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HIMALAYAS: THE COLLIDED RANGE. PRESENT KNOWLEDGE OF THE CONTINENTAL ARC

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> Je m'émerveille de l'inconnue que tu deviens
> Une inconnue semblable à toi
> Semblable à tout ce que j'aime
> Qui est toujours nouveau
>
> Paul Eluard

ABSTRACT. From a presentation of the geological and geophysical characteristics of the Himalayas, the author tries to draw the main features of mountain building. After a common Precambrian story, the Higher and Lesser Himalayas separate in two basins, the northern one on a continental thinned margin, the southern one intracratonic under shallow marine and continental influences. The beginning of this distinct evolution may be traced in both domains by a widespread spilite keratophyre episode. Caledonian and Hercynian periods are only marked by epeirogenic movements and limited volcanism. The four phases of deformation and the three intervenient phases of metamorphism (the third being a retrogression) all belong to the Tertiary orogeny.

The orogeny is composed of distinct cycles. The first ends with collision of the Indian and China plates at the beginning of the Tertiary; it leads to the formation of the Transhimalaya range and probably develops the first phase of folding and metamorphism in the Himalayas. The second cycle (Miocene) is thoroughly intracontinental with a very large scale subduction along the Main Central Thrust; such movements provide a simple and elegant explanation of the inverted metamorphism observed all along the Himalayas, together with particular tectonic features. The amplitude of the intracontinental subduction seems to be limited in time; it brings a high rate of erosion whose products are partly accumulated in the foredeep of the range. When movement resumes, after 10 m.y., it takes place along a weaker, more southerly line. The fossilized movements of the Himalayas are now in action along the Main Border Thrust.

INTRODUCTION

The Himalayan arc, very well defined geographically, extends over 2500 km, from west-northwest (Indus river, Nanga Parbat, 8125 m) to the east (Brahmaputra river, Namche Barwa, 7755 m), convex toward the south. On its northern side, it is separated from the Transhimalayan zone by the rather depressed area of the Indus-Tsangpo valleys. Toward the south it is fringed by the very low Gangetic plain. Between these limits, the Himalayas are 200 to 250 km wide, covering an area roughly equivalent to that of France.

According to Bordet (1961) and Gansser (1964), the Himalayas may be subdivided into five geographical and political transverse divisions; from west to east (fig. 1):

Punjab Himalayas (including Kashmir Himalayas), 550 km long, from the northwest syntaxis to the Sutlej valley;
Kumaun Himalayas (including Garhwal Himalayas), 320 km long, from the Sutlej to the Kali river;
Nepal Himalayas, 800 km long;
Sikkim and Bhutan Himalayas, 400 km long;

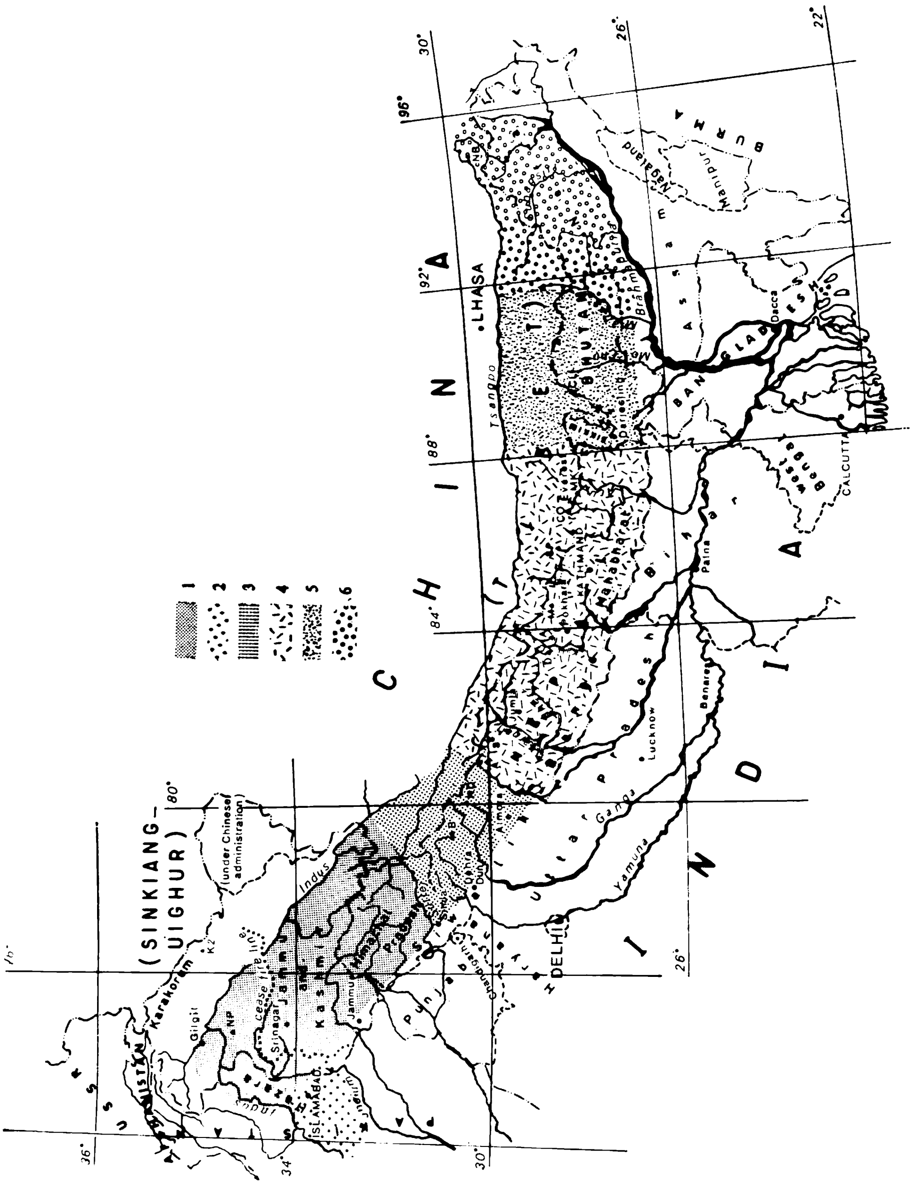

Fig. 1. Physical and political divisions of the Himalayas. (1) Punjab Himalayas, (2) Salt Range, (3) Kumaun Himalayas, (4) Nepal Himalayas, (5) Sikkim and Bhutan Himalayas, and (6) Nefa Himalayas.

Nefa (North East Frontier Agency) or Assam Himalayas, 400 km long.

In the western corner, the Salt Range is a southern prolongation of the Himalayas.

Longitudinally, the Himalayas can also be divided into three geological strips that one can follow along their entire length—from the south to the north:

Sub-Himalayas;
Lesser or Lower Himalayas;
Higher Himalayas in which one sometimes distinguishes the Tibetan or Tethys Himalayas as a separate north strip.

THE HIGHER HIMALAYAS SERIES

The Tibetan sedimentary series (Colchen, 1974; and fig. 2).—From Cambrian up to Eocene, the different systems have been recognized, though they often appear to be incomplete and reveal important gaps.

The base of the succession is unkown. The Cambrian is the oldest paleontologically recognized system in Kashmir and Spiti (*trilobites*). Elsewhere, pre-Ordovician series are metamorphosed. Ordovician is known through the entire Himalayas with a large development of carbonates. Silurian and Lower-Middle Devonian are paleontologically well defined (*graptolites, tentaculites,* . . .), but Upper Devonian has never been proved and may be missing. Lower Carboniferous is also well characterized, the "Lower Thini Chu formations" of Nepal being most probably the lateral equivalent of the "*Fenestella* shales" of the western Himalayas; an important and general discontinuity separates it from Permian. Permian generally begins with polygenic conglomerate levels slightly discordant (agglomeratic slates of Kashmir), of tilloidic nature (Kumaun and Nepal), often associated with spilitic volcanic rocks (Kashmir and Nepal locally). In some places (central Nepal), the disconformity is underlined by thin coal beds. *Fusulines* are restricted to Punjab Himalayas.

Triassic is predominantly carbonated with abundant *Ammonite* faunas. Jurassic is irregular in its development and shows frequent lacunas (Nepal); black schists with carbonated nodules (Spiti shales) occur generally in the upper part. Cretaceous is well developed from Kumaun to the Eastern Nepal Himalayas; it generally begins with plant-remain bearing levels (Nepal) followed by marine sediments interbedded with green sandstones containing basic volcanic debris. Eocene *Nummulites* bearing limestones represent the last marine sediment of the Higher Himalayas.

From Cambrian to Middle Devonian, no important interruption in the sedimentation happens, no disconformity, no echo, even feeble, of the Caledonian orogeny. On the contrary, the following period, up to Triassic, presents numerous lacunas, diversified lithofacies, basic volcanic activity; it may be considered the epeirogenic counterpart of the

Hercynian orogeny. Stability is never totally regained, but later epeirogenic movements are of more local extension.

The Tibetan Slab (a term coined by Lombard, 1958).—It represents the highly metamorphic and tectonized basement of the Paleozoic and Mesozoic Tethyan sediments. Therefore, the Tibetan Slab is a metamorphic and tectonic unit, a tectonic stage—corresponding to the "infrastructure". Its lower boundary lies in the MCT ("Main Central Thrust", Gansser, 1964). Its upper boundary crosscuts the Tethyan stratigraphy and has been arbitrarily set in Central Nepal with the pyroxene-amphibole isograde and the sudden opening of the tight isoclinal folds. As a consequence, there is no discordance between the Tibetan Slab and the Tibetan sedimentary pile.

The Tibetan Slab has been recognized all along the Himalayas since the beginning of geological exploration and so received a good number of local names such as the "Vaikrita group" of Spiti, the "Annapurna Gneiss complex" of Central Nepal, the "Central Crystalline" of Kumaun, the "Himalayan gneiss zone", the "Takhtstang gneiss" of Bhutan. How-

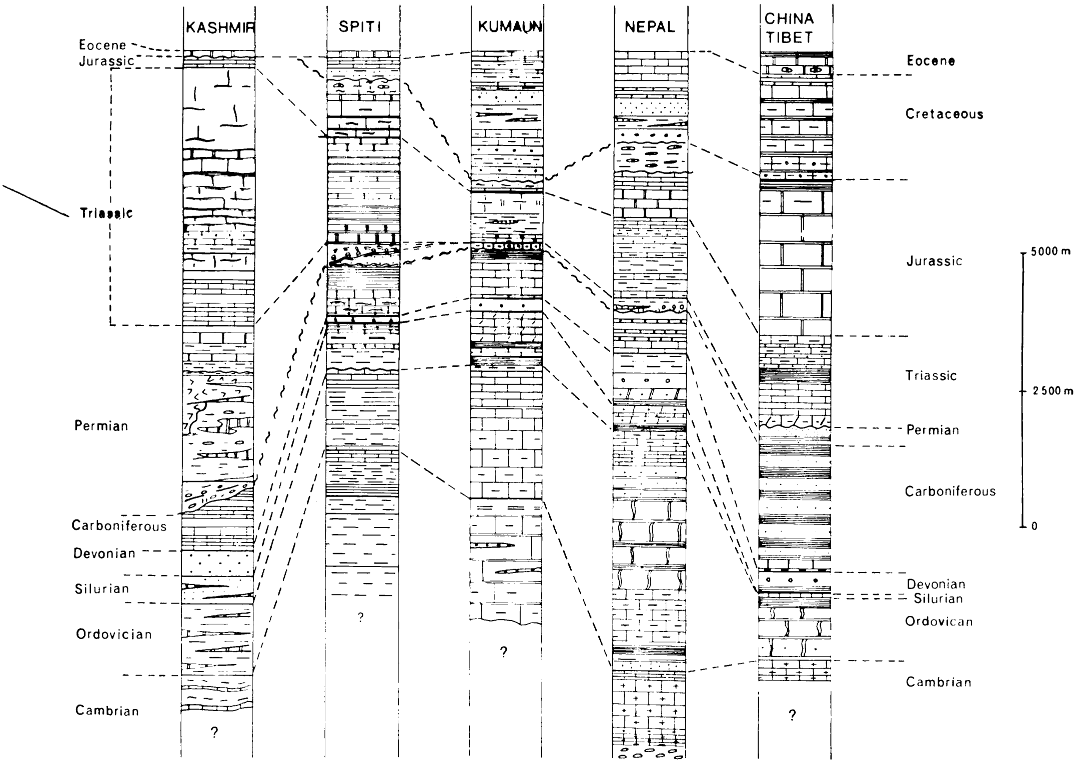

Fig. 2. Synthetic stratigraphical logs and correlation of the Tibetan sedimentary series (Colchen unpub.). Compiled from [Mu] An-Tze and others (1973). Bodenhausen and others (1969), Colchen (1971, 1974), Fuchs and Frank (1970), Gansser (1964), Mouterde (1971), Shah (1972), Singh (1973), Valdiya and Gupta (1972).

ever, its lithologic composition, tectonics, geochemistry, and even petrography are poorly known; the main reason for this is probably because of the difficulty of access to these rocks which constitute the main part of many steep southern slopes of the High Himalayan Range (fig. 3, opposite p. 6).

Let us present the Tibetan Slab in Central Nepal (Annapurna-Manaslu ranges) where we have been able to make a good number of detailed cross sections. There dipping homoclinally to the north-northeast (10° to 50°) the Tibetan Slab can be divided into three formations (fig. 4):

Formation I at the base consists of kyanite to sillimanite-garnet-two micas banded gneisses of pelitic to arenaceous composition. The apparent thickness of this formation varies considerably (say from 1400 m up to more than 5000 m) but continuously; when rather thin, only kyanite is present (Kali Gandaki); when it grows thicker, the sillimanite appears toward the top of the formation, together with increasing mobilization upward. Augen gneisses are frequent in this upper part. A series of thin lime silicate or/and quartzitic intercalations occur.

