was only in the Quaternary period that the Himalaya rose to great heights — in the order of 3000 to 4000 m[(102)]. The rate of uplift was particularly fast in the period 0.8 to 0.9 m.y. ago when the pace of erosion reached its acme[(213)].

The reactivation of faults rejuvenated the mature geomorphology of the Lesser Himalaya very dramatically. As the mountain ranges rose, the antecedent rivers — which had established their drainage well before the mountain walls developed — continued cutting their channels deeper and deeper without deviating from their original channels (Fig. 8.1). The outcome was the development of deep gorges and chasms with practically vertical to convex walls, particularly in the proximity of active faults, and where tributary rivers or streams plummeted down into main rivers. The rivers were thus entrenched in their meandering or winding courses. Eventually, the terrane became very rugged on the whole.

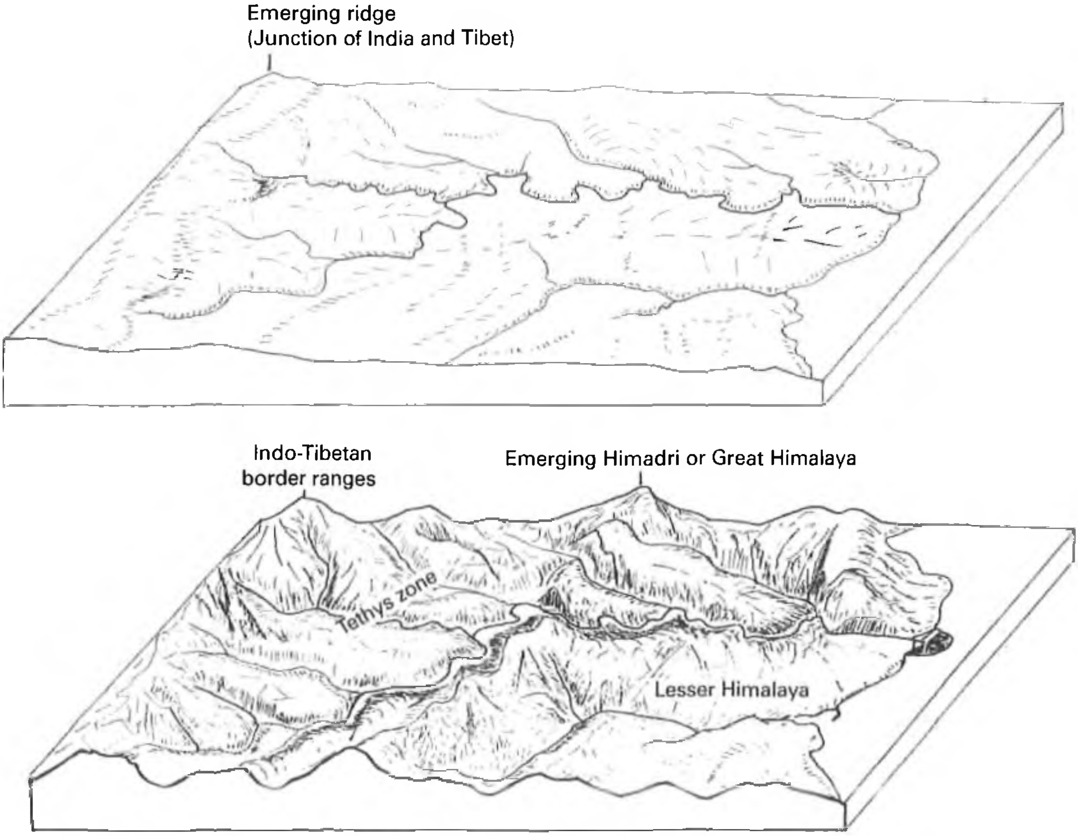


Fig. 8.1 *Tectonic resurrection of the Himalaya related to dramatic revival of movements on active faults resulted in geomorphic rejuvenation of the terrain. The gentle, mild topography of yore became rugged and the swinging rivers got entrenched in their former channels.*

8.3 Strengthening of monsoon and formation of snow cover

According to P. Molnar et al.,[172] about 8 m.y. ago when the Tibetan plateau suddenly rose by 1000 to 2500 m, there was an abrupt change in the climate, including strengthening of the monsoon over the larger part of the Himalaya and development of arid conditions in northern Pakistan. The continued and particularly high rise of the mountain ranges in the Quaternary period caused profound perturbations in the circulation of winds, including moisture-laden air. This development culminated in the initiation of the unique monsoon system in Asia, including the Indian landmass. It brought heavy rains from the southwesterly air currents during summers and cold precipitation from the northeasterlies during winters (Fig. 1.1).

Diversion of the even flow of winds and creation of large cool areas caused snowfall on the elevated mountains in the Himādri terrane and the Pir Panjal–Dhauladhar ranges. While the Siwalik and Lesser Himalayan terranes were beaten and washed by heavy rains, in the lofty Himādri packs of snow and ice grew thicker and thicker. The 'Abode of Snows' — the *Himalaya* — thus came into existence.

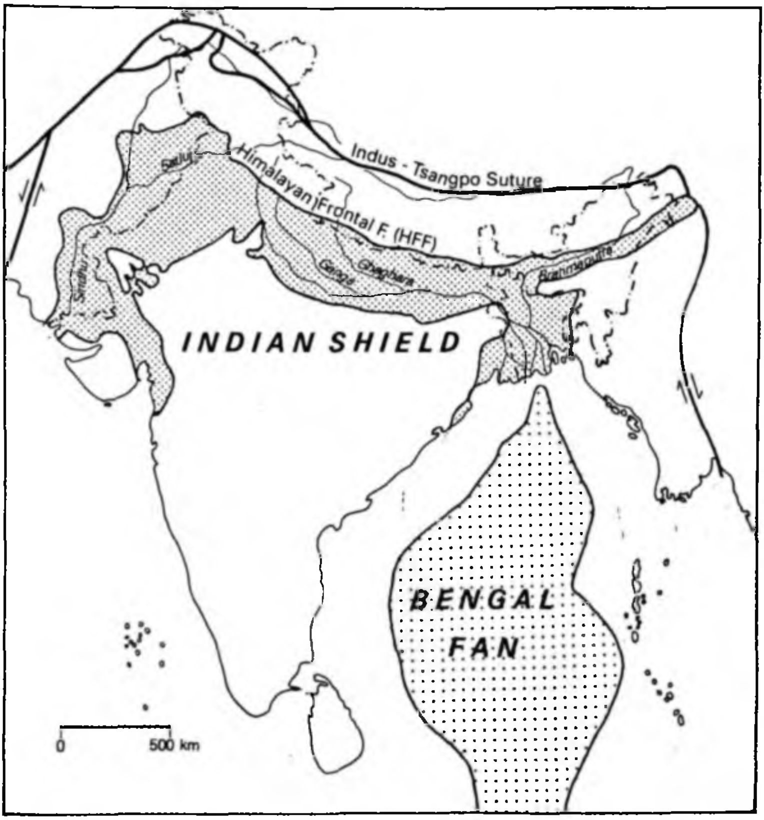


Fig. 8.2 *Extent of the Indo-Gangetic Basin. The Himalayan Frontal Fault (HFF) partitioned the formerly large Himalayan Foreland Basin into two unequal parts, the southern wider belt subsiding into the depression of Sindhu–Ganga–Brahmaputra — the Indo-Gangetic Basin (after D.W. Burbank, 1992).*

8.4 Pleistocene glaciation

Cold conditions — precursors to glaciation — had set in as early as 2.5 m.y. ago in the Kashmir Valley as testified by the fossils of rodents such as *Kilarcola* and *Microtus* (which were prolific in the colder regions of contemporary Europe) found in the upper part of the sedimentary succession of the Karewa Lake[140]. Glaciers spread far and wide over Potwar, Kashmir, Kangra and in the Ladakh–Tibet region. There were indeed four successive advances of glaciers from the higher mountains — the oldest glaciers descending to the level of now 1675 m above sea level, and the youngest to now nearly 2400 m[76,341].

These glaciers left behind gravelly detritus in the valleys and also peculiarly banded varvites in parts of the Karewa Lake. Remarkably, the periods of glaciation alternated with interludes of warm humid climatic conditions when forests grew luxuriantly and formed lignite, peat and several layers of carbonaceous soil, particularly in the last 25,000 years [189,263]. The glaciation period was immediately followed by a time when fierce dry winds blew in the Kashmir Valley, depositing a 10–20 m thick layer of loess atop the Karewa Lake succession[189].

8.5 Partitioning of the Himalayan Foreland Basin

Sometime in the later part of the Pleistocene, intense squeezing of the Siwalik domain culminated in the breaking up of the foreland basin (Figs. 7.13 and 7.14) along a series of steep faults[285] described as the *Himalayan Frontal Fault* (HFF) by T. Nakata[179][181] or *Main Frontal Fault* by A. Gansser[101]. It broke the large Himalayan Foreland Basin into two unequal parts—the northern 25–45 km wide part becoming the Siwalik terrane and the southern 200–450 km wide subsiding southern part developing into what is called the *Indo-Gangetic Basin* (Fig. 8.2). The Himalayan Frontal Fault cuts the Siwalik obliquely so that the more than 45 km wide Siwalik terrane of the Jammu region is attenuated to less than a 20 km belt in the east (Fig. 7.14).

8.6 Floor of the foreland basin

Magnetic and electrical surveys demonstrate the existence of a series of long linear E–W, ENE–WSW and NE–SW trending highs and depressions (Fig. 8.3). These subdivide the Sindhu–Ganga basin into a number of sub-basins, some of which are quite deep at their northern ends. The deep Sharada and Gandaki depressions with 1500–2500 m thick recent sediments provide examples of the staggeringly rapid subsidence of the sub-basins as a result of the growing pile of sediment brought by the Himalayan rivers in the Holocene (in the last 11,000 years), and due to the flexing down of the crust[157]

If one were to uncover the sediments of the Indo-Gangetic Plains, one would see northward extensions of the Precambrian orogenic (mountain) belts of the Indian shield[92,230,237]. These are prong-like ranges hidden under a thick pile of sediment — the hidden ranges of the Delhi–Sargodha–Kirana High, the Aravali–Haridwar Horst, the

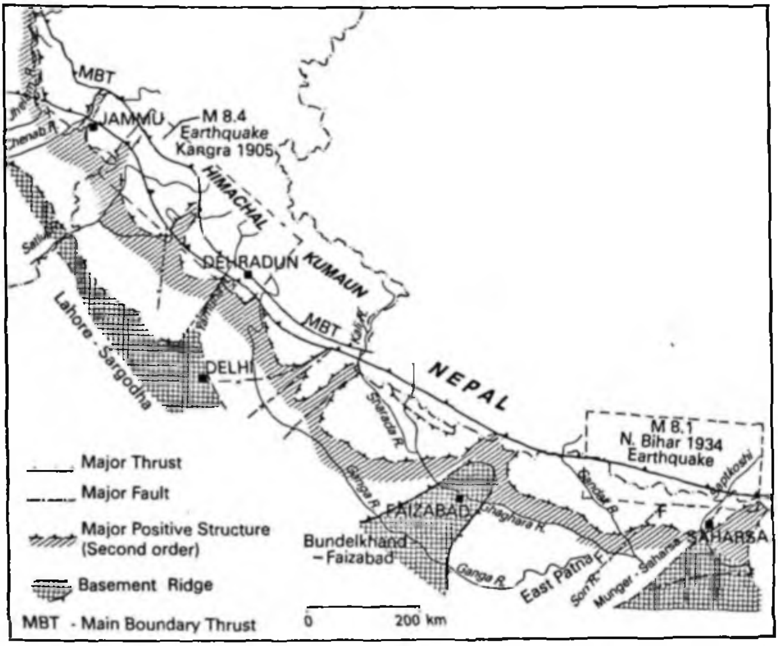


Fig. 8.3 *Beneath the cover of thick sediments there are many hidden ranges, representing the northerly extension of the orogens of the Indian shield (after V. Raiverman et al., 1983).*

Bundelkhand–Faizabad Ridge, the Satpura–Munger–Saharsa Horst and the Meghalaya–Mikir High (Fig. 8.3).

Tectonic movements affected accumulation of sediments in the Indo-Gangetic Basin from the very beginning, though the influence waned with the passage of time[201,202]. Beneath the ubiquitous succession of the Siwalik sedimentary rocks, the floor of the Indo-Gangetic Basin varies from sub-basin to sub-basin — gneisses and granites in the larger Panjab and western Uttar Pradesh (west of Faizabad Ridge), the Bijawar–Vindhyan succession in eastern U.P. and western Bihar, and the Bijawar–Gondwana sequence in eastern Bihar (Fig. 8.4).

