

Research Paper

RIVER PROFILES ALONG THE HIMALAYAN ARC AS INDICATORS OF ACTIVE TECTONICS

L. SEEBER and V. GORNITZ

Lamont-Doherty Geological Observatory of Columbia University, Palisades, N.Y. 10964 (U.S.A.)

(Received August 20, 1981; revised version accepted July 6, 1982)

ABSTRACT

Seeber, L. and Gornitz, V., 1982. River profiles along the Himalayan arc as indicators of active tectonics. *Tectonophysics*, 92: 335–367.

Longitudinal profiles along sixteen major transverse Himalayan rivers add important constraints to models of active continental subduction and its evolution. These profiles are characterized by a zone of relatively high gradient that cannot be associated with differential resistance to erosion in all cases. The base of the zone of increased gradients correlates with (1) the topographic front between the Lesser and High Himalayas, (2) the narrow belt of intermediate-magnitude thrust earthquakes, (3) the Main Central Thrust zone (MCT). These features define a small circle in the central portion of the Himalayan arc. These correlations suggest that the discontinuity in the river profiles and the other features are controlled by a major tectonic boundary between the rising High Himalayas and the Lesser Himalayas. No sharp increases in gradient are observed near the Main Boundary Thrust (MBT), except on a few rivers, such as the Jhelum or Kandar, where the MBT lies close to both the MCT and the seismic belt. Thus, it is unlikely that the MBT is a major tectonic boundary. The diversion of river courses along the MBT and around anticlines in the Sub Himalayas has probably been caused by aggradation near the erosion-deposition boundary, upstream of uplifts in the Mahabharat range and Sub Himalayas.

A parallel is drawn between the Himalayas and New Guinea based on the hypothesis that continent-arc collision, of the type occurring in northern Australia, preceded continent-continent collision in the Himalayas. The present sedimentary/tectonic phase in New Guinea resembles the Subathu (Paleocene-Eocene) phase in the Himalayas. Incipient counterparts of the major Himalayan structures, including the MCT and the MBT, are recognized in New Guinea. The drainage patterns in the Himalayas and in New Guinea bear a similar relation to major structures. This suggests that (1) the tectonic evolution of the Himalayas has been rather uniform since early stages of collision, and (2) the Himalayan drainage was also formed at these early stages and is therefore antecedent to the rise of the High Himalayas.

INTRODUCTION

The average topographic profile across the Himalayas exhibits two distinct gradients: a relatively gentle slope across the Sub Himalayas and Lesser Himalayas,

which rises to 3 km at the boundary between the Lesser and High Himalayas, and a steeper slope through the High Himalayas. The average topography finally levels off and extends at about 5 km from the High Himalayas, across the Indus–Tsang–Po suture and into Tibet (Wager, 1937; Bird, 1978). Thus, the High Himalayas are essentially a topographic front rather than a ridge. This topographic front is sharply defined over most of the arc (Fig. 1).

The topographic front is associated with a narrow belt of intermediate-magnitude thrust earthquakes (hereafter referred to as the seismic belt, Fig. 1). The trace of the Main Central Thrust (MCT), for the most part, follows the topographic front (Figs. 1 and 2). In the central part of the Himalayan arc, the topographic front, the seismic

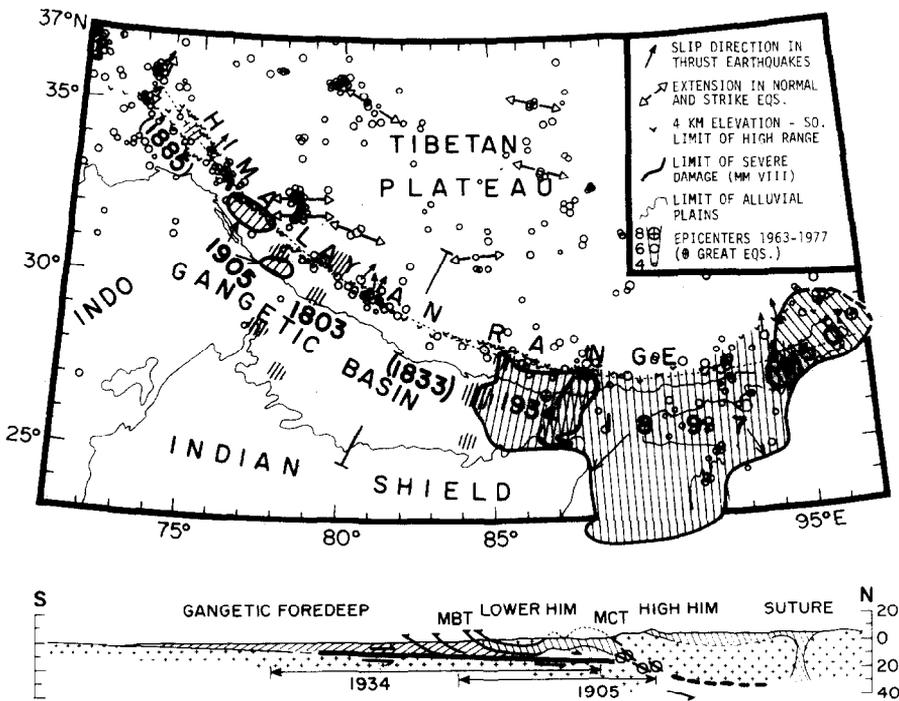


Fig. 1. Epicentral Map of the Himalayas (NOAA, 1963–1977; size of circle proportional to magnitude) with Modified Mercalli VIII intensity contours of well documented great Himalayan earthquakes (pre-1897 areas may be intensity < VIII). Representative fault-plane solutions are shown by arrows: single arrow = slip direction of thrust events, double arrows = T -axes of normal and strike slip events (Molnar et al., 1977). Note the close correlation between the belt of moderate magnitude thrust earthquakes, the topographic front (threshold of 4 km elevations) and a small circle fitted to the Himalayan arc (dotted line: center at 42.45°N , 91.10°E , radius 1,695 km). The cross section is for the central portion of the arc, with hypocenters constrained by body wave modelling projected along the arc (line through hypocenters indicates one of the two nodal planes). At both extremities of the Himalayan arc the seismic belt and the topographic front deviate from the best-fit small circle but continue to track each other (from Seeber and Armbruster, 1981).