Formation II often begins with a coarse quartzite bed several tens of meters thick. It has a very dominant calcitic character and is composed mainly of an alternation of pyroxene (amphibole) calc gneisses and marbles. Toward the top Formation II is made up of more fine banded calc gneisses with an increasing amount of micaceous layers. The apparent thickness (about 3500 m) remains fairly constant.

The contact with Formation III (about 1500 m) is somewhat arbitrary and seldom well exposed. Formation III is characterized by a more pelitic to graywacke character and a frequent occurrence of feldspathic layers of an embrechitic type. The top of the formation is made of a 300 m thick level of coarse augen gneisses (up to 30 cm in diameter)

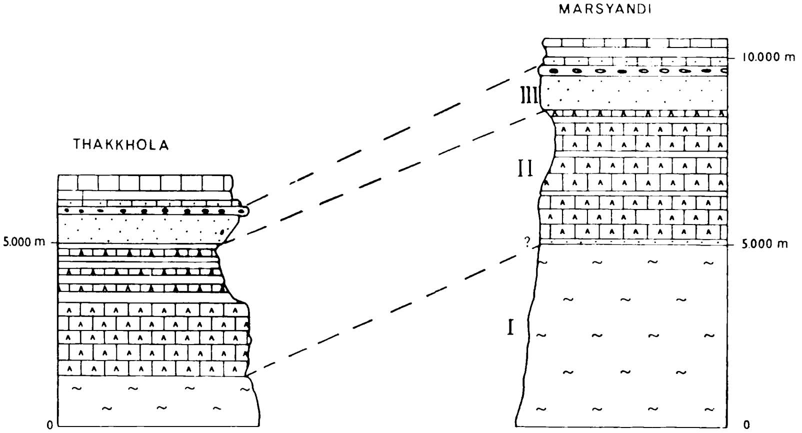

Fig. 4. Synthetic sections of the Tibetan Slab in Thakkhola and Marsyandi valley (Annapurna range, Central Nepal). Roman figures correspond to the three recognized formations. See text for details.

of very constant chemical composition. A few enclaves have been observed. On top of it, concordantly, a few beds of sandstone with graded bedding mark the transition toward a thick formation of metamorphic limestones (Larjung limestones, 1000 to 1500 m thick).

As suggested on cross section 2, figure 5 (opposite p. 22), it is possible that Formation II represents a huge recumbent folding of overlying Larjung limestones with the same chemical composition and a roughly doubled thickness. If such is the case, Formation III is equivalent to the upper part of Formation I. The size of such folds is on the order of 50 km but is not yet proven.

Both Formation II and Larjung metamorphic limestones exhibit a very low Mg and a very high K_2O and volatile content (dolomite sub inexistant, microcline frequent, scapolite up to 15 percent or more, micas, tourmaline). These chemical characters are consistent with a confined milieu of sedimentation and may be parallelized to the Salt Range Cambrian salt deposits. Larjung limestones are known to be older than the subincumbent Lower Ordovician Nilgiri limestones (table 1) and so could well be of Cambrian age. According to the same hypothesis, Formation III (and top of Formation I) augen gneisses could represent the trace of some acid volcanic activity toward the base of Cambrian, and Formation I some flysch-like deposit during late Precambrian time (compare the Lesser Himalayas). This hypothesis enables one to make thorough correlations of the Tibetan Slab along a good part of the known Himalayas (from Kumaun to Bhutan).

THE LESSER HIMALAYAS FORMATIONS (TABLE 1)

In the Lesser Himalayas we have to distinguish between two groups of formations:

The Blaini-Krol-Tal group, paleontologically dated though fossils are scarce.

The pre-Blaini group largely unfossiliferous.

In addition, some outcrops of fossiliferous Tertiary formations appear here and there, mainly in the southern part of Kumaun and Nepal Himalayas.

The lack of fossils.—There is a general absence of fossils in the Lesser Himalayas. This lack can be explained partly by:

the milieu of sedimentation, unpropitious to the development of life and conservation of fossils;

the metamorphism and tectonics, whose intensity contributes to wipe out fossil forms;

the non-thorough state of field investigation, the lack of search for microfossils, nanofossils, pollens . . . and the poor knowledge of certain forms.

However, one should stress the paucity of fossils of the Infra Krol formation of the Lesser Himalayas; this is in contrast with the Sub Himalayas and the Higher Himalayas and for many authors is an indication of a preCambrian time of deposition.

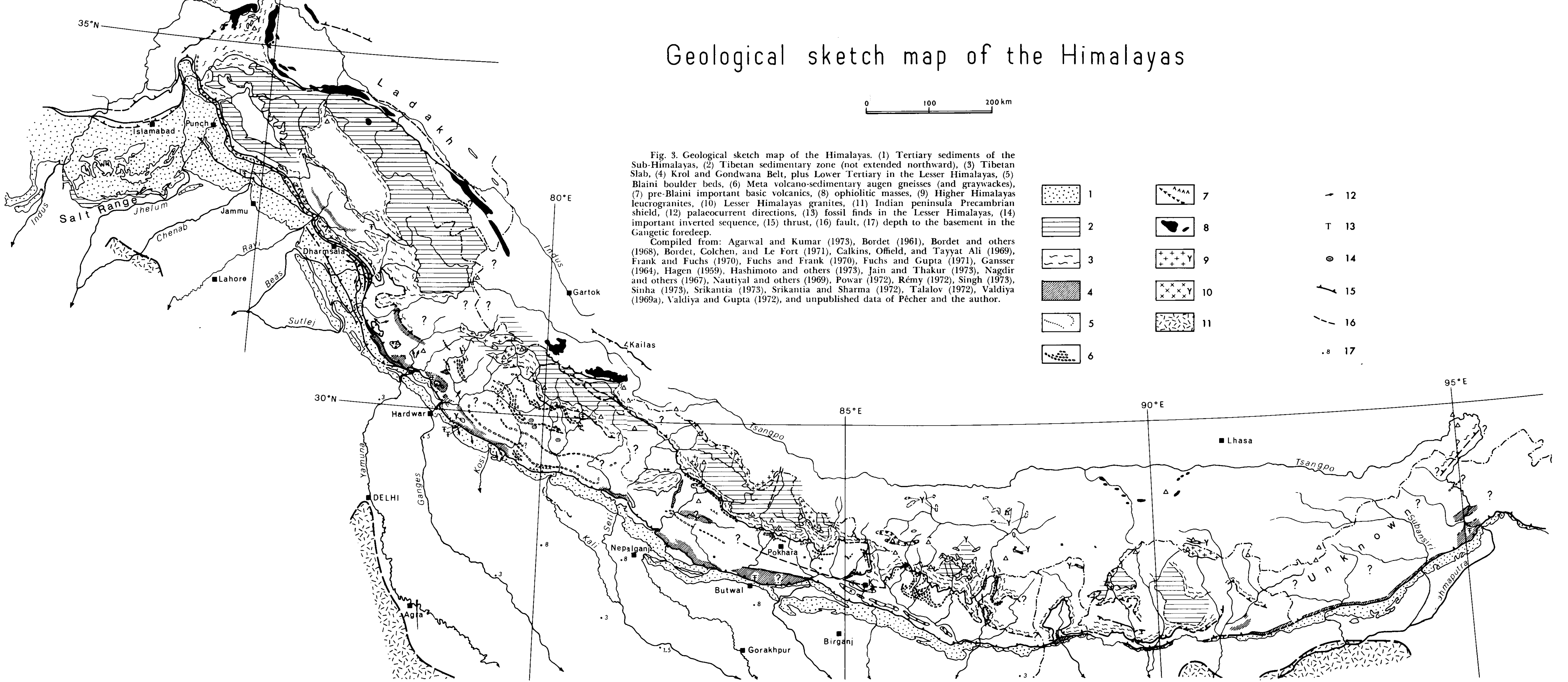

Fig. 3. Geological sketch map of the Himalayas. (1) Tertiary sediments of the Sub-Himalayas, (2) Tibetan sedimentary zone (not extended northward), (3) Tibetan Slab, (4) Krol and Gondwana Belt, plus Lower Tertiary in the Lesser Himalayas, (5) Blaini boulder beds, (6) Meta volcano-sedimentary augen gneisses (and graywackes), (7) pre-Blaini important basic volcanics, (8) ophiolitic masses, (9) Higher Himalayas leucrogranites, (10) Lesser Himalayas granites, (11) Indian peninsula Precambrian shield, (12) palaeocurrent directions, (13) fossil finds in the Lesser Himalayas, (14) important inverted sequence, (15) thrust, (16) fault, (17) depth to the basement in the Gangetic foredeep.

Compiled from: Agarwal and Kumar (1973), Bordet (1961), Bordet and others (1968), Bordet, Colchen, and Le Fort (1971), Calkins, Offield, and Tayyat Ali (1969), Frank and Fuchs (1970), Fuchs and Frank (1970), Fuchs and Gupta (1971), Gansser (1964), Hagen (1959), Hashimoto and others (1973), Jain and Thakur (1973), Nagdir and others (1967), Nautiyal and others (1969), Powar (1972), Rémy (1972), Singh (1973), Sinha (1973), Srikantia (1973), Srikantia and Sharma (1972), Talalov (1972), Valdiya (1969a), Valdiya and Gupta (1972), and unpublished data of Pêcher and the author.

TABLE 1

Correlations of the Lesser Himalayas formations. Compiled mainly from Bhargava (1972), Frank and Fuchs (1970), Gansser (1964), Jain and Thakur (1973), Nagdir and others (1967), Raha and Sastry (1973), Srikantia (1973), Srikantia and Sharma (1972), Valdiya (1969a), and Le Fort and Pêcher (unpub. data).

Punjab		Kumaun		Nepal		Sikkim-Bhutan	NEFA	
				Western	Central			
Fossiliferous section Beginning middle Cambrian (see table)		Tal (2200)		Tal ∓ (~~~)				Cretaceous to late Triassic
		Krol (1000-1300)		Krol (500-2000)				Triassic (?)
		Infra-Krol (600) Blaini		Infra Krol (0-100) Blaini (20-1500)		Gondawa ∓ boulder beds	Gondawa ∓ boulder beds	Upper Paleozoic
↓	Chail	Sanjauli (1600) Chhaosa (1300)	Naghtat (1500) Chandpur ○○○ (1300-800)	Frank and Fuchs Naghtat (20-1000) Chandpur-Chail (up to 300) ~= Caledonian Jangla group	Upper formation (1400) ○○○ Lower formation (3000) Midland group	Buxa (dolomite) (600) Jainti (quartz) (600) ○○ Sinchu La (ss.+gw.) (750) Buxa group ○?○	~~~ ? Abor traps Miri group ↓	Lower to Middle Paleozoic
Dogra Hazara slates (2500)	Simla slates	Kunihar (500) Basantpur (1000)	Mandhali (400-1000)	Frank and Fuchs Simla slates (>1000)		Daling	Siang group ?	Epiprotozoic to Eocambrian
Salkhalas (?) - Jutogh (2000-3000) (500) (also Jammu lms. ∓)		Shali (lms.) (3400)	Deoban (lms.)	Shali (lms.)	lms.			Neoprotozoic (Riphean)
Sundernager (quartz) Darrang traps [base unknown]		Sundernager-Berinag (quartz) Bhimtal volcanics [base unknown]			qz. + volc.			

Figure 5 gives a synthetic log of the Kumaun section; figure 4 gives a typical example of Central Nepal log. Indications of thickness are given in meters (brackets).

Here are, up to 1973, the main paleontologic discoveries:

Middle Riphean (?) columnar stromatolites belonging predominantly to the *Baicalica* group from the Pithoragarh limestones of Kumaun (Valdiya, 1969b; Misra and Valdiya, 1961), Middle Riphean to Vendian stromatolites from the Simla series, lower to Middle Riphean algal stromatolites from the Jammu limestones (Raha and Sastry, 1973), and lower to Upper Riphean stromatolites from the Shali limestones of Simla Hills (Sinha, 1973).

Remains of gymnospermous wood in the upper phyllites of undifferentiated Chandpur-Naghtat formation of Kumaun (Power and Phansalkar, 1971).

An unique Salopina Brachiopod from a rolled specimen of white quartzite (Naghtat?) that would set an Upper Silurian to Lower Devonian age (Gupta, 1972).

Correlations in the pre-Blaini group.—Lithologic correlations are rendered uncertain because of the absence of fossils in tectonically and metamorphically complicated regions. Fortunately, the formations have a very wide extension and may be traced, usually on hundreds of kilometers. Still, lateral variations of lithology and differences in thickness do exist; in part they are responsible for the incredible prolixity of local names given to every member of each local section.

Numerous tentative correlations have been suggested by Gansser (1964); more recent attempts include those of Valdiya (1969b), Frank and Fuchs (1970); Jain, Bhandari, and Bhanot (1971), and Bhargava (1972) for the Krol Belt; Saxena (1973).

Correlations lie on resemblance of definite levels or set of lithologic units, supposedly unique:

Boulder beds have been used since the beginning of Himalayan geology as a fundamental marker of glacial origin and Permo-Carboniferous age by comparing them to the Indian Peninsular Talchir boulder beds. Unfortunately, it has been found that they were not unique and that their glacial origin is not certain (Bhattacharya and Niyogi, 1971; Valdiya, 1973).

Stromatolites bearing limestones, definite levels of quartzites, shales, and graywackes with characteristic sedimentological features, banded iron formations (O'Rourke, 1962) have been diversely used. They have resulted in a lot of cross correlations.

The metamorphic grade also has been used to correlate widely separate areas and in the dating of formations (Pilgrim and West, 1928, in the Jutogh's for example).

In Central Nepal, the Midland group of meta-volcanics and sediments[1] comprises (fig. 6):

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[1] Other names have been used by previous workers, such as the Nakakot "nappes" of Hagen (1959), the Kunchha series and Scale zone of Bordet (1961), Bordet, Colchen, and Le Fort (1972), corresponding respectively to the lower and upper formation of the group, the Chails and "lower crystalline nappe" of Fuchs and Frank (1970), the Midland metasediments and crystalline sheets of Hashimoto and others (1973). These names have to be dropped because of their tectonic implications and because of the misunderstanding of the nature and role of the so called "crystallines" (see p. 25).

A lower arenaceous and phyllitic formation with basic volcanic intercalations (amphibolites, amphimolitic schists) representing at the most 2 to 3 percent of the total thickness. A very widespread acidic horizon of augen gneisses of volcano sedimentary origin (Ulleri augen gneisses, 0-1000 m) is found toward its top. The top of the formation is made of a persistent white quartzite (Gandrung quartzite, 30 to 150 m).

An upper formation made of limestones and dolomitic limestones interbedded with schists and carbon bearing schists together with a few beds of quartzite.

The group has been investigated and mapped in detail by Pêcher and the author. From the western side of Kali Gandaki to the northeast of Kathmandu (200 km east-west) and from the MCT to the south of

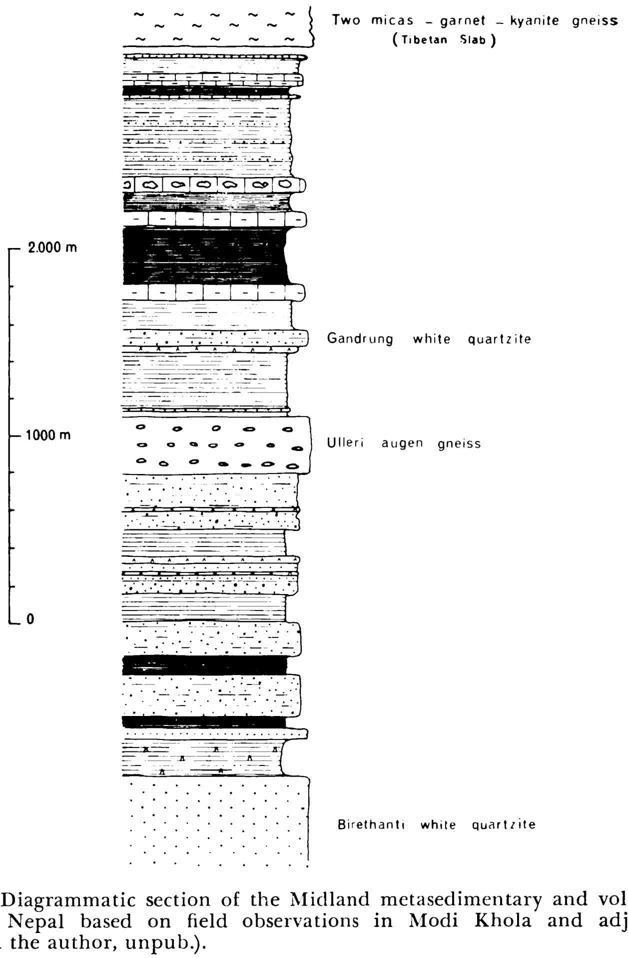


Fig. 6. Diagrammatic section of the Midland metasedimentary and volcanic group of Central Nepal based on field observations in Modi Khola and adjacent areas (Pêcher and the author, unpub.).

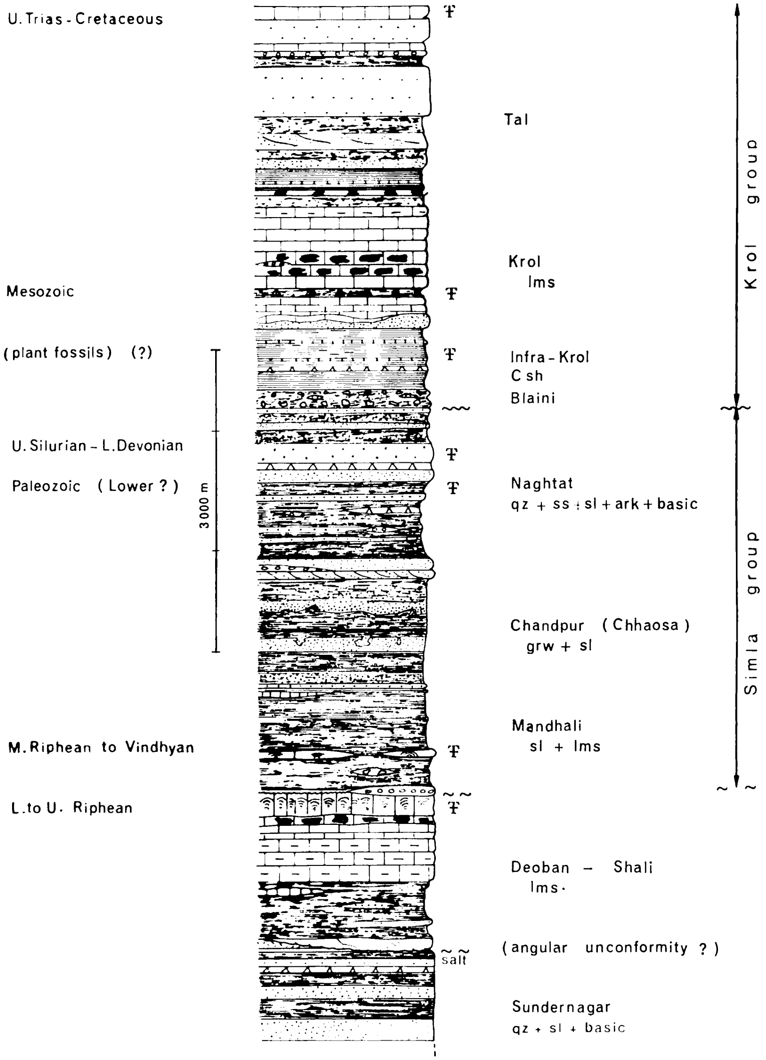


Fig. 7. Litho-stratigraphy of the Lesser Himalayas' formations of Kumaun. Compiled from Bhargava (1972), Bhattacharya and Niyogi (1971), Gansser (1964), Gupta (1972), Maithani (1972), Powar and Phansalkar (1971), Sinha (1973), Srikantia (1973), Srikantia and Sharma (1972). Fossil finds are tentatively shown with age attribution on the left: ark = arkose, csh = carbon bearing shale, grw = graywacke, lms = limestone, qz = quartzite, sl = slate, ss = sandstone. Names of formations as in table 1.

Pokhara at the latitude of the east-west valley of the Trisuli (40 km north-south) it covers an area of some 6000 km^2. But from authors' descriptions (Bordet, 1961; Frank and Fuchs, 1970; Hashimoto and others, 1973), the Midland group extends in Nepal from the western to the eastern border (fig. 3).

Table 1 tries to give a view of the present possible correlations, taking into account the latest fossil finds and data; figure 7 illustrates a synthetic log of the Kumaun formations. It is an attempt and should not conceal some of the main unsolved problems linked to a better datation of the formations, a better study of the sedimentological and geochemical characterization, and a thorough knowledge of their tectonics (inverted units in particular).

The volcanosedimentary origin of the augen gneisses.—The existence of sheets of augen gneiss amidst sedimentary formations has puzzled Himalayan geologists since the beginning. These sheets are thoroughly foliated and show strong imprints of cataclasis. Their thickness is highly variable, and they are almost lenticular when mapped. Due to the high feldspar content, they have been taken for high-grade metamorphism products ("crystallines"), either tectonically emplaced or metasomatically granitized in situ (or both). Some workers have even claimed that they were remnants of Hercynian, Caledonian, or Precambrian intrusive granites (see Saxena, 1973a; also Gansser, 1964, maps some of them as granites-granodiorites mostly Pre-Miocene).

Figure 3 shows approximately how far the author has been able to trace the augen gneisses in the Himalayas according to the available literature and taking into account incomplete descriptions (1200 km roughly from western Kumaun to eastern Bhutan, but Nefa Himalayas are poorly known).

Thrusted contacts are generally assumed arbitrarily (Gansser, 1964, p. 100), but actually, no discordant or sharp contacts have been observed (Gansser, 1964, p. 99; Das and Pande, 1973); instead there is a grading of micaschists to schistose gneisses. At a mapping scale, there is a remarkable lithologic control of the gneisses by quartzite, carbonaceous schist levels, and more or less dolomitic limestones that play a marker part all along the 1200 km recognized (Gansser, 1964, p. 100; maps of Hashimoto and others, 1973, p. 20, 40, and 73, figs. 4 and 5).

When augen gneiss masses are lenticular, as in Central Nepal, blue purple quartz bearing microconglomerates are found in between, with the same lithologic position (Pêcher and author's observations). In the Bhikiasen area (Kumaun) S. P. Saxena (1973) observed that the Almora crystallines pass westward to the slaty and phyllitic Chandpur formation.

Inside the mass itself there are marked changes in the composition, numerous intercalations somewhat lenticular of schists and quartzites, and considerable variations in the grain size and mineralogical composition; graded beddings are likely to be suspected. Powar (1972, in northern Kumaun) observed large ellipsoidal grains of purple quartz, up to 10 cm, grading upward into well bedded augen gneiss. Thin bands of schists often alternate with the gneisses (Das and Pande, 1973).

The feldspar porphyroblasts are mainly rounded but sometimes subrectangular in shape. Authors have hardly been concerned with the nature of the feldspars; it can be K feldspar, but in several cases, it appeared to be only pure albite (Harvard microprobe). This observation takes care of some published chemical analysis with a high Na_2O content (see Kashyap, 1972, Ramgarh area for example). Zircons have been studied by Powar (1972); they include both euhedral and rounded grains. Concerning other minerals, they show no metamorphic disconformity with the surrounding paragenesis, but metamorphic isogrades seem sometimes to be reversed, according to the regional metamorphic pattern.

Tectonically, the highly heterogeneous augen gneisses are strongly foliated and lineated (mineral lineation), but they show the same tectonic pattern as the surrounding or intercalated rocks.

A few absolute age data have been published so far; unfortunately they are not very accurate, and the petrographic field denomination varies from gneiss to "granite" (table 2). The closer to the MCT, the younger the age, in zones of mesozonal reverse metamorphism (Ulleri, East Nepal, Trisuli?) the rocks were subjected to a strong Himalayan rejuvenation. The other determinations point to a Paleozoic age of formation, somewhere around Devonian (I.U.G.S., 1966). Mobilization of deeper situated horizons may be responsible for the occurrence of some Lesser Himalayas' granites.

According to the above observations, there is no reason to build tectonic nappes or injected scales of old crystalline material (Hagen, 1969; Bordet, 1961; Gansser, 1964; Hashimoto and others, 1973; and so on) to explain the presence of the Lesser Himalayas' augen gneiss masses. They are the result of acid volcanic activity sedimented within the Lesser Himalayas' sequence. They constitute a definite lithologic horizon broadly equivalent to the upper part of the lower Midland metasedimentary formation of Nepal or to the Chandpur formation of Kumaun. They are often accompanied by amphibolites and amphibolitic schists of spilitic nature and thus seem to be part of a spilite-keratophyre episode within the Paleozoic (?) filling of the Lesser Himalayas' basin. The spilite-keratophyre nature of the volcanism is consistent with its taking place on top of a sialic basement (Rocci and Juteau, 1968). According to paleontological and absolute age evidences, it could well be of Siluro-Devonian age and so could be the marker of the rebound of the Caledonian orogeny claimed by Fuchs (this solution is the one represented on table 1). Another possibility is that the Lesser Himalayas' augen gneisses are coeval with the pre-Ordovician augen gneisses of the Tibetan Slab (figs. 4 and 5). It is an interesting possibility, as it would link the two domains and mark the beginning of their specific sedimentological history.

TABLE 2

Available age determinations of Lesser Himalaya augen gneisses

Sample No.	Rock denomination	Location	Author	Method	Analyzed sample	Age (10^6 yr)
KA 122	Ulleri augen gneiss	Central Nepal Lower Midland granite	Krummenacher 1971	K-Ar	biotite	53
KA 352	Almora augen gneiss	Kumaun	”	”	K feldspar	315 ± 5
KA 351	Almora “granite”	”	”	”	”	363 ± 5
KA 102	granitic pebble Eocene conglomerate	west Nepal	”	”	”	354
	metasomatic augen gneiss	east Nepal (27°24′,87°38′)	Talalov, 1972	”	total rock	120
	Trisuli “granite”	central Nepal (27°48′,84°55′)	”	”	”	126
	Dandeldhura “granite”	west Nepal	”	”	”	265
PH 51-4	Mandi “granite”	Punjab	Jäger, Bhandari, and Bhanot, 1971	Rb-Sr	”	500 ± 100

PALEOGEOGRAPHIC REMARKS

Compared to the Lesser Himalayas, the Higher Himalayas appear to be a relatively homogeneous marine paleogeographic domain, with a strong Tethian imprint. However, Gondwanian influence crept in during the Permo-Carboniferous times and seemed to intermingle with strong Tethian characters. Only the southern part of the Tibetan realm is known in some detail; as a whole, dominant detrital and platform carbonate lithofacies precede and follow emersions of rather short duration (Gansser, 1964; Kummel and Teichert, 1970; Colchen, 1974).