8.7 Sedimentation in the Ganga Basin

Structurally yoked to the rising Himalaya, the Indo-Gangetic Basin progressively deepened as layer after layer of sediment was laid down by rivers draining the tectonically tormented mountains. The result of the combined process of floor subsidence and rapid voluminous sediment accumulation is the development of one of the largest fluvial deposits, forming the

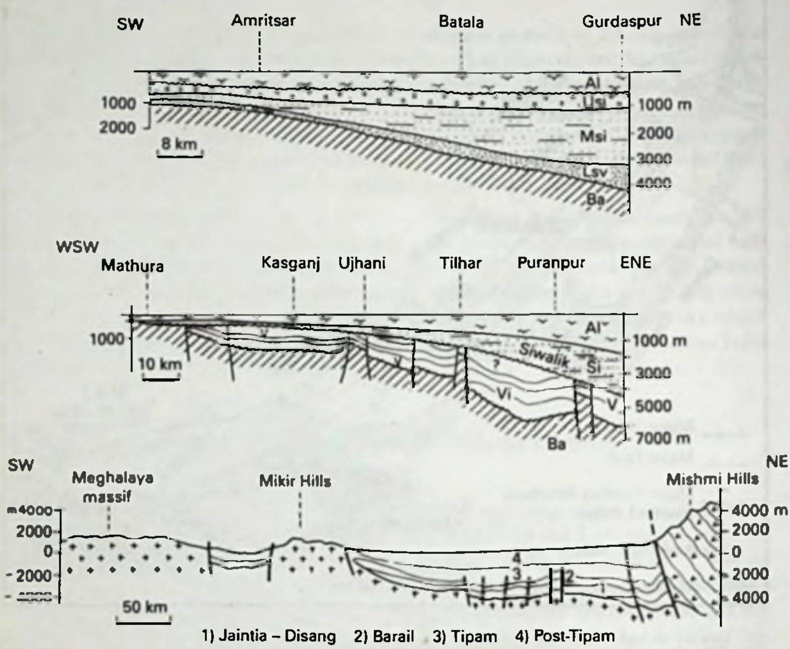


Fig. 8.4 *Cross sections of the Indo-Gangetic Basin showing the variable nature of the floor. Ba=Basement of Bundelkhand Granite; Vi = Vindhyan (Purāna) sediments; Lsi, Msi, Usi = Lower, Middle, Upper Siwalik; Al=Alluvial sediments (Quaternary). (First and second sections after R.K. Agrawal, 1977, third section after A. Ranga Rao, 1983.)*

great Indo-Gangetic Plains, now 30–300 m above sea-level (Fig. 8.2). The thickness of the sediments is less than 500 m in the south and increases progressively northwards to as much as 1500–2500 m in the Gorakhpur–Motihari tract in the proximity of the active HFF.

The Indo-Gangetic Basin was filled up transversely (Fig. 8.5) by rivers, forming a multitude of mega-alluvial cones and lobes[(190)]. The rapidly growing fans pushed the rivers Yamuna, Ganga and Brahmaputra to flow 200–300 km south of the mountain front. Increased influx of sediments made the deltas grow progressively seawards, encroaching upon the realm of the Indian Ocean (Figs. 7.10 and 8.2). S. Gartner's[(104)] analysis indicates that the rate of sediment accumulation in the Bengal Fan abruptly shot up from the earlier rate of 20–70 m per m.y. to 200m per m.y. about 800,000 years ago. Indeed, about 0.8 m.y. ago there was abrupt excessive influx of very coarse sediments implying sudden uplift of the Himalayan province[(85)]. This was then the time when the Indo-Gangetic Basin was filled maximally and intensively.

(A)

(B)

Plate 13(A) Ophiolitic melanges (o) north of Spongtang in Ladakh. (Photo by M.E. Brookfield)
(B) Sediment-filled depression occupied by the river Sindhu.

(A)

(B)

Plate 14(A) The holiest of the holy mountains of the world, Mount Kailas, is made up of conglomerates and pebbly felspathic sandstones deposited by rivers in the Palaeogene period 65 to 23 m.y. ago. (Photo by Anup Sah)

(B) Holy peak of Badarinath (Chaukhamba) in Garhwal is made up of bodies of 22–20 m.y. old granite formed by partial melting of the metamorphic rocks that build up the bulk of the Himādri. (Photo by K.S. Valdiya)


(A)


(B)


(C)


(D)

Plate 15 Siwalik animals which lived during the period 9.5 to 2.5 m.y. ago. **(A)** *Stegodon ganesa* **(B)** *Hexaprotodon sivalensis* **(C)** *Colossochelys atlas* **(D)** *Hipparion*.
(Photos by A.C. Nanda)

Plate 16 Plaster of Paris model of the primate *Sivapithecus*, believed to be in the ancestral line of the humans who lived 12 to 7 m.y. ago in the Siwalik terrain. (Photo by A.C. Nanda)

(A)

(B)

Plate 17(A) Three levels of terraces developed at the bends of Bhilangana river in Garhwal. (Photo by K.S. Valdiya)
(B) Naini Lake of southcentral Kumaun originated as a result of the movements on an active fault 50,000 to 40,000 years ago. (Photo by K.S. Valdiya)

Plate 18 The Indian landmass is pressing Asia very hard, and the Himalayan faults become active time and again. (Photo by K.S. Valdiya from a picture in a Japanese museum in Shimane Prefacture)

Plate 19 Himalayan ranges are rising in elevation as a result of movements on active faults. Kedarnath peak in Garhwal. (Photo by K.S. Valdiya)

(A)

(B)

Plate 20(A) The present-day gentle topography of geomorphic maturity of the Lesser Himalaya recalls the landscape that it might have been just before the beginning of the Quaternary period. Only the elevation was quite much less. (Photo by K.S. Valdiya)

(B) Relics of the past drainage that escaped major changes brought about by the Himalayan tectonic revolution. The meandering rivers in the anomalously wide valleys in the Lesser Kumaun Himalayan terrain of very mild relief indicate that in the beginning of the Quaternary period the terrain was mild with very gentle relief and slope. (Photo by K.S. Valdiya)

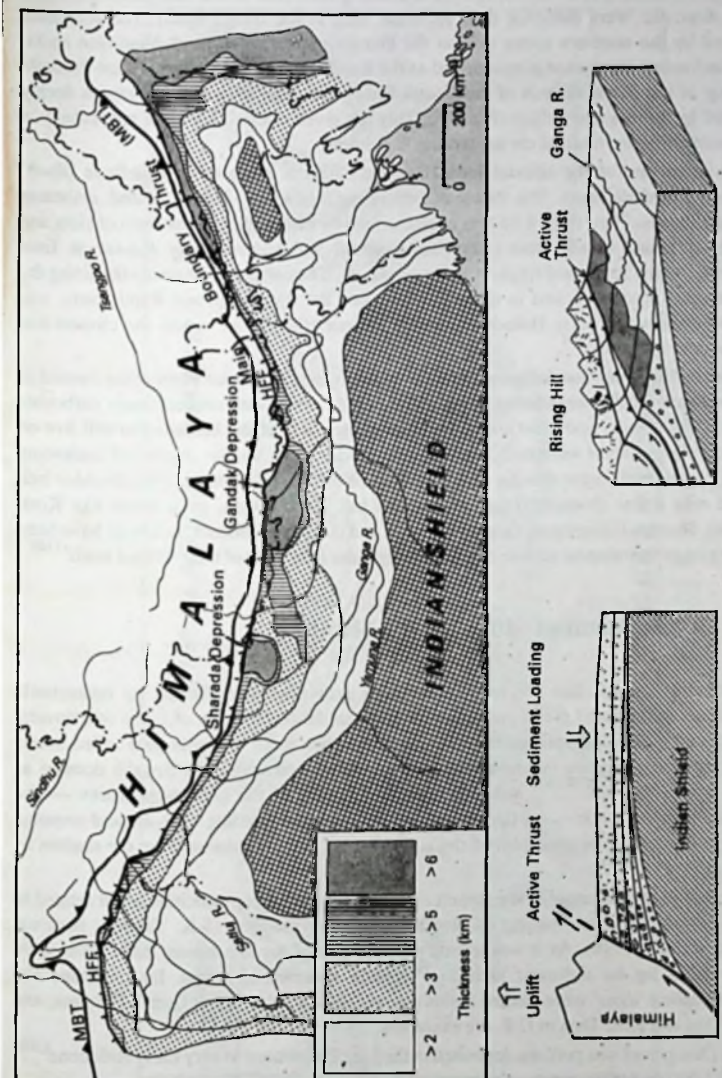


Fig. 8.5 *Sedimentation in the Ganga Basin is related to movement along active faults and the load of detritus. There is progressive thickening northwards (after D.W. Burbank, 1992).*

8.8 Indo-Gangetic Plains

Not only the Himalayan rivers but also those draining the Indian shield such as the Chambal, Betwa, Son, etc. were dumping their sediment load in the Ganga Basin. The sediments delivered by the southern rivers rest on the Precambrian Bundelkhand–Vindhyan rocks. These sediments form what is recognized as the Banda Plain[(48)] in southern Uttar Pradesh. Made up of the oldest deposit of the Ganga Basin, the undulating Banda Plain is deeply dissected by ravines and gullies (Fig. 8.6). This has given rise to a badland, particularly in the Chambal–Betwa tract where the terrane is uplifted.

The larger part of the alluvial Indo-Gangetic Plains is made up of interfluve (*doab*) highlands called *Bhangar*. The *Bhangar*, occupying a relatively higher ground, embraces the vast Varanasi Plain (Fig. 8.6). It is characterized by distribution in the form of clots and clusters of grains of abundant calcareous material and concretionary *Kankar* in finer sediments, which form sand ridges, sand mounds, etc. The calcareous material including the concretionary *Kankar*, found in the region between the Ramganga and Rapti rivers, was formed between the Early Holocene period to about 6000 yr BP when the climate had become cold and arid[(274)].

In the humid times that followed, terraces of the younger '*Khadar* plain' were formed in the floodways of the meandering rivers. Made up of clays with concretionary carbonate (*kankar*), the *Khadar* sediment contains entombed remains of the animals that still live on the land. A large part of western U.P. and Panjab is made up of *Khadar*. Aprons of coalescing fans of gravels and coarse detritus in the foothills of the Siwalik constitute the *Bhabhar* belt formed only a few thousand years ago. In the last 10,000 years, great rivers like Kosi, Gandaki, Sharada (Ghaghara), Ganga, Yamuna and the now vanished Saraswati have been building huge fan-shaped accumulations or megafans (Fig. 8.6) of their detrital loads[(168)]

8.9 Development of 'duns' in the Siwalik

The Siwalik domain, like the main Himalayan province, was affected by neotectonic movements in the last 1.6 m.y, which is reflected in the reactivation of faults and thrusts. Consequently, elongate uplifted ridges delimited on two sides by faults (and called horsts and elongate depressions or grabens of sorts) were formed within the Siwalik domain as shown by T. Nakata[(179,181)] and D.P. Rao [(209)]. Uplift of the faulted-up blocks — the so-called hanging walls — on the downstream side caused ponding of rivers and streams, and formation of lakes upstream of the active faults. This is evident from the studies of K.S. Valdiya[(318,319)].

Another plausible cause of the stream impoundment is pop-up anticlinal uplift related to ramps of thrust planes leading to reversal of stream gradient (S.K. Tandon, personal communication, 1996). As it was a time of rapid rise of the mountains, these lakes were swiftly filled up by sediment including sizeable volumes of gravel. Intermontane flat stretches called '*duns*' were formed in this manner (Fig. 8.7(a)). Pinjor Dun in Haryana, and Dehra Dun and Kota Dun in U.P. are examples.

The Dun gravel was perhaps deposited in the Late Pleistocene to very Early Holocene[(209)] about 22,000 to 7,000 yr. BP.

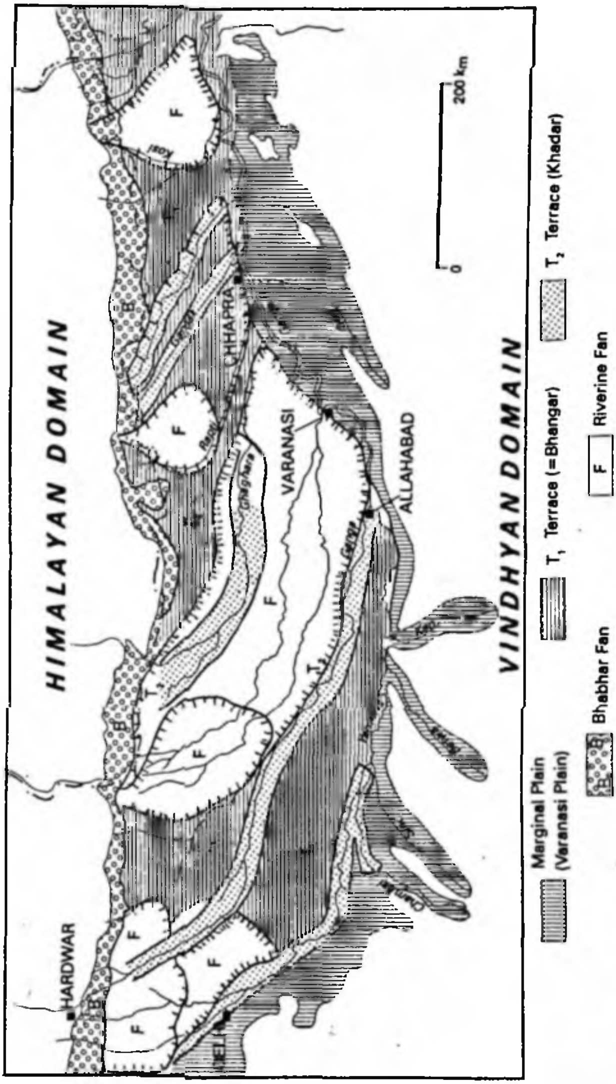


Fig. 8.6 Physiographic and lithostratigraphic units of the Ganga Plain (based on I.B. Singh, 1995).