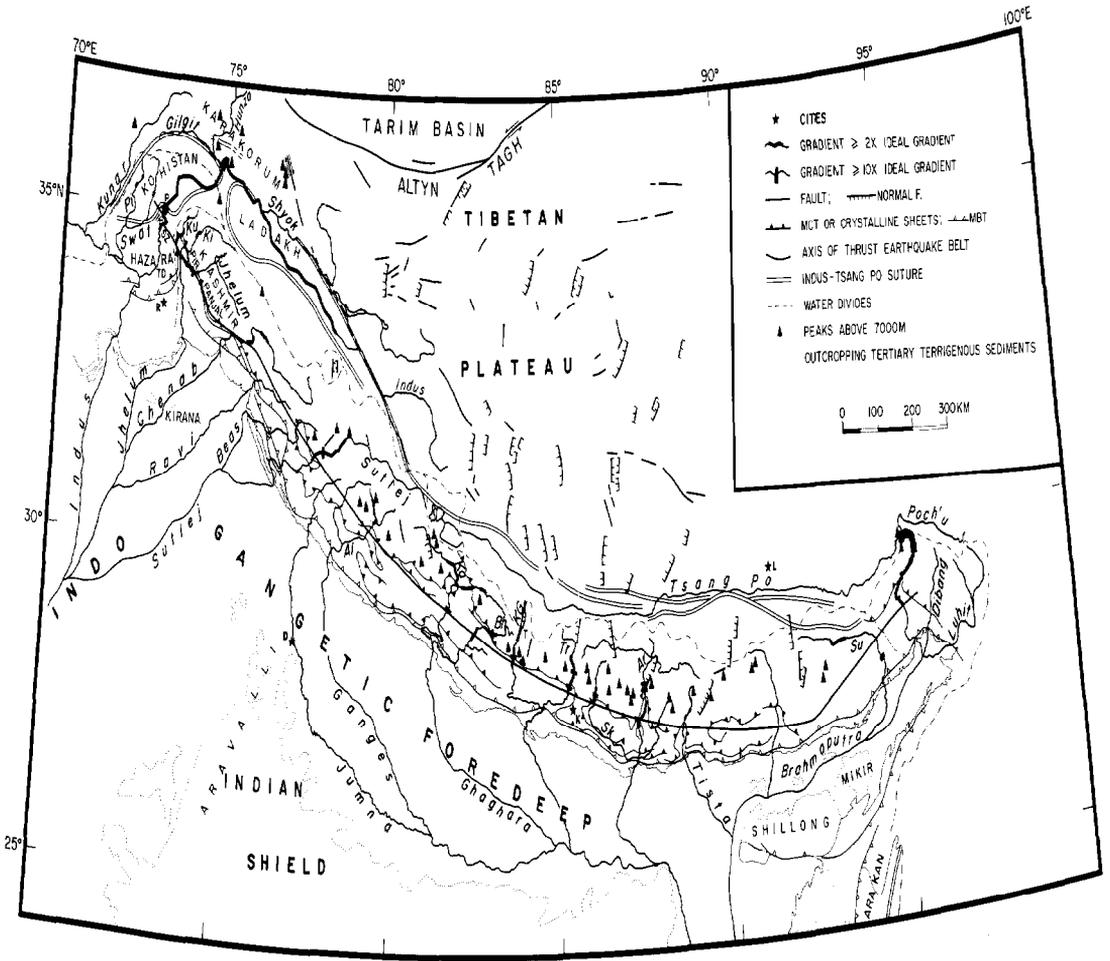


Fig. 2. Morphotectonic features of the Himalayas. Wide bands on rivers represent reaches with high gradient ($SL/K \geq 2$; see text); very wide bands indicate reaches with very steep gradient ($SL/K \geq 10$). Barbed lines represent major thrusts; blank barbs = MBT, solid barbs = MCT and its extension below the crystalline thrust sheets of the Lesser Himalayas. Ticked lines indicate normal faults. Small triangles show peaks with elevations above 7000 m. Dashed line indicates watershed between the Indus-Tsango-Po drainage to the north and the major Himalayan rivers to the south. Abbreviations for the rivers (from west to east) are: Pi = Pinjkora, Ki = Kishanganga, Ku = Kunder, Jh = Jhelum, Ch = Chenab, Su = Sutlej, Al = Alaknanda, Ka = Karnali, Bh = Bheri, KG = Kali Gandaki, Tr = Trisuli, SK = Sun Kosi, Ar = Arun, Su = Subansiri. Other abbreviations: IKSZ = Indus Kohistan seismic zone, MMT = Main Mantle Thrust, TD = Tarbela dam, P = Pattan, T = Thakkola graben, K = Kathmandu, D = Dehli, R = Rawalpindi, L = Lhasa.

belt and the MCT lie approximately along a small circle with a radius of 1700 km. At the eastern and western ends of the Himalayan arc, topographic break, seismic belt and MCT deviate from the small circle but are still near each other, except in the Hazara arc (see below). The close correlation among these important features and the smooth curve they define suggest that they are the expression of the same fundamental active structure (Seeber et al., 1981).

At the Hazara–Kashmir syntaxis, the MCT (Panjal thrust) and the MBT (Murree thrust) bend sharply to the south and then continue westward following the southwardly convex Hazara arc (Wadia, 1931; Calkins et al., 1975). On the other hand, the Indus Kohistan Seismic Zone (IKSZ)—a direct extension of the Himalayan thrust earthquake belt—cuts across the mapped surface structures and extends the Himalayan trend northwestward through the Hazara arc. A sharp topographic break associated with steep gradients along all the cross-cutting rivers, including the Indus, lies along the IKSZ (compare Figs. 1 and 2; Armbruster et al., 1978; Gornitz and Seeber, 1981). In general, the trace of the topographic front appears to be less convolute than the MCT, and topography may be a better indicator of active sub-surface tectonics than surface structures along the Himalaya.

Tectonic models

In the current widely accepted tectonic model of the Himalayas, the zone of plate convergence shifts progressively toward the foreland, simulating at the megascale the forward progression of the leading edge of deformation in a fold and thrust belt. In this model, convergence occurred first along the Indus suture (Cretaceous–Eocene), then an intracontinental thrust (the MCT) formed south of the suture (Miocene) and finally another intracontinental thrust, the MBT, formed still further south (Pliocene–Pleistocene). At each stage, the convergence is concentrated on the youngest of these structures, closest to the Indian foreland (e.g., Mattauer, 1975; LeFort, 1975; Stöcklin, 1980; Fig. 3A). In this evolutionary model, the basement structure of the Himalayas evolves in a sequence of distinct tectonic phases.

In the evolutionary model, the MBT and MCT are tectonically equivalent faults of different ages. The MBT is now active, whereas the MCT has been inactive for about 15 m.y. Different levels of exposure due to uplift and erosion account for the contrasting surface expressions of these faults. Portions of the MCT now exposed are characterized by a wide shear zone formed under mid-crustal *P-T* conditions (Andrieux et al., 1977; Brunel and Andrieux, 1977; Pecher, 1977). On the other hand, the MBT is a young active thrust and brittle deformation characterizes its surface trace. At depth, the MBT should now be subjected to the same kind of deformation that is fossilized along the MCT. A new thrust may form south of the MBT in the future, and the surface trace of the MBT may then resemble the present MCT (LeFort, 1975).