The thick pile of sediments of the Higher Himalayas is typical of a platform domain. It may have accumulated on a thinned margin along the edge of a continent widely open on the Tethys. The very long subsiding history, spanning a length of time on the order of 5×10^8 yrs has permitted the slow accumulation of several tens of kilometers of mainly shallow water sediments (fig. 2). Isostatic equilibrium was always almost reached, and rate of subsidence was probably directly related to density distributions as suggested by Kinsman (1973). The creation of this northern Indian margin is a very poorly documented question; yet it is responsible for the later sediment deposition history including its well ordered north to south and east to west variations.

Though merely hypothetical, one may wonder if the history of the Higher Himalayas did begin in Late Precambrian times as a cratonic interior basin or with the rifting of the Pangaea continent ancestor, along a line roughly parallel to the present Himalayas trend. According to the second hypothesis, the Higher Himalayas would represent the continental terrace of an old trailing margin of Atlantic type, a trailing margin sedimentary basin. The occurrence of evaporite in the Cambrian of Salt Range (as well as in the Tibetan Slab?) would mark the early history of the newly rifted basin (Kinsman, 1973). The northern oceanic crust formed during this process has been totally absorbed by the later plate history with the exception of a few exotic blocks and of the Indus-Tsangpo suture.

The thickness of the Lesser Himalayas sediments is important (up to 9.2 km for the pre-Blaini according to Hashimoto and others, 1973, and even 50 km for Talalov, 1972, p. 227!). They constitute a remarkable series of rocks deposited in shallow water, tidal, lagoonal, or even continental conditions with a few exceptions. Flysch-like turbiditic formations have been described; Simla slates and their lateral equivalents (Dogra slates) being the main one; Valdiya (1970) called them "the Precambrian flysch of the Himalayas"; yet this distal facies of a shaly flysch shows algal limestones in the midst (fig. 7).

The deposition took place in several basins more or less parallel to the present Himalayan trend (Frank and Fuchs, 1970; Jain, Banerjee, and Mithal, 1971; Bhargava, 1972) that probably became individualized after the Simla slates sedimentation.

Valdiya (1969a) has emphasized the similarity of the "unfossiliferous" sediments of the Lesser Himalayas to the corresponding groups of late Precambrian age, not only of India (Vindhyans and Pre-Vindhyans) but also of Burma, China, north and western Australia, and even America. Since Precambrian stromatolites are more and more documented, it seems conceivable that the likeness between the India Peninsula and Lesser Himalayas' Precambrian sediments is not casual and that both were part of the same basin system during these early times.

Following West, it is a widely held opinion that the Himalayas were formed of two major geosynclines—the Lesser miogeosyncline and the Higher eugeosyncline—running parallel and separated by a cristalline axis or Central Himalayan geanticline (Wadia, 1957). In brief, the Himalayas very much resemble the Alps (Hagen, 1959; Krishnaswamy and Swami Nath, 1965; Valdiya, 1969c). In our opinion, unless the term *geosyncline* is taken in the broad acceptance of any (elongated) sedimentary basin of large dimensions, regardless of its setting and development, there is no major reason to use it in the Himalayas, no more than in the Sahara basin for example. In fact, two major basins existed, separated by a ridge that provided the material for detritic deposition on both sides (north of the Lesser Himalayas and south of the Higher Himalayas). Possibly the ridge came into existence in the Late Precambrian-Early Paleozoic or Siluro-Devonian times and was accompanied by volcanic activity.

THE SUB-HIMALAYAS DEPOSITS

Table 3 gives an idea of the Tertiary series of the Sub-Himalayas. Whilst the Subathus made of shales, limestones, sandstones, and occasional carbonaceous shales represent a shallow marine, neritic, and lagoonal environment, the Dagshais made of shale and sandstones represent a transitional coastal environment with a dominant terrestrial influence (Bhattacharya and Niyogi, 1971). The following Siwalik series represent an entirely terrestrial sequence with an overall decrease in the rate of subsidence which controls much of the sedimentological and fossil density variations; the thickness is considerable (say 5000 m) (Johnson and Vondra, 1972). They represent a molassic basin very similar in nature to the present Ganges' plain sediments. A few paleocurrents are shown on figure 3.

Some idea about denudation and erosion of the Himalayas is given by the study of the metamorphic accessory detrital minerals. The given figure resembles a progressive unroofing of a normal metamorphic suite (Raju, 1967):

A. Epidote-staurolite impersistent at the beginning of the Siwaliks.

B. Kyanite (and staurolite) locally abundant from the base of the middle Siwaliks, together with the occurrence of a few pebbles of granitic rocks (Nagdir and others, 1967).

C. Hornblende and sillimanite generally characteristic of the Boulder conglomerate stage (upper Siwaliks).

However, this normal sequence sets a problem, as a good part of the Himalayan isogrades are inverted.

Tertiary formations are also known to occur in the Lesser Himalayas as small basins or thin elongated belts, such as the upper Cretaceous-Eocene "Tosh Suite" in south Nepal (Talalov, 1972, p. 32), the lower Tertiary Barikot basin of west Nepal (Fuchs and Frank, 1970), or the very large lacustrine and glacio-fluvial Karewa deposits correlated with three different glacial cycles, of Plio-Pleistocene age (see Farooqi, 1973).

GRANITES

Apart from the Transhimalayas where a variety of plutonic and effusive rocks have been documented, Himalayan granites are scanty

TABLE 3

Tertiary nomenclature of the Sub-Himalayas compiled from various sources (indicative thicknesses in meter)

Age (10^6 yr)	Stages		NORTHWEST	CENTRAL HIMALAYAS	
				Sub group	Formation
	Holocene		(Terraces)		(Terraces) (up to 1000)
	Pleistocene		Upper Karewa (300-500)		
1.5-2					Upper (Boulder conglomerates) (1000-2400)
		U			
	Pliocene	M	Lower Karewa (700-1600)	Siwalik	Middle (L-U alternations) (1500-4500)
		L	?		
7		U			Lower (Nahan) (1100-1600)
12					
	Miocene	M			Kasauli (600)
18-19					
		L		Dharamshala	
26					Dagshai (?-1000)
		U			
	Oligocene	M			
31-32			Murree (>2000)		
		L			
37-38					
		U			
45					
	Eocene	M			
49					
		L	Subathu	Subathu (30-200)	
53-54					
		U			
58.5	Paleocene				
		L			
65					
	Cretaceous				

and of a very homogeneous type. They occur as two dotted lines of massifs, one in the Higher Himalayas, close to the main range, one in the Lesser Himalayas, close to the MBT (fig. 3).

The Higher Himalayas leucogranites (Le Fort, 1973, 1974a, c).—They build up elongated massifs with a more or less parallel trend to the general elongation of the range. In the upper part, the granite in large concordant sheets inserts itself into the surrounding formations. At least some of them have a zonal arrangement of muscovite-biotite foliated and muscovite-tourmaline non-foliated granites. Lower contacts appear to be gradational with increasing density of surrounding rock enclaves. Homogeneity of the granite, not only in single massifs but all along the Himalayas, corresponds to eutectic composition. They exhibit a huge aplopegmatitic network of dikes, pneumatolitic secondary reactions, and are set on regional mesozonal metamorphic domes. Their upper contacts show a very reduced metamorphism, though they intrude up to Jurassic in Bhutan and Cretaceous in Nepal. The anatectic roots of the granites lie in Formation I of the Tibetan Slab. Their absolute age is very constant and ranges by K/Ar methods from 14 to 17 ± 2 m.y. B.P. (Middle Miocene).

The granites of the Lower Himalayas.—Surprisingly, they are not well documented. They seem to be mainly muscovite-biotite and/or tourmaline porphyroblastic plutons with a regional concordant setting and a local intrusive character. They may be divided into two categories: foliated and non foliated. Contact metamorphism is somewhat limited, but regional metamorphism isogrades emphasize their shape (see fig. 9).

Pneumatolitic variations are frequent, but the aplopegmatitic network is rather limited as compared to the Higher Himalayan granites.

Absolute age measurements (table 4) show a wide range of values partly explainable by the diversity of methods and the intense tropical weathering, and rejuvenation of older feldspathic formations is also possible. These ages are globally older than the metamorphism dated in the surrounding country rocks (see Krummenacher, 1971).

TECTONICS

Deformational events.—Many papers have been written that deal with tectonic analysis in different regions of the Himalayas. At first, one is surprised by the real homogeneity of the observations (table 5).

Four main sets of deformation have been recognized, two major (D_1, D_2) and two minor (D_3, D_4). Table 5 suggests they can be followed throughout the entire Himalayas with the exception of D_1 which has not been observed in the Sub Himalayas nor in the Krol and Gondwana belts of the southern fringe. No deformation prior to D_1 has been noted. On the other hand, D_1 does affect mesozoic formations, mainly in the Tibetan sedimentary zone, up to Upper Cretaceous, but also in the northern part of the Lesser Himalayas where calcschists and limestones contain middle Jurassic marine fossils highly distorted by S_1 (Powell and Conaghan, 1973a).

TABLE 4

Selected age determinations of Lesser Himalayan granites

Granite	Location		Method	Analyzed sample	Age (10^6 yr)
Dharam shala	Punjab	Nagpal, Gupta, and Mehta, 1973	Fission-track	apatite	4.7 ± 1.1
Mandi	"	"	"	"	36.0 ± 1.2
"	"	Jäger, Bhandari, and Bhanot, 1971	Rb/Sr	total rock	20.5 ± 0.8
"	"	"	"	biotite	24.0 ± 2.4
"	"	"	"	"	31.4 ± 2.9
Chor	Kumaun (30°49′,77°23′)	"	"	"	50 ± 10
"	"	Nagpal and Nagpal, 1973	Fission-track	muscovite	48 ± 24
"	"	Nagpal, Gupta, and Mehta, 1973	"	apatite	15.0 ± 0.2
Palung	Central Nepal (27°29′,85°04′)	Khan and Tater, 1970	K/Ar	muscovite	51 ± 3
"	"	Krummenacher, 1971	"	?	48

Consequently, at present, we have no evidence of pre-Tertiary strong deformation. It is an important point, very much debated by defenders of the existence of older orogenies, such as Fuchs (1968) who suggests a Caledonian orogeny for paleogeographic reasons or Saxena (1973a, b) who suggests four pre-Tertiary orogenies. This absence of pre-Tertiary orogenic deformations does not preclude the existence of important epeirogenic movements; a good example of such movements is given by the Eocene Subathus formation that unconformably overlies the Precambrian Simla formation west of Solan, Himachal Pradesh (Bhattacharya and Niyogi, 1971).

All four deformations are probably related to large scale structures. However, large scale expressions of D_1 have not yet been detected in the Lesser Himalayas. D_1 and D_2 are sometimes considered to be stages in a continuous deformation, sometimes separated by a large gap of time and metamorphism, especially when not coaxial. In the Higher Himalayas, F_1 folds are sometimes overturned to the north-northeast in definite areas (see fig. 5; Bordet, 1961; Fuchs and Frank, 1970; Colchen, 1971; Bordet, Colchen, and Le Fort, 1972). It seems to correspond to an important thickening of the sedimentary sequence toward the south and thus could be achieved by the same system of compression but applied to non-horizontal surfaces of reference. D_3 and D_4 are the most conspicuous through the Lesser Himalayas, as they give kilometric synclines and anticlines ordered in a broad or tight pattern, depending on the region, that have resulted in culminations and depressions of the previous folds and thrusts.

How to recognize a thrust (and say it)?.—Well known as a major characteristic of Himalayan geology, thrusting phases have been multiplied, invading the tectonic literature of the past decades with an endless list of names. Yet with a few exceptions (Naha and Ray, 1971), it is very difficult to understand which criterion actually points out their existence. Here are some of the effects suggested by various authors:

A. Abnormal superposition (very difficult to prove unless fossiliferous formations are involved, as in the case of MBT) suggested on the basis of an assumed stratigraphic sequence.

B. Sharp modification of the lithology.

C. Cataclasis and diaphtoresis on a large scale.

D. Injection of basic sills (amphibolites).

E. Apparent jump in the intensity of the metamorphism.

F. Reverse metamorphic zonation.

G. Retrogression effects.

H. Change in the tectonic pattern.

I. (Previous recognition).

These features stumble generally against the very peculiar character of the Himalayan thrusts. Thrusted and thrusting formations are in general accordance; due to their deep seated origin and the metamorphic environment, cataclasis is seldom well expressed; a jump of metamorphism in such a relatively high pressure type metamorphism is very difficult to prove, and mistakes have arisen due to the confusion between grade of metamorphism and variation in the chemical composition of the formations (feldspathic charge for example).

In Central Nepal, south of the Annapurna Range, the following observations have been made concerning the MCT (Pêcher and author, unpub.):

A. The lithology changes in 10 to 20 m from thinly bedded alternations of metamorphic gray standstones, white quartzites, carbon bearing schists, brown to green schists to an upper monotonous arenaceous pelitic formation. No basic sills appear (fig. 4).

B. Within a few meters of this lithologic change, crystals of kyanite appear upward. Both formations show a great abundance of milky quartz segregations. Retrogression has affected the major part of the zone (chloritization, chlorite, and muscovite rims around garnet and kyanite, epidote, amphibole instead of pyroxene). A very peculiar spinach green mica forms large flakes or even small monomineralic beds almost determined as eastonite (Kingery, ms).

C. Rocks are highly sheared on several tens or hundred of meters. The most conspicuous structural element is a north-northeast—south-southwest mineral streaking lineation (see below). One also finds striated planes of slipping that dip more strongly toward the north than the general schistosity (S_1-S_2).

The "meridian" mineral lineation.—A mineral streak lineation, similar to the one mentioned above in the southern Annapurna region

TABLE 5

Summary of the small scale deformations of the Himalayas according to its main divisions. Synthetized from various sources, particularly: Bhattacharya and Niyogi (1971), Calkins, Offield, and Tayyab Ali (1969), Colchen (1974), Le Fort (1974b), Mukhopadhyay and Gangopadhyay (1971), Pande and Kumar (1972), Powell and Conaghan (1973a), Ray and Naha (1971), and Colchen, Le Fort, and Pêcher, 1972-1973 campaign in Central Nepal.