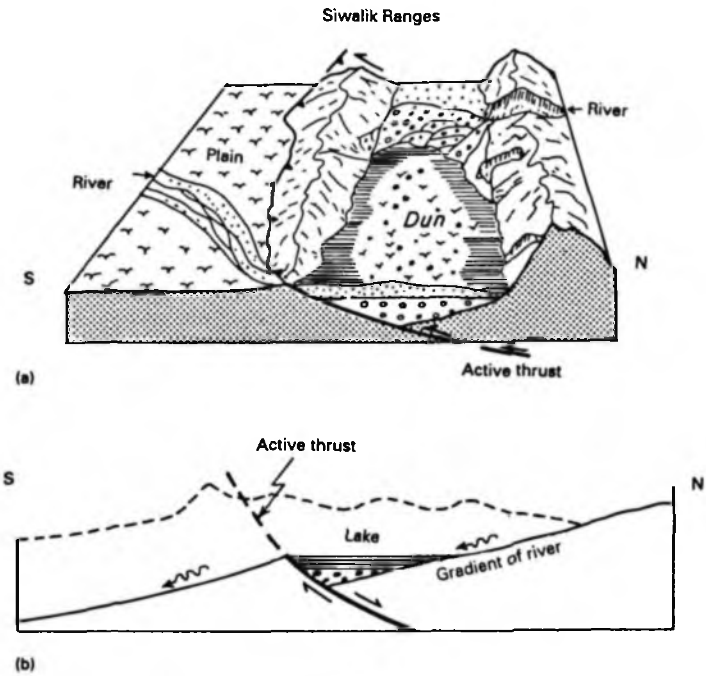


Fig. 8.7 *Development of the dun and palaeolake in the Siwalik domain as a result of reactivation of intra-basinal fault and thrust which caused ponding of the stream.*

8.10 Damming up of Himalayan rivers

The Himalayan river valleys are lined by paired and unpaired terraces throughout the Lesser Himalaya (Fig. 8.8 and Plates 17A). These terraces are the mainstay of agriculture in the Himalayan world. The paired terraces are the remnants of palaeolakes. The Lesser Himalayan rivers were evidently ponded in many places due to uplift in the downstream part of the block on the upper side of the fault plane when the faults were reactivated during the Pleistocene tectonic unrest (Fig 8.7(b)). The faulting and folding up of rocks must have caused decrease in river gradients and consequent slackening of flow and deposition of sediment. Formation of lakes in the fluvial regime of rivers was particularly common between the MBT and MCT. The lakes were soon filled up, and later drained out due to bursting of the natural dams, probably following violent revival of movements on the active faults. In the faulted mountains, the upper reaches of streams were also ponded and lakes formed up the mountain slopes, such as in the Nainital region in Kumaun. Since these streams

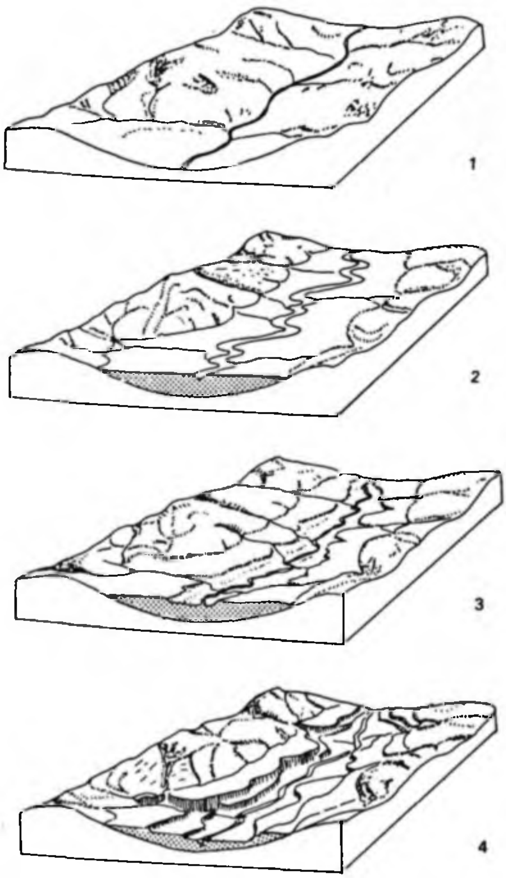


Fig. 8.8 *Pleistocene palaeolakes formed in the fluvial regime of Lesser Himalayan rivers are represented by paired terraces lining the wide valleys (after W.K. Hamblin, Earth's Dynamic Systems, MacMillan, New York, 647pp. (1992)).*

carried little or no sediment, the lakes persist (Plate 17B). Thermoluminiscence dating of the powdery pulverized material in the zone of fault (called gouges), done by A. Singhvi and associates[262], and dating of charcoal in the lake sediments carried out by G. Rajagopalan indicate that the Kumaun lakes were formed 50,000 to 40,000 years ago[142][262][324].

The Tethyan domain, north of the Trans-Himādri Fault, was also affected by Pleistocene movements, culminating in the formation of lakes in river valleys such as at Garbyang in Kumaun, Thakkhola in Nepal, and Toksar and Lamayuru in Ladakh. The Lamayuru palaeolake, for example, comprises 200 m of sediment deposited in the interval 35,000 years to 1,000 or 500 years BP[84]. Significantly, the lake sediments contain, among various remains of plants and animals, conspicuous rosettes of gypsum. This evaporite mineral which formed as a result of evaporation of shallow lake water is a pointer to a spell of warm arid conditions in a region which presently is a cold desert at a height above 4000 m. Charcoal, aggregating to 2.5 m in thickness in the sediments of lake Toksar, records frequent forest fires[20]. Similar forest fires occurred in the basins of the lakes and palaeolakes of Kumaun such as Naukuchiatal near Nainital[142], Hawalbagh near Almora and Wadda near Pithoragarh[324]. The forest fires in the Kumaun lake basins date back to between more than 45,000 to 3,000 years. Lightning possibly had set the forests on fire. Heavy rains that followed the forest fires washed down pieces of charcoal to the lakes below. Deposits of debris avalanches containing charcoal pieces in the Kumaun lakes seem to lend support to this assumption.

It is obvious that the Later Pleistocene period witnessed not only the establishment of monsoon climate but also experienced hot dry summers of forest fires and heavy downpours that caused debris avalanches and landslides during the rainy seasons. A situation very similar to that of the present time had developed by the close of the Pleistocene Age.

9 *Continuing Tectonic Unrest*

9.1 The squeeze

India continues to drift northward at the rate of a little more than 56 ± 4 mm/yr. The Himalaya is being continually pressed, rather squeezed by a clash between the Indian continent and mainland Asia (Plate 18). It is therefore in a strongly stressed state. Strain is building up where rock piles are moving over one another or sliding past one another in the zones of under-thrusting and over-riding nappes, and in the shear zones of faults. Some of the faults are oriented transverse to the mountain trend. The build-up of strains is manifest in the movements that have taken place or are taking place on the many east–west faults in Tibet as well as on the multiplicity of faults and thrusts in the Himalayan province itself.

In Tibet, diverse crustal blocks as pointed out by P. Molnar[170] are being pushed out of the way of India and Asia. Up-and-down movements in the direction of dips and sideways sliding of crustal blocks in the direction of strikes on the boundary thrusts are taking place within the Himalayan province. This is evident from the deformation, displacement and tearing apart of geomorphic features that were formed by rivers and glaciers and formed by landslides and within lakes in the last 1.6 m.y. or less[318][319]. Continuing movements on active faults is further obvious from the intimate association of faults and earthquake epicentres (Fig. 2.8), and from the increasing heights of the Himalayan ranges, particularly in the Himādri terrane (Plate 19). According to A. Gansser[102], the Himalaya rose more than 3000 to 4000 m in the last 1.6 m.y. of the Quaternary period. Going by the sudden excessive delivery of sediments to the Indian Ocean about 0.9 m.y. ago[234] resulting from abrupt acceleration of erosion, one is inclined to believe that the Himalaya registered a very rapid rise in the last 900,000 to 800,000 years.

9.2 Reactivation of faults

Movements in the last 1.6 m.y. along the HFF, MBT, MCT, T-HF (Fig. 9.1) and hundreds of other thrusts and faults in the four geological terranes have not only made the Himalaya the world's highest mountain, but also rendered its land extremely rugged and difficult. The pilgrim route along the Ganga from Haridwar to Badarinath and the highway connecting Haldwani with Munsiari in Kumaun provide clear exposures of the active faults. Through millennia of unrelenting denudation, the Lesser Himalaya had been practically peneplaned — flattened to undulating plains — even as the rivers and streams flowed sluggishly and meandered locally in their wide valleys filled with sediments at bends (Plate 20A). The very gentle (less than 6°) hill slopes of the undulating landscape and terraces were covered with a thick carpet of soil — the products of protracted weathering under tectonically stable

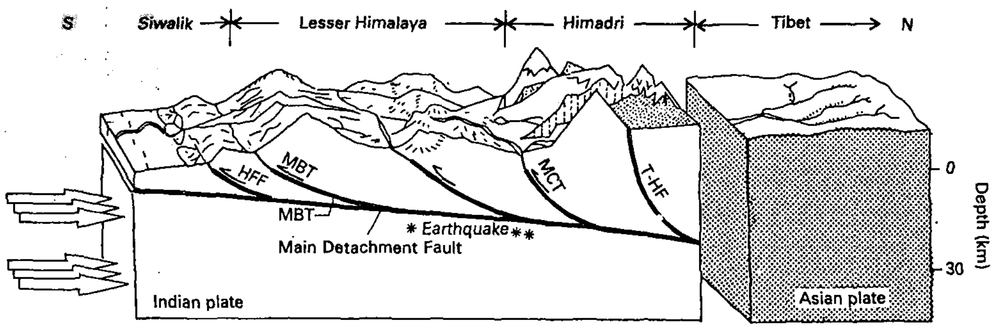


Fig. 9.1 *Movements have been taking place time and again on the terrane-bounding thrusts (MCT, MBT, HFF) ever since they were formed. Stronger, longer and repeated movements in zones of the MCT and MBT have given greater height and ruggedness to, respectively, the Himādri and Outer Lesser Himalayan Ranges. Hypocentres of earthquakes (foci), located close to the Detachment Fault deep down, testify to the faults being active even at the present time (modified after M. Jackson and R. Bilham, 1994) [HFF = Himalayan Frontal Fault, MBT = Main Boundary Thrust, MCT = Main Central Thrust, T-HF = Trans-Himādri Fault].*

conditions. All these features indicate that the terrane had already attained a stage of geomorphic maturity when the streams had a profile of equilibrium, and lateral erosion predominated down-cutting. The uplift of this terrane initiated and renewed the cycle of geomorphic sculpturing (Plate 20B). Since the movements were stronger, longer and more frequent in the zones of the MCT and MBT, the overlying Himadri and the Outer Lesser Himalaya belt grew taller and became more rugged, respectively (Fig. 9.1).

In the southern belt of Kumaun, the Siwalik front abruptly rises 60–90 m above the plains of the Ganga Basin. The Holocene riverine lobes and fans of rock fragments, accumulated at the hill base (which rest on the Late Pleistocene Dun Gravel), are tilted 6 to 15° northwards. They are gently folded in some places (Fig. 9.2(a)) adjacent to the reactivated HFF, along which sediments were lifted up forcibly[(181)(312)(319)]. In the valley of the river Kosi in Kumaun, the tilted gravel is overlain by fluvial terraces at three successively higher levels (Fig. 9.2(b)), implying that after the tilting of the Dun Gravel, at least three spurts of uplift occurred in the last nearly 11,000 years of the Holocene[(319)]. The oldest terrace, 67 m above the bed of the Ramganga at Kalagarh in southeastern Garhwal (Fig. 9.2(c)), has yielded pieces of pottery of the historical Kushan period, dating back to the second to fourth century AD. The pottery factory, then located at the river bed, has been lifted up 67 m in the last 1800 to 1600 years[(319)].

Movements on active faults and related folding of rocks, which caused a decrease in stream gradients and a consequent decrease in their velocity within the Siwalik terrane, blocked or slackened the flow of rivers and streams, giving rise to ponds (Fig. 9.3) and swamps such as are seen in the foothill belt of Darjiling–Siliguri–Bhutan[(179)(181)] or in the lakes now filled up completely with sediments as seen in the Ramganga and Kosi valleys in the Corbett National Park (Fig. 8.7). This process has given rise to what could be described as *Neoduns*. An example is the Dhikala area within the Jim Corbett National Park. Geodetic measurements confirm the continuing uplift of the Dehradun Valley in southwestern Kumaun at the rate of 1 mm/yr with respect to the Saharanpur plains[(203)] as a consequence of continuing growth and rise of the Mohand anticline related to the active HFF[(346)].

The MBT is possibly the most active of all the active faults in the Himalaya. In the Darjiling foothills, recent movements on the MBT have brought Precambrian rocks of the Lesser Himalaya nearly 15–20 km south upon the more recent alluvial plain through gaps in the Siwalik Range[(116)] near Siliguri in northern Bengal. In the Ladhiya Valley on the Nepal–India border, recent river gravel perched atop the Lower Siwalik is crushed under Precambrian rocks brought by movements on the MBT (Fig. 9.4(a)). Southeast of Nainital in the Balia Valley (near Nainital), sub-recent fluvial terraces (Fig. 9.4(b)) and comparatively younger landslide debris cones have been cut and lifted up 30–40 m as a result of movements on the MBT[(312)(318)(319)(323)].