In an older model, discussed by Powell and Conaghan (1973), after the Tethys

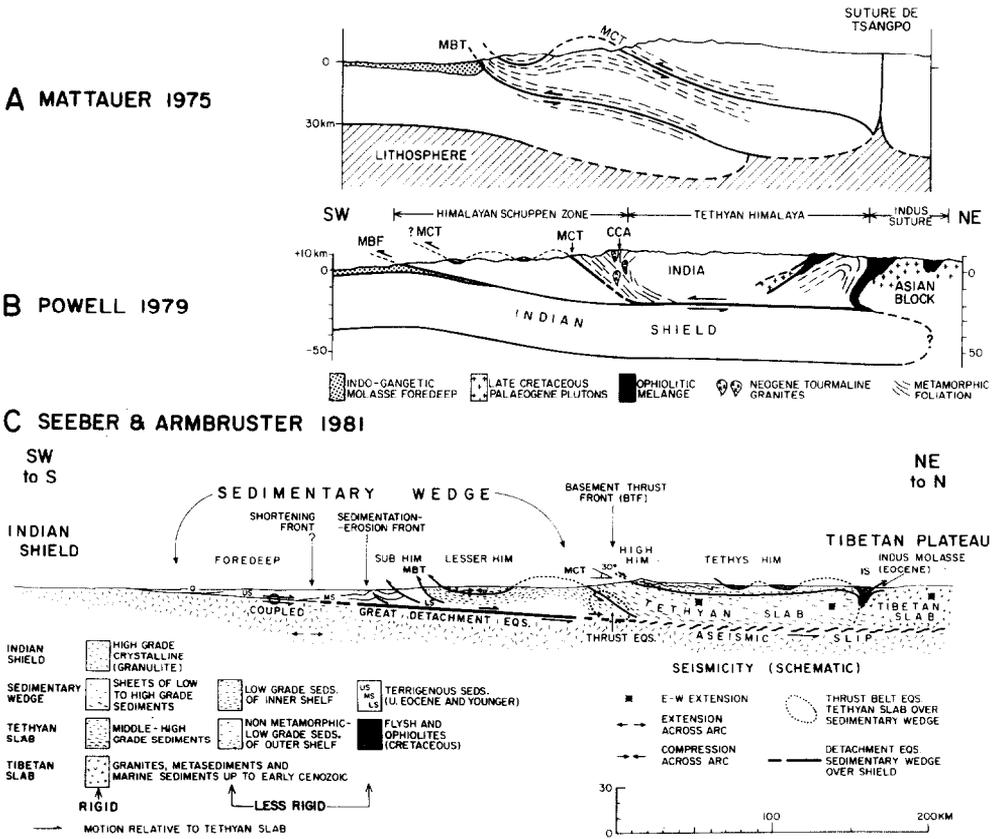


Fig. 3. Comparison of tectonic models of the Himalayas.

A. After Mattauer (1975). The onset of slip on the MBT follows the cessation of slip on the MCT. The faults are similar intracrustal thrusts. This model is named “evolutionary” in this paper.

B. After Powell and Conaghan (1973) and Powell (1979). The MCT and the MBT are fundamentally different structures in this model.

C. After Seeber and Armbruster (1981). All the elements in this model are active simultaneously and subduction proceeds without fundamental changes in the structure. Thus, it is named the “steady-state” model.

ocean is closed along the Indus–TsangPo suture, India underthrust its leading edge (Fig. 3B) and then, rather than by stacking successive slivers of crust under the Himalayas, India moved northward by underriding Tibet. This kind of continental subduction is in many ways similar to oceanic subduction. In particular, large amounts of convergence can occur without drastic changes in the tectonic regime at the convergence zone. Accordingly, we name this the steady state model.

In its latest version, the steady-state model can explain many geologic and geophysical features of the Himalayas (Seeber et al., 1981; Seeber and Armbruster, 1981; Barazangi and Ni, 1982; Fig. 3C). Three main structural units are identified:

the subducting Indian plate; the overriding Tethyan slab; and the sedimentary wedge—the easily deformed prism of shelf sediments from the precollisional passive margin of India, derived clastic sediments and crystalline thrust sheets. The sedimentary wedge is trapped between the more rigid converging slabs and is pervasively deformed. The active contact between the converging slabs—the basement thrust—does not reach the surface. At the Basement Thrust Front (*BTF*; Fig. 3C), the basement thrust splits into a shallow-dipping detachment that separates the underlying Indian shield from the sedimentary wedge, and a steeper dipping fault between the Tethyan slab and the sedimentary wedge. The detachment is a blind, low-angle thrust whose displacement decreases updip and is completely taken up by internal deformation within the young sediments of the wedge before it reaches the surface. This active detachment below the Himalayan fold and thrust belt is inferred from an analogy between the Himalayan fold and thrust belt and other better known collision belts, as the likely source of the great earthquakes along the Himalayan front (Seeber and Armbruster, 1981) and from microearthquake data (Seeber and Armbruster, 1979). The more steeply-dipping structural boundary between the Tethyan slab and the sedimentary wedge should have more obvious surface expressions. In the steady state model, this boundary is identified with the MCT. Thus, the MCT provides a crucial test since it is active in the steady state model and inactive in the evolutionary model. Evidence in support of an active MCT from river profiles and other data are discussed below.

The BTF is recognized as a fundamental structural element along the Himalayan subduction zone, independently from any model. It demarcates the transition between seismic (updip from the BTF) and aseismic (downdip from the BTF) thrust movement. The narrow belt of thrust earthquakes near this transition may represent slip on a steeper portion of the basement thrust (Fig. 1; Seeber et al., 1981) or on the deeper part of the MCT as it merges into the basement thrust (Fig. 3C). The major topographic front that coincides with the BTF also suggests a fundamental structural boundary separating portions of the overriding element which are affected differently by thrusting. South (updip) of the BTF, the average elevation of the sedimentary wedge increases northward and may be primarily the function of shear stress on the detachment (Elliott, 1976; Chapple, 1978). The BTF marks an abrupt northward increase in average elevation from 3 to 5 km. North of the BTF the average elevation remains constant or decreases slightly into the Tibetan Plateau (Bird, 1978). This high uniform elevation is probably in static equilibrium with the thickened crust and the elastic strength of the flexed underthrust lithosphere.

River drainage and tectonics

The drainage pattern of rivers contain unique information about the past and present tectonic regime. The longitudinal profile of a river is sensitive to the ongoing process of uplift and can be used to recognize active structures. In a steady-state

system erosion keeps pace with uplift. River gradients, which determine the rate of erosion are adjusted so that differential rates of uplift are matched by differential rates of erosion. Thus, abrupt changes in slope along river profiles may indicate active faults that cross these rivers. On the other hand, the drainage network is not as easily disrupted by tectonic movements because the rivers are entrenched in deep gorges and they tend to maintain their courses throughout the tectonic evolution (antecedence). Consequently, the drainage pattern may be used to infer the early stages of this evolution.

The main objective of this study is to relate the drainage network, and river profiles to Himalayan tectonics, past and present. We analyze longitudinal profiles of the main transverse Himalayan rivers to determine the morphologic expression of major subsurface tectonic structures and add some constraints on the proposed models. Furthermore, the drainage patterns and the geology of the Himalayas and New Guinea are compared to test the hypothesis that the ongoing continent-arc collision in New Guinea resembles the early stages in the collision between non-oceanic portions of the Indian and Asian plates.

Methods

A river is referred to as "graded" when gradient, width and depth of its channel are in equilibrium with discharge and load (Mackin, 1948). The gradient of a graded river usually decreases downstream as the discharge increases, and the longitudinal profile of this river can be often approximated by a straight line in a semilogarithmic plot:

$$H = C - K \ln L$$

where H = elevation, L = distance from the source, and C and K are constants.

K , the slope of this idealized profile, is called the *gradient index* (Hack, 1973a) and can be evaluated by:

$$K = (H_i - H_j) / (\ln L_j - \ln L_i) \quad (1)$$

where i and j refer to two points along the river profile. K can be used to characterize a relatively short reach of the river as well as the entire profile. By comparing river profiles to ideal semilogarithmic profiles, the significance of anomalous gradients can be evaluated in the context of the discharge increasing downstream.