Higher Himalayas	Tibetan Sediments	F_1: nearly isoclinal to open, fading upwards, overturned northeast or southwest	F_2: nearly coaxial refolding, recumbent, generally overturned southwest	F_3: chevron, steep axial plane, conjugate set	F_4: kink bands
		S_1: axial plane	S_2: crenulation cleavage	(S_3): rare crenulation	
		L_1: intersection	L_2: intersection	(L_8)	
		trend: west-northwest—east-southeast	trend: northwest-southeast		
	Tibetan Slab	F_1: nearly isoclinal to isoclinal, tight, recumbent	F_2: isoclined to very tight, overturned southwest	F_3: open to tight, similar, conjugate (?)	F_4: open, steep axial plane
		S_1: axial plane schistosity with metamorphic layering	S_2: axial plane schistosity with metamorphic layering	S_3: crenulation cleavage	
		L_1: intersection	L_2: intersection	(L_3): intersection	
		L_{1m}: mineral (mainly toward the base)?	L_{2m}: (according to the author)		
		trend: northwest-southeast, but northeast-southwest to north-northeast—south-southwest in certain areas (Sikkim	trend: northwest-southeast	(trend: north-northwest—south-southeast, northeast-southwest)	

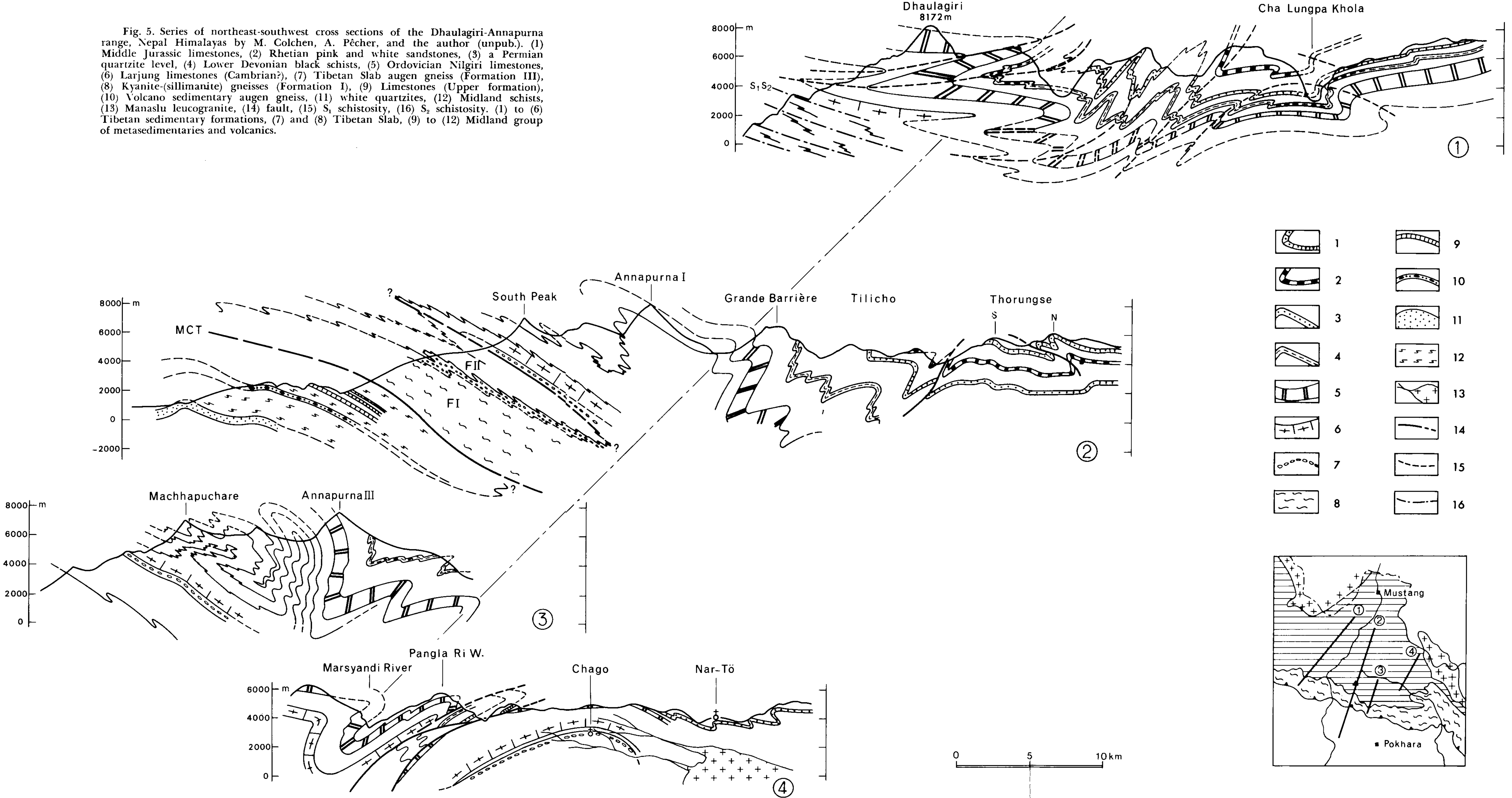
Lesser Himalayas	Midland Belt including Nappes	F_1: nearly isoclinal to tight assymetrical, recumbent to reclined, overturned toward south (?)	F_2: penetrative, nearly isoclinal to drag folds, assymetrically inclined, overturned southwest	F_3: non penetrative, kink-bands, conjugate open assymetrical, upright	F_4: open to chevron, conjugate, steep axial plane
		S_1: axial plane schistosity with metamorphic layering	S_2: crenulation foliation, strain slip cleavage	(S_3): crenulation cleavage, retrogressive recrystallization	
		L_1: intersection	L_2: intersection	(L_3): intersection	
		L_{1m}: mineral streaking at an angle to L_1-F_1. (Powell and others)	L_{2m}: (according to the author)		
		trend: highly variable, mainly west-east to northwest-southeast (but north-south at the northwest syntaxis)	trend: mainly west-east to northwest-southeast, but also north-northwest to south-southeast	(trend: highly variable)	(trend: highly variable)
	Krol Belt and Gondwana Belt	(not observed)	F_2: assymetrical, disharmonic and pickers, recumbent, overturned to the southwest	F_3: open, assymetrical, sometimes conjugate, steep axial plane	F_4: drag minor folds, upright to incline, fanning axial plane
			S_2: Slaty cleavage (sometimes) (L_2): rare trend: northwest-southeast	(S_3): strain slip cleavage (L_3): intersection trend: northwest-southeast	
	Sub-Himalayas	(not observed)	(similar to Krol Belt where thrusted under)	F_3: broad gentle flextures	

TABLE 6

Comparison of central Indian Ocean evolution compiled from Le Pichon and Heirtzler (1968), Fischer, Sclater, and McKenzie (1971), McKenzie and Sclater (1973), and Himalayan events

Anomaly no.	Age (10^6 yr)	Central Indian Ocean		Himalayas
1	0	Spreading rate: 4 to 5 cm/yr		Underthrusting along MBT
3	4-5	(Possible readjustment)		
5	9-10	Movement resumes		
6	20-21	Slow down	Himalayan cycle	K/Ar ages of leucogranites. Rapid uplift and erosion. Himalayan metamorphism.
12	35	Movement resumes toward N 35° E		Lack of sedimentation
18	45		Transhimalayan cycle	Rb/Sr age of Ladakh granite—*collision*—
21	55	Important slow down (stop ?)		Transhimalayan metamorphism
		Rapid movement of India, slightly E of N Half spreading rate up to 8 cm/yr		(Deccan traps to the South, 60-65)
32	75	Oldest recognized magnetic anomaly		Indus-Tsangpo ophiolitic suite
	100	Gondwana in four blocks		Basic volcanism in Thakkhola
	140	Gondwana in two blocks		Concordant deposition of Kampa flysch
	180	Beginning of Gondwana partition		Marine sedimentation in Lesser and Higher Himalayas

Fig. 5. Series of northeast-southwest cross sections of the Dhaulagiri-Annapurna range, Nepal Himalayas by M. Colchen, A. Pêcher, and the author (unpub.). (1) Middle Jurassic limestones, (2) Rhetian pink and white sandstones, (3) a Permian quartzite level, (4) Lower Devonian black schists, (5) Ordovician Nilgiri limestones, (6) Larjung limestones (Cambrian?), (7) Tibetan Slab augen gneiss (Formation III), (8) Kyanite-(sillimanite) gneisses (Formation I), (9) Limestones (Upper formation), (10) Volcano sedimentary augen gneiss, (11) white quartzites, (12) Midland schists, (13) Manaslu leucogranite, (14) fault, (15) S_1 schistosity, (16) S_2 schistosity. (1) to (6) Tibetan sedimentary formations, (7) and (8) Tibetan Slab, (9) to (12) Midland group of metasedimentaries and volcanics.



is known in the Lesser Himalayas from one end to the other (Calkins, Offield, and Tayyab Ali, 1969; Powell and Conaghan, 1973a; Hashimoto and others, 1973; Mukhopadhyay and Gangopadhyay, 1971; Gansser, 1964, p. 250). It is restricted to the metamorphic Midland belt and to the basal part of the Tibetan Slab (Formation I) where it fades upward and finally disappears. It is marked by the stretching of micas, amphiboles, feldspars, and quartz and is parallel to the elongation of conglomeratic pebbles when present. It is specially well developed in competent levels (limestones, quartzites, and augen gneisses of the Midland rocks). Its direction is somewhat close to the perpendicular of the Himalayas' trend. Authors generally link it to D_1 (table 5), and Powell and Conaghan (1973a) suggest that it lies in the kinematic *a* direction of F_1 folds and that possibly it continued to develop after the generation of F_1 folds, together with the syn- to post-D_1 metamorphism M_1.

In our opinion, the development of L_m is very closely linked to the second phase of deformation, D_2, meaning that D_2 corresponds to the same event on both sides of the MCT. Unfortunately, stretching in the MCT zone is so strong that D_1 and D_2 are almost impossible to distinguish. One has to get away from this zone to recognize D_1 independently and D_2 as the second major deformation linked to L_m.

This mineral lineation thus accompanies the huge MCT overthrusting and is probably a good indication of its former existence in the denuded parts of the Lesser Himalayas. In this perspective, it is interesting to notice that the fossiliferous Siluro-Devonian outcrops, south of Kathmandu, are devoid of L_m whilst it is present in the underlying rocks.

Thrusting-folding relationship.—Thrusts are not all contemporaneous. The two main ones, namely the Main Central Thrust (MCT) and the Main Boundary Thrust (MBT) are clearly of different age.[2] MCT is linked to Miocene metamorphism, whilst MBT overrides the Siwaliks (Miocene to Pleistocene).

Nearly all workers suggest the close relationship of D_2 with the large scale overthrusting of MCT type. These early thrusts are consequently folded by D_3 and D_4, generally in broad undulations (Bhattacharya and Niyogi, 1971; Naha and Ray, 1971).

The existence of large scale recumbent folds in the Tibetan Slab and Lesser Himalayas is poorly documented. Valdiya (1969a) and figures 3 and 5 suggest their existence with a size of several tens of kilometers. If such is the case, it is a possibility that thrusting was initiated by folding. The part played by the unobserved basement is speculative.

The Himalayan syntaxis.—On both sides of the Himalayas, the gentle pattern of the broad structures of Kashmir and Nefa abruptly turn back upon themselves. Due to difficult conditions of exploration,

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[2] Notice also that thrusts are not always made of one single plane but may consist of a series of more or less parallel accidents that sometimes relieve one another. This is particularly evident in the case of the MBT (fig. 3). Figure 3A also suggests that MCT is made of several thrusts with an en-échelon pattern at an Himalayan scale.

the northeastern syntaxis is poorly documented. The northwest syntaxis was first discribed by Wadia (1931). Its northern part (Nanga Parbat) was investigated by Misch in 1934; its southern part (southern Hazara) has been studied and mapped in detail (Calkins, Offield, and Tayyab Ali, 1969) (fig. 8).

With essentially unbroken continuity, the major geologic units can be followed in the syntaxis zone. They form tight loops or reentrants with a horse-shoe shaped pattern, but the sharpness of the curvature decreases northward. The core of the syntaxis, about 15 km wide, contains the youngest rocks (Murree formation and even Siwaliks) wrapped on both sides with successively older rocks pushed on each other by reverse faults whose thrusting character is not always evident. The two major accidents are the prolongations of the MBT (Murree Thrust of Kashmir) and Panjal Thrust next to the north, along which both reverse as well as left lateral movements have taken place. They follow a kind of en-échelon structure; in the meridian parts of it they draw nearer and tend to straighten up, whilst in the east-west parts they dip northward and show thrusting evidences. The relative vertical movement is significant (kilometric) but varies considerably in direction and intensity

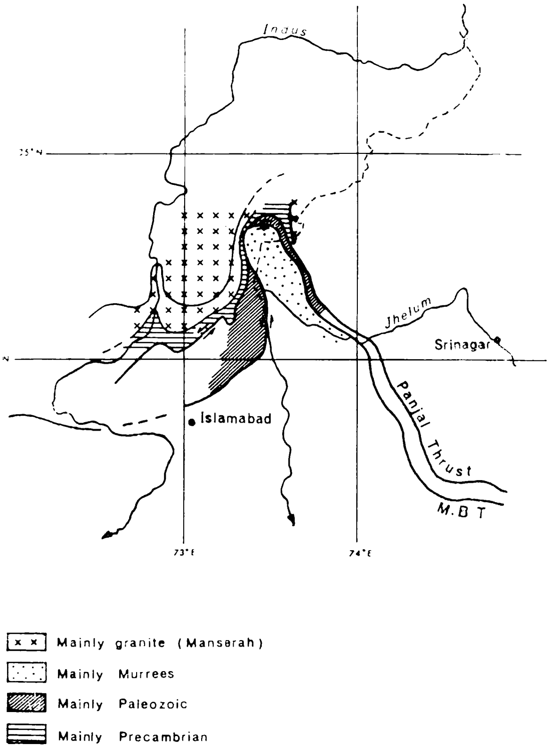


Fig. 8. The northwestern syntaxis after Calkins, Offield, and Tayyab Ali (1969).

along the same fault. In addition, Calkins, Offield, and Tayyab Ali (1969) suggest that vertical movements occurred during the Paleozoic and Mesozoic, although they were not necessarily related to the present observed accidents.

Finally, one should note that the influence of the northwest syntaxis is discernible as far as the Pamir range (some 700 km to the north).

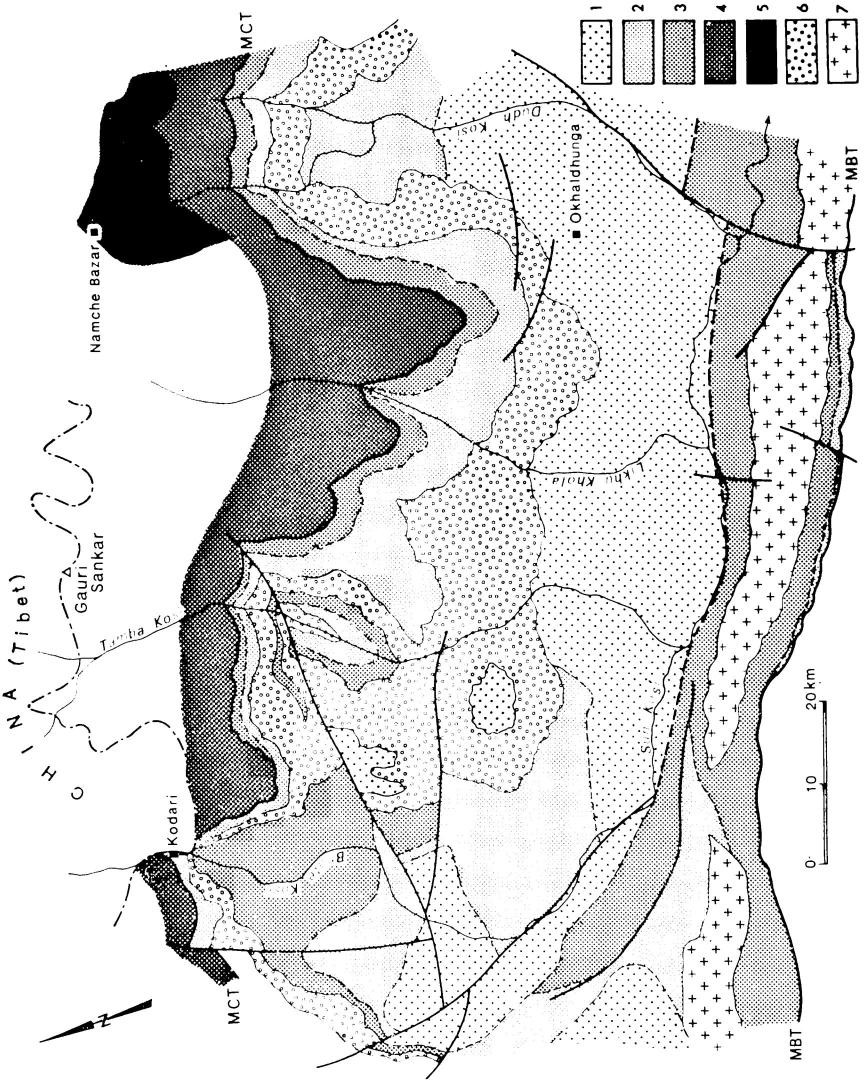
METAMORPHISMS

Over the years a good collection of samples has been collected, and their metamorphic assemblage has been described (see Hashimoto and others, 1973, app., for example). There is a fairly good homogeneity all along the Himalayas with regard to metamorphic phases, mineral species represented, and even habitus of the minerals.

Two phases of metamorphism, M_1 and M_2, together with a third phase of retrogression, M_3, are generally assumed. The main phase between M_1 and M_2 is a disputed question. According to our knowledge of Central Nepal, M_1 and M_2 are syn- to post-D_1 and D_2 respectively. In most areas, M_1 is shaded by M_2 linked to D_2; in particular, the most conspicuous inverted metamorphism (see below) belongs to the second phase. Maximum metamorphic grade is attained in the Tibetan Slab (see fig. 9). Arguments given above about tectonics are valid here: metamorphism cannot be pre-Tertiary in age (see also Naha and Ray, 1970).

The great majority of authors agree that a medium pressure type of metamorphism (Barrovian type) occurs in both the Higher and Lesser Himalayas. Chloritoid, staurolite, kyanite, and sillimanite are the typical metamorphic minerals met in sufficiently aluminous rocks. Apart from the granites, andalusite has been mentioned twice (Hashimoto and others, 1973, app.) but remains doubtful; cordierite occurs rarely (about a dozen quotations), mainly in sillimanite bearing migmatite of the Higher Himalayas or in hornfelses (?) of the Lesser Himalayas. Glaucophane (?) has been mentioned in the Lesser Himalayas of East Nepal (Hagen, 1969) and again in the middle Indus valley (Desio, 1974, p. 367). Recently in a study of the metabasites of the Naini Tal area, pumpellyite—prehnite and stilpnomelane—(hydrogarnet) were found (Varadarajan, 1973). Amphiboles are frequently bluish, of a subcalcic type. Scapolite is quite common in metamorphic limestones. Another characteristic of the metamorphism is the occurrence of large crystals of kyanite in equilibrium within the first lenses of segregated granitic mobilization; when the mobilization increases, sillimanite occurs, but muscovite remains.

As far as the Higher Himalayas are concerned, the relatively high pressure required for the metamorphism is in good agreement with the known thickness of the pile of sediments: a minimum of 15 to 20 km on top of the last occurrence of sillimanite in central Nepal. In the Lesser Himalayas, the metamorphism is not as easy to characterize;


CHINA (Tibet)
Gauri Sankar
Namche Bazar
Tamba Ko
Kodari
MCT
MCT
Dudh Kosi
Okhaldhunga
Likhu Khola
MBT
MBT
N
1
2
3
4
5
6
7
0
10
20km

several authors suggest that metamorphism may be of a little less medium pressure type (?).

Both in the Lesser and High Himalayas, the granitic intrusions seem to develop, at least in their upper part, a contact metamorphism whose characteristics are unfortunately poorly documented.

Inverted metamorphism, the facts.—"One of the most problematic facts of the whole Himalayan range" (Gansser, 1964, p. 99). For more than a century (Medlicott in 1864) it has been observed all along the Himalayas (Kashmir excepted) that more crystalline rocks lie structurally and topographically over less crystalline ones. In the Darjeeling area, Ray (1947) observed and mapped the systematic appearance in reverse order of five index minerals: chlorite, biotite, garnet, kyanite (and staurolite), sillimanite (see also Mukhopadhyay and Gangopadhyay, 1971). With the possible exception of chlorite, these index minerals crystallized during the second phase of metamorphism and sometimes outlasted it. In a less detailed manner, such observations are scattered all along the Lesser Himalayas (fig. 9).

Several times it has been noticed that the metamorphic isogrades cut across stratigraphic or lithic boundaries (Auden, 1935, in the Arun valley; Ray, 1947, in the Darjeeling area; Powell and Conaghan, 1973a, in the Punjab Himalayas).

The previous explanations.—Three explanations have been offered:

A. The series is normal, there is neither fold nor thrust involved in the phenomenon (Mallet, 1875; Auden, 1935). The reverse metamorphism may be explained by the injection and connate metamorphism of a granitic magma under stress such as the migmatite zone of the Higher Himalayas or the granitic bodies (Chor granite, Palung granite, and so on) of the Lesser Himalayas. This simple explanation is in contradiction with the apparent posteriority of the granites which superimpose a slight contact metamorphism to the regional metamorphism. Also it does not express the tectonic pattern observed.

B. Presence of an enormous recumbent fold posterior to the main metamorphism(s) (Loczy, 1907; Heron, 1934; Heim and Gansser, 1939; Ray, 1947). In this case, the series as well as the metamorphism should be reversed. But reverse series seem almost to be the exception.

C. Presence of a thrust between the high grade metamorphic schists and gneisses and the lower grade schists (Wager, 1965 and 1934). The

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← Fig. 9. Metamorphic zonation East of Kathmandu, Nepal Himalayas (modified from Hashimoto and others, 1973).

Contours and isogrades are tentative. The latter refer supposedly to the main metamorphism—the highest grade attained by the rocks. The grade of the Midland augen gneisses has not been represented, as their granitic composition does not favor the development of typical metamorphic minerals. They usually present two micas and occasionally garnet.

Note in the north the parallelism of the isogrades with the trace of the MCT. Toward the south, the situation is more complicated, disturbed by the presence of granitic massifs. The metamorphism stops abruptly on the MBT.

(1) chlorite, (2) biotite, (3) garnet, (4) kyanite, (5) sillimanite, (6) Midland augen gneiss, (7) Lesser Himalayas' granite.

multiplicity of such thrusts may account for an apparent reverse order (Pilgrim and West, 1928, for Jutogh over Chail over Blaini over Simla, Bordet, 1961, Hagen implicitly, Nagdir and others, 1967; Hashimoto and others, 1973; Saxena, 1973a). This hypothesis is so widely favored nowadays that some authors take it as a fact and deduce the existence of thrusting phases from the limit of the inverted isogrades. . . . If such is the case, the inverted metamorphism is prior to the thrusting and may be a strong pretectonic phase, or even older, of prealpine age (Frank and Fuchs, 1970). Zones of reversed metamorphism are very likely to indicate abnormal superposition of increasing stratigraphic age together with deeper metamorphic and structural level, but inside every thrusted sheet, the stratigraphy may be normal.

This widely held explanation is inconsistent with our knowledge of tectonics and metamorphism relationship.

A pressure-temperature effect of large underthrusting.—A coherent explanation should take into account the following facts:

A. Metamorphic isogrades are inverted in the upper levels of the Lesser Himalayas. Incidently, it is not limited to the MCT but also occurs within the base of the Tibetan Slab.

B. Metamorphic isogrades run roughly parallel to the MCT for very long distances (fig. 9).

C. The main metamorphism is syn- to post-D_2, which is itself a Tertiary (post Cretaceous-Eocene) phase of deformation.

In my opinion, the observed facts are a direct thermodynamic consequence of large scale underthrusting of two continental slabs. Thermal models of oceanic downgoing slabs have been suggested by Toksöz, Minear, and Julian (1971), Hasebe, Fujii, and Uyeda (1970), and Oxburgh and Turcotte (1971). Because of the number and complication of parameters, numerical methods have been used. According to Toksöz, Minear, and Julian (1971) the principal contributions made to the heating of the downgoing slab are, in decreasing order of importance:

conductive and radioactive heating,
adiabatic compression,
shear stress heating,
phase changes.

Already important in the island arc model, conductive and radiative heat transport will be even greater in a continental case.

Temperature and pressure have a slight and contradictory influence on the volume coefficient of thermal expansion, but accurate estimates are difficult to give for broad scale geological conditions. Adiabatic compression heating is likely to be much less important than in island arcs models as the subduction zone has a more gentle dipping owing to the buoyancy of the lower slab. Presently, the dip of the MCT is very variable, partly because of later undulations but probably also because of differences in the rate of erosion between both sides of the main range and consecutive isostatic readjustment. A tentative northward dipping of 10° has been taken for figure 10 and may even be too large.

An estimate of the shear-strain is extremely difficult; it depends on the viscosity, the thickness of the shear zone, together with the relative velocity of the movement. Some of the shear strain energy will escape in seism, but most if it will contribute to heating. Depending on its values, the reverse part of the temperature isogrades will be totally situated in the downgoing slab or partly run in the upper slab (Toksöz, Minear, and Julian, 1971, figs. 7 and 8). The latter solution has been been drawn on figure 10, but this does not imply any large modification of the observed metamorphism. Overpressure in the drag zone is very likely, but in regard to the probable fluid saturation, it cannot be very important, a few hundred bars at the maximum; as the overpressure is a function of the thickness of the drag zone, this thickness must be somewhat reduced. This is supported by field observations, where it seems to be limited to a few hundred meters (see above).

Endothermal reactions of progressive metamorphism take place mainly in the downgoing slab. Dehydration reactions expel an extremely important quantity of water upward; consequently, water pressure must be very close to total pressure and promote the granitic melting under adequate P-T conditions. Nowadays, circulation of water is exemplified by numerous hot water springs ("Tato pani") scattered along the MCT. Note that such P-T conditions are easily met in the upper slab (fig. 10), where partial melting absorbs energy and in a first step tends to pinch the temperature isogrades whereas a further up-welling of granitic melt pushes them upward (not taken into account on fig. 10). Temperature dependent mineral isogrades have a tracing somewhat similar to the temperature ones. This fact is valid for biotites, garnets, kyanite, sillimanite, and explains the rough parallelism of mineral isogrades to the MCT surface in the field.

A few remarks may be added. All parameters being otherwise stable, the steepness of temperature isogrades is a function of the spreading velocity and of the time elapsed since the beginning of subduction. These two parameters will be discussed later.

During subduction, prograde reactions of metamorphism and dehydration increase the density of the lower slab, diminish buoyant forces, and in a certain way help the subduction mechanism to proceed.

If subduction movement stops for a while, temperature isogrades in the lower slab will begin to move upward; time necessary to reach a new equilibrium is on the order of 10^7 yrs. If at any time in this new situation, subduction starts again along the same plane, it is very likely to produce under new $P–T–P_{H_2O}$ conditions an appreciable amount of granitic melt.

At any time, isostatic equilibration leads the surface level to rise and erosion to attack the upper slab. Rate of denudation of the Himalayas since Miocene time deduced from Bengal deep sea fans reaches the value of 0.7 mm/yr (Curray and Moore, 1971), though it does not take into account sediments of the Gangetic foredeep. Also, it is an

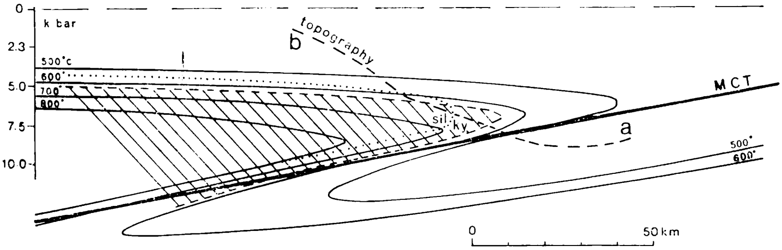


Fig. 10. Thermal regime of two thrusted slabs, diagram based on field observations of the Main Central Thrust in Central Nepal. Temperature isogrades are tentatively drawn together with the corresponding kyanite-sillimanite boundary and the muscovite granite excess water solidus of figure 11. Heat transfer by magma and water movements is not taken into account. The present topographical surface is also indicated (a-b). See text for details.

average figure for the Ganges and Brahmaputra basins that actually corresponds to a very uneven erosion rate. Anyway, such an erosion rate tends to deplete the temperature isogrades of the upper slab and, when the movement slows down and stops, helps cooling of the system.

The present topography of figure 10 has been reported on the P_{H_2O}–T diagram of figure 11, where it shows the succession of metamorphic paragenesis observed in the field (actually along the Marsyandi river between Annapurna and Manaslu ranges). It is also in good agreement with other cross sections whose paths may be obtained by moving the line ab a few kilometers, upward or downward. In Thakkola for example (Le Fort, 1971b), the line ab is nearly tangent to the muscovite granite solidus curve and does not cross the sillimanite isograde.

GLOBAL TECTONICS OF THE HIMALAYAN OROGENY

Following Wegener (1929), Argand (1924), and others, many authors have recently suggested the Himalayas as a typical example of continent to continent collision in the broad frame of plate tectonics. Among them, several geologists have made an attempt to present their knowledge of Himalayas geology in a global tectonic framework (Gansser, 1966; Le Fort, 1971a; Powell and Conaghan, 1973b). Others (Dewey and Bird, 1970; Dewey and Burke, 1973; Le Pichon, Francheteau, and Bonin, 1973) have tried to build a large systematic model applicable to other mountain ranges and orogenies.

Geophysical data.—Geophysically, it is one of the least studied part of the world, although the cradle of the concept of isostasy (Airy, Everest, Pratt).

Seismicity under the Himalayas and Tibetan plateau is not very important and is restricted to shallow earthquakes (fig. 12). Its spatial distribution under the Himalayas presents a certain alignment parallel to the Himalayan front and some 70 km north-northeast of it (fig. 12A). Calculated focal mechanisms of a few earthquakes (Fitch, 1970; Srivastava, 1973) show that apart from normal faulting, slip vectors are consistent with thrusting along a plane roughly parallel to the Himalayan front, dipping toward the north-northwest at a variable angle (around 30° in Kumaun and only 10° in Nefa). This thrusting plane lying some 40 km beneath MCT can very well correspond to the MBT trace observed at the surface level. Under the Tibetan plateau, seismicity has a scattered pattern. Both syntaxes show a marked increase in the intensity of seismicity, somehow prolonging that of the Owen-Murray and Ninety East fractures.

The thickness of the crust has been evaluated from seismic and gravimetric studies. Starting from an average 30 to 40 km for the Indian peninsula, it thickens beneath the Himalayas with a possible maximum of 80 km south of the high range and a mean value of 60 km under the Tibetan Plateau (Qureshy, 1969, 1971). The maximum thickness corresponds roughly to the alignment of shallow earthquakes.

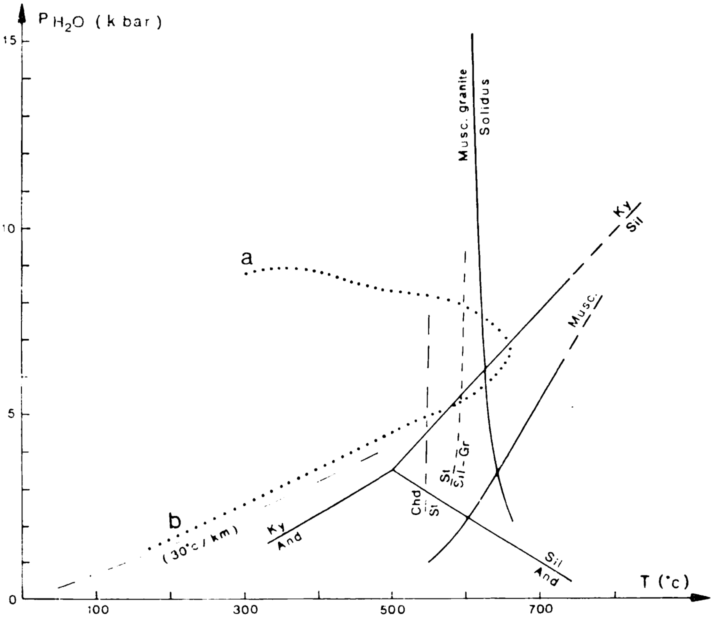
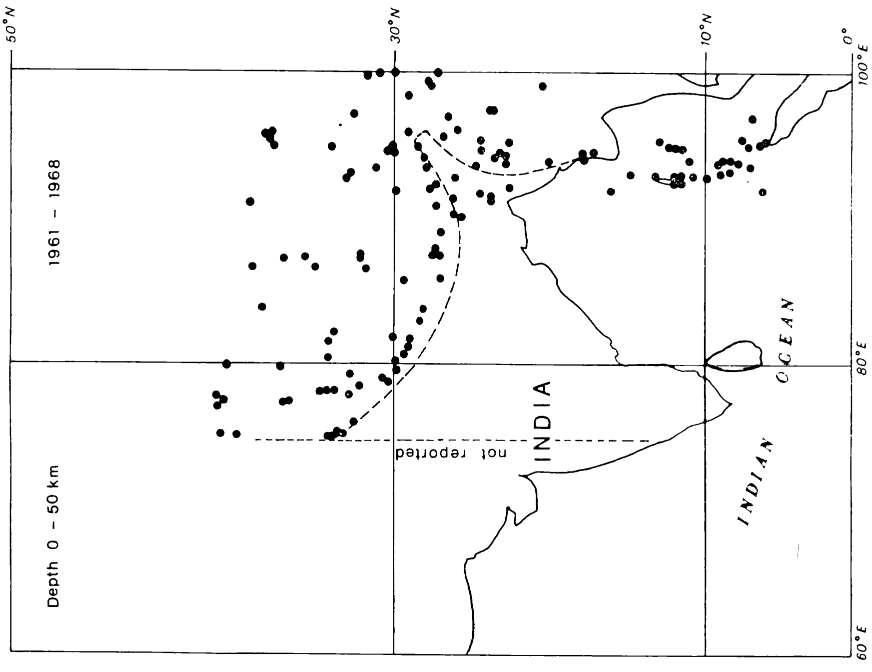
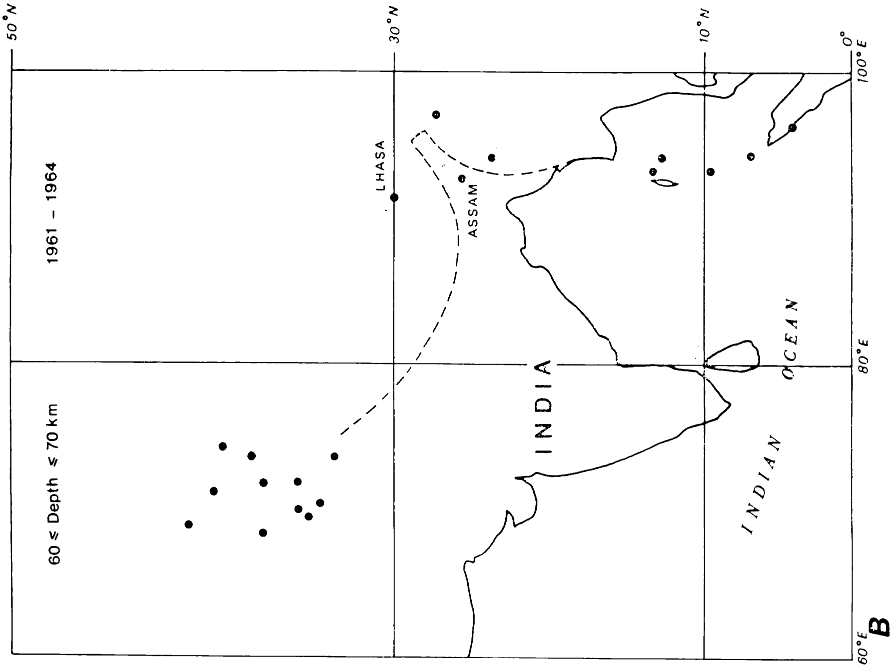


Fig. 11. P_{H_2O}-T diagram for quartz bearing rocks around the MCT. Muscovite granite solidus with excess water is taken from Huang and Wyllie (1973); other mineral stability limits as in Hyndman (1972). The heavy dotted line ab represents the present topographical path of figure 10.


Depth 0 - 50 km
1961 - 1968
50°N
30°N
10°N
0°
100°E
80°E
60°E
not reported
INDIA
INDIAN OCEAN

A


60 ≤ Depth ≤ 70 km
1961 - 1964
50°N
30°N
10°N
0°
100°E
80°E
60°E
LHASA
ASSAM
INDIA
INDIAN OCEAN

B

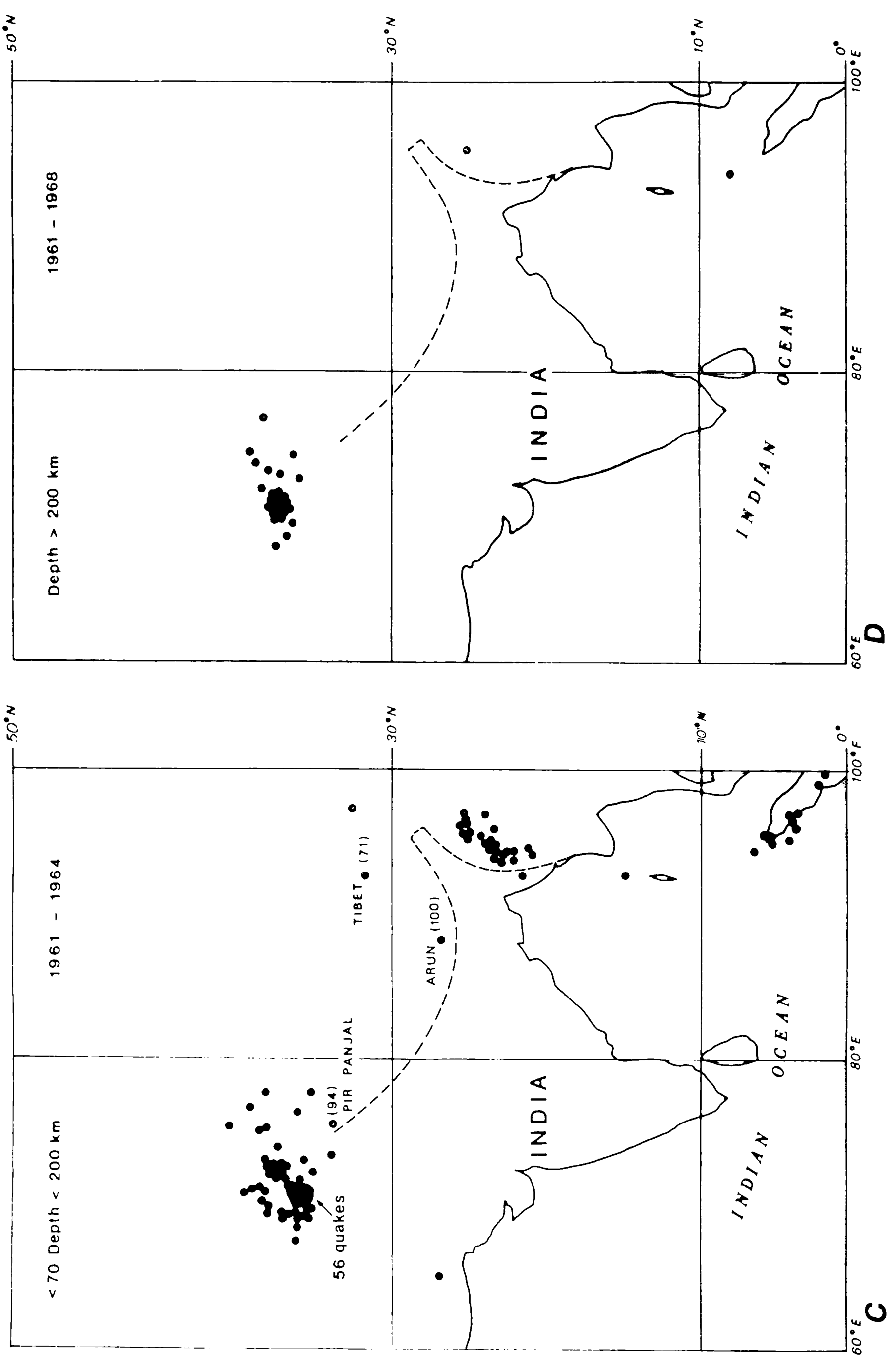


Fig. 12. Seismicity-depth relations in the Himalayas and surrounding regions. (A) is taken from Fitch (1970). The dotted line corresponds to the Himalayas front.

Fig. 13. Simplified physiographic map of the Indian Ocean and the Himalayas (after Gansser, 1966). (1) Precambrian shields, (2) Deccan traps, (3) ophiolites zones, (4) trenches, (5) major thrusts, (6) faults and fractures, (7) submarine platforms, (8) deltas.

Indian Ocean as witness (fig. 13).—Oceanographic work has given some precision about the sea-floor spreading history of the Indian Ocean (Le Pichon and Heirtzler, 1968; Fischer, Sclater, and McKenzie, 1971; McKenzie and Sclater, 1973), since the breakup of Pangaea in Triassic times (Dietz and Holden, 1970). In the central part of the ocean, rate and direction of spreading have met with important variations (table 6). Twice the movement has slowed down, even stopped (Upper Eocene, Lower Miocene); twice it has resumed (Lower Oligocene?, Upper Miocene).

The movement is a rotation whose center has changed at least once since the beginning of the Indian plate wandering: from about 2°N, 26°E to 29°N, 27°E (Le Pichon and Heirtzler, 1968, Le Pichon, Francheteau, and Bonin, 1973). These rotation of centers on the western side of the plate imply a more important northward move of the eastern side than of the western side of the Himalayas.

But the Indian Ocean is only one part of the problem: the relative behavior of the northern plate of "China" during Mesozoic and Neozoic times is unknown. Orogenies with ophiolitic emplacement occurred in Late Jurassic-Early Cretaceous times in both the Tien-Shan and Kun-Lun ranges; recent volcanism is suggested in Kun-Lun (Gansser, 1964). In the Pamir range, orogeny is alpine, and at both ends of the Himalayas, the influence of the syntaxis extends northward for a long distance (Gansser, 1964; Shi Zhen-Liang and others, 1973; Talalov, personal commun.).

Thus the undivided mass of Asia came into being not so long ago, during the time of Indian Ocean spreading and Indian continent wandering.

Collision.—There is common consent among believers of the plate tectonics theory to consider the Transhimalayas as an Andean type margin, the result of the subduction of the Tethys ocean floor (Dewey and Bird, 1970). This process was interrupted when the Indian continent began to impinge on China, about 45 m.y. B.P., along a zone corresponding to the former trough of the consuming plate boundary. The curvature whose concavity was directed toward the China overriding plate was preserved in the shape of the Indus Tsangpo suture zone.

The shape of the colliding margins had no reason to be parallel (even if Tibet were formerly part of the Indian continental mass as suggested above). Indian bulges met China first and induced sliding and thrusting movements.

Another consequence may be that in these areas the first segments of margins to collide now exhibit the most cryptic suture of ophiolite, whilst the last show more extensively exposed masses of oceanic crust. The latter regions will undergo less underthrusting, thus less uplift and erosion. This may explain the better state of preservation of the northwest Punjab Himalayas together with large ophiolite outcrops (fig. 3).

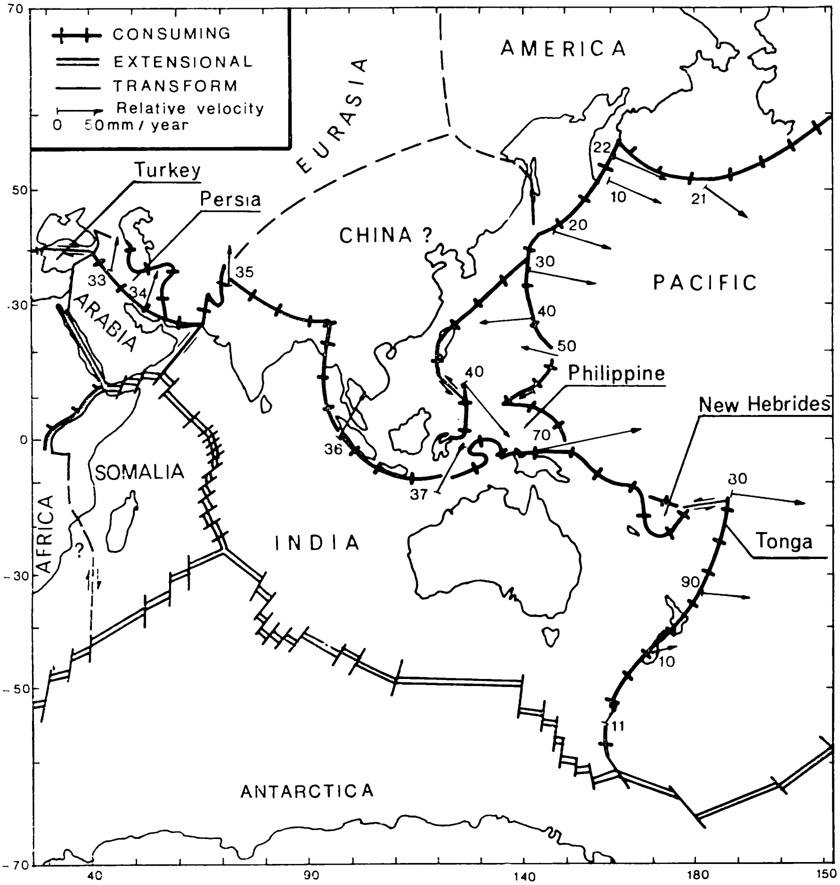


Fig. 14. Present Indian plate kinematic setting according to the twelve plate model of Morgan (after Le Pichon, Francheteau, and Bonin, 1973).

It may also be responsible for the larger width of the elevated Tibetan Plateau in the east than in the west.

Thus collision is a slow and complicated process during which the tendency of the Indian continent to be subducted by the Chinese is only limited to buoyancy constraints. It results in Eocene marine transgression (table 6). Also it may take part in the slowing down of the Indian Ocean spreading rate and change of the center of rotation. As for the former ocean-bearing part of the plate, it probably breaks off and sinks within the mantle. Slowing down or stop of relative movement permits isostatic readjustment (Oligocene regression) and beginning of denudation to take place.

Because of our scant knowledge of the Indust-Tsangpo suture and its southern fringe, it is difficult to conceive the exact tectonic and metamorphic consequences of the collision. However, one is tempted to make a relation between the collision and the first phase of deformation and metamorphism D_1-M_1, generally parallel to the suture line except in definite regions (Darjeeling, for example) where a different trend could be the result of slippage along the suture zone.

Post-collision history.—When movement resumes gradually, the intracontinental compression is not able to move the thickened, metamorphosed, and granitized Indus-Tsangpo suture any further. A new line of weakness takes the relay; whether it comes to existence at this time or whether it already existed as a deep crustal fracture originated during the collision is a matter of speculation. As stated by Powell and Conaghan (1973b), mountain building is now produced "indirectly by underthrusting" of one continental slab along a deep fracture developed within the colliding plate. Relative movement causes the second phase of folding and metamorphism as described above. Style of folding and type of metamorphism probably depend very much on the thickness of the slabs, attitude of the crustal fracture, and velocity and duration of relative movement. Secondary parameters such as time elapsed since collision, petrographic nature of the slabs, and tectonics of the collision are also likely to play an important part and to confer a particular physiognomy to similar orogenies.

The development of an important inverted metamorphism is very dependent on the first set of parameters. In the case of the MCT, a velocity on the order of 5 cm/yr is likely for a span of time of some 10^7 yr. The original dip of the MCT is small, probably fixed by the compression and nature of the rocks; it cannot vary very much. As for the thickness of the slab, it is always of the same order of magnitude at the beginning, but folding may increase it greatly (see fig. 5). Thus, the inverted metamorphism and eventually the mineral lineation depend very much on how quick and how far the underthrusting proceeds.

According to some authors (Powell and Conaghan, 1973b; Le Pichon, Francheteau, and Bonin, 1973), underthrusting may proceed for hundreds of kilometers at the base of the continental crust, peeling off the lower part of the lithosphere (fig. 15). Others (Dewey and Bird, 1970; Dewey and Burke, 1973) limit it to a "splintering". It is argued that the first is more likely because it is the only one to enable sufficient crustal shortening. Crustal shortening may be estimated in different ways. From geological observations of thrusting and folding (see Gansser, 1966), 350 to 650 km may be a reasonable figure. From the present thickness of the crust up to the Indus-Tsangpo suture, taking into account erosion and fluid expulsion, and depending on the initial thickness, a maximum of 600 to 700 km is obtained. From spreading of the central Indian Ocean ridge since anomaly 12 (35 m.y. B.P.), 1300 km of new ocean floor has been created, but it does not mean that all of it has resulted, through rigid plates, in crustal shortening in the Himalayas. Finally, from estimates of present plate convergence (Le

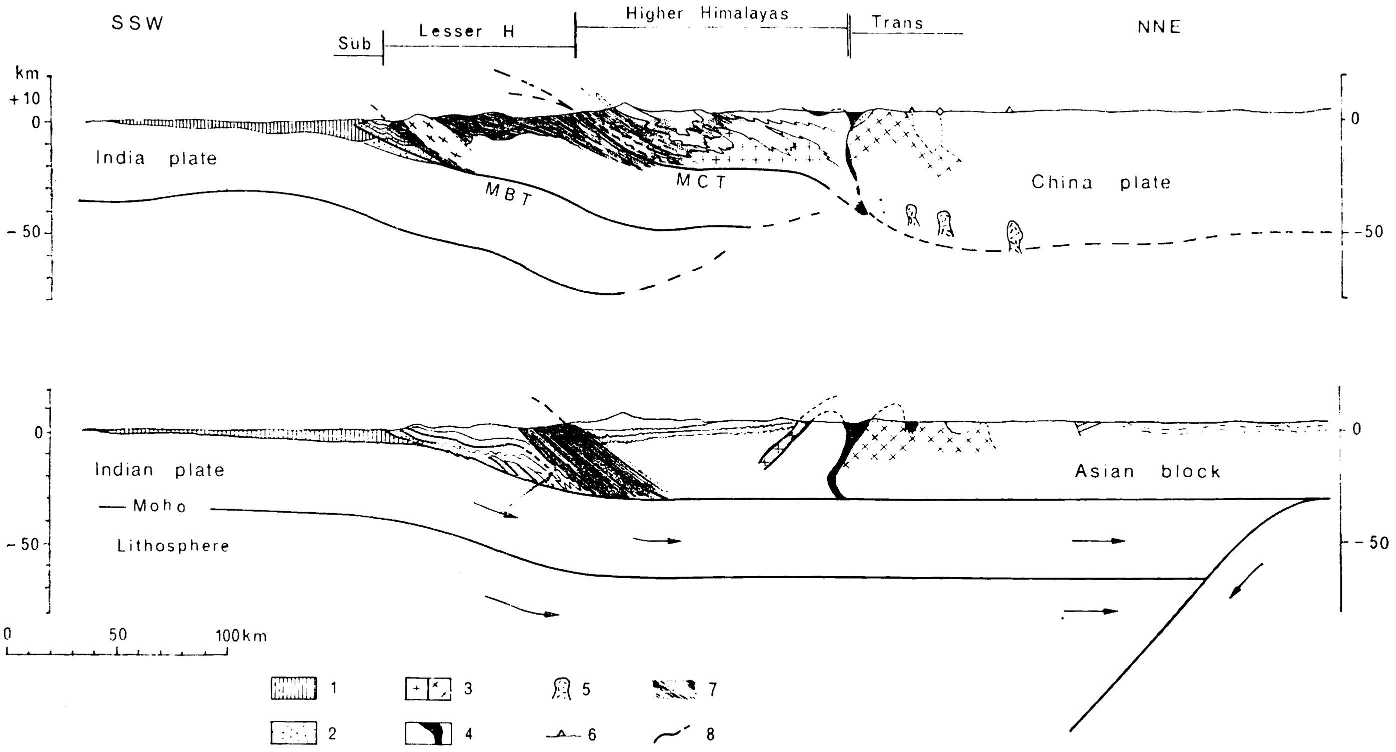


Fig. 15. Present structure of the crust in the Himalayas. Below: according to Powell and Conaghan (1973b). Above: according to the author.

Pichon and Heirtzler, 1968), a mean value of 5 to 6 cm/yr is assumed in the Himalayas. Considering the uncertainty of these figures, none of them seem to be really inconsistent with a contraction limited to the Himalayas.

Another argument in the first case is that the height of the Tibetan Plateau, over 4 km, is a consequence of doubling of the crust by superposition (Le Pichon, Francheteau, and Bonin, 1973; Powell and Conaghan, 1973b). But in this case, one wonders why the Andes show a similar feature in their 200 to 300 km wide Alti Plano. The lenticular shape of the Tibetan Plateau has in fact been limited by two Andean type margins of opposite vergence and probably different age.

On the contrary, buoyancy constraints, physical behavior of the underthrusted slab, and abnormal structure of the upper mantle near the former suture zone probably limit the possible length of underthrusting. This explains the relay in time of one thrust by another, the MBT playing presently the role played before by the MCT. This is shown on the upper part of figure 15 and emphasizes the polarity of the mountain belt. In a few million years, a new intracontinental thrust is probably going to appear further south.

Thus in the Himalayas, one can at the same time observe the past effects of a deeply eroded thrust and the present mechanism of a working thrust. Hopefully, a lot more data will be gathered and compared in the next few years that may solve some of the debatable ideas presented here and enable thorough comparison and understanding of other collided mountain ranges.

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