9.3 Uplift and landform changes

The once mature terrain of the Lesser Himalaya was geomorphically rejuvenated during the Pleistocene. The three levels of terraces lining all rivers imply three spurts of uplift in this epoch. Where active faults cross these rivers, many more than three levels of terraces can be seen. For example, in the region of the Tehri Dam in Garhwal, six levels of terraces are developed in the Bhagirathi Valley in the stretch where the active Shrinagar Thrust crosses

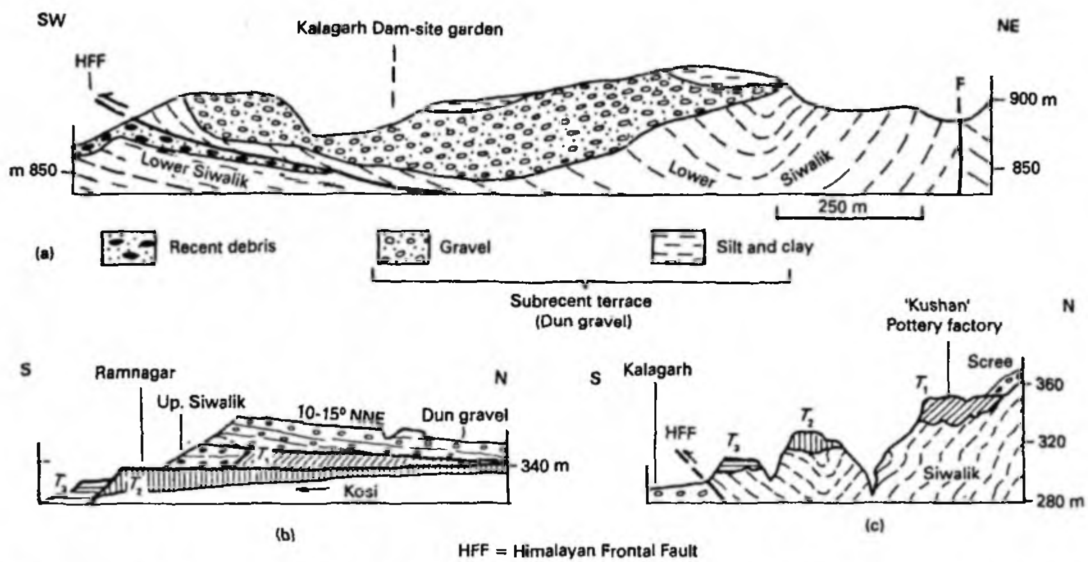


Fig. 9.2 *Evidence of deformation and uplift on the Himalaya Frontal Fault (HFF) in the last 11,000 years of the Quaternary — tilting and uplift of recent sediments (K.S. Valdiya, 1993).*

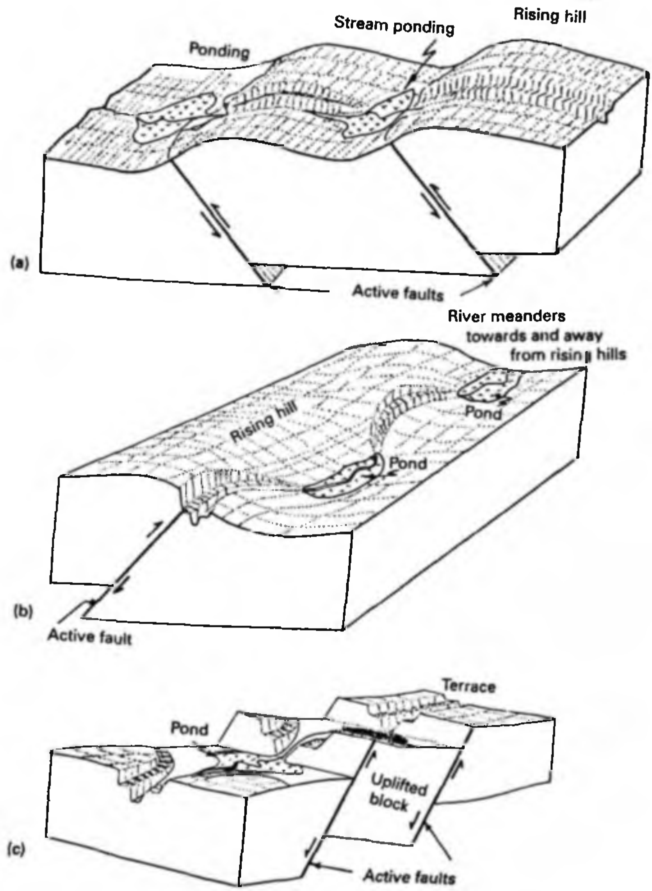


Fig. 9.3 *Formation of lakes due to subsidence or uplift of faulted blocks that caused ponding of streams (after G. King et al., 1994).*

the valley immediately after the narrow gorge in the zone of active faulting. This fact implies three more spurts of uplift in the last 11000 years of the Holocene after the earlier three episodes in the Pleistocene[319].

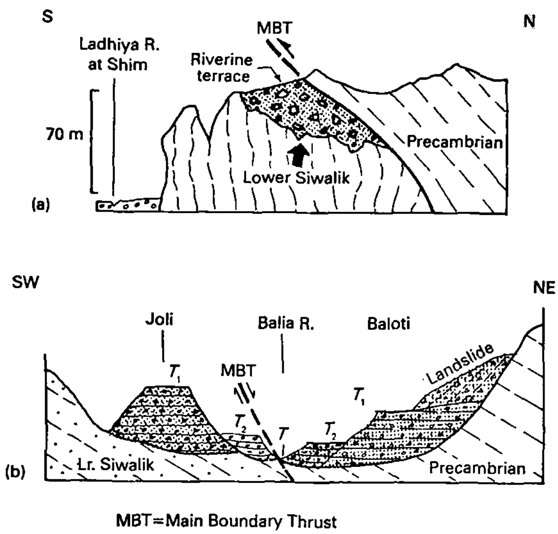


Fig. 9.4 *(a) Recent movements have lifted up river gravel and crushed it under the Precambrian rocks which rode on the Main Boundary Thrust (MBT) in the Ladhiya valley. (b) Fluvial terraces of two ages — the older one (T_1) having been uplifted more than the younger one (T_2) on the MBT during successive reactivation in the Balia Valley near Nainital.*

The extent of uplift varies from region to region and belt to belt. The faulted blocks rose up more rapidly, particularly where there is intersection of longitudinal and transverse faults[308][315]. The NW–SE trending Barigad Fault in northwestern Nepal, for example, registers a strike-slip movement at the rate of 12 mm/yr[180]. The faulted Pir Panjal rose up at the rate of 3.5 – 10 mm/yr during the long period of the Karewa sedimentation[60].

The faulting up of the Karewa Lake sediments on the northern flank of the Pir Panjal (Fig. 7.20) has given rise to mountain-slope terraces called '*Marg*' — as Gulmarg, Khillanmarg, Sonmarg, etc.[43]. Stone-Age man was a witness to this uplift of the lake terraces and the evolution of the *Margs* [222].

The maximum rate of uplift of the Lesser Kumaun Himalaya deduced by revelling is 5 mm/yr[203]. According to K. Arita[11] it is 3–7 mm/yr in Nepal if the interval between the latest Pliocene and Holocene is considered, but much faster (12 mm/yr) if only the last 600,000 years are taken into consideration. Spirit-level data of the period 1977–1990 from the central sector of Nepal[124] indicates the current rate of uplift in the Himadri domain at 7 ± 2 mm/yr (maximum) and of the outer Lesser Himalaya in the order of 2–3 mm/yr (Fig. 9.5).

Evidently the Himadri has risen up at a much faster rate. The movements have been recurrent and prolonged. This explains its great and increasing height and awesome ruggedness. The Nanga Parbat rose at the rate 5.5 mm/yr in the Neogene period [298]. Movements on the north–south trending Raikot Fault (Figs. 7.4 and 7.20) folded the 50,000

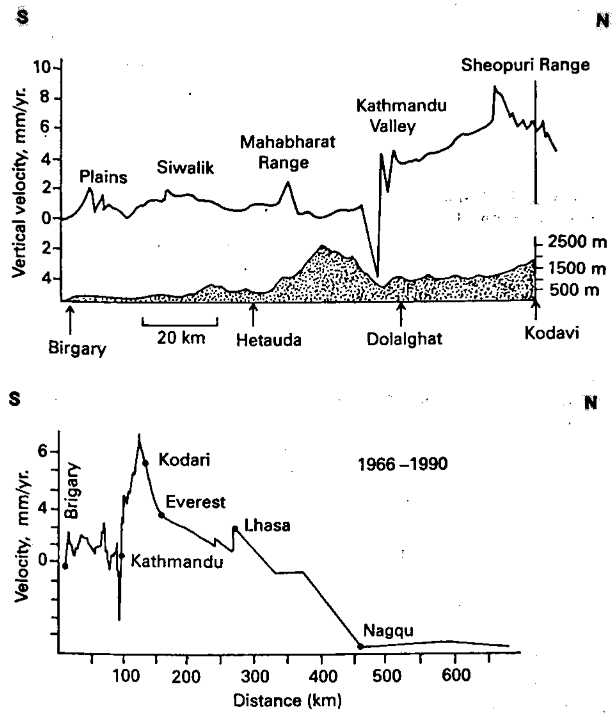


Fig. 9.5 *Spirit-level data of the period 1977–1990 from the central sector of Nepal shows uplift rate of the Great Himalaya to be a little less than 8 mm/yr (7 ± 2 mm/yr) (M. Jackson and R. Bilham, 1994).*

year old fluvioglacial deposits in the Sindhu Valley and offset its course by atleast 15 km, thus bringing Precambrian metamorphic rocks upon the recent river gravel(255). Deformation of recent lake sediments at Takula in the Tons Valley in northwest Garhwal(9), the 34–103 m uplift of fluvial deposits coupled with drainage deflections in the Loharkhet area in northern Kumaun(188), and the uplift of young glacial features like cirque, moraines and talus cones of rock fragments at the base of the Dhaulagiri in northwest Nepal(223) bear testimony to strong neotectonic activity in the MCT zone. The Barigad Fault of the MCT zone in northwest Nepal has registered horizontal movements at the rate of 12mm/yr(180). Recent and recurrent movements in the Tethyan terrane are testified by characteristic seismites — sedimentary features which developed in the lake, and river bed sediments due to violent shaking of the ground. This is seen in the Sumdo–Kaurik belt in the Spiti region which has been repeatedly rocked by earthquakes including the one of magnitude 6.8 that occurred on January 19, 1975(169).

9.4 Appearance of Man

The climatic conditions ameliorated after the end of the Pleistocene glaciation. Beautiful, bountiful and verdant as the Himalayan province then was, Early Man was naturally attracted to come and settle down in its luxuriously vegetated valleys. He came from the accessible plains of Potwar, Panjab and Rajasthan where Stone-Age people had their flourishing colonies (Fig. 9.6).

The testimony of spores and pollen grains entombed in the sediments of the Lunkaransar and Didwana lakes in western Rajasthan indicates that there was a wet spell between 10,800 and 3,500 years before present (BP) (Fig. 9.7). The later 5000 to 3500 years BP period was a time of very heavy rainfall — three times higher than that of the present period[(58)]. Southern Tibet likewise experienced warm and moist climate from 7500 to 3000 years BP[(88)]. These periods of heavy rainfall must have made Rajasthan and Tibet lush green, and rich in food and other resources.

One of the places in the Himalayan province which Stone-Age people found most attractive and suitable for settlement was the flat stretch of the Karewa Lake terraces nestling between the Zanskar and Pir Panjal ranges. This is borne out from the archaic human relics, including stone artefacts, burnt bones of animals and pieces of charcoal. The Karewa Lake sediments forming terraces are covered by a mantle of wind-borne sediments known as loess. On this loess mantle, the Neolithic people established settlments at Pampur, Sambur, Burzahom, Gufkal, etc. in the Kashmir Valley [(5,76,222)]. They lived in oval shaped pits wide at the top (Fig. 9.8) with some sort of wooden superstructure overhead. They buried their dead in a crouching position along with their pet animals using ash, lime and potshard.

Location of characteristic habitats with stone artefacts, ritualistic funerary remains and stone hearths in far-flung and presently at forbiddingly high (1600 to 3900 m) places in the Himalaya suggest that the mountain domain was extensively populated (Fig. 9.6) by Palaeolithic, Mesolithic and Neolithic people. Gaik, Kiari, Khalsi, Pashkyun and Kargil in Ladakh[(185,327)], the Karewa Lake in Kashmir, Lahaul in northern Himachal, the valleys of Chenab, Beas, Ravi, Tarnah, Ban, Sirsa, Soan and Ghaggar in the Siwalik belt of Jammu–Himachal[(109)], Ranihat in the Alaknanda (Ganga) Valley, Kimin and Gwaldam in the Pindar Valley, Malari in the upper reaches of the Dhauli Ganga[(182)], Baijnath in the Gomati Valley, Dalband and Lakhudyar in the Suyal Valley, Devidhura in the Ramganga Valley[(133)] and Patu in southwestern Nepal[(70)] — all these places reveal tell-tale evidence of settlements by Stone-Age people. Their artefacts were made out of the rocks available locally. However, the style of making them, and the designs of the products are uncannily similar all over. This implies interaction among the people living in distant and different places.

Charcoal pieces recovered from stone hearths along with unburnt wood and animal bones at Gaik in the Sindhu Valley (Ladakh) are 6710 ± 130 years old[(252)]. Even if the bones and charcoal pieces were to be attributed to brief forays of intrepid adventurers in the wilderness, one cannot explain away the design of dwelling pits and the singularly unique burial modes with their funerery relics, clay balls and stone hearths, almost similar all over these places, without interpreting them as indicators of settlements. It is possible that these were seasonal camps of the nomads. But then the sites were repeatedly and successively occupied. It seems that the the region embracing Ladakh and Tibet was a much frequented terrain. This could not have been possible unless the region was easily accessible through negotiable paths.

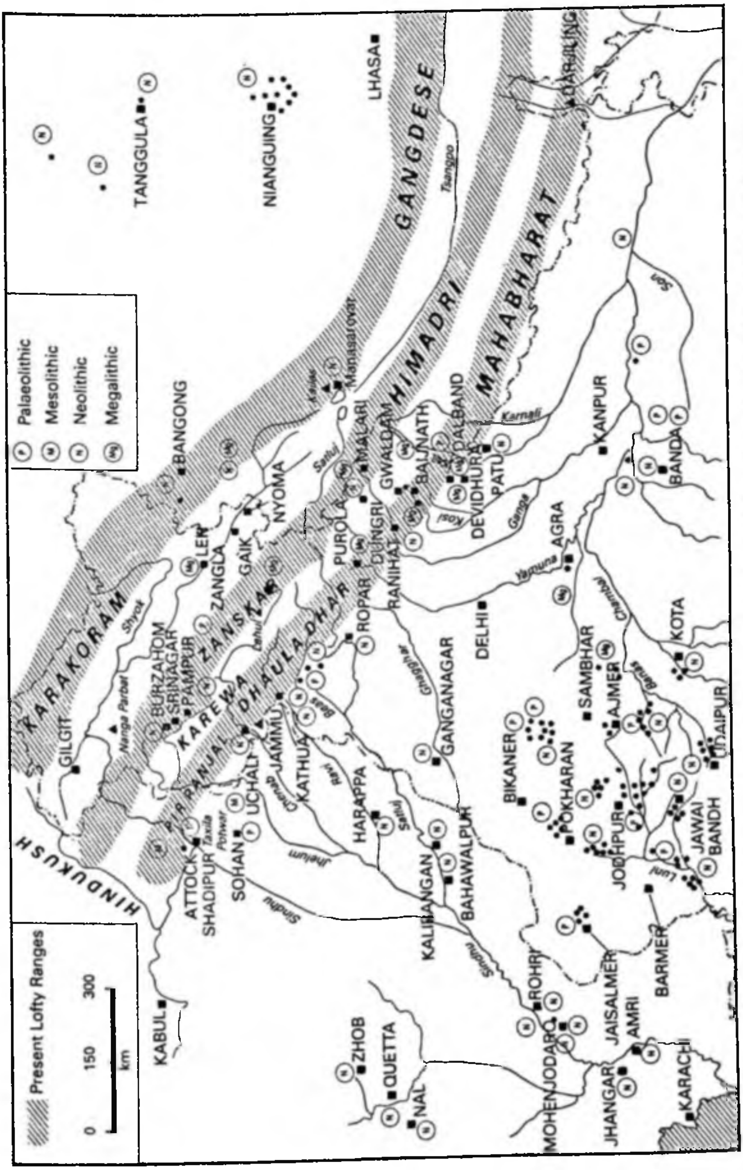


Fig. 9.6 Sites of settlements of Stone-Age people in the Himalayan province and neighbouring regions. Solid circles indicate settlements.

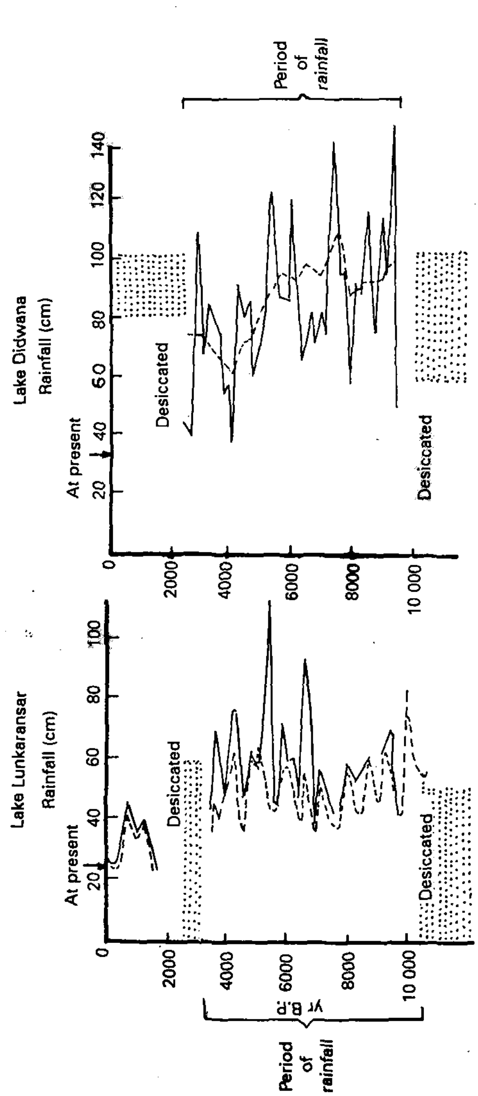


Fig. 9.7 *By the Mid Holocene time, the climate of the land embodying western Rajasthan and Tibet had become very congenial, due to higher rainfall (after Bryson and Swaine, 1981).*

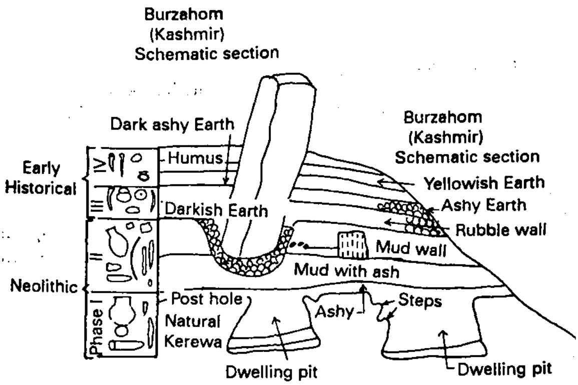


Fig. 9.8 *Stone-Age people in the Karewa terraces lived in pits with superstructure of wood overhead (after D.P. Agrawal et al, 1989).*

It seems that the Stone-Age primitives — who had no skill in building bridges across rivers, no knack of mountaineering and had no compulsion for moving out beyond their hunting range — freely moved in the Himalayan province (Fig. 9.6) and had easy contact and socio-cultural intercourse with their contemporaries in Tajikistan, China and Tibet in the north, Dardistan and Potwar in the west, and Panjab, Rajasthan and Gujarat in the south. It is obvious that there were no effective barriers to the inter-migration of Stone-Age people(222)(319). To put it differently, the mountain ranges were not as high or as difficult and formidable as they are today. At the time when the green expanses of the Indo-Gangetic Plains with their congenial climate and flat stretches of fertile lands with abundant water, vegetal and animal resources were available for settlement and reclamation, it is unthinkable that the primitive people chose to settle down in mountainous places where the climate was cold and harsh and the terrain extremely difficult. It seems more likely that when the nomads of the Stone Age established their settlements in the Himalayan province, its topography was invitingly gentle, the relief quite moderate and the climate very congenial(319). It was only after they had established themselves comfortably in the Himalayan domain that it rose up rapidly. Subsequently, mountain barriers evolved and isolated the Himalayan people from their contemporaries elsewhere.

Thus the high Himalaya — *Nagādhirāj* — that we see today appears to have been the result of very recent tectonic development.

9.5 'Future Shocks'

The northward movement or push of the Indian plate continues with the Indian shield pushing the Himalaya persistently and strongly. This movement is being converted into elastic strain, which is stored progressively in the rocks of the zones of active faults, particularly the MBT. A segment of the crust must have ruptured repeatedly during earlier great earthquakes. However at present, despite continued strain build-up, the segment between the Satluj and Kosi rivers has so far not been ruptured by great earthquakes. Indeed, great earthquakes alone can adequately release the enormous strain energy that has accumulated in the last few hundred years. Four times in this period (Fig. 9.9), the Himalayan arc has been ruptured by great earthquakes, of magnitude above 8.0—in 1897 in northern Meghalaya (M 8.7), in 1905 in Kangra (M 8.4), in 1934 in southcentral Nepal (M 8.1) and in 1950 in northeastern Arunachal Pradesh (M 8.7). Quite large parts of the very active MBT have remained locked or stuck for the last few hundred years. R. Bilham's[47] analysis of the seismicity condition demonstrates that no great earthquake has occurred within the long central sector since the Kathmandu earthquake of AD 1255. The devastating earthquake of 1833 in central Nepal (of magnitude $7.5 < M < 7.9$) occurred close to the rupture of the 1934 earthquake of magnitude M 8.1.

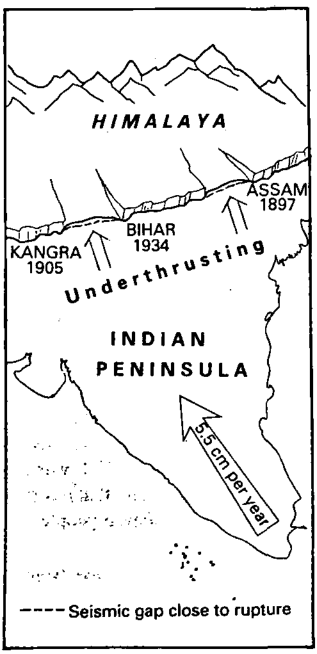


Fig. 9.9 *Four great slips and earthquakes that have ruptured the Himalayan plate boundary over the past 100 years, leaving three seismic gaps between them that may be already close to rupturing (V.K. Gaur, 1993).*

In Garhwal in the central sector, the seismicity condition is not much different from that prevailing in southcentral Nepal. Faults have been found to be quiet active. Levelling along the Saharanpur–Mussoorie line done in this century shows that strain is building up continually in the Siwalik of the Dehradun sector. Quite an appreciable part of the estimated convergence is causing accumulation of recoverable elastic strain in the upper crust. Significantly, minor or moderate earthquakes are not occurring regularly or periodically as one would expect in such an extraordinarily stressed belt.

Unlocking of the active faults accompanied by sudden release of the stored strain energy will certainly shake the region violently — and destructively — once that happens. One does not know when this unlocking will take place, but happen it will certainly someday in the future.

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Glossary

[Extracted largely from **Earth's Dynamic Systems** (Sixth Edition) by W. Kenneth Hamblin, (Macmillan, New York, 647 pp., 1992) with additions from other sources]

Alluvial fan A fan-shaped deposit of sediment, built by a stream where it emerges from an upland or a mountain range into a broad valley or plain (Fig. G-1). Alluvial fans are common in arid and semi-arid climates but are not restricted to them.

Ammonite An invertebrate marine animal characterized by a thick strongly ornamented shell with a suture — the line of junction of the septum or partition — having finely divided lobes and saddles. *Range*: Jurassic to Cretaceous.

Amphibole An important rock-forming mineral group of ferromagnesian silicates. Amphibole crystals are constructed from double chains of silicon–oxygen tetrahedra. *Example*: hornblende.

Amphibolite A metamorphic rock consisting mostly of amphlibole and plagioclase felspar.

Andesite A fine-grained igneous rock composed mostly of plagioclase feldspar and 25 to 40% amphibole and biotite, but no quartz or potash felspar. It is abundant in mountains bordering the Pacific Ocean, such as the Andes Mountains of South America, from which the name was derived. Andesitic magma is believed to originate from fractionation of partially melted basalt.

Angular unconformity An unconformity in which the older strata dip at a different angle (generally steeper) than the younger strata (Fig. G-2).

Annelid A worm-like invertebrate characterized by a segmented body with a distinct head and appendage.

Anticline A fold in which the limbs dip away from the axis. After erosion, the oldest rocks are exposed in the central core of the fold (Fig. G-3).

Arkose A sandstone containing at least 25% feldspar.

Ash Volcanic fragments of the size of dust particles.

Asthenosphere The zone in the Earth directly below the lithosphere, from 70 to 200 km below the surface, where seismic velocities are distinctly lower. It is therefore believed to be soft and yielding to plastic flow.

Axial plane With reference to folds, an imaginary plane that intersects the crest or trough of a fold so as to divide the fold as symmetrically as possible (Fig. G-4).

Badlands An area nearly devoid of vegetation and dissected by stream erosion into an intricate system of closely spaced, narrow ravines.

Basalt A dark-coloured, fine-grained igneous rock composed of plagioclase (over 50%) and pyroxene. Olivine may or may not be present. Basalt and andesite represent 98% of all volcanic rocks.

Base-level The level below which a stream cannot effectively erode. Sea-level is the ultimate base level, but lakes form temporary base-levels for inland drainage systems.

Basement complex A series of igneous and metamorphic rocks lying beneath the oldest stratified rocks of a region (Fig. G-5). In shields, the basement complex is exposed over large areas.

Batholith A large body of intrusive igneous rocks exposed over an area of at least 100 square km (Fig. G-6).

Biomass Amount of vegetation such as roots, trunks, branches, twigs, leaves, etc. in a particular area.

Biotite 'Black mica'. An important rock-forming ferromagnesian silicate with silicon–oxygen tetrahedra arranged in sheets.

Block faulting A type of normal faulting in which segments of the crust are broken and displaced to different elevations and orientations.

Blueschist A fine-grained schistose rock characterized by high-pressure, low-temperature mineral assemblages, and typically blue in colour.

Boulder A rock fragment with a diameter of more than 256 mm (about the size of a volleyball). A boulder is one size larger than a cobble.

Brachiopod A solitary marine invertebrate characterized by a circular or horse-shoe shaped feeding organ around the mouth and two bilaterally symmetrical valves. *Range*: Early Cambrian to Present.

Braided stream A stream with a complex of converging and diverging channels separated by bars or islands. Braided streams form in places where more sediment is available than can be removed by the discharge of the stream.

Breccia A general term for sediment consisting of angular fragments set in a matrix of finer particles. *Examples*: Sedimentary breccias, volcanic breccias, fault breccias,impact breccias.

Bryozoan An invertebrate animal characterized by chiefly colonial growth of calcareous skeleton. *Range*: Ordovician to Present.

Calcite A mineral composed of calcium carbonate ($CaCO_3$).

Carbonaceous Containing carbon.

Carbonate rock A rock composed mostly of carbonate minerals such as limestone and dolomite.

Cascade A series of small falls descending over a steep slope — a shortened rapid, or closely spaced waterfalls in a stepped series.

Cenozoic An era stretching from a time 65.5 m.y. ago to the present embraces the Teritiary (65.5 to 1.6 m.y. ago) and the Quaternary (1.6 m.y. to present) periods.

Cephalopod A marine mollusk characterized by definite head with a mouth surrounded by part of the foot that is modified into lobe-like precesses.

Chert A sedimentary rock composed of granular cryptocrystalline silica.

Clastic (1) Pertaining to fragments (such as mud, sand, and gravel) produced by the mechanical breakdown of rocks. (2) A sedimentary rock composed chiefly of consolidated clastic material.

Clay Sedimentary material composed of fragments with a diameter of less than 1/256 mm. Clay particles are smaller than silt particles.

Cleavage The tendency of a mineral to break in a preferred direction along smooth planes.

Cobble A rock fragment with a diameter between 64 mm (about the size of a tennis ball) and 256 mm (about the size of a volleyball). Cobbles are larger than pebbles but smaller than boulders.

Compression A system of stresses that tends to reduce the volume of or shorten a substance.

Concretion A spherical or ellipsoidal nodule formed by chemical accumulation of mineral matter after deposition of sediments.

Conglomerate A coarse-grained sedimentary rock composed of rounded fragments of pebbles, cobbles or boulders, set in the matrix of finer material.

Contact metamorphism Metamorphism of a rock near its point of contact with hot magma.

Continental drift The theory that the continents have moved in relation to one another.

Continental margin The zone of transition from a continental mass to the adjacent ocean basin. It generally includes a continental shelf, continental slope and continental rise.

Continental shelf The submerged margin of a continental mass extending from the shore to the first prominent break in slope, which usually occurs at a depth of about 120 m.

Continental slope The slope that extends from a continental shelf down to the ocean deep.

Convergent plate boundary The zone where the leading edges of converging plates meet. Convergent plate boundaries are sites of considerable geological activity and are characterized by volcanism, earthquakes and crustal deformation. See also ***Subduction zone***.

Craton The stable continental crust, including the shield and stable platform areas, most of which have not been affected by significant tectonic activity since the close of the Precambrian era.

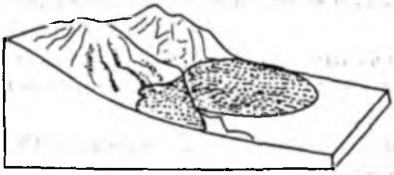
Cross-bedding Stratification inclined to the original horizontal surface upon which the sediment accumulated. It is produced by deposition on the slope of a dune or sand-wave (Fig. G-8).

Crust The outermost layer or shell of the Earth. It is generally defined as the part of the Earth above the Mohorovicic discontinuity. It represents less than 1% of the Earth's total volume (Fig. G-9).

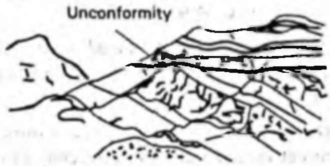
Crustal warping Gentle bending (upwarping or downwarping) of sedimentary strata.

Debris flow The rapid downslope movement of debris (rock, soil and mud).

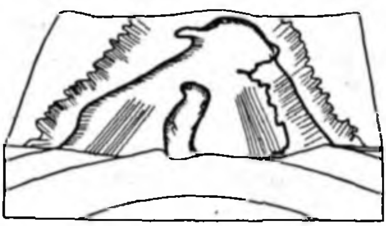
Deciduous A plant that sheds its leaves annually or regularly within a year of their production.



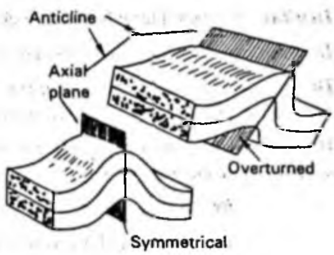
G-1 Alluvial fan



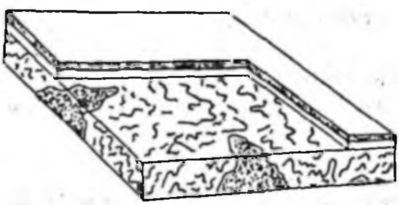
G-2 Angular unconformity



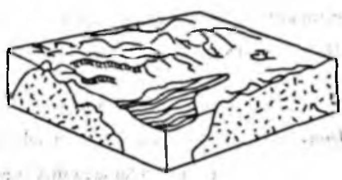
G-3 Anticline



G-4 Axial plane

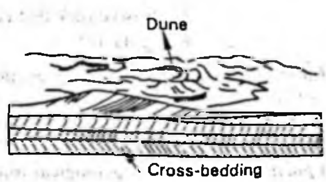


G-5 Basement complex



G-6 Batholith

G-7 Crater



G-8 Cross-bedding

Delta A large, roughly triangular body of sediment deposited at the mouth of a river. Figure G-10 shows a delta.

Denudation The combined action of all of the various processes that cause the wearing away and lowering of the land, including weathering, mass wasting, stream action and groundwater activity.

Deranged drainage A distinctly disordered drainage pattern formed in areas affected by recent movements or in a recently glaciated area. Irregular direction of flow, few short tributaries, swampy areas and many lakes (Fig. G-11).

Desiccation The process of drying out. With reference to sedimentation, the loss of water from pore spaces by evaporation or compaction.

Detrital (1) Pertaining to detritus. (2) A sedimentary rock formed from detritus.

Detritus A general term for loose rock fragments produced by mechanical weathering.

Diastrophism Large-scale deformation involving mountain building and metamorphism.

Diorite A medium-grained intrusive igneous rock consisting mostly of intermediate plagioclase feldspar and pyroxene, with some amphibole and biotite.

Discharge Rate of flow; the volume of water moving through a given cross section of a stream in a given unit of time.

Disconformity An unconformity in which beds above and below are parallel.

Dissolved load The part of a stream's load that is carried in solution.

Divergent plate boundary A plate margin formed where the lithosphere splits into plates that drift apart from one another. Divergent plate boundaries are areas subject to tension, where new crust is generated by igneous activity. Synonymous with *spreading centre*.

Dolomite (1) A mineral composed of $CaMg(CO_3)_2$. (2) A sedimentary rock composed primarily of the mineral dolomite.

Dome (1) (Structural geology) An uplift that is circular or elliptical in map view, with beds dipping away in all directions from a central area (Fig. G-12). (2) (Topography) A general term for any dome-shaped landform.

Downwarp A downward bend or subsidence of a part of the Earth's crust.

Drainage basin The total area that contributes water to a single drainage system. Figure G-13 shows a drainage basin.

Drainage system An integrated system of tributaries and a trunk stream which collect and funnel surface water to the sea, a lake or some other body of water.

Dyke A tabular intrusive rock that occurs across strata or other structural features of the surrounding rock (Fig. G-14).

Entrenched meander A meander cut into the underlying rock as a result of regional uplift or lowering of the regional base-level (Fig. G-15).

Epicentre The area on the Earth's surface that lies directly above the focus of an earthquake.

Epoch A division of geological time; a subdivision of a period. *Example*: Pleistocene epoch.

Erosion The processes that loosen sediment and move it from one place to another on the Earth's surface. Agents of erosion include water, ice, wind and gravity.

Escarpment A cliff or very steep slope. Scarp.

Evaporite A rock composed of minerals derived from evaporation of mineralized water. *Examples*: rock salt, gypsum.

Extrusive rock A rock formed from a mass of magma that flowed out on the surface of the Earth. *Example*: basalt.

Fan A fan-shaped deposit of sediment. *Examples*: *alluvial fan, deep-sea fan.*

Fault A surface along which a rock body has broken and been displaced.

Fault block A rock mass bounded by faults on atleast two sides (Fig. G-16).

Fault scarp A cliff produced by faulting.

Feldspar A mineral group consisting of silicates of aluminium and one or more of the metals potassium (K), sodium (Na) or calcium (Ca). Example: K-feldspar, Ca-plagioclase, Na-plagioclase.

Felsite A general term for light-coloured, fine-grained igneous rocks. *Example*: rhyolite.

Fissure An open fracture in a rock.

Flood basalt An extensive flow of basalt erupted chiefly along fissures. Synonymous with *plateau basalt* (Fig. G-17).

Floodplain The flat, occasionally flooded area bordering a stream.

Fluvial Pertaining to a river or rivers.

Focus The area within the Earth where an earthquake originates.

Fold A bend or flexure in a rock (Fig. G-18).

Foliation A planar feature in metamorphic rocks, produced by the secondary growth of minerals. Three major types are recognized: slaty cleavage, schistosity and gneissic layering.

Footwall The block beneath a dipping fault surface (Fig. G-19).

Foraminifera A protozoan animal characterized by a test having chambers that are composed of secreted calcite or agglutinized particles. *Range*: Cambrian to Present.

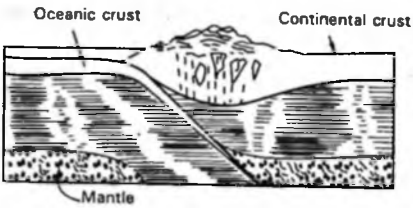
Formation A distinctive body of rock that serves as a convenient unit for study and mapping.

Fossil Naturally preserved remains or evidence of past life, such as bones, shells, casts, impressions and trails.

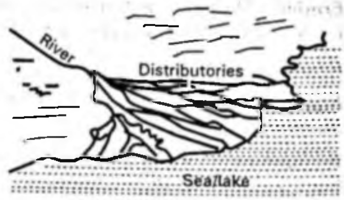
Fossil fuel A fuel containing solar energy that was absorbed by plants and animals in the geological past and thus is preserved in organic compounds in their remains. Fossil fuels include petroleum, natural gas and coal.

Fracture zone (1) A zone where the bedrock is cracked and fractured. (2) A zone of long, linear fractures on the ocean floor, expressed topographically by ridges and troughs. Fracture zones are the topographic expression of transform faults.

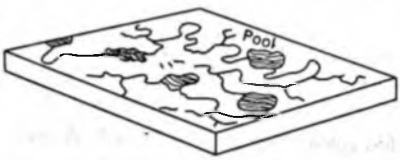
Gabbro A dark-coloured, coarse-grained rock composed of Ca-plagioclase, pyroxene and possibly olivine, but no quartz.



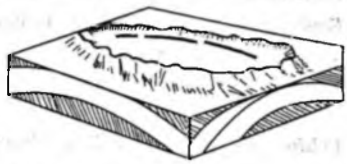
G-9 Crust



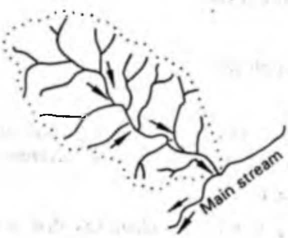
G-10 Delta



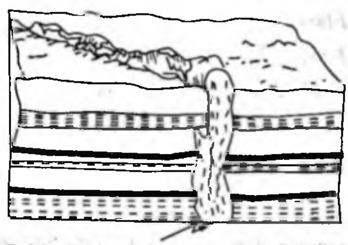
G-11 Deranged drainage



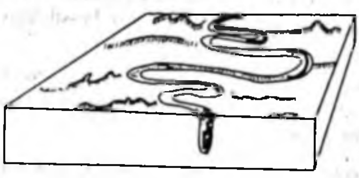
G-12 Dome



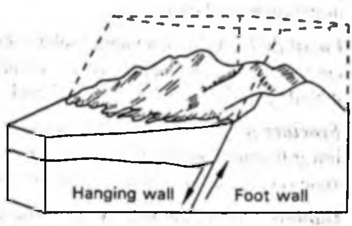
G-13 Drainage basin



G-14 Dyke



G-15 Entrenched meander



G-16 Fault block

Gastropod A mollusk characterized by a single calcareous shell that is closed at the apex, sometimes spirally coiled and not chambered. *Range*: Late Cambrian to Present.

Geological (lithostratigraphic) column A diagram representing divisions of geological time and the rock units formed during each major period.

Geological cross section A diagram showing the structure and arrangement of rocks as they would appear in a vertical plane below the Earth's surface.

Geothermal Pertaining to the heat of the interior of the Earth.

Geothermal energy Energy useful to human beings that can be extracted from steam and hot water found within the Earth's crust.

Glacier A mass of ice formed from compacted, recrystallized snow that is thick enough to flow plastically.

Glossopteris flora An assemblage of late Palaeozoic fossil.plant names for the seed fern *Glossopteris*, one of the plants in the assemblage. These flora are widespread in South America, Africa, Australia, India and Antarctica, and provide important evidence for the theory of continental drift.

Gneiss A coarse-grained metamorphic rock with a characteristic type of foliation and layering, resulting from alternating layers of light-coloured and dark-coloured minerals. Its composition is generally similar to that of granite.

Gondwanaland The ancient continental landmass that is thought to have split apart during Mesozoic time to form the present-day continents of South America, Africa, India, Australia and Antarctica.

Graben An elongate fault block that has been lowered in relation to the blocks on either side. Also called rift (Fig. G-20).

Graded bedding A type of bedding in which each layer is characterized by a progressive decrease in grain size from the bottom of the bed to the top (Fig. G-21).

Gradient (stream) The slope of a stream channel measured along the course of the stream.

Grain A particle of a mineral or rock, generally lacking well-developed crystal faces.

Granite A coarse-grained igneous rock composed of potash-feldspar, plagioclase and quartz, with small amounts of micas and other ferromagnesian minerals.

Greywacke An impure sandstone consisting of small-sized rock fragments and grains of quartz and feldspar in a matrix of clay-size particles.

Halite An evaporite mineral composed of sodium chloride ($NaCl$).

Hanging valley A tributary valley with the floor lying ('hanging') above the valley floor of the main stream or shore to which it flows (Fig. G-35). Hanging valleys commonly are created by deepening of the main valley by glaciation, but they can also be produced by faulting or rapid retreat of a cliff.

Hanging wall The surface or block of rock that lies above an inclined fault plane (see Fig. G-19).

Headwater erosion Extension of a stream headward up the regional slope of erosion.

Heat flow The flow of heat from the interior of the Earth

High-grade metamorphism Metamorphism that occurs under high temperature and high pressure.

Hornblende A variety of the amphibole mineral group.

Horst An elongate fault block that has been uplifted in relation to adjacent rocks (Fig. G-20).

Hot spot The expression at the Earth's surface of a column of hot, buoyant rock rising in the mantle beneath a lithospheric plate.

Hyolith Bilaterally symmetrical solitary metazoan having a generally conical shell with a single aperture. *Range*: Earliest Cambrian to Late Permian.

Ice sheet A thick, extensive body of glacial ice that is not confined to valleys. Localized ice sheets are sometimes called *ice caps*.

Igneous rock Rock formed by cooling and solidification of molten silicate mineral (magma). Igneous rocks include volcanic and plutonic rocks.

Intrusion (1) Injection of a magma into a pre-existing rock. (2) A body of rock resulting from the process of intrusion.

Intrusive rock Igneous rock that, while it was fluid, penetrated into or between other rocks and solidified. It can later be exposed at the Earth's surface after erosion of the overlying rock.

Island arc A chain of volcanic islands. Island arcs are generally convex towards the open ocean. *Example*: the Andaman–Nicobar Islands.

Joint A fracture in a rock along which no appreciable displacement has occurred.

Knee fold Zigzag fold.

Knick point A break or interruption of slope; abrupt change in the longitudinal profile of a stream or its valley.

Laccolith A concordant igneous intrusion that has arched up the strata into which it was injected, so that it forms a pod-shaped or lens-shaped body with a generally horizontal floor (Fig. G-22).

Lamellibranch (Pelecypod) A bottom-dwelling aquatic mollusk characterized by bilaterally symmetrical double-valve shells, a hatchet-shaped foot and sheet-like gills. *Range*: Ordovician to Present.

Landslide A general term for relatively rapid types of mass movement such as debris flows, debris slides, rockslides and slumps.

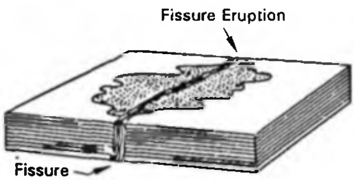
Lapilli Tiny fragments, 2 to 6 mm in size, of volcanic rocks or solidified or still viscous lavas.

Laterite A soil that is rich in oxides of iron and aluminium formed by deep weathering in tropical and subtropical areas.

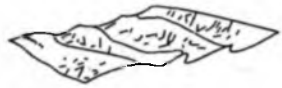
Lava Magma that reaches the Earth's surface and spreads around.

Limestone A sedimentary rock composed mostly of calcium carbonate ($CaCO_3$).

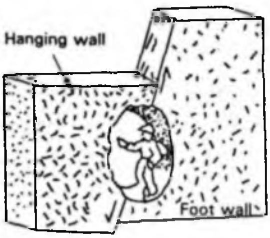
Lineament A topographic feature or group of features having a linear configuration. Lineaments commonly are expressed as ridges or depressions or as an alignment of features such as stream beds, volcanoes or vegetation.



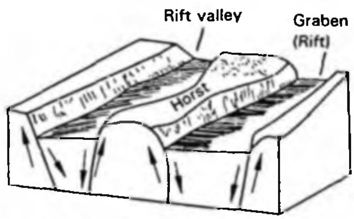
G-17 Flood Basalt



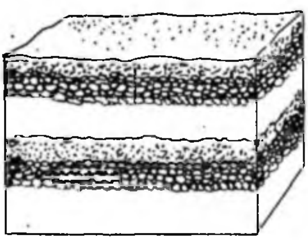
G-18 Fold



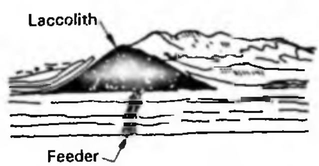
G-19 Footwall and Hanging wall



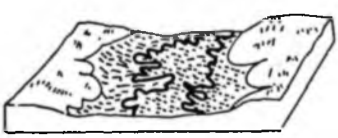
G-20 Horst and Graben



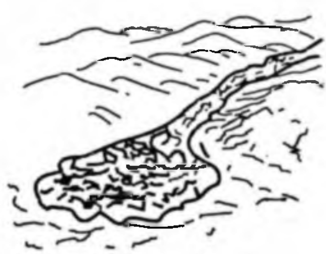
G-21 Graded bedding



G-22 Laccolith



G-23 Meander



G-24 Mudflow

Lithification The processes by which sediment is converted into sedimentary rock. These processes include cementation and compaction.

Lithosphere The relatively rigid outer zone of the Earth, which includes the continental crust, the oceanic crust, and the part of the mantle lying above the softer asthenosphere.

Load The total amount of sediment carried at a given time by a stream, glacier or wind.

Loess Unconsolidated, wind-deposited silt and dust.

Low-grade metamorphism Metamorphism that is accomplished under low or moderate temperature and low or moderate pressure.

Mafic or basic rock An igneous rock containing more than 50% ferromagnesian minerals.

Magma A mobile silicate melt, which can contain suspended crystals and dissolved gases as well as liquid.

Mantle The zone of the Earth's interior between the base of the crust (the Moho discontinuity) and the core.

Mantle plume A buoyant mass of hot mantle material that rises to the base of the lithosphere. Mantle plumes commonly produce volcanic activity and structural deformation in the central part of lithospheric plates.

Marble A metamorphic rock consisting mostly of metamorphosed limestone or dolomite.

Mass movement The transfer of rock and soil downslope by direct action of gravity without a flowing medium (such as a river or glacial ice). Synonymous with *mass wasting*.

Meander A broad, looping bend in a river (Fig. G-23).

Mechanical weathering The breakdown of rock into smaller fragments by physical processes such as frost wedging. Synonymous with *disintegration*.

Mesozoic The era of geological time from the end of the Palaeozoic era (225 m.y. ago) to the beginning of the Cenozoic era (65 m.y. ago).

Metamorphic rock Any rock formed from pre-existing rocks within the Earth's crust by changes in temperature and pressure and by chemical action of fluids.

Metamorphism Alteration of the minerals and textures of rocks by changes in temperature and pressure and by a gain or loss of chemical component.

Mica A group of silicate minerals exhibiting perfect cleavage in one direction.

Microcontinent A relatively small, isolated fragment of continental crust. *Example*: Madagascar.

Migmatite A mixture of igneous and metamorphic rocks in which thin dykes and stringers of granitic material intimately mixed up or interfinger with metamorphic rocks.

Mountain A general term for any landmass that stands above its surroundings. In the stricter geological sense, a mountain belt is a highly deformed part of the Earth's crust that has been injected with igneous intrusions and the deeper parts of which have been metamorphosed. The topography of young mountains is high, but erosion can reduce old mountains to flat lowlands.

Mud crack A crack in a deposit of mud or silt resulting from the contraction that accompanies drying.

Mudflow A flowing mixture of mud and water (Fig. G-24).

Nappe Faulted and overturned folds; uprooted sheets of rock-piles.

Nautiloid A valve resembling hollow cone, which may be straight or curved or coiled, and is divided into chambers.

Nodule A small, irregular, knobby or rounded rock that is generally harder than the surrounding rock.

Normal fault A steeply inclined fault in which the hanging wall has moved downward in relation to the footwall (Fig. G-25). Synonymous with *gravity fault.*

Oceanic crust The type of crust that underlies ocean basins (Fig. G-9). It is about 5 km thick and is composed predominantly of basalt. Its density is 3.0 g/m^3. The velocities of compressional earthquake waves travelling through it exceed 6.2 km/sec. Compare with *continental crust.*

Offshore The area from the low tide seaward.

Olivine A silicate mineral with magnesium and iron but no aluminium [$(MgFe)_2SiO_4$].

Oolite A limestone consisting largely of spherical grains of calcium carbonate in concentric spherical layers (Fig. G-26).

Ooze Marine sediment consisting of more than 30% shell fragments of microscopic organisms — slimy mud.

Ophiolite A sequence of rocks characterized by ultramafic (ultrabasic) rocks at the base and (in ascending order) gabbro, sheeted dykes, pillow lavas, and deep sea sediments. The typical sequence of rocks constituting the oceanic crust.

Orogenic Pertaining to deformation of a continental margin to the extent that a mountain range is formed.

Orogeny A major episode of mountain building.

Outcrop An exposure of bedrock.

Overturned fold A fold in which at least one limb has been rotated through an angle greater than 90 degrees (Fig. G-4, right).

Oxbow lake A lake formed in the channel of an abandoned meander.

Palaeocurrent An ancient current which existed in the geological past, with a direction of flow that can be inferred from cross-bedding, ripple marks and other sedimentary structures.

Palaeogeography The study of geography in the geological past, including the patterns of the Earth's surface, the distribution of land, oceans, ancient mountains and other landforms.

Palaeomagnetism The study of ancient magnetic fields, as preserved in the magnetic properties of rocks. It includes studies of changes in the position of magnetic poles and reversal of magnetic poles in the geologic past.

Palaeozoic The era of geological time from the end of the Precambrian era (600 m.y. ago) to the beginning of the Mesozoic era (225 m.y. ago).

Partial melting The process by which minerals with low melting points liquify within a rock body as a result of an increase in temperature or a decrease in pressure (or both) while other minerals in the rock are still solid. If the liquid (magma) is removed before other components of the parent rock have melted, the composition of the magma can be quite different from that of the parent rock.

Passive margin A lithospheric plate margin at which the crust is neither created nor destroyed. Passive plate margins generally are marked by transform faults. Contrast with *Active margin*.

Peat An accumulation of partly carbonized plant material containing approximately 60% carbon and 30% oxygen. It is considered an early stage or rank in the development of coal.

Pebble A rock fragment with a diameter between 2 mm (about the size of a match head) and 64 mm (about the size of a tennis ball).

Pelagic sediment Deep-sea sediment composed of fine-grained detritus that slowly settles from surface waters. Common constituents are clay, radiolarian ooze and foraminiferal ooze.

Peneplain An extensive erosion surface worn down almost to sea-level (Fig. G-27). Subsequent tectonic activity can lift a peneplain to higher elevations.

Peninsula An elongate body of land extending into a body of water.

Peridotite A dark-coloured igneous rock of coarse-grained texture composed of olivine, pyroxene and some other ferromagnesian minerals, but with essentially no feldspar and no quartz.

Physiography The study of the surface features and landforms of the Earth.

Pillow lava An ellipsoidal mass of igneous rock formed by extrusion of lava under water.

Plagioclase A group of feldspar minerals with a composition range from $NaAlSi_3O_8$ to $CaAl_2Si_2O_8$.

Plastic deformation A permanent change in a substance's shape or volume that does not involve failure by rupture.

Plate A broad segment of the lithosphere (including the rigid upper mantle plus oceanic and continental crust) that floats on the underlying asthenosphere and moves independently of other plates (Fig. 5-9).

Plateau An extensive upland region.

Plate tectonics The theory of global dynamics in which the lithosphere is believed to be broken into individual plates that move in response to convection in the upper mantle. The margins of the plates are sites of considerable geological activity.

Pleistocene The epoch of geologic time from the end of the Pliocene epoch of the Tertiary period (about 1.6 million years ago) to the beginning of the Holocene epoch of the Quaternary period (about 11,000 years ago).

Plunging fold A fold with its axis inclined from the horizontal.

Plutonic rock Igneous rock formed deep beneath the Earth's surface.

Point-bar A crescent-shaped accumulation of sand and gravel deposited on inside of a meander bend (Fig. G-28).

Precambrian A long period of geological time encompassing the eras Proterozoic (2500 to 570 m.y. ago) and Archaean (> 3800 m.y. to 2500 m.y. ago).

Pressure ridge An elongate uplift of deposits resulting from the pressure of underlying rocks.

Proterozoic Era commenced 2500 m.y. and ended 570 m.y. ago. It is divided into Early Proterozoic (2500–1600 m.y. ago), Middle Proterozoic (1600–900 m.y. ago) and Late Proterozoic (900–570 m.y. ago) periods.

Pyroclastic Pertaining to fragmental rock material formed by volcanic explosions.

Pyroxene A group of rock-forming silicate minerals composed of single chains of silicon–oxygen tetrahedra. Compare with *amphibole*, which is composed of double chains.

Quartz An important rock-forming silicate mineral composed of silicon–oxygen tetrahedra joined in a three-dimensional network. It is distinguished by its hardness, glassy lustre and conchoidal fracture.

Quartzite A sandstone recrystallized by metamorphism.

Quaternary The latest geological period encompassing the epochs Pleistocene (1.6 m.y. to 11000 years before present) and Holocene (11000 yr B.P. to present).

Radiolarian An actinopod living in marine pelagic environment characterized mainly by a siliceous, lattice-like skeleton.

Radiometric dating Determination of the age (in years) of a rock or mineral by measuring the proportions of an original radioactive material and its decay product. Synonymous with *radioactive dating*.

Recharge Replenishment of a groundwater reservoir by the addition of water.

Recrystallization Reorganization of elements of the original minerals in a rock resulting from changes in temperature and pressure and from the activity of pore fluids.

Recumbent fold An overturned fold, the axial plane of which is horizontal or nearly so.

Reef A solid structure built of shells and other secretions of marine organisms, particularly coral.

Regolith The blanket of soil and loose rock fragments overlying the bedrock.

Rejuvenated stream A stream that has had its erosive power renewed by uplift or lowering of the base-level or by climatic changes.

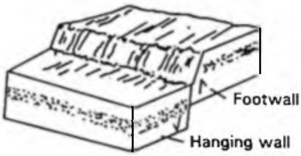
Relief The difference in altitude between the high and the low parts of an area.

Reverse fault A fault in which the hanging wall has moved upward in relation to the footwall; a high-angle thrust fault (Fig. G-29).

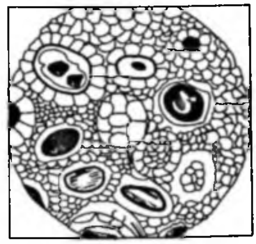
Rhyolite A fine-grained volcanic rock composed of quartz, potash–feldspar and plagioclase. It is the extrusive equivalent of a granite.

Rift valley A valley of regional extent formed by block faulting in which tensional stresses tend to pull the crust apart, resulting in dropping down of elongate blocks. Synonymous with *graben*. The downdropped block along divergent plate margins (Fig. G-20).

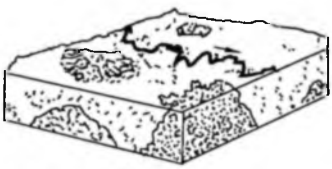
Ripple marks Small waves produced on a surface of sand or mud by the drag of wind or water moving over it.



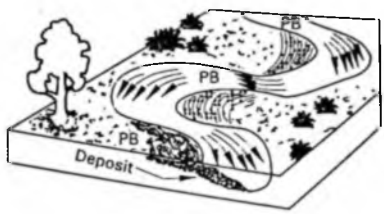
G-25 Normal fault



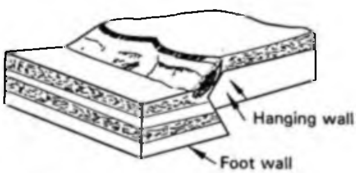
G-26 Oolite



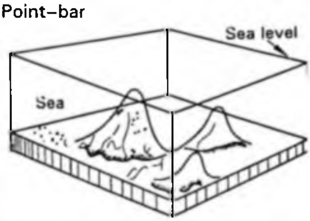
G-27 Peneplain



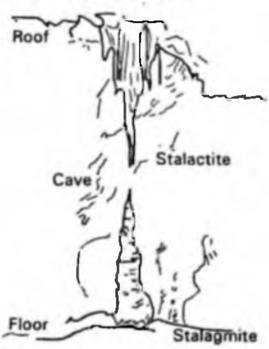
G-28 Point-bar



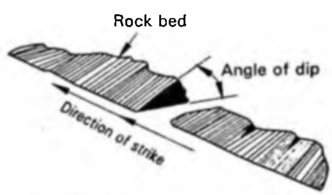
G-29 Reverse fault



G-30 Seamount



G-31 Stalagmite



G-32 Strike

Rockfall The most rapid type of mass movement in which rocks ranging from large masses to small fragments are loosened from the face of a cliff.

Runoff Water that flows over the land surface.

Sag pond A small lake that forms in a depression or sag, where active or recent movement along a fault has impounded a stream.

Sand Sedimentary material composed of fragments ranging in diameter from 0.0625 to 2 mm. Sand particles are larger than silt particles but smaller than pebbles. Much sand is composed of quartz grains, because quartz is abundant and resists chemical and mechanical disintegration. Other materials, such as shell fragments and rock fragments, can also form sand.

Sandstone A sedimentary rock composed mostly of sand-sized particles, usually cemented by calcite, silica or iron oxide.

Savana Wide treeless grassy plain in a tropical region.

Scarp A cliff produced by faulting or erosion (Figs. G-25 and G-29).

Schist A medium-grained or coarse-grained metamorphic rock with strong foliation (schistosity) resulting from parallel orientation of platy minerals such as mica, chlorite and talc.

Schistosity The type of foliation that characterizes schist, resulting from the parallel arrangement of coarse-grained platy minerals such as mica, chlorite and talc.

Sea-floor spreading The theory that the sea-floor spreads laterally away from the oceanic ridge as new lithosphere is created along the crest of the ridge by igneous activity.

Seamount An isolated, conical mound rising more than 1000 m above the ocean floor (Fig. G-30). Seamounts are probably submerged shield volcanoes.

Sediment Material (such as gravel, sand, mud and lime) that is transported and deposited by wind, water, ice or gravity; material that is precipitated from solution; deposits of organic origin (such as coal and coral reefs).

Sedimentary environment A place where sediment is deposited and the physical, chemical, and biological conditions that exist there. *Examples*: rivers, deltas, lakes, shallow marine shelves, etc.

Seismic Pertaining to earthquakes or to waves produced by natural or artificial earthquakes.

Seismic wave A wave or vibration produced within the earth by an earthquake or artificial explosion.

Shale A fine-grained clastic sedimentary rock formed by consolidation of clay and mud.

Shield An extensive area of a continent where igneous and metamorphic rocks are exposed and have approached equilibrium with respect to erosion and isostasy. Rocks of the shield are usually very old (that is, more than 600 million years old).

Shore The zone between the waterline at high tide and the waterline at low tide. A narrow strip of land immediately bordering a body of water, especially a lake or an ocean.

Silicate A mineral containing silicon–oxygen tetrahedra, in which four oxygen atoms surround each silicon atom.

Sill A tabular body of intrusive rock injected between layers of the enclosing rock.

Silt Sedimentary material composed of fragments ranging in diameter from 1/256 to 1/16 mm. Silt particles are larger than clay particles but smaller than sand particles.

Siltstone A fine-grained clastic sedimentary rock composed mostly of silt-size particles.

Slate A fine-grained metamorphic rock with a characteristic type of foliation (slaty cleavage), resulting from the parallel arrangment of microscopic platy minerals, such as mica and chlorite.

Slump A type of mass movement in which material moves along a curved surface of rupture.

Snowline The line on a glacier separating the area where snow remains from year to year from the area where snow from the previous season melts.

Soil The surface material of the continents, produced by disintegration of rock. Regolith that has undergone chemical weathering in place.

Soil profile A vertical section of soil showing the soil horizons and parent (rock) material.

Sorting The separation of particles according to size, shape or weight. It occurs during transportation by running water or wind.

Spreading centre A plate boundary formed by tensional stress along the oceanic ridge. Synonymous with *divergent plate boundary, spreading edge.*

Stalactite An icicle-shaped deposit of dripstone hanging from the roof of a cave (Fig. G-31).

Stalagmite A conical deposit of dripstone built up from a cave floor (Fig. G-31).

Stock A small, roughly circular intrusive body, usually less than 100 km^2 in surface exposure.

Strata Plural of *stratum.*

Stratification The layered structure of sedimentary rock.

Stratum (plural *Strata*) A layer of sedimentary rock.

Stream load The total amount of sediment carried by a stream at a given time.

Stream piracy Diversion of the headwaters of one stream into another stream. The process occurs by headward erosion of a stream having greater erosive power than the stream it captures.

Stream terrace One of a series of level surfaces in a stream valley representing the dissected remnants of an abandoned floodplain, stream bed or valley floor produced in a previous stage of erosion or deposition.

Stress Force applied to material that tends to change its dimensions or volume; force per unit area.

Striation A scratch or groove produced on the surface of a rock by a geological agent, such as a glacier or stream.

Strike The bearing (compass direction) of a horizontal line on a bedding plane, a fault plane or some other planar structural feature (Fig. G-32).

Strike-slip fault A fault in which movement has occurred parallel to the strike of the fault (Fig. G-33).

Subduction Subsidence of the leading edge of a lithospheric plate into the mantle (Fig. G-9).

Subduction zone An elongate zone in which one lithospheric plate descends beneath another. A subduction zone is typically marked by an oceanic trench, lines of volcanoes, and crustal deformation associated with mountain building.

Subsidence A sinking or settling of a part of the Earth's crust with respect to the surrounding parts.

Suspended load The part of a stream's load that is carried in suspension for a considerable period of time without contact with the stream bed. It consists mainly of mud, silt and sand. Contrast with *bed load* and *dissolved load.*

Syncline A fold in which the limbs dip towards the axis. After erosion, the youngest beds are exposed in the central core of the fold.

Talus Rock fragments that accumulate in a pile at the base of a ridge or cliff (Fig. G-34).

Tectonics The branch of geology that deals with regional or global structures and deformational features of the Earth.

Tension Stress that tends to pull materials apart.

Terminal moraine A ridge of material deposited by a glacier at the line of maximum advance of the glacier (Fig. G-35).

Terrace A nearly level surface bordering a steeper slope, such as a stream terrace or wave-cut terrace (Fig. G-37).

Terrain An area of land having its distinctive landscape.

Terrane A geological subprovince characterized by distinctive topographic outlay and lithotectonic setting, and delimited by tectonic boundaries like faults and thrusts, which evolved through a succession of tectonic, magmatic-volcanic and sedimentation events.

Tertiary A period that started 65.5 m.y. ago and ended 1.6 m.y. ago. It includes the epochs Palaeocene (65.5–57.8 m.y. ago), Eocene (57.8–36.6 m.y. ago), Oligocene (36.6–23.7 m.y. ago), Miocene (23.7–6.5 m.y. ago) and Pliocene (6.5 to 1.6 m.y. ago).

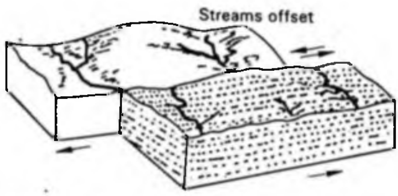
Thrust fault A low-angle fault (45 degrees or less) in which the hanging wall has moved upward in relation to the footwall (Fig. G-36). Thrust faults are characterized by horizontal compression rather than by vertical displacement.

Tidal flat A large, nearly horizontal area of land covered with water at high tide and exposed to the air at low tide. Tidal flats consist of fine-grained sediment (mostly mud, silt and sand).

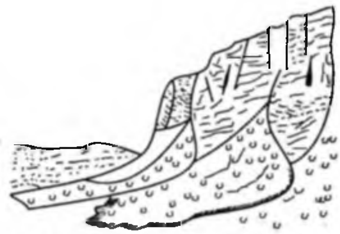
Till Unsorted and unstratified glacial deposit.

Tillite A rock formed by lithification of glacial till (unsorted, unstratified glacial sediment)

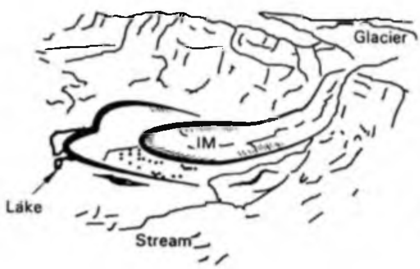
Topography The shape and form of the Earth's surface.



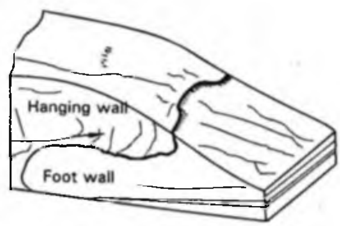
G-33 Strike-slip fault



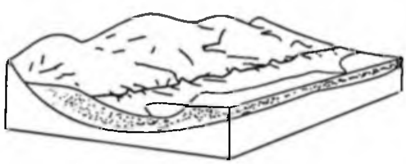
G-34 Talus (Scree)



G-35 Terminal moraine

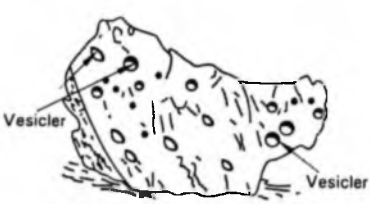


G-36 Thrust fault



G-37 Terrace

G-38 Turbidity current



G-39 Vesicle

G-40 Volcanic bomb

Transcurrent fault A large-scale fault cutting across more than one terrane along which horizontal movements have taken place.

Trench (marine geology) A narrow elongate depression of the deep-ocean floor oriented parallel to the trend of a continent or an island arc.

Trilobite A marine arthropod characterized by a three-lobed ovoid to elliptical external skeleton which is divisible longitudinally into axial and side regions, and posterior. ***Range***: Early Cambrian to Permian.

Tuff A fine-grained rock composed of volcanic ash.

Turbidity current A current in water caused by differences in the amount of suspended matter (such as mud or silt) laden with suspended sediment. These move rapidly down continental slopes and spread out over the very deep floor (Fig. G-38).

Ultramafic (ultrabasic) rock An igneous rock composed entirely of ferromagnesian minerals.

Unconformity A discontinuity in the succession of rocks, containing a gap in the geologic record. A buried erosion surface. See also *angular unconformity, non-conformity* (Fig. G-2).

Upwarp An arched or uplifted segment of the crust.

Vascular plant A plant with a well-developed conductive system and differentiation of structures.

Vesicle A small hole formed in a volcanic rock by a gas bubble that became trapped as the lava solidified (Fig. G-39).

Volcanic ash Dust-size particles ejected from a volcano.

Volcanic bomb A hard fragment of lava that was liquid or plastic at the time of ejection and acquired its form and surface markings during flight through the air. Volcanic bombs range from a few millimetres to more than a metre in diameter (Fig. G-40).

Volcanism The processes by which magma and gases are transferred from the Earth's interior to the surface.

Weathering The processes by which rocks are chemically altered or physically broken into fragments as a result of exposure to atmospheric agents and the pressures and temperatures at or near the Earth's surface, with little or no transportation of the loosened or altered materials.

Index

Dynamic Himalaya aims to apprise readers of the natural events and processes that were in operation before the emergence of the giant edifice of the Himalaya. Based on the author's own studies and the analysis of the works of the world's leading Himalayan geologists, the book is an up-to-date account of the history of the evolution of the Himalaya in simple language sans technical jargon.

The author demonstrates that the process of evolution of the Himalaya has not ceased, and that it is still growing and undergoing structural changes and landscape reshaping. The text is supplemented with exhaustive data, maps, figures and colour photographs.

Prof. K S Valdiya is Bhatnagar Research Fellow at the Jawaharlal Nehru Centre for Advanced Scientific Research, Bangalore. With over forty years of research and teaching experience, Prof. Valdiya has been the recipient of a number of awards including the DN Wadia Medal of the Indian National Science Academy (1995), the National Mineral Award of the Ministry of Mines, Govt. of India (1993), and the SK Mitra Award of the Indian National Science Academy (1991).

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