In this study the gradient index of all the rivers examined is computed from (1) with H_j and L_j taken at the base level of the profiles, usually at the entrance to the alluvial plains, and H_i and L_i arbitrarily taken 1000 ft below (in elevation) the highest topographic contour crossed by the river. Except near the source, the gradient index of a short reach can be conveniently approximated by the "SL" number:

$$SL = (\Delta H / \Delta L) L \quad (2)$$

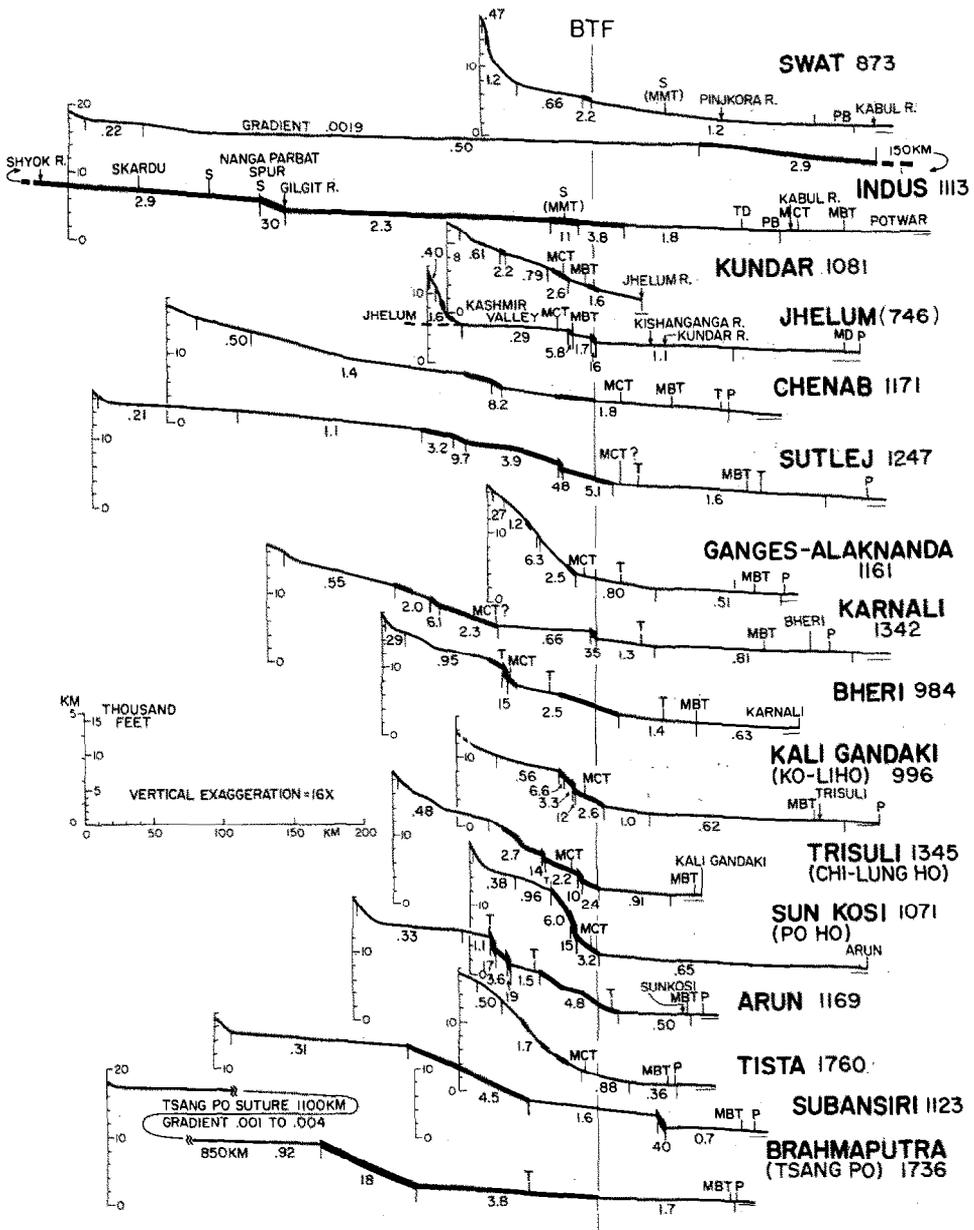


Fig. 4. Longitudinal profiles of most of the major Himalayan rivers (see Table I) arranged from west (on top) to east (on bottom). As in Fig. 2, reaches of steep ($SL/K \geq 2$) or very steep ($SL/K \geq 10$) gradients are shown on the profiles by wide or very wide bands, respectively. S = suture zone, T = thrust, P = entrance into Indo-Gangetic plains. The positions of the MMT (Main Mantle Thrust), the MBT and MCT (where well-documented) are also indicated. The vertical line is the BTF, as defined by the seismic belt (and the topographic break) (Figs. 1 and 2). The number near the name of each river is the K -value for that river (in meters); numbers along the profiles give the ratio of the K_i for reaches where SL varies by < 2 (between downward tics), and the K -value for the entire river (see text). In the Jhelum profile, a tributary, somewhat shorter than the main branch, is plotted above the 5,500 ft contour, thus the K_i and K values given for this river are somewhat incorrect.

where $(\Delta H/\Delta L)$ is the slope of the reach (taken as constant) and L is the distance from the source of the river to the midpoint of the reach (Hack, 1973a, b).

In this study the longitudinal river profiles (elevation vs. distance) are obtained primarily from 1:1,000,000 Operational Navigation Charts (ONC) (1972–1977). 1:250,000 maps (U.S. D.O.D. Joint Operation Graphic) are used for the Swat, Kunder and part of the Jhelum and Indus rivers. The distance along the rivers between consecutive contour crossing (usually 1000 ft intervals) is measured, neglecting minor bends. The SL numbers (in meters) are calculated from (2) for each reach between the consecutive contour crossings. The SL number of each reach between consecutive topographic contour crossings is compared to the gradient index (K) of the entire profile. In Figs. 2 and 4 we distinguish reaches where the gradients are significantly steeper ($SL/K \geq 2$) and much steeper ($SL/K \geq 10$) than the ideal profiles. The profiles are also subdivided into reaches where the gradient index, as indicated by the SL numbers, varies relatively little ($< \times 2$). The gradient indices for these subdivisions as computed from (1) are indicated in Fig. 4.

RESULTS

Eleven out of seventeen major Himalayan rivers between and including the Sutlej and the Brahmaputra originate north of the High Himalayas and drain across the range most of the area north of the range and south of the suture (Fig. 2; Table I). These are the trans-Himalayan rivers (Table I). The other four major rivers drain exclusively the southern flanks of the High Himalayas. West of the Sutlej, the topographic front broadens and bifurcates into two subparallel fronts, one on either side of the Kashmir valley. All the major rivers in the western Himalayas cross the front closest to the foreland, the Pir Panjal range on the southwest side of Kashmir, or its extension in Hazara, associated with the IKSZ (Fig. 2). The Ravi and the Beas, in the transition zone between the central and the western Himalayas, are not readily classified.

The trans-Himalayan rivers in the central Himalayas, exhibit a low gradient in the Tibetan Plateau south of the suture (Tethys Himalayas), a steep gradient across the High Himalayas and a low gradient in the Lesser Himalayas, the Sub-Himalayas and the alluvial plains (Fig. 4). Although the rivers at both extremities of the arc traverse a more complex tectonic environment, their profiles resemble those of the central Himalayan rivers. Thus, the profiles of all the trans Himalayan rivers deviate sharply from the typical semilogarithmic profile of a graded river. On the other hand, the Ganges–Alaknanda (Fig. 4) which drains only the south flank of the Himalayas, has a nearly ideal semilogarithmic profile, as does the Swat, at the western termination of the Himalayan front.

Reaches with a gradient significantly higher ($\geq \times 2$) than the semilogarithmic profiles are detected on all rivers. The downstream limit of these steep reaches is consistently associated with the BTF, except for the Subansiri. Typically, gradients

remain high for a number of contour crossings upstream of the BTF, in a zone of increased gradient. Very-high gradients or knickpoints (arbitrarily defined here as $\times 10$ of ideal gradient) occur on short reaches, usually contained between two consecutive contour crossings. All knickpoints occur at or upstream of the BTF and in many cases they can be associated with the MCT, or other known surface faults (Figs. 2 and 4; Table I). Details of the correlation between structures and river gradients are discussed from west to east in the next paragraphs.

The profiles of rivers that cross the western terminus of the Himalayan front, the Hazara arc (Fig. 2), exhibit anomalously high gradients at or slightly north of the Indus Kohistan seismic zone (IKSZ), the western terminus of the BTF (Gornitz and Seeber, 1981; minor differences between the location of knickpoints described in that paper and in Fig. 2 are due to a revised definition of "knickpoint"). The correlation between high river gradients and seismicity in Hazara is particularly significant because in this area the surface structures are discordant and decoupled from the active basement structures (Seeber and Armbruster, 1979). Both MCT and MBT (the western extension of the Panjal and Murree thrusts; see Tahirkheli, 1980) lie south of the IKSZ and do not show high river gradients.

In the Hazara–Kashmir syntaxis, the MCT and MBT (Panjal and Murree thrusts, Wadia, 1931; Calkins et al., 1975) lie north (upstream) of the IKSZ–BTF (Seeber and Jacobs, 1977; Fig. 2). High gradients are detected on both the Jhelum and the Kundar rivers at the BTF, and somewhat downstream of the MBT, where the rivers cut through the Cenozoic terrigenous, non-metamorphosed sediments.

West of the Sutlej river, along the Kashmir Himalayas, the MBT and the MCT lie close together and to the BTF. This is the only portion of the Himalayan front where anomalously steep river gradient are associated with the MBT.

River profiles in the central portion of the Himalayan arc (Sutlej to Tista, included) not only show zones of increased gradient which consistently correlate with the BTF, but also exhibit knick points which are often correlated with the MCT (Fig. 4; Table I). Of the nine rivers analyzed in the central Himalayas, five cross the MCT near the base of unusually steep reaches. The position of the MCT at the crossing of the Sutlej and the Karnali is uncertain but it may also fit into a similar pattern (Gansser, 1964, plate 1; 1977; Bordet, 1973; Hashimoto et al., 1973, plate 4). The position of the MCT along the Arun is somewhat controversial. The lowermost of the subparallel thrusts considered by Akiba et al. (1973) to represent the MCT in the Arun valley is at the base of the zone of increased gradient.

Thus, the most consistent feature of Himalayan rivers is the correlation between the belt of thrust earthquakes (BTF) and the base of the zone of increased gradient. Knickpoints often coincide with the MCT, defined as the most northerly outcrop of the basal thrust of the Tethyan slab. On the other hand, extensions of the MCT into the Lesser Himalayas, as the basal thrust of crystalline klippen, do not correlate with knickpoints on the major rivers.

The profile of the Subansiri is the major exception to the above-cited pattern.

TABLE 1 - DRAINAGE FEATURES VS. MAJOR STRUCTURES

RIVERS	REGION	LONGITUDINAL STRUCTURE				TRANSVERSE STRUCTURES	
		MBT	MCT	Eq. Belt	Other Faults	ALONG RIVERS	ALONG RIVERS
<u>Swat</u>	A Kohistan, Hazara	---	---	* Extension of IKSZ(6)		WSW LL's along lower Swat Valley(6)	
<u>Indus</u>	A Tibet, Kohistan, Hazara, Potwar	Murree (5)	Panjaj (5)	▲ IKSZ (6)	** Nanga Parbat Uplift, MPT(10)	NW along suture; west along Panjal-Hazara (Murree) thrusts(1)	South LL's and horst anticline reentrant between Patan and Tar-bela Dam (5,6)
<u>Kundar</u>	A Hazara-Kashmir Syntaxis	* Murree	* Panjal	▲ IKSZ		South along Panjal-Murree thrusts west of syntaxis (5)	Hazara-Kashmir Syntaxis
<u>Kishanganga (6)</u>	A Hazara-Kashmir Syntaxis	Murree	Panjaj	?		NW along Murree thrust east of syntaxis (5)	
<u>Jhelum</u>	A Kashmir, Jhelum-Reentrant	* Murree	* Panjal	▲ IKSZ		NW along IKSZ and across the syntaxis(6)	Jhelum Reentrant(1)
<u>Chenab</u>	A Kashmir, Jammu		?	▲		NW along Murree-Panjaj thrusts(1)	Reentrant at the Sub-himalaya(1)
<u>Ravi</u>	? Kashmir	ND	ND	ND		Reentrant at MBT and Subhimalaya(1)	
<u>Beas</u>	? Himachal Pradesh	ND	ND	ND		NW along folds in Sub-himalaya(1)	Kangra Reentrant(1)
<u>Sutlej</u>	A Tibet, Himachal Pradesh		▲ (2)?	▲	** (1)	NW and SE along structures in Subhimalaya(1)	Anticlinal structure north of Simla(1)
<u>Jumna</u>	No Himachal/Uttar Pradesh	ND	ND	ND			
<u>Ganges-Alaknanda</u>	No Uttar Pradesh		▲ (1,2)	▲		Offset along Subhimalayas(1)	

<u>Kali-Sarda</u>	No	Uttar Pradesh/ West Nepal	ND	ND	ND	
<u>Karnali</u>	A	West Nepal	*	(1,3)	▲	NW along MBT then SE along Subhimalaya(1,2,3)
<u>Bheri</u>	A	West Nepal	**	(1,3,4)	▲	NW along Subhimalaya(3)
<u>Kali Gandaki</u>	A	Central Nepal	**	(3,4)	▲	East along Lesser Himalaya(3)
<u>Irisuli</u>	A	Central Nepal	**	(2,3)	▲	West along Lesser Himalaya(3)
<u>Sun Kosi</u>	A	East Nepal	▲	(2,3)	●	East along Subhimalaya(3)
<u>Arun</u>	A	East Nepal			▲	* (3)
<u>Tista</u>	?	Sikkim	▲	(2,3) ?	●	Anticline through High and Lesser Himalaya(3,8)
<u>Torsa</u>	?	West Bhutan	ND		ND	Anticline through Lesser Himalaya(1)
<u>Sunkosh (Ho-Chu)</u>	A	West Bhutan	ND		ND	
<u>Kuru</u>	A	East Bhutan	ND		ND	
<u>Bhareli</u>	No	West Arunachal	ND		ND	
<u>Subansiri</u>	A	Arunachal	?		?	
<u>Tsang-Po Brahmaputra</u>	A	Tibet-Arunachal	?		▲	** (9) East along suture(1) Antiform-reentrant through Lesser and High Himalaya(9)

*(**) Structure approximately correlates with local relative high (very high) gradient.

▲ Structure approximately correlates with base of zone of high gradient.

A Transhimalayan (antecedent) river - originates north of High Himalaya.

● River crossing of these features is close or coincides.

LL Landsat lineament ND No river profile data

Directions are downstream --- River does not cross structure

BLANK No apparent effect on river morphology ? Position of structure is uncertain.

- (1) Gansser, 1964, plate 1
- (2) Gansser, 1977
- (3) Hashimoto et al., 1973
- (4) Fuchs and Frank, 1970
- (5) Calkins et al., 1975
- (6) Gornitz and Seeber, 1981
- (7) Bordet et al., 1971
- (8) Bordet, 1961
- (9) Jain et al., 1974
- (10) Tahirkheli et al., 1979

This river drains an area of the eastern Himalayas where the BTF is poorly defined and beyond which the BTF deviates northward from the small circle (Fig. 2). The anomalous profile of the Subansiri (Fig. 4) may reflect a tectonic complexity at this transition zone, but it may also be in error, because of unreliable topographic data (ONC H-10, 1972).

The two main longitudinal rivers, the Indus and the Tsang-Po–Brahmaputra, cross the Himalayas at the two extremities of the arc to form a remarkably symmetrical drainage pattern. As in the transverse rivers, the lowest reaches with anomalously steep gradients correlate with the BTF. In addition, both rivers are very steep ($SL \gg K$, Figs. 2 and 4) for several contour crossings along the reaches where they finally cut through the Himalaya after their longitudinal course.

The southward bend of the Tsang-Po may correspond to the locus of the capture of this river by the Brahmaputra away from the Luhit river. This hypothetical former path of the Tsang-Po is marked by the long continuous Poch'u-Nagong valley now a tributary of the Tsang-Po and by the upper reach of the Luhit river (Fig. 2). However, a major low-angle thrust (Jain et al., 1974) a possible extension of the Tsang-Po suture zone (Gansser, 1964, plate 1; 1980, Fig. 2), intersects the Brahmaputra at the base of the reach with high gradient and therefore a tectonic origin for it cannot be ruled out.

Local differential uplift seems more likely than river capture for the steep gradient of the Indus across the Nanga Parbat spur, a major transverse anticline/horst. This structure is bounded on three sides by the southern branch of the Indus suture, also termed the Main Mantle Thrust (MMT) west of the Nanga Parbat (Tahirkheli et al., 1979), and corresponds with a major isolated topographic high. Ongoing uplift of the Nanga Parbat spur is suggested by the topography, by the river gradient and by fission track ages (Zeitler et al., 1981). Thus, the Early Cenozoic Indus suture may be currently reactivated in proximity of the Nanga Parbat. Downstream from the Nanga Parbat the profile of the Indus steepens as it crosses the MMT and the Indus Kohistan seismic zone (IKSZ) which nearly coincide at that crossing (Fig. 2). Although the steep gradient may indicate ongoing slip on the MMT, this is probably only of local significance since the major topographic feature in this area is associated with the IKSZ and not the MMT. Fifty km west of the Indus, no steep gradient occurs where the Swat river crosses the MMT. In this same area fission track data suggest that no significant uplift has occurred across the MMT within the last 15 m.y. (Zeitler et al., 1982).

DISCUSSION

A tectonic origin for the high gradients in Himalayan river profiles

Reaches of high gradients or knickpoints along rivers can originate in several ways. They can develop from a eustatic lowering of the base level of erosion (usually

sea level), which steepens the gradient in the newly exposed level of the river and increases the amount of down-cutting there. The resulting high gradients are not stable and will migrate upstream by headward erosion and disappear, as the river is regraded to the lower base level. The regional base level for Himalayan rivers is the Indo-Gangetic alluvial plains. Since terrigenous Siwalik sediments have accumulated continuously at least since Mid-Miocene without any major break (Karun Akaran and Ranga Rao, 1976; Johnson et al., 1979), it is unlikely that lowering of the base level has contributed significantly to the formation of the Himalayan river knick-points.

Sharp changes in gradient in a graded river profile can also occur at the intersection with a large tributary or where the resistance to erosion of the bedrock changes. Appalachian rivers with similar discharge can differ in slope as much as an order of magnitude. These differences can be ascribed to lithology (Hack, 1979). In the Himalayas the correlation between erosion-resistant rocks and high river gradients is generally good. In the south slope of the High Himalayas, where the high-grade metamorphic rocks of the Tethyan slab are exposed, river gradients are steep. In the Lesser Himalayas, where rocks are generally low-grade sediments which are more easily eroded, the gradients are low. Accordingly, the MCT, as the structural boundary between the crystallines of the Tethyan slab and the sediments of the Lesser Himalayas, corresponds in many instances to the transition from high to low river gradients (Figs. 2 and 4; Table I).

However, many inconsistencies appear when the correlation between river gradients and lithology is examined in detail. The erosion-resistant rocks of the Tethyan slab recur in the Lesser Himalayas as overthrust sheets (Gansser, 1977) or klippen (Stöcklin, 1980). Yet, relatively steeper river gradients are not found in the Lesser Himalayas (except possibly along the Subsansiri). For example, gradient and lithology do not correlate along the Arun (Fig. 5). Lack of correspondence between gradient and lithology is also observed in the Hazara–Kashmir syntaxis, where the river gradients (Kundar and Jhelum) steepen significantly within the Sub-Himalayan terrigenous sediments of the Murree Formation (Calkins et al., 1975), and in the Hazara arc, where increase in gradient along the Indus and Swat rivers occur, respectively, within the Tethyan sediments north of the MCT and within the Kohistan island arc terrain north of the suture (Tahirkheli et al., 1979). No steepening of gradient accompanies the sharp change in lithology across the MBT, except where this fault zone lies close to the BTF (e.g., Jhelum, Kundar, Fig. 4, Table I).

Steady-state elements in a tectonic system, such as the long-term rate of displacement across a fault, may also generate deviations from an ideal profile in a graded (stable) river. A steep gradient can be expected on the upthrown side of a dip-slip fault, if this side is upstream. In a steady-state morphotectonic regime, differential uplift must be balanced by differential erosion. In such a regime the graded (or equilibrium) state requires more energy (higher velocity) and hence a steeper

SKETCH OF TECTONIC MODEL

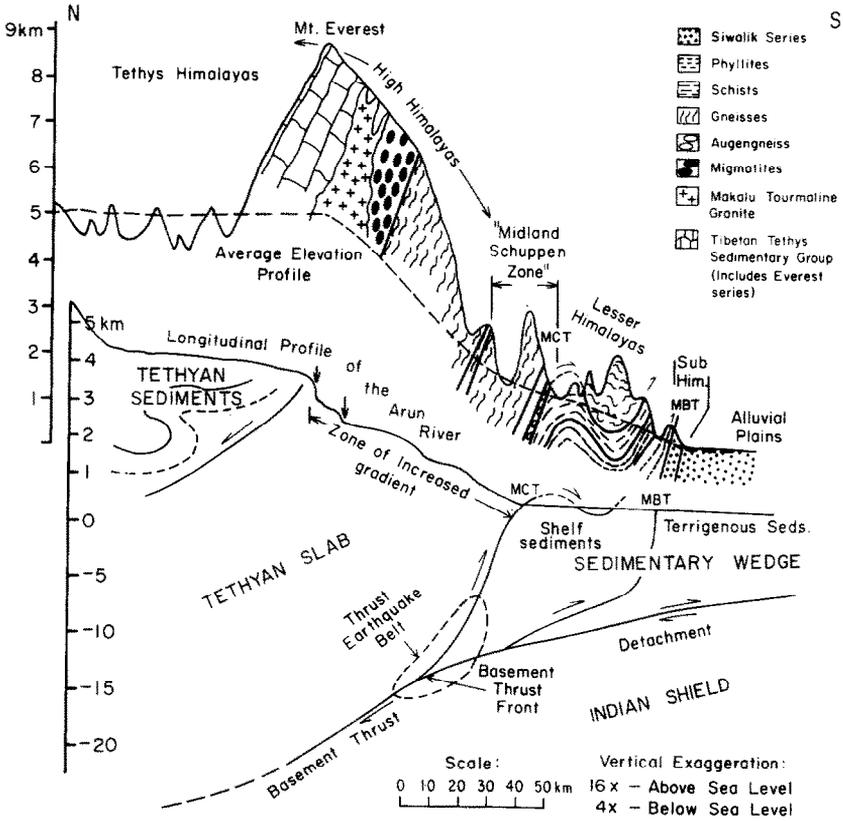


Fig. 5. Topographic and geologic sections (modified from Akiba et al., 1973) west of and adjacent to the Arun River, along 87°E longitude and between 28°30' and 26°30'N latitude. The longitudinal profile of the Arun river and the average topographic profile across the central Himalayas (from Bird, 1978) are also shown. Subsurface active structures are sketched according to the steady state model. Compare with Fig. 3C.

gradient in the areas that are differentially uplifting. Inconsistencies between lithology and steep river gradients described above suggest that the role of differential erosion is secondary to the role of tectonics in shaping the profiles of Himalayan rivers. Moreover, the persistent correlation between the BTF, as delineated by the thrust earthquake belt, and the base of the zone of increased gradients, even where lithology does not play a role, strongly suggests that the increased gradients are the result of differential uplift of the High Himalayas, the southern edge of the Tethyan slab thrust over the Lesser Himalayas (Fig. 3; Wadia, 1931, p. 436).

Plio-Pleistocene beds in the Thakkhola half graben (*T* in Fig. 2) are generally flat along the axis of this transverse basin, except near the southern end of the basin

where they tilt northward and are eroded off (Fort et al., 1980). If extended 20–30 km to the south, this tilt would imply that the High Himalayas has uplifted about 8 km with respect to the Tibetan Plateau since the Thakkhola formation was deposited. Differential uplift of the High Himalayas is also suggested by the height of Recent river terraces along the Kali Gandaki. The highest terraces above river level are found in the gorges through the high range (Bordet et al., 1971; Monique Fort, pers. commun., 1981). Wagner (1937) observed similar behavior of river terraces along the Arun. The fastest downcutting (erosion) is occurring where the hard rocks of the Tethyan slab offer the strongest resistance to erosion. Although this pattern of erosion could be interpreted as a snapshot view of a backward-eroding unstable steep gradient, the occurrence of a high rate of differential erosion in erosion-resistant rocks strongly suggests differential uplift.

The Arun river section (Fig. 5) typifies the relationship between the various structural and morphologic elements in the central part of the Himalayas, where the Basement Thrust Front (BTF) traces a small circle on the earth's surface (Figs. 1 and 2). The N–S longitudinal profile of the river is compared to topographic and geologic sections west of the river and to the average topographic profile. The relatively flat upper stretch of the river near its source (av. gradient 0.02) traverses parts of the Tethyan and the High Himalayas. The zone of increased gradient (average gradient = 0.09 between the 12,000 ft and 1,000 ft contour; two knickpoints are included) begins near the highest peaks and ends near the thrust (MCT?) at the base of the "schuppen zone" where the slope decreases to 0.003. This drastic change in slope also correlates with the BTF, as expressed by the seismicity. From this point on, the slope of the river remains low for 45 km through the Lesser Himalayas, the MBT and beyond.

The MCT versus the MBT

The High Himalayas correspond to the upturned southern edge of the Tethyan slab thrust above the Lesser Himalayas on the MCT. In the steady state model this is an active process and the MCT is an active fault. Evidence is provided by the thrust earthquakes (Seeber et al., 1981) and by the river profiles and uplifted terraces discussed above. Additional evidence is provided by the *P-T* conditions of fluid inclusions near the MCT (Pecher, 1979). The equilibrium pressure of fluid inclusions in a 50 km profile across the MCT is generally lower than the metamorphic pressure deduced from the mineral assemblages in the rocks. Moreover, the inclusion pressure increases gradually by about 2 kbar from 2 km in the Lesser Himalayas to 3.5 km on the Tethyan slab. These results strongly suggest that (1) considerable uplift and erosion followed the main phase of metamorphism associated with ductile shearing on the MCT and preceded equilibrium of the fluid inclusions; and (2) the Tethyan slab has differentially uplifted, perhaps by as much as 8 km, with respect to the Lesser Himalayas across the MCT *after* the fluid inclusions had reached equilibrium.

Thus, an active MCT must separate the Tethyan slab from the sedimentary wedge. The brittle shallower portion of this structure may consist of a zone of bedding plane faults, subparallel and adjacent to the fossil MCT (Gansser, 1964, plates II and III; Akiba et al., 1973; Brunel and Andrieux, 1977; Pecher, 1978; Valdyia, 1980). Such a fault zone may not be readily recognized in the field as an important tectonic boundary.

The upturning of the Tethyan slab at the BTF is also manifested by the recumbent folds with anomalous northward vergence which are recognized on many sections across the northern flank of the High Himalaya (Gansser, 1964; plate III and p. 122; Fuchs and Frank, 1970; Bordet et al., 1971; Hashimoto et al., 1973, p. 201; LeFort, 1975; Stöcklin, 1980). These prominent folds affect only the Tethyan sediments suggesting a detachment at the top of the Tethyan slab (Figs. 3c and 5). In the Thakkola region this detachment corresponds to the Larjung limestones, lithologically similar to, and possibly coeval with, the Eocambrian salt formation of the Salt Range (LeFort, 1975; Pecher, 1978, p. 205) which is associated with the Himalayan detachment in Hazara (Seeber and Armbruster, 1979). Thus, the discordant folds may reflect gravitational backward (northward) sliding of the Tethyan sediments above the Tethyan slab, as the southern edge of the slab is uplifted and tilted northward. This interpretation requires that the discordant north-verging folds are younger than the dominant south-verging system of the Tethyan Himalayas (Pecher, 1978; Calkins et al., 1975), and that the north-verging folds occur only on the northern flank of the High Himalayas.

The upturning of the Tethyan slab can be caused in part by pressure from the sedimentary wedge. This pressure is high since the resulting horizontal force applied over the ≈ 20 km thick back side of the wedge must balance the horizontal force resulting from the drag over the ≈ 200 km wide detachment (Fig. 3C). The upturning of the Tethyan slab can also represent isostatic readjustment to the rapid erosion rate on the High Himalayas, which removes material from the surface, while underthrusting adds material from below. Equilibrium is maintained by a structural rise (but not necessarily an average topographic rise) along the High Himalayas (Wager, 1937). In this process, the BTF migrates downdip along the basement thrust (Fig. 3C) and the base of the Tethyan slab is exposed at the trace of the MCT.

The MCT is usually recognized as a ductile shear zone indicative of *P-T* conditions of the lower crust (LeFort, 1975; Mattauer, 1975; Pecher, 1977; Mehta, 1980). In the steady state model this shear zone is interpreted as the deeper portion of the thrust which has been uplifted and is now inactive. Thus, the age of the metamorphism on this fossil shear zone (≈ 15 m.y.) corresponds to the time it takes for the base of the Tethyan slab to rise from the BTF (15–20 km deep) to the surface, at about 1–1.3 mm/year. This value is consistent with the Plio-Pleistocene rate of uplift on the northern flank of the High Himalayas obtained from paleobotany (Hsu, 1976); with the somewhat lower rate of uplift obtained from Rb-Sr mineral dates (0.7–0.8 mm/year; Mehta, 1980); or with the erosion rate estimated

from the sediment load carried by the rivers (0.7 mm/year; Curray and Moore, 1971). The latter two values represent an average for both the High and the Lesser Himalayas. Similar rates of uplift and erosion and hence an invariant average topography are predicted by the steady-state model.

In the evolutionary model (Fig. 3A; see above) the MBT and the MCT are similar intracontinental basement thrusts active in succession, whereas in the steady-state model (Fig. 3C; see above), these faults play different roles and they have both been simultaneously active. Thus, the history of the main faults can provide constraints for the tectonic models.

Post-Subathu terrigenous sedimentation (Siwalik and Murree) are absent north of the MBT, except in isolated basins (Gansser, 1964, p. 246; Stöcklin, 1980). This absence suggests that the MBT has been active and has kept the upthrown block, the Lesser Himalaya, above the level of deposition, at least since early Miocene and probably since Upper Eocene (Karun Akaran and Ranga Rao, 1976), while the MCT was concurrently active. Tilted and faulted Holocene terraces and scree (Heim and Gansser, 1939; Krishnaswami et al., 1970; Bordet et al., 1971; Jaros and Jalvoda, 1978) and fault-creep measurements (Sinval et al., 1973) clearly demonstrate that the MBT is currently active. Thus, both MBT and MCT probably were, and still are, active simultaneously as predicted by the steady-state model. In the collision boundary of New Guinea, structures comparable to the MBT and MCT are being generated simultaneously (see below).

In contrast to the MCT, the MBT does not produce a significant increase in slope on any of the river profiles examined, except along the Kashmir Himalayas, where it is near the seismic belt and the MCT (Jhelum and Kunder rivers, Fig. 2). Furthermore, neither the great Himalayan earthquakes (Seeber and Armbruster, 1981) nor the small earthquakes in Hazara (Seeber and Armbruster, 1979) can be associated with the MBT. This suggests that the MBT, rather than being a major tectonic boundary as in the evolutionary model, is prominent primarily as a lithologic and perhaps a rheologic boundary between terrigenous sediments and precollisional sediments of the former passive continental margin. In the steady state model the MBT is one of several imbricate thrusts which contribute to the shortening of the sedimentary wedge. Imbricate thrusts of this kind are found in the sedimentary wedges (accretionary prisms) at oceanic subduction zones (Karig, 1977). Evidence from uplifted terraces (e.g., Plafker and Ruben, 1978) suggests that these imbricate thrusts slip in discrete events, possibly great earthquakes, but that the repeat time for these events is much longer and the slip rate is much lower on these faults than on the underlying megathrust or detachment.

The MCT and the MBT differ not only in the way they affect river gradients, but also in the way they affect river courses. Steep gradients are associated with the MCT and not with the MBT, whereas lateral deflection of river courses are generally associated with the MBT and related thrust/folds of the Sub-Himalayas but not with the MCT. The latter characteristic of the drainage has been often considered

evidence for an active MBT versus an inactive MCT (e.g., Valdiya, 1980).

Alternatively, differential uplift of the High Himalayas has led to entrenchment of the antecedent drainage in deep gorges and made it not readily susceptible to diversions. Instead, diversions near the erosion–deposition boundary may be facilitated by the low river gradients in this area. Local uplift and backward tilting, such as the growth of the Mahabharat range during the Plio-Pleistocene (Sharma et al., 1980; Stöcklin, 1980) accompanies the folding and thrusting that accounts for shortening in the wedge. These movements can effectively divert the aggrading portions of river courses, such as is now occurring along the outer belt of Sub Himalayas at the erosion/deposition boundary (e.g., the Sutlej, Fig. 2). This boundary is south of the MBT along most of the Himalayan front, except in the east near the Bengal basin. It is possible that lateral deviation of drainage just north of the MBT has occurred elsewhere (e.g., Indus, Karnali, Kali Gandaki, Sun Kosi) when the erosion–deposition boundary may have been somewhat to the north of the MBT.

Antecedence vs. capture in the evolution of trans-Himalayan rivers

The water divide between the longitudinal drainage of the Indus–Tsang-Po system and the south-flowing trans-Himalayan rivers lies north of the highest elevations. This fact has been widely interpreted to indicate that the major Himalayan rivers are antecedent to the uplift of the High Himalayas (Holmes, 1945, p. 200, 201; Medlicott, 1868; Wadia, 1961, p. 29; Parkash and Goel, 1977). An alternate possibility is capture of originally north-flowing tributaries of the Indus–Tsang-Po systems by headward erosion of rivers draining the southern flanks of the Himalayas (Hayden, 1907; Heron, 1922). The southern watershed has more relief and receives more rain than the northern watershed and is therefore subject to higher rates of erosion.

If the divide was primarily controlled by headward erosion and capture its position would probably be irregular with respect to the main longitudinal structures of the Himalayan front. Capture of the sluggish longitudinal drainage along the suture and/or coincidence of the high peaks with the divide would seem likely, depending on the relative effectiveness of uplift and erosion along the Himalayan front. Neither is observed except near the extremities of the arc (see above). Thus, the consistent location of the water divide along a narrow zone of relatively low relief between the longitudinal drainage (of the Indus–Tsang-Po) and the high peaks suggest that this drainage pattern reflects an earlier topographic profile.

Early Pleistocene deposits in the Thakkola valley north of the topographic front indicate a period of northward drainage following southward drainage in the Pliocene (Fort et al., 1980). This temporary reversal to northward drainage in Thakkola does not fit a pattern dominated by headward erosion, but suggest that, overall, uplift and erosion are equilibrated. North–south grabens seem to control the

location of several trans-Himalayan rivers (Kali Gandaki, Arun, and possibly Trisuli, Sun Kosi and Tista). A pre-Himalayan uplift age of these structures would be consistent with an antecedent drainage.

Clastic sedimentation

Transitions between main stages in the tectonic evolution of the Himalayas are probably accompanied by changes in the pattern of uplift and denudation and may be detected in the sedimentary record. The main basins are along the Indus–Tsang-Po suture, north of the Himalayas, and the foredeep, south of the Himalayas.

Along the suture, intensely deformed late Tertiary Indus flysch and ophiolites are overlain unconformably by Upper Cretaceous to Eocene volcanoclastic and shallow marine sediments. During this period, the trans-Himalayan granitic plutons, presumably the root of an island arc, were emplaced north of the suture (Bally et al., 1980; Gansser, 1980). Post-Eocene sedimentation along the suture and within the Himalayas is limited to isolated intramontane basins.

Most of the clastic sediments in the foredeep, instead, are post-Eocene to present. The widespread Subathu transgression (north India) marks the initial disruption of the precollisional passive margin. These Upper Paleocene to Upper Eocene platform sediments record the deepening of the shallow sea toward the north (Karun Akaran and Ranga Rao, 1976). The last marine sedimentation and uplift along the suture coincides with the Subathu transgