Himalaya : Geological aspect

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Sinha Anshu K & Upadhyay R. 1995. Himalaya : Geological aspect. *Palaeobotanist* **44** : 9-28.

In the present communication a generalised account of geology of the Himalaya has been discussed. This communication is rather an exercise for a beginning which should not be treated as a research note but a simplified version, taken from different published notes. Himalaya is beautiful but environmentally fragile, youngest mountain belt, prone to ecological unstability, intense seismicity but dotted with diverse mineral wealth of both nonrenewable and renewable types. Hence, it is still an enigma to understand the mystery of Himalaya.

Key-words — Geology, Seismicity, Tectonic activity, Himalaya (India)

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साराँश

हिमालय : भूवैज्ञानिक दृष्टिकोण

अंशु कुमार सिन्हा एवं राजीव उपाध्याय

प्रस्तुत शोध-पत्र में हिमालय के भूवैज्ञानिक अध्ययन की विवेचना की गई है। यह शोध-पत्र इस विषय में प्रारम्भिक अनुसन्धान कर्त्ताओं के लिए है तथा इसे विभिन्न प्रकाशित शोध-पत्रों से लेकर संश्लेषित किया गया है। हिमालय अपने में बहुत सुन्दर है लेकिन पर्यावरण की दृष्टि से मृदु, पारिस्थितिकीय दृष्टि से अस्थिर, अत्याधिक विवर्तनिक गतिविधियों आदि गुणों से युक्त है। अतएव हिमालय का रहस्य जानना अभी तक भी एक गूढ़ रहस्य ही बना हुआ है।

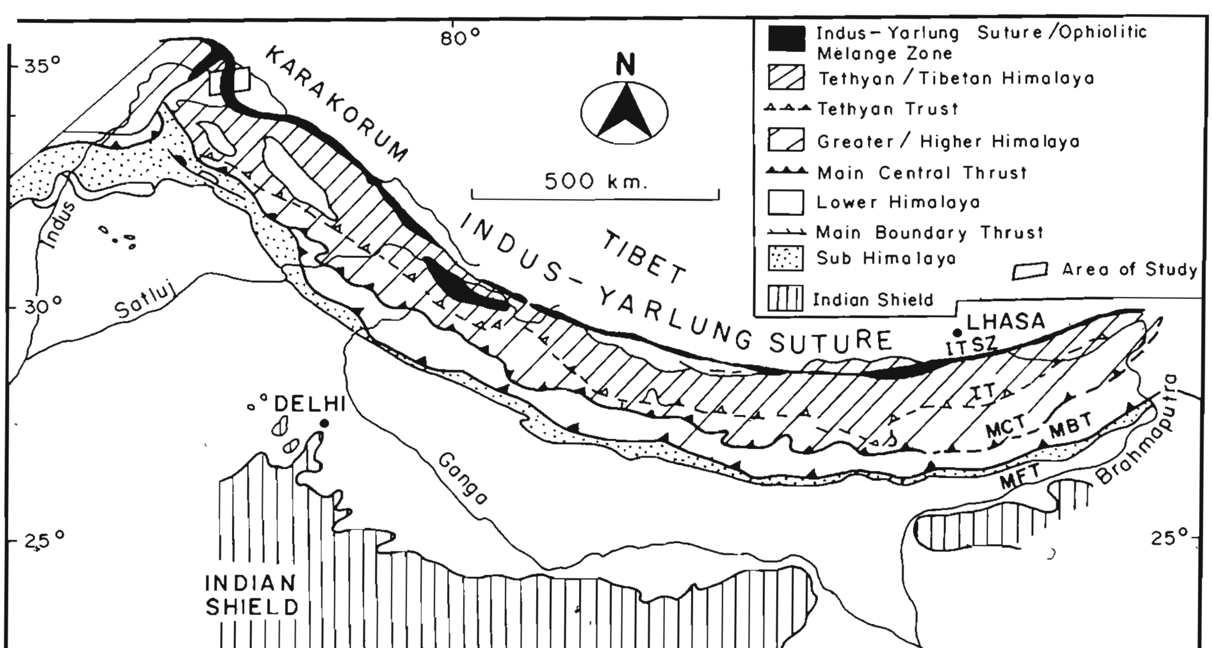
IT is an interesting question asked by a common man to mountain climber: 'Why do you want to climb Mt. Everest?' A famous mountaineer once replied: 'Because it is there!' The splendour and glory of magnificent Himalayan mountains has been immortalised earlier in the poetry of the great ancient Indian poet *Kalidas* : 'In the northern part there is a mighty mountain, Himalaya by name, the abode of perpetual snow - fittingly called the Lord of Mountains, animated by Divinity as its soul and iternal spirit or, in other words, Divinity Incarnate. Spanning the wide land from the scale of the earth, sea, he stands as it were, like the eastern to the eastern' (Olschak, Gansser & Buhrer, 1987; cf. Sinha, 1992).

HISTORICAL BACKGROUND OF HIMALAYAN GEOLOGY

The Himalayan mountain system is part of the world's largest concentration of mountain ranges in the central part of Eurasia (Text-figure 1). The mighty Himalaya, embodying the largest concentration of lithospheric mass, grew south of the Pamir mass. It consists a fascinating geological record of Pre-Cambrian to present and terminates both east and west with spectacular syntaxial bends. The Himalayan arc extends about 3,000 km from northwest to southeast (Text-figure 2) incorporating from west to east the loftiest peaks, viz., Nanga Parbat (8, 125 m), Everest (8, 848 m) and Namcha Barwa (7, 755m). The width of the belt varies from 250-350 km. This highest and youngest mountain range on the earth is still reverberating with dynamism. The uplifting process is still going on at about one centimeter per year along with continued erosion and denudation (although the rate differs from time to time and place to place). The eroded material from its rugged topography is repeatedly and regularly being shed into different depositional settings within the Himalaya to Bay of Bengal and Arabian Sea by youthful rivers and drainage network. Eversince the advent of advancement in geoscientifc studies in western Europe and activity of Geological Survey of India which was founded in Calcutta, the evolution of the Himalayan mountain chain has long been debated. Even without the aid of modern forms of transport, such as jeeps and helicopters, the pioneers

Text-figure 1 — Location map of Himalaya and neighbouring region (after Sinha, 1992).

managed to study remote and inaccessible areas of the Himalayan mountains. The results of these early geological investigations, carried out by British and Austro-Hungarian geologists, serving the GSI, were mostly of a generalised and stratigraphical nature. The real recognition of the complicated structures involved came much later, despite the fact that important overthrusts Cnappes and klippens) were discoverd in the Himalaya (Loczy, 1907), long before such phenomena were discovered in the Alpine mountain chains. Argand's synthesis in his La tectonique de l'Asie (1924) was perhaps the first generalised attempt to put forward a theory of genesis of the Himalayan mountains after the publication of the first edition of the classic work : *A sketch of the geography and geology of the Himalayan mountains and Tibet* by the stalwarts of Survey of India at Dehradun and Geological Survey of India at Calcutta (Burrard & Hayden, 1907). Onwards many Indian and western geologists (including scientists of the Wadia Institute of Himalayan Geology, Geological Survey of India and faculty members of different Indian universities) have worked on Himalaya, viz., Heim and Gansser (1939), Wadia (1957), Gansser (1964), Valdiya (1980, 1984, 1988), Sinha (1989, 1992), Searle (1991), Pande (1992), Thakur (1992) and many other references cited therein. It is a well known fact that more than hundred years of history of the geological investigations in the Himalaya led to the culmination of two different concepts : fixism as well as mobilism, viz., (i) concept of geosyncline vis-a-vis deep fracture vertical tectonics and the trans-Asiatic lineaments, (ii) concept of plate



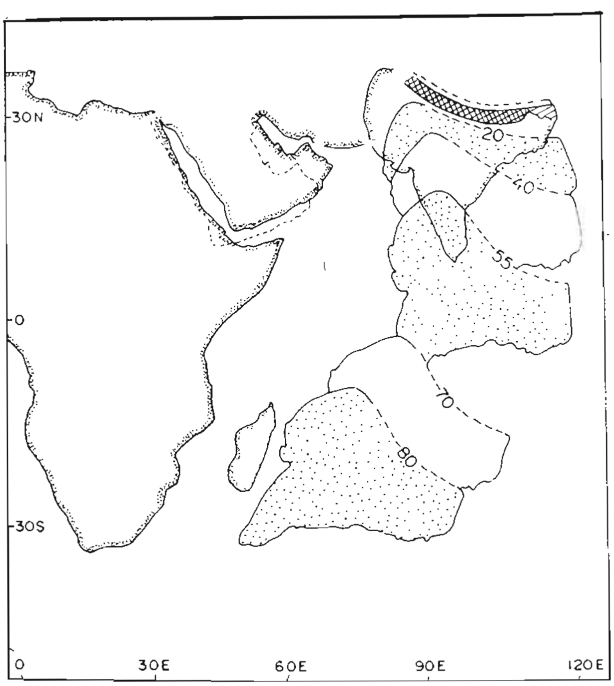
Text-figure 2 — Sketch map showing the northwest to southeast extension of Himalaya (after Gansser, 1964).

tectonics (continent to continent collision between Indian and Eurasian plates and terrane accretion). Presently, the second concept is widely accepted.

GEOLOGY OF HIMALAYA : BROAD REGIONAL CONFIGURATION

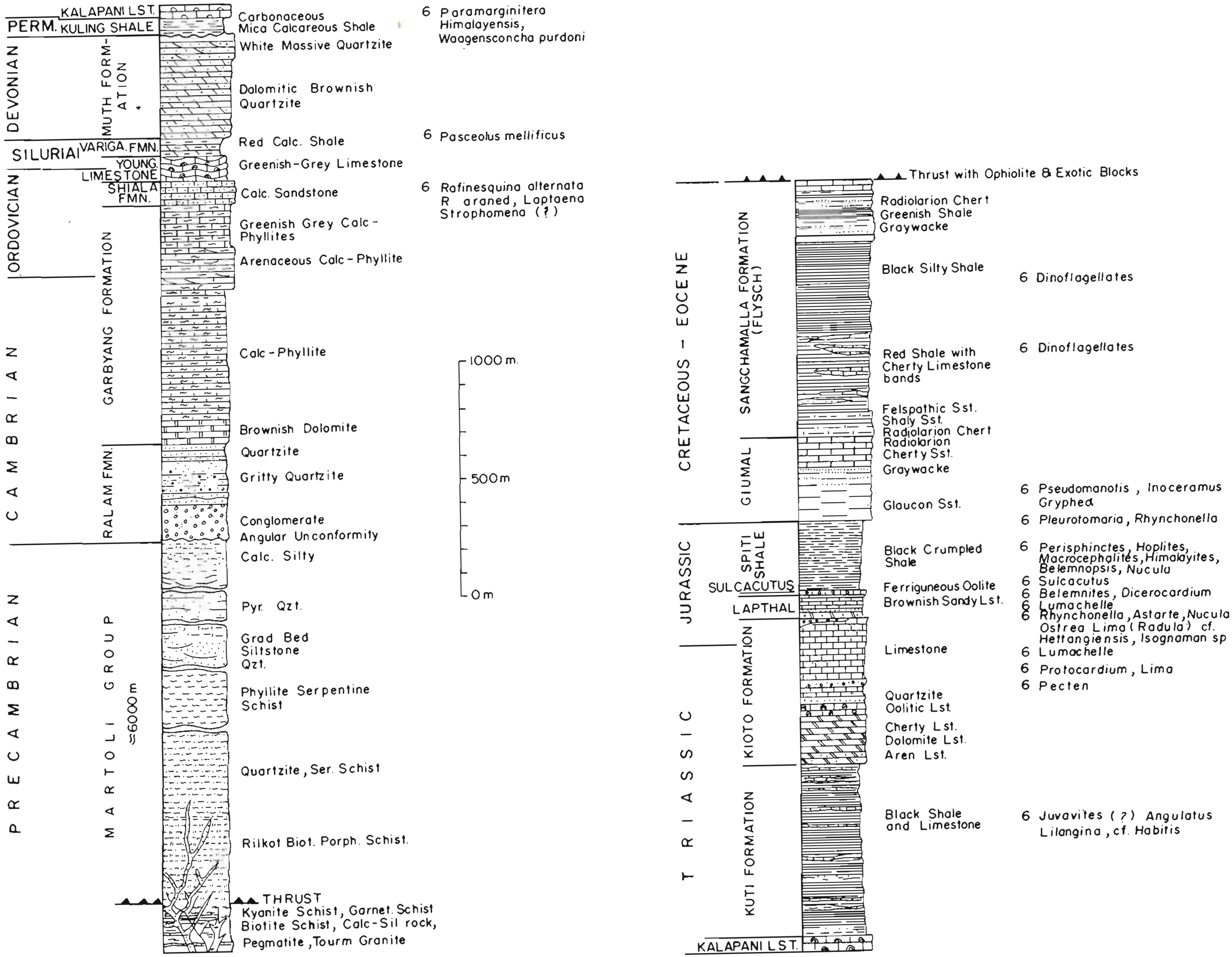
It has been proposed that the terminal phase of suturing of the Indian and the Eurasian plates was marked by the closing of the Neotethys (Text-figure 3) the so-called Tethys Ocean which separated the Indian and the Eurasian plates till collision that took place around 45 Ma. The closure of Neotethys produced a complex and intense structural deformation, regional metamorphism, plutonism and the formation of the post-collision continental sedimentary basins besides the rejuvenation of pre-collision marine sedimentary basins. A series of continuous thrusts (Text-figure 2) divide the long Himalayan arc into four tectonically distinct and stratigraphically contrasted domains which have multi-faceted histories of sedimentation, magmatic activities, metamorphism and tectonism. These tectonic domains extend continuously from east to west and sharply delimited by the major thrusts (Sinha, 1989, 1992). From north to south these zones are (Text-figure 2) ;

1. Trans Himalaya including the Indus-Tsangpo Suture Zone of Ladakh and Karakoram ranges.
2. Higher Himalaya or Great Himalaya including the central Himalayan Crystalline and Tethys Himalaya.
3. Lesser Himalaya or southern Himalaya between Higher Himalayan zone stopping the monsoon clouds and sub-Himalayan Siwalik zone.
4. Sub-Himalayan, outer Himalaya, foot-hills, fore-deep or Siwaliks.

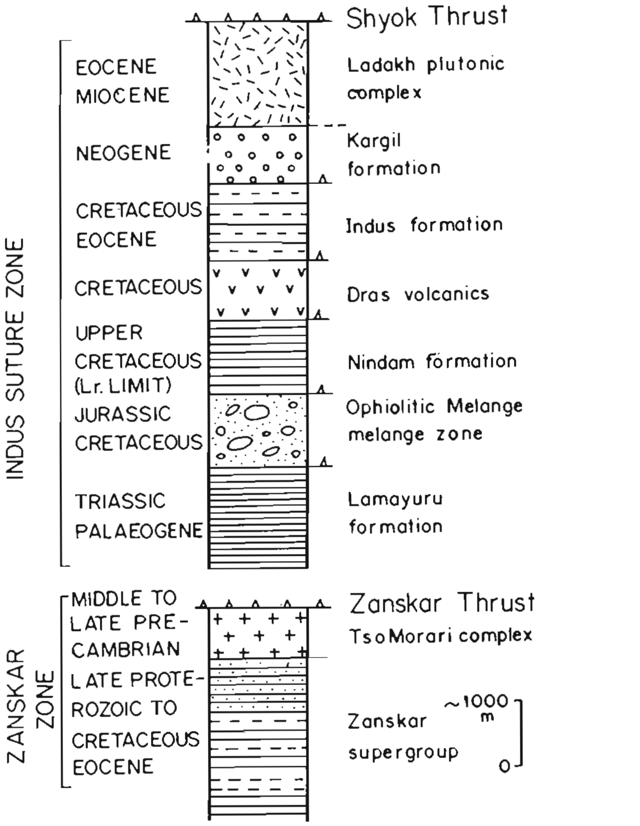


Text-figure 3 — Cartoon depicting the northward flight of India since the Cretaceous up to its present position and successive closure of Tethys (in Sinha, 1992).

As mentioned above, the Himalaya is undergoing rapid uplift. It has consequently experiencing rapid erosion with the deposition of a thick terrigeneous sequence dating from Miocene in the sub-Himalaya basin. These comprise the Siwalik Molasse conglomerates and extend southwards into the gangetic basin where they are eventually bounded by the Main Frontal Thrust (MFT) in the south. The Lesser Himalayan rocks consist of Precambrian-Palaeozoic-Tertiary sediments and low grade metasediments. These rocks are thrusted over the Sub-Himalaya along the Main Boundary Thrust (MBT). However, these rocks are overthrusted by the nappes of gneisses of the Higher Himalaya to the north. The general elevation of the Lesser Himalaya ranges from 1,500-3,000 m. The higher or Great Himalaya encompasses some of the world's highest peaks and reach altitudes of over 8,000 m. These consist of a basement of Precambrian gneiss overlain by Palaeozoic and Mesozoic sediments of the Tethyan affinity (Text-figure 4). The unit is thrust over the Lesser Himalaya along the Main Central Thrust (MCT). It is intruded by granites of Pan-African orogeny (500-600 Ma) of Lower Palaeozoic age and granites of Miocene (Tertiary) age which is supposed to be originated by the remobilization of the lower crust. Several large ophiolitic klippe were also thrust over the higher Himalayan (Tethyan) sediments in Palaeocene time, i.e., Spongtang klippe in Zanskar and Jungbwa in SW Tibet. The Trans-Himalaya, situated to the north of the higher (Tethys) Himalaya. It consist rocks of the Indus-Tsangpo (Yarlung-Zangbo) Suture Zone and Karakoram Himalaya (Text-figure 5). The Indus Tsangpo Suture Zone in Ladakh lies between the backthrusted Tethys Himalaya (Higher) of Spiti and Zanskar (Zanskar Supergroup) in the south and Karakoram Zone (Karakoram thrust) in the north. The



Text-figure 4 — Lithostratigraphic framework of the Tethyan Garhwal-Kumaun Higher Himalaya (after Sinha, 1981, 1989).

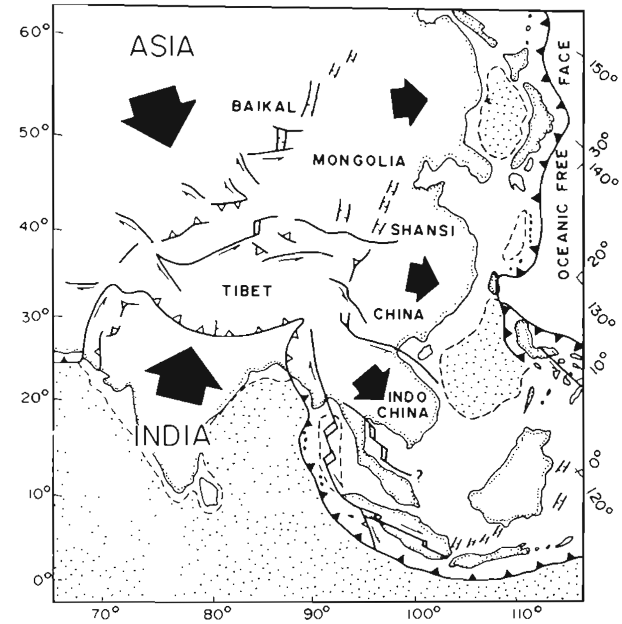


Text-figure 5 — Tectonostratigraphic column in western Ladakh along Indus Suture Zone (after Sinha & Upadhyay, 1993, 1994).

major boundary which separates the two is known as Indus Suture Thrust (Zanskar thrust) in NW Indian Himalaya whereas its further westward extension is commonly known as the Main Mantle Thrust (MMT) in Pakistan (Kohistan) Himalaya. The Triassic-Pliocene rocks of Indus Tsangpo Suture Zone in Ladakh collectively depict abundant evidence in favour of Late Cretaceous convergence (Subduction) and Cenozoic collision (45 Ma) of the Indian and the Eurasian Plates. This zone is also supposed to be the junction between these two plates (Text-figure 6) hence referred to as 'Suture'. Now we would like to briefly elaborate these tectonic divisions, keeping in mind the alloted space and the mighty Himalaya.

1. Trans-Himalaya

As defined earlier the Trans-Himalaya comprises a discrete set of different tectonostratigraphic rock units. This zone includes rocks of Indus Tsangpo Suture Zone and Shyok Suture Zone in Ladakh, Kohistan arc sequence, Karakoram Zone of northwestern Himalaya.



Text-figure 6 — Depiction of aftermath effect of collision leading to building of Himalayan mountain-chain and tectonic escape in Southeast Asia (after Sinha, 1992).

Whereas, its eastern continuation is further marked by the ophiolites, flysch and molasse association of Kailash range, the Yarlung-Tsangpo belt along with Lahasa block of southern Tibet (Sinha, 1981; Thakur, 1981, 1992). However, very scanty literature or no record has yet been available for Trans-Himalaya in Arunachal sector.

Indus Tsangpo Suture Zone

The major tectonostratigraphic units of Indus Tsangpo Suture Zone can be represented by (Text-figures 5, 7, 8).

(i) Tso Morari Crystalline Complex — As revealed by the literature, the basement rocks can be demarcated by the inception of Tso Morari Crystalline Complex. Overall, the Tso-Morari crystallines form a very large doubly plunging anticlinal fold, referred to as "dome" (Sinha, 1981; Thakur, 1981). This domal complex includes metamorphic rocks of Precambrian age altogether with Lower Palaeozoic granites and sedimentary rocks of Upper Carboniferous-Lower Triassic age. The metamorphic rocks comprise mainly paragneisses, quartz sericite schists with intrusive granite and amphibolite and quartz-sericite schists with subordinate marble and basic rocks. Kyanite and sillimanite metamorphism appears near the core and decreased

progressively N and S to garnet, biotite to clorite grade. The granites are coarse grained, foliated and porphyritic with muscovite, biotite and amphibole. The distribution is widespread and occurs as stock. Besides, there are some concordant granitic body, they are coarse-grained, porphyritic foliated to unfoliated and contains muscovite, biotite, hornblende and tourmaline. Xenoliths of phyllite, sandstone and gabbro are dominant. Surrounding metasediments have been hornfelsed, and intruded the coarsegrained granite. These granites are as Polkong La granite and Rupshu granite (Sinha, 1981).

The metasediments such as calcareous schist and crystalline limestone of Tso Morari Complex yielded deformed bivale-shells, crinoid stems and thin layers of phosphatic limestone. Microfossils recorded from sediments are conodonts and ostracods and indicate a Permian age to Taglang La Formation (Thakur, 1981).

(ii) Lamayuru Formation — The syn-rift deep marine fine grained turbidites of the Lamayuru Formation has a thickness of about 2,500-3,000 m. These sediments could be regarded as typical pre-orogenic flysch sediments of Indian passive margin (Sinha & Upadhyay, 1993). Thus plays a crucial role in understanding the details of Neotethys closure. It consists of shales, siltstones, fine grained sandstones and calcareous bands. The NW-SE striking rock units of the Lamayuru Formation are tectonically intercalated between the over-riden or backthrusted Mesozoic Zanskar platform sediments of the Indian passive margin in the south and the Jurassic-Cretaceous Ophiolitic Melange Zone of the active (convergent) margin of the Indus Suture in the north. The age range of Lamayuru Formation could be assigned between Triassic-Eocene on the occurrence of Triassic *Daonella indica*, Jurassic ammonites and Late Cretaceous to Early Eocene foraminiferal remains. However, shelf, forereef and basin margin (slope) olistoliths (exotic blocks of limestone) of Permian-Jurassic age are tectonically juxtaposed within the Lamayuru Formation (Sinha & Upadhyay, 1993).

(iii) Ophiolitic Melange Zone — The ophiolitic Melange Zone is supposed to be the dismembered remnant of Jurassic-Cretaceous oceanic crust of Neotethyan floor. The ophiolitic Melange Zone is exposed as a discontinuous linear belt along the Indus Suture Zone in Ladakh. This zone is tectonically underlain by the overthrusted south dipping Lamayuru Formation and overlain by Nindam Formation with a thrust contact to the north. It is distinguished from the overlying Lamayuru Formation and the underlying Nindam Formation by generally disorganised ophiolite breccias, the scarcity of mudstones, the occurrence of several metre-sized olistoliths of mafic volcanics, pillow lavas, shallow water and pelagic limestones, disrupted turbidites, red-green-grey-white chert, magnesite, harzburgites blueschists, amphibolites, scaly cleaved serpentinites and serpentinite shear zones (Upadhyay & Sinha, 1994). Thus it represents a unique association of olistolith and olistostromes. The olistostromes of the ophiolitic Melange Zone are predominantly composed of ophiolite debris which could be seen as slivers of intraformational heterogeneous assemblage called the polymict ophiolite breccia. Despite olistostromal occurrences there is variable amount of dark green to black, sometimes vesicular basalt fragments, radiolarian bearing red chert, siliceous mudstones, light green mafic gabbro and pyroxenites, serpentinites, shallow water limestone present as olistoliths. Recently, K/Ar dates of some tectonic blocks of gabbro reveals that they are the fragments of oceanic islands (Sinha & Mishra, 1992). It has also been proposed that they were embeded in the Neotethyan oceanic crust between Albian and Maastrichtian. Major, trace and rare earth geochemical data indicate alkaline to subalkaline nature of the magma with remarkable enrichment of LREE and fractionation of HREE. These geochemical data further suggest that the ocean island basalt are within plate type and presumed to have been a protolith for blueschist rocks of Ophiolitic Melange (Sinha & Mishra, 1992). However, in the eastern Ladakh an ophiolite sequence consisting of ultramafic rocks, gabbros and pillow lavas, occurs in the area between Nidar and Kyun Tso (Thakur, 1981). The ultramafic rocks consist primarily of pyroxenite together with peridotite and dunite. The gabbros are massive and layered and show intrusive relation with ultramafics. The pillow lavas constitute the topmost layer of the ophiolite sequence and consist of a basic to intermediate volcanic assemblage with pillow structures together with interbedded layers of lava, chert, jaspar, grit and sandstone. The ophiolitic Melange Zone has been considered as remnant of the ancient convergent zone (Trench) between Indian and Eurasian plate.

(iv) Nindam Formation — The Nindam Formation is a coherent flysch unit, tectonically overlain and underlain by rocks of the ophiolitic Melange Zone (Sinha &

Upadhyay, 1994). It is characterised by ubiquitous red and green shales, siltstone, conglomerate, chert and occasional limestone bands of turbiditic origin. The upper and lower limits of the Nindam Formation are invariably a tectonic contact with rocks of the Ophiolitic Melange, marked by a sudden change in lithological association, serpentinized shear zones and very thin mylonitized zones. Recent studies infer that the trench and trench slope sediments of Nindam Formation are Late Cretaceous- Early Palaeocene in age. These syn-orogenic volcanogenic sediments also depict that the source region was a volcanic arc and Ophiolitic Melange, i.e., Dras island are volcanism and older oceanic crust of the Ophiolitic Melange Zone (Sinha & Upadhyay, 1994).

(v) Dras Volcanics — The volcanic rocks mainly consist of andesitic and basaltic lavas. There are local occurrences of pillow lava, rhyolite, agglomerate and other volcaniclastic products along with radiolarian chert, jasper and limestone. The limestone has yielded *Orbitolina, Hippurites* and bryozoa of Middle and Late Cretaceous age. The volcanic material have petrochemical characters of arc-tholeiites, calc-alkaline lavas and shoshonites and were interpreted as having been formed in an island-arc environment as a result of magma generation in the upper mantle or the upper part of a descending slab of oceanic lithosphere. The age of this volcanics is Cretaceous (Thakur, 1981).

(vi) Indus Formation — The Indus Formation represents a thick wedge (4,000-5,000 m) of clastic sediments such as conglomerate, sandstone, siltstone and shale. This formation is separated from Dras volcanics, ophiolitic Melange Zone and Tso-Morari crystalline complex by a steep thrust to the south. Whereas, the northern boundary appears to be at some places as transgressive with Kargil molasse. Otherwise it is having a thrusted contact on either side. It has also been observed that the conglomerate, sandstone, siltstone and occasional shale successions do also contain sills of dolerite about one meter thick besides 30 m thick calcareous bands (Thakur, 1981). The pebbles in the conglomerate are of volcanic rocks (basalt, andesite and rarely rhyolite), vein quartz, carbonates, sandstone, shale, granite and gneiss. On the basis of lithological association, sedimentary features, faunal assemblages and petrological signatures it has been proposed that the sediments of the Indus Formation represent a flysch sequence of Early Cretaceous-Eocene. A basinal setting of forearc or arc- trench gap has also been assigned to the syn-orogenic sediments of the Indus Formation.

(vii) Kargil Formation — The Kargil Formation is about 1000 m thick clastic continental molasse sediments of the Indus Suture Zone. It rests directly and transgressively on the Ladakh plutonic complex. It consists of conglomerate and sandstone with occasional shale bands. The pebbles in the conglomerate are more or less similar to that of Indus Formation, i.e., granite, vein quartz, radiolarites, carbonates, volcanic rocks and gneiss. The sandstone has yielded freshwater molluscs, plant remains and well established vertebrate fossil. This indicate a Neogene (Upper Oligocene-Lower Pliocene) age for Kargil Formation. Similar molasse sediments has also been reported from eastern Ladakh and known as Liyan Formation (Thakur, 1981).

(viii) Ladakh Plutonic Complex — The Ladakh Plutonic Complex forms a batholithic body. This is exposed along the NW-SE trending Ladakh range which runs parallel to the Indus Suture Zone. The composition varies from tonalite and granodiorite to granite. It has also been observed that there are bodies of mafic igneous complex ranging in composition from gabbro, gabbro-norite, gabbroic anorthosite to diorite. Petrochemical studies suggest that the plutonic suite has calc-alkaline affinities altogether with multiphase intrusive history. Recently, based on K/Ar, Rb-Sr and other radiometric age record, it has been assigned that the Ladakh plutoic complex has evolved through a multiple phase of magmatic activity. These ages are 100 Ma, 40 Ma and 20 Ma (Thakur, 1981, 1992).

(ix) Khardung Formation — A volcanogenic formation having associated with are : rhyolite, trachyte, keratophyre, dacite and andesite together with tuff and agglomerate and a minor proportion of basalt. Whereas, interbedded chert, limestone and shale occur in the upper part of the formation. The rocks of Khardung Formation have intrusive relations with the Ladakh plutonic rocks and assigned a Oligocene age (Thakur, 1981).

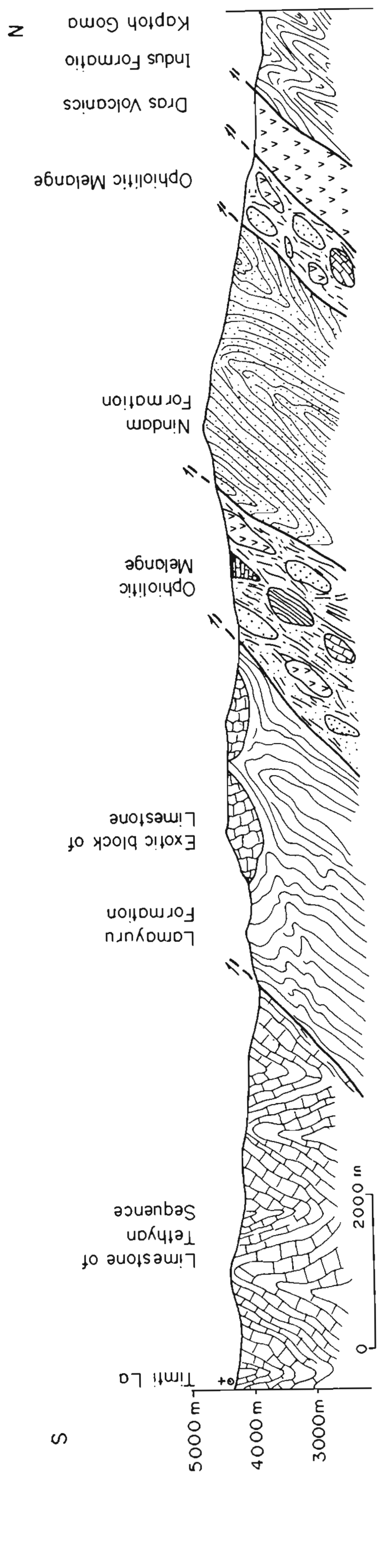
Shyok Suture Zone

The rocks of Shyok Suture Zone are tectonically intercalated between the rocks of Indus Tsangpo Suture Zone to the south and Karakoram Zone to the north. The major boundry thrusts which delimit both the southern and northern end are commonly known as Shyok thrust and Karakoram thrust, respectively. The major tectonostratigraphic units of Shyok Suture Zone (Table 1) could be shown as follows :

Table 1—Tectonostratigraphic units of Shyok Suture Zone

Tectonic zone	Stratigraphic units	Rock types	Age
Karakoram	Karakoram Thrust		
	Saltoro-molasse kole molasse	Conglomerate, sandstone and variegated shale of magmatic origin.	Miocene
	Saltoro andesites	andesites	?
	Nubra Ophiolitic Melange	Volcanics, shale, limestone conglomerate, slate, serpentinite peridotite, etc	Cretaceous
Shyok Suture Zone			
.... Thrust			
	Hundri Formation Luzarmu Formation Diong Formation	Pink-white, phyllite, limestone and quartzite showing flyschoid character	Cretaceous Lower Eocene
.... Thrust			
	Shyok volcanics	Fine to medium grained basalt, andesites	Cretaceous
		Thrust	
	Khalsar Formaton	Metasedimentaries, migmatic gneiss calcareous phyllites, chlorite, mica schist, limestone, etc.	Cretaceous Permian
Indus Suture Zone	Khardung Formation	Oligocene (after Thakur, 1992)	

The Shyok Suture Zone as revealed from most of the literature represent the relict of back arc basin.



Text-figure 7 — A geological cross section across Indus-Tsangpo Suture Zone in western Ladakh Himalaya (after Sinha & Upadhyay, 1993, 1994).

Karakoram Zone

The basement crystalline rocks of Karakoram Zone commences with the appearance of Precambrian Pangong Tso Group. The Pangong Tso Group consists of metamorphic sequence of phyllite, limestone, garnet, staurolite schists, migmatites, kyanite and sillimanite gneisses and amphibolite with intrusives of granite. These rocks are tectonically underlain by over-riding Karakoram thrust to the south. However, overlying Karakoram Supergroup rocks which are predominantly sedimentary, belong to Upper Palaeozoic-mesozoic. These rocks are predominantly sedimentary. The rocks of Karakoram plutonic complex is depicted by granitic rocks which form a NW-SE trending belt. This plutonic complex consists mainly of granite and granodiorite besides tonalite plutons. These rocks have been dated as 90-100 Ma, 40 Ma, 20 Ma, which is more or less time equivalent with the Ladakh plutonic complex of Indus Tsangpo Suture Zone (Thakur, 1992).

Higher Himalaya, Great Himalaya, Central Himalayan Crystalline and Tethys Himalaya

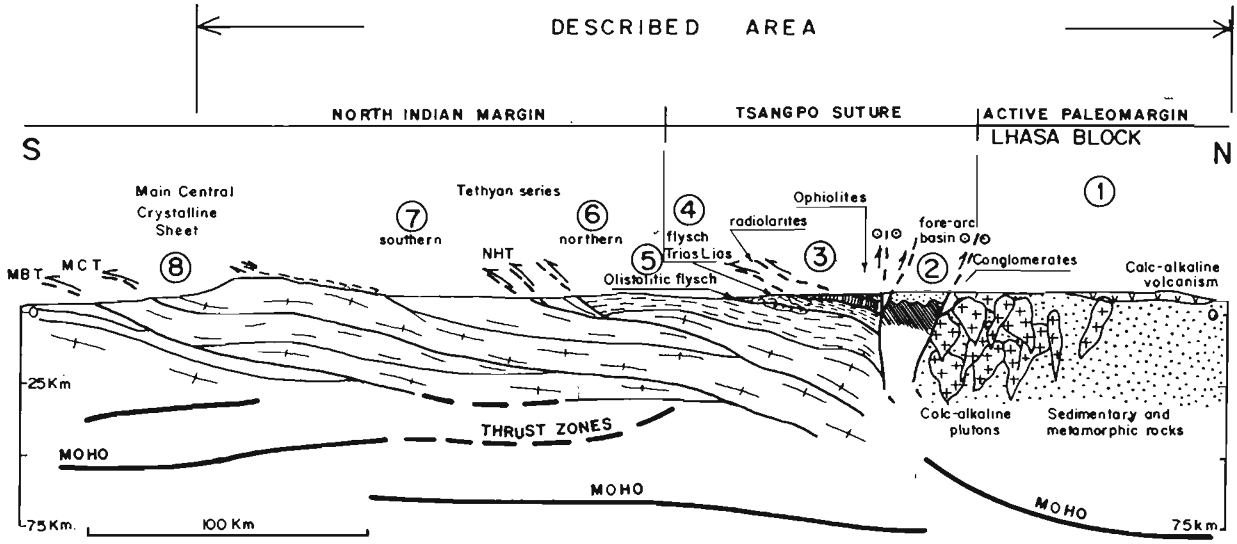
In this section we would like to briefly deal the Higher Himalaya collectively with Tethys Himalaya.

Higher Himalaya (Central Crystalline)

The Higher Himalaya is made up of "Central Crystallines" or high grade metamorphics (Text-figures 2, 4, 8) including granitoids migmatites. The rocks of Higher Himalaya extend in a NW-SE trending belt and form the basement for the Tethyan sediments or Tethys Himalaya (Sinha, 1981, 1989). It has been observed and proposed that the rocks of Central Crystallines represent a moderately inclined homoclinal structure throughout the eastern and central Himalayan sectors and folded west of Satluj River (Sinha, 1981, 1989). It has also been proposed that as a result of this folding the rocks of Higher Himalayan Range are bifurcated in Kashmir into the southern Pir Panjal and the northern Zanskar ranges. This Higher Himalayan Crystalline Rocks are primarily consist of older, Precambrian, high grade metamorphics which show progressive regional metamorphism of the Barrovian type. This is known as the Vaikrita Group in Himachal and Kumaun, the Upper Crystallines, the Annapurna Gneissic Complex, the Central Himalayan gneisses in western Nepal, the Khumbu in eastern Nepal, the Darjeeling Gneiss in Sikkim Himalaya, the Thimpu or the Chasilakha-Sure-Tashigong gneisses in Bhutan and the Sela Group in the Kameng District of Arunachal Pradesh. Throughout its extent this high grade metamorphic rock unit is intruded by granites of 500 Ma (Early Proterozoic-Cambrian) and young Tertiary granites. The 500 Ma granites of Almora, Chaur, Mandi, Dalhousie, Jispa, Nanga Parbat, Plokong La, etc. have been correlated with the Pan-African orogenic event (Thakur, 1992). The MCT defines the southern limit of the Higher Himalaya with respect of the rocks of lesser Himalaya. Several Higher Himalayan Crystallines thrust sheets or klippen and nappe have been observed resting over the Lesser Himalayan sedimentaries. These are Banali and Satengal klippen Lansdowne klippe, Ramgarh nappe, Almora nappe, Askot and Baijnath klippen, Jutogh klippe of Garhwal, Kumaun and Himachal Lesser Himalaya.

Tethys Himalaya

Resting over the Precambrian Higher Himalayan Crystalline basement, the rocks of the Tethys Himalaya extend north of the Higher Himalaya (Text-figures 2,4,8). Thus the rocks of the Tethys Himalaya lie between the Indus-Tsangpo Suture Zone and the Higher Himalayan Crystallines. To the north, the Tethys Himalayan sequence is separated from the Indus Suture Zone by a south hading thrust, called Zanskar Thrust, whereas to the south, the sequence overlies the Higher Himalayan Crystallines along a tectonic contact, known as the Tethyan Thrust. All along the Himalayan arc this zone is presumed to have been extended from Pir Panjal-Dhauladhar-Leo Pargial-Badrinath-Nanda Devi-Nampa- Dhaulagiri-Everest-Kanchanjangha, etc. The Tethys Himalaya Zone comprises over 10 km thick sequence of sedimentary rocks which are predominantly fossiliferous and ranging in age from Late Precambrian to Cretaceous and even Eocene (Sinha, 1989; Thakur, 1992). In the following section we would like to highlight the general lithostratigraphic framework of Tethys Himalayan Zone in a tabular form. Despite some local facies variation the rocks of Tethyan zone are more or less similar in lithotectonostratigraphic disposition. However, local names could differ as a result of provincial boundary change. For that region we are only taking into account the Garhwal-Kumaun Tethys Himalaya including Malla Johar region, Spiti and Zanskar regions of western Himalayan sector.



Text-figure 8 — A representative tectonic model of northern edge of Indian Plate vis-a-vis Himalaya (after Burg, 1992).

(i) Garhwal-Kumaun Tethys Himalaya — The lithostratigraphic divisions of Garhwal-Kumaun Tethys Himalaya could be depicted by (Text-figure 4). This shows a complete stratigraphic record of Precambrian-Eocene rocks (Sinha, 1981, 1989).

The NW-SE regional fold axis of the Palaeozoic sedimentary zone changes to N-S in the Mesozoic sequence. The Martoli Formation shows cross-folds plunging NW-SE, and this folding is absent in all the younger rocks. Characteristic secondary folds generally reflect the competence of various formations. The Garbyang Formation, especially at its base has been involved in a series of north and north-west directed gravity structures, producing a feature that may be termed tooth paste folding, including flat or low angle-dislocations. A continuous zone of such structures characterizes the entire Lower Garbyang belt along the Girthi Ganga valley. Here the normal regional folding prevails. The Kuti shales are involved in a series of disharmonic folds and local thrusts. The pattern of folding undergoes a definite change in the Mesozoic rocks, especially within the Kioto Limestone and Lapthal Formation. Not only does the fold axis change gradually to N-S, but these rocks have also suffered a high degree of shallow seated tectonic deformation producing a series of en-echelon structures within which the less competent Spiti shale has developed disharmonic folding (Sinha, 1989). E-W croospuckers have also developed in the Lapthal Formation, leading to a fluted appearance of outcrops of the Sulcacutus Member, the younger unit having suffered this folding. No large scale thrusting is reported in Kumaun and eastern Kumaun. The boundary between the metamorphosed Vaikrita Group and the pile of sedimentaries differs from that in the eastern region by being faulted and truncating most of the Martoli Formation. The major faults of this region can be described: (1) essentially strike slip faults which however become occasionally strike slip faults and trend NW-SE and NNW-SSE, (ii) NE-SW to E-W transverse faults. An important fault of the first category is the site of hydrothermal mineralization of barytes and copper ore near Barmatiya (Sinha, 1977, 1981, 1989).

(ii) Kiogad exotics in Garhwal-Kumaun Tethys Himalaya — A sheet of exotics comprising the limestone of the Permian to Lias Chitichun facies and serpentinites together with lavas are thrust on the sole of flyschoid sediments of the Sangcha Malla Formation (Sinha, 1981, 1989). Von Kraft (1904) had earlier reported the presence of slickenside structures near the contact between the exotic rocks and the Sangcha Malla Formation. Heim and Gansser (1939) regarded this contact as the thrust plane. However, it has been proposed that the occurrence of a large number of smaller blocks of limestone, serpentine, etc. within the rocks of the Sangcha Malla Formation below the above mentioned contact, cannot be accounted for by the supposed thrust. To overcome this objection Ganseer (1964) subsequently placed this thrust within the Flyschoid sediments in his structural section. While the contact of the Sangcha

Malla Formation with the exotic is highly disturbed and generally marked by basic to ultrabasic extrusives and intrusives, the sequence below is uniformly undisturbed in the Sangcha Malla region with little strike faulting and there is no evidence whatsoever to postulate a large scale thrust within it (Sinha, 1981).

(ii) Tethys Himalaya in Spiti — Table 2 shows the Lithostratigraphic disposition of Tethys Himalaya in a part of Spiti Valley.

Table 2 —Lithostratigraphic divisions of Tethys Himalaya in Spiti Valley

Time Unit	Litho-units	Lithology
Late Cretaceous	Chikkim Formation	Fossiliferous limestone, shale
Cretaceous	Guimal sandstone	Fossiliferous black shale, limestone and interbedded sandstone
Late Jurassic	Spiti shale	Black shale and quartzite fossiliferous, ammonite dolomitic limestone, quartzite
Jurassic	Kioto Limestone	Limestone is fossiliferous including Megaloden
Triassic	Lilang Group	Shale and highly fossiliferous limestone, quartzite, etc.
Permian	Kuling Formation	Productus shale, red-black-brown siliceous shale, dolomites, siltstone, Calcareous quartzite, etc.
Upper Carboniferous	Ganmachidam Formation	Polymictites, quartzites, siltstone, shale, etc.
Upper Carboniferous	Po Formation	Alternating beds of shale and quartzite, fossiliferous including plant remains
Lower Carboniferous	Lipak Formation	Limestone, salt, shale, quartzite, slate, fossiliferous
Devonian	Muth Quartzite	White quartzite, brownish quartzite, grey calcareous quartzite siliceous limestone
Silurian	Pin Dolomite	Dolomite, dolomitic limestone, nodular dolomite fossiliferous, siltstone, shale, quartzite
Cambrian-Ordovician	Shian Quartzite	Conglomerates, grits, thick bedded quartzite, shale
........................Cambro-Ordovician boundary, Angular unconformity		
Cambrian to Late Precambrian	Haimanta Group	Grey, green and purple quartzites, black carbonaceous phyllites, grey-green slates, coarse sandstone, shale, dolomite, etc.

(after Thakur, 1992)

3. *Southern Zanskar*

Table 3 depicts the lithostratigraphic disposition of Tethys Himalaya in the southern Zanskar.

Table 3 —Lithostratigraphic divisions of Tethys Himalaya in southern Zanskar

Time unit	Litho-units	Lithology
Lower Eocene	Chulung La Formation	Thick bedded limestone, Purple green slates, siltstone, etc.
Palaeocene	Spanboth Formation	Limestone, sandstone, fossiliferous
Maastrichtian	Kangi La Formation	Sandy and silty slates fossiliferous
Early Turronian	Chikkim Formation	Thick bedded grey dense limestone fossiliferous
Aptian Cenomanian	Guimal sandstone	Dark grey sandstone, shale, etc.
Oxfordian	Spiti Shale	Black shale, marl, siltstone with nodules
Callovian	Ferruginous Oolite Formation	Fossiliferous ironstone, shale, quartzite Oolitic arenites, etc.
Late Triassic-Late Lias	Kioto Limestone	Fossiliferous, limestone, quartzite, etc.

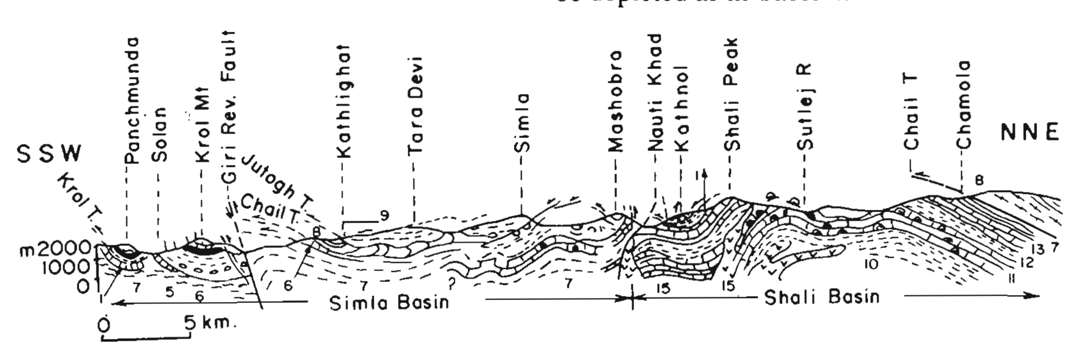
Time unit	Litho-units	Lithology
Rhaetian	Quartzite Series	White-green fine grained sandstone
Norian	Zozar Formation	Fossiliferous, dolomite, dolomitic limestone, micaceous siltstone, etc.
Ladinian	Hanse Formation	Fossiliferous, limestone, marl, etc.
Scythian	Thamba Kurkur Formation	Nodular, grey thin to medium bedded limestone shales, etc.
Late Permian	Kuling Formation	Sandstone, shale and thin bands of limestone, fossiliferous
Early Permian	Panjal Trap	Volcanics mainly basalt
Late Carboniferous	Ganmachidam Formation	Coarse gritty sandstone, conglomerate, quartzite, black shale
Early Carboni-ferous	Lipak Formation	Grey, pale pink limestone, siliceous limestone, dolomite, quartzite, grey shales, gypsum
Devonian	Muth quartzite	Quartzite mainly
Middle Ordovician	Thaple Formation	Conglomerate
Middle-Late Cambrian	Kurgiakh Formation	Bioturbated pelites, nodular dolomite with few basalt tuff layers
Cambrian	Karsha Formation	siltstone, dolomite etc.
Upper Cambrian to Late Precambrian.	Phe Formation	green grey slates, sandstone, greywacke, limestone, etc.

(after Thakur, 1992)

(iii) Spongtang klippe in Zanskar Tethys Himalaya — The Spongtang klippe is composed of ultramafic and gabbroic rocks with poorly developed cummulates and dykes in a thrust nappe overlying a melange unit with volcanics, limestone and chert blocks. It has also been proposed that the ophiolite rests tectonically on a thrust plane over Tethyan sediments ranging in age from Eocene to Jurassic. Recently Reuber *et al.* (1992) studied the mylonitic and ductile shear zones in peridotite of spongtang klippe and suggested that the ophiolite formed at a transform boundary. They further assigned an age of 180-130 Ma. These rocks have been tectonically derived from the Indus Tsangpo Suture Zone of Ladakh Trans-Himalaya.

3. Lesser Himalaya

It has been observed that a set of approximately 1,300 m thick, Precambrian-Lower Palaeozoic and Eocene age, weakly metamorphosed sedimentary rocks and volcanics, tectonically bounded on north and south by two major thrust, i.e., Main Central Thrust (MCT) and Main Boundary Thrust (MBT), respectively (Text-figure 2), belong to the remains of a large intra-cratonic basin in the Lesser Himalayan region (Valdiya, 1980a, b; Sinha, 1989; Thakur, 1992). As mentioned earlier, associated with this Lesser Himalayan rocks very interestingly, are klippen units, inliers or large thrust sheets of Central Crystallines (Text-figure 9). Litho-tectonostratigraphically the rocks of Lesser Himalaya could be depicted as in Table 4.



Text-figure 9 — A geological cross-section of Simla Himalayan region (Sinha, 1981). **1**, Subathu with nummulitics; **2**, Krol C,D; **3**, Krol B; **4**, Infra Krol; **5**, Blaini; **6**, Jaunsar; **7**, Simla; **8**, Chail-phyllite, metavolcanics and gneiss; **9**, Jutogh; **10**, Khaira quartzite; **11**, Lower Shali limestone; **12**, Shali slate; **13**, Upper Shali limestone; **14**, Madhan slate; **15**, Basic volcanics.

Table 4 —Litho-tectonostratigraphic divisions of Lesser Himalaya

Time unit	Litho-units		Lithology
	Jutogh-Almora Group		Thrust sheets of Metamorphic rocks
	------Jutogh Thrust......... Chail-Ramgarh Group		Containing granite bodies as occurred in the Central Crystallines
...........Chail Thrust			
Upper Cretaceous Lower Eocene	K	Subathu Formation	Fossiliferous limestone
Lower Cambrian	R O	Tal Formation	Phosphoritic chert, carbonaceous shale, greywacke, quartzite, slate, sandstone, limestone, etc.
Middle Riphean-Late Vendian	L	Krol Formation	Limestone, grey-green-purple slate, siltstone, massive dolonite abundant stromatolites etc.
	G R	Infra- Krol Formation	Grey-green siltstone, shale, greywacke, Pyritous shale, slate, thin quartzite, etc.
	O U	Balaini Formation	Conglomerate (boulder bed) carbonaceous shale,siltstone, minor quartzite, purple dolomitic limestone, etc.
	P	Nagthat Formation	Purple fawns white-green quartzite, slate, local volcanics
		Chandpur Formation	Phyllites, metasiltstone, greywacke, local metavolcanics
Upper Riphean to Vendian	S D G I A R M M O L T U A H P A	Rauthgara Formation	Muddy quartzite, green-purple slates, basic sills, dykes and lava flows, etc.
		Chakrata Formation	Mainly turbidites consist purple, grey- geen grey-wacke, siltstone and slates
Upper Riphean to Early Vendian	S T G H E R	Mandhali Formation	Carbonaceous slate, marble, quartzite, conglomerate, phyllite, limestone with stromatolites, etc.
Lower to Middle Riphean	A J O L A U I M P	Deoban Formation	Limestone, cherty dolomite, dolomitic limestone, grey slate, magnesite, abundant stromatolites, etc.
Middle Proterozoic		Berinag Formation/Khaira Formation	Coarse grained to pebbly, sericitic quartzite white green-purple in colour, metamorphosed amygdaloidal and vesicular basalts, tuffites

(Modified after Valdiya, 1980a; Sinha, 1989; Thakur, 1992)

Recently it has also been observed that the complexity and tenacity of Lesser Himalayan rocks still have an outrageous atmosphere among geoscientists as far as time events of some of the important lithostratigraphic units are concerned. In the inner Lesser Himalaya the crystalline klippen and scales of the schuppen zones overlies a vast thrust sheet of Berinag quartzites and penecontemporaneous basic volcanics. Whereas the synclinorial Krol nappe comprises, in addition to the Berinag nappe several other formation of Precambrian-Early Palaeozoic age. Outcrops of these rock successions are widespread in vast windows in the inner Lesser Himalaya. These rock successions could be divisible into the Mandhali, Chandpur (Flyschoid), Nagthat (quartzite with contemporaneous basic volcanics), Balaini (flyschoid assemblage with an diamictites), Infra Krol (carbonaceous shale, slate), krol (carbonates) and Tal (diamictites, phosphatic rocks, sandstones and limestones) (Valdiya, 1980b). The Tal is locally capped by the Subathu of Lower Eocene age. The rocks of Krol nappe are confined in the very southern belt in the central sector, however, in the eastern Himalaya these rocks are depicted by a narrow strip of the Gondwana rocks. Thus a large part of this old and geomorphically mature zone is made up of Riphean sedimentaries occurring in the lowest structural level. In the central sector these sedimentaries are autochthonous tightly folded and repeatedly faulted, whereas in the north-western and eastern sectors they have been thrust southward over the Siwalik zone. However, all along the belt the basal succession consists a flyschoid assemblage known as the Sundernagar in Himachal, the Rautgara in Kumaun, the Kunchha in Nepal, the Sinchula-Jainti in Sikkim, the Phuntsholing in Bhutan and the Bichom in western Arunachal. The flyschoid assemblage is normally followed by the Middle Riphean stromatolitic carbonates designated the Jammu = Sirban = Great Limestone in the northwestern sector, the Shali in Himachal, the Deoban in Kumaun, the Buxa in Bhutan and the Dedza in western Arunachal (Valdiya, 1980b; Sinha, 1989). However, the calcareous assemblage grade into an argillocalcareous assemblage called the Basantpur in Himachal, the Mandhali in Kumaun and the Saleri in Arunachal. Imbricately underlying the Almora nappe is a thrust sheet of little metamorphosed Early Riphean flyschoid assemblage penetrated by voluminous granitic porphyroids. These highly sheared and mylonitized rocks have been thrust over the sedimentaries of Precambrian-Early Palaeozoic age, which are known as the Chail in Himachal, Ramgarh sheet in Kumaun, the Lower Midland Formation in western Nepal, the Daling in the Sikkim Himalaya, the Samchi or Shumar in Bhutan and the Tenga in western Arunachal Pradesh (Valdiya, 1980b).

In the north the uppermost thrust sheet of Lesser Himalaya is depicted by pronouncedly mylonitized, pervasively retrograde metamorphic rocks, Precambrian augen gneisses, synkinematic granodiorite and post-kinematic granites. These rocks are sandwiched between the Vaikrita and Main Central Thrusts at the base of Higher Himalaya. The medium-grade metamorphics are intruded by granite-granodiorite of igneous suite. This unit is called the Salkhala in Kashmir, the Jutogh in Himachal (Text-figure 9), the Munsiari-Almora (the former being the root of the latter) in Kumaun, the Upper Midland Formation in West Nepal, the Kathmandu in central and east Nepal, the Paro in Sikkim Himalaya and the Bomdila in Arunachal. It has been observed that in the central sector the crystallines have suffered considerable erosion and denudation so that the once continuous sheet is now represented by synclinal klippen and nappes. However, in the northwestern and eastern sectors the crystalline rocks have been thrust southwards considerably so that they have reached the proximity of the foot-hills (Valdiya, 1980b). Offcourse, the Main Boundary Thrust (MBT) marks the southern boundary of the Lesser Himalaya.

4. Sub-Himalaya, Outer Himalaya, footh-hills, Fore-deep or Siwaliks

As defined vividly, an spectacular sedimentary basin which is supposed to be formed as a result of Tertiary orogenic movement in the Himalayan region. Thus a fore-deep had been created in front of rising Himalaya (Text-figure 2). The uplifting processes associated with continued erosion and denudation shed sediments of diverse provenance into the fore-deep trough. Subsequently, these sediments got tectonically juxtaposed accordingly within the outer-periphery of main Himalayan rock units. This youngest phase of the Himalayan sediments are therefore named as sub-Himalaya, outer Himalaya or foot-hills. This Tertiary zone is over-ridden by the various units of the Lesser Himalaya along the Main Boundary Thrust (MBT), whereas the southern limit can be demarcated by the Main Frontal Thrust (MFT) or Himalayan Frontal Thrust (HFT). This sedimentary zone is made up of Early Tertiary Subathu, Dagshai-Kasauli-Murree and the Late Tertiary-Quaternary orogenic clastic molasse sediments of Siwalik formations (Valdiya, 1980b). It has also been observed that the rocks are folded and split by faults at several places. This sedimentary pile is supposd to be around 9,500 m thick and ranging in age from Palaeocene-Upper Pleistocene. Besides different rock association, the Karewa deposits of the Kashmir Valley and the rocks of Peshawar and Cambellpore basins are located physiographically within the Lesser Himalaya. These rocks have been designated as Karewa intermontane sediments of the outer Himalaya. The sediments of outer Himalaya are marine, mixed and freshwater. A remarkable association of vertebrates and microvertebrates shows a unique identity for outer Himalayan sediments. The fossils of man, elephants, Proamphibos, rhino, camel, pigs, hippo, giraffe, horse, crocodiles, snakes, fish, rodents, etc. mark an ideal place to study ancesteral biodiversity and as well as age. Recently, Kumar *et al.* (1994) provided a comprehensive geological account of the Siwaliks. Table 5 depicts very briefly the major lithostratigraphic subdivisions of outer Himalayan sector.

Table 5 —Lithostratigraphic subdivision of Siwalik Group

	Sub Group	Formation	Magnetostratigraphic dates	Lithology	Characteristic Fossils
		OLDER ALLUVIUM			
--- GRADATION ---					
UPPER	(Upper Pliocene to Lower Pleistocene)	Boulder Conglomerate ------------------------------ Pinjor Formation -------Volcanic tuff------- Tatròt Formation	0.22 Ma 0.72 Ma 1.6 Ma (Neogene-Quaternary Boundary) Ma (Tatrot-Pinjor faunel boundary)	Coarse boulder conglomerates, clays, sands, grits etc. Conglomerates, sandstones, clays Sandstones, clays, conglomerates	Elephas nomadicus Equus, Cannelus, Buffelus etc. Elephas Planiferous, Hemibos, Stegodon Hyppophys, Leptobos
--- 5.44 Ma (Mio-Pliocene boundary) ---					
MIDDLE	(Upper Miocene to Lower Pliocene)	D Dhokpathan Formation ------------------------------ Nagri Formation ------- Volcanic tuff -------	6.5 Ma 7.8 Ma-8.5 Ma 9 ± 0.5 Ma	Sandstones, shales, clays, pebbly at the top Massive sandstones, shales, red clays	Stegodon, Mastodon, Giraffoid, Sus Mastodon, rripparian, Prostegodon, Ramapithicus
LOWER	(Middle Miocene)	Chinji Formation ------------------------------ Kamlial Formation ------------------------------ -	14.3 Ma 18.3 Ma	Nodular shales, clays, sandstones Dark compact sandstones, red and purple shales.	Distriodon, Amphicyon, Giraffokery, Tetrabelodon Accratherium, Telemastodon Tetrabelodon, Anthropoids
--- Conformable and gradational ---					
		KASAULI FORMATION (Upper Murrees)			

modified after Kumar, 1895

ARUNACHAL HIMALAYA

Table 6 represents the major litho-tectonostratigraphic disposition of different rock units in Sikkim, Bhutan and Arunachal Himalaya. Inaccessibility and remoteness of Arunachal sector of Himalayan domain led to the scanty record of research, is comparision with the western Himalaya. Nevertheless, the geoscientifc efforts during early 1970-1980 in Kameng, Siang and Lohit divisions virtually represents a good account of regional geological framework of this region. The lithological and tectonic set up suggest that the MBT and MCT could be traced from Sikkim-Bhutan to Arunachal. It has been observed that the crystalline pile could be divided into two different sheets.

Table 6 —Litho-tectonostratigraphic divisions of eastern Himalaya

Time unit	Darjeeling and Sikkim	Bhutan	Arunachal	Lithology
Late Precambrian-Cambrian to Cretaceous	Tethys Himalaya zone · Tso Lhamo Formation Lachi Formation Everest Limestone Formation Haimanta Formation	Tethys Himalaya zone : Mesozoics Palaeozoic Chekha Formation		
---------- Tethys Thrust ----------				
Early Precambrian (1,800-2,000) Ma	Central crystallines . Darjeeling group Paro group	Central Crystallines Vaikrita Group (Chasilka, Suru and Tsshigang units) Paro group	Central Crystallines Sela Group Paro group	High grade crystallines, schist, gneisses, migmatites, granites, basic intrusions
---------- Main Central Thrust ----------				
Precambrian	Daling unit	Daling - Shumar Unit	Bomdila unit	Sericitic quartzite, limestone, gypsum, phyllitic schist, fine and coarse grained gneisses, amphibolite veins
	Outer Crystalline (=Chail) Thrust			
Late Precambrian to early Palaeozoic	Buxa unit	Buxa unit	Miri unit	Boulder quartzite, pink-white quartzite, iron-ore mineralization, cherty limestone, bands of slates, calcareous shale with pebbles of limestone
---------- Thrust ----------				
Permian	Gondwana group Rangit pebble slate	Gondwana group Diuri Formation	Gondwana group Rangit peeble slate,	Pebble, boulder, slate, thin bands of siliceous tuffs, sandstone
	Damuda sandstone	Damuda Formation	Damuda sandstone	Black shale, slate, coal seam, micaceous and gritty sandstone, mudstone, quartzite plant fossils
---------- Main Boundary Thrust ----------				
Neogene	Siwalik group	Siwalik group	Siwalik group	Salt, pepper sandstone, grey silt and mudstone, soft sandstone, sand, clay, shale, conglomerate, etc.

1. The lower Bomdila unit consists of low grade metamorphic and correlated with the Chail of western Himalaya, Daling Shumar of Sikkim - Bhutan.
2. The Upper Sela unit consists of high grade rocks and correlated with Vaikrita/Jutogh of western Himalaya, Darjeeling of Sikkim and Bhutan.

The eastern syntaxis emerged as an important tectonic feature of the region. It has also been proposed that the curvature is not like the Nanga Parbat syntaxis where all the litho-tectonic belts take a narrow swing from NW-SE to NE-SW around a pivot or "Knot" of the Indian shield. However, in the eastern sector various litho-tectonic belts in Siang District trend NE-SW and abut against the NW-SE trending belts of Lohit District. This suggests that the syntaxial bend might not be related with the simple bending of tectonic belts but rather 'interference' of differently trending belts. Apart from this, one of the most significant outcome is the presence of marine Early Permian fauna from the Gondwana belt of Subansiri District and its extension in Kameng and Siang districts. The Abor volcanics, a basic volcanic sequence which is interbanded with Miri quartzites, have been proposed to represent Early Palaeozoic rift phase activity contemporaneous with sedimentation.

GEOPHYSICAL CONSTRAINTS

The Himalaya become an inevitable testing ground for the study of isostatic equlibrium since the invention of gravity metres. Gravity anomalies across the Himalayan mountain chain (Das *et al.*, 1979) and Gangetic plain show that the two are not in isostatic equilibrium. An increase in the Bouger gravity gradient from 1 m Gal Km^{-1} over the Himalaya implies a marked steepening of the Moho and therefore, a greater flexure of the Indian Plate beneath the Himalaya (Molnar, 1988). In 1977, explosion seismology, deep seismic sounding by so-called refraction profiles, was initiated by the Institute of Geophysics, Chinese Academy of sciences. Data interpretation suggests a strong heterogeneity, lacking the continuity of even major interfaces across the strike defining different crustal blocks, as well as lack of continuity of surface tectonic features down through the whole lithosphere (Hirn, 1988). It has been suggested that thickening by imbrication of both the upper crustal and the lower crust-upper mantle level has taken place. The mantle is identified as lying about 80 km beneath the surface, or 75 km beneath sea level, crustal material reaches 65 km in thickness, i.e., extends over 60 km below sea level, and a 10-15 km transition layer in between allows to model the low frequency seismograms (Hirn, 1988). It has also been suggested that the passage from crust to mantle might look different if it could be resolved with shorter wavelength signals. This large crustal thickness was measured in the region situated about 30-50 km north of the loftiest Himalayan peaks, nearer to them than to their border with Tibetan terranes at the Indus Tsangpo (Yarlung-Zangbo) suture. However, Molnar (1988) contradicted the contention of Hirn, Le'Pine and Sapin, and inferred that the results from explosion seismology indicate an increase in crustal thickness from the Indo-Gangetic plain across the Himalaya to southern Tibet. He is of the opinion that several seismological studies provide evidence consistent with a continuity of the Indian shield and its cold thick lithosphere beneath the Himalaya. Fault plane solutions and focal depths of the majority of moderate earthquakes in the Himalaya are consistent with their occurring on the upper surface of a gently flexed, intact Indian Plate that has underthrust the Lesser Himalaya roughly 80-100 km or more. It has also been argued that the mass deficit beneath the Indo-Gangetic plain, inferred from the deviation from isostatic equilibrium, probably exists because the Indian Plate is flexed down, and the excess mass over the Lesser Himalaya would be part of the mass load that flexes the earth down (Sinha, 1992).

MORPHOGENIC PHASE AND RECENT MOVEMENTS

Looking back into the history of evolution of the Himalaya, it has been established that along with the basin of sedimentation the deformation belt has progressively shifted southwards over time.

Gansser (1982), however, proposed that the morphology of the high mountains is invariably related to substantial vertical uplifts, not yet compensated by erosion. So, it is important to realise that morphogeny is a follow-up of orogeny by a remarkable change from mostly horizontal compressional movements to vertical uplifts (Sinha, 1992). It has also been estimated that the annual rate of uplift is approximately one-fifth of the horizontal movement during the orogenic phase. Again it is very interesting to note that the leucogranites of the Himalaya are concentrated within the highest peaks of the range from Nanga Parbat in the west towards Badrinath (Sinha, 1989), Mustang, Manaslu, Shisha Pangma, Everest, Makalu, and Bhutan in the east (Gansser, 1982). The metamorphic peaks related plutonism are the precursory 'happenings', which trigger the important morphogenic event. In the Himalayan and Tibetan region a substantial uplift of over 4,000 m since the Early Pleistocene has taken place at the rate of 5mm/year. The effect of such activity is reflected in the increasing monsoon in the south and desiccation of the main plateau in the north. The rapid uplift followed the acid magmatic intrusions of about 40 Ma which produces a relief of approximately 6,000 m height (Text-figure 10). Significantly, the molasse between the MBT and Himalayan Frontal Fault (HFF or MFT) is being considerably compressed and thus uplifted at the rate of 0.8 mm a^{-1} in Dehradun Valley (Valdiya, 1988). Differential movements along the faults by 20 to 30 m have given rise to depressions and rises in the Dehradun area, which, in turn have been filled with gravel of recent age.

MINERAL DEPOSITS

Jammu and Kashmir — Base metals, bauxite (aluminium), borax, coal, lignite, graphite, gypsum, Kaolin, limestone, sapphire, sulphur, cromite, and some atomic minerals.

Himachal Pradesh — Baryte, limestone, gypsum, rock salt and minor occurrences of antimony, asbestos, mica, beryl, clay, coal, copper, iron, lead, zinc, phosphorite, pyrite, etc.

Garhwal and Kumaun — Base metal, dolomite, limestone, gypsum, phosphorite, baryte, magnesite, mica, talc and some atomic minerals, etc.

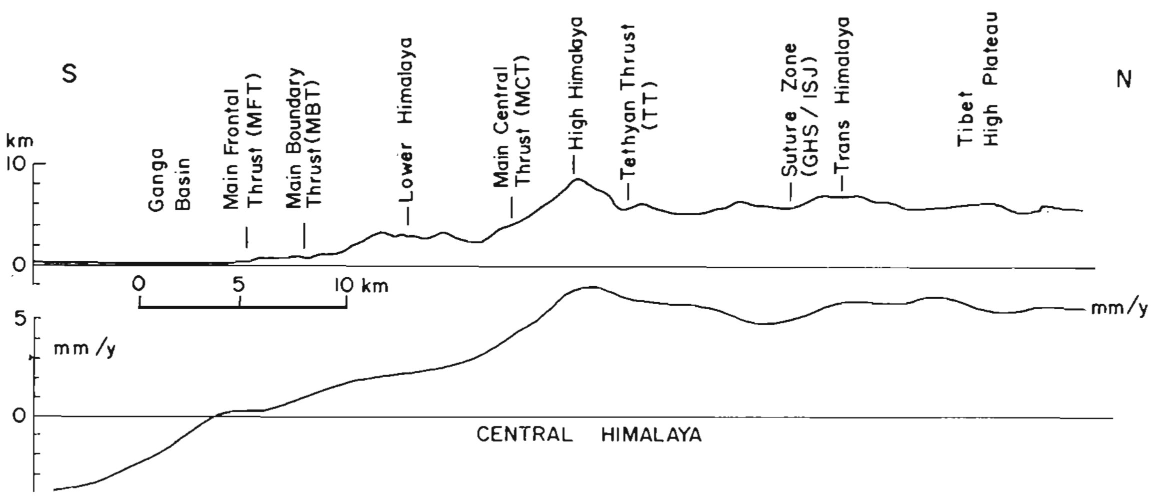
Sikkim — Copper, lead and Zinc, coal, limestone, steatite, graphite, etc.

Darjeeling — Kaolin, limestone, copper, lead, zinc, coal, etc.

Arunachal Pradesh — Lead, Copper, gold, pyrite, dolomite, graphite and flux grade limestone, etc.

CONCLUDING REMARKS

It has been contended that Himalayan mountain building is the product of a collision between the Indian and Eurasian plates which began during the Eocene epoch. This collision between the Indian and Eurasian continents has been considered to be one of the major tectonic event in the Cenozoic Era. An initial collision age of about 50 MA has been estimated with an average convergence rate of about 50 mm per year, although a direct measurement of the amount of shortening is often not possible and each method has yet remained controversial in the case of Himalayan orogeny and associated Tibet. On the basis of palaeomagnetic data, after considering the motion of the Indian Plate, it has been calculated that the total amount of North-South crustal shortening which followed the collision is in the order of 2600 ± 900 km. Crustal shortening in major orogenic belts involves, in addition to folding, one or several modes of deformation, subduction of continental crust in the wake of pre-existing oceanic subduction, and



Text-figure 10 — Morphogenic phase of Himalayan mountain building with estimated calculation of rise in mm/year (in Sinha, 1992) sideways escape of crustal blocks along major strike-slip fault.

Throughout the north of the Himalayan arc the basement crystalline complex is mainly overlain or overthrust by Precambrian to Tertiary sediments, whereas in the southern part Precambrian, Palaeozoic, Mesozoic and Tertiary rocks have been overthrust from N to S by a succession of three and four thrust sheets. The main axial lineament of the Himalaya (Sinha, 1981, 1989, 1992) is characterized by vertically dipping crystalline rocks, with divergence in the disposition of the southern and northern limbs intruded by younger granites. An uplift rate of 7 mm/year and the age of the main thrusting of 15 Ma have also been proposed.

The central Himalayan segment is divided from S to N into sub- parallel structural facies zones. The Main Boundary Thrust (MBT) plays the role of an important tectonic element dividing the Siwalik Molasse along the foot-hills of the Himalaya against the para-autochthonous and allochthonous tectonic units of the southern Himalaya. The Main Central Thrust (MCT) tectonically separates the carbonate para-autochthonous zone of the southern Himalaya from the metamorphosed crystalline 'Vaikrita Complex'.

The Vaikrita Central Crystalline Complex in turn is separated from the huge pile of the sedimentary Tethyan complex by the 'Tethyan Thrust' (TT). Further north the 'Indus Tsangpo Suture' divides the northern extremity of Himalaya from Karakoram orogenic belt. This Suture provided excellent conditions for the study of mantle remains on the oceanic crust with the occurrence of an ophiolitic Melange, which was the result of subduction of a continental type plate and abduction of oceanic material.

The intense compression from south to north by the Indian Plate made the crust overlap, and thereby became shortened thickened and isostatically adjusted to give rise to the Himalayan mountain chain.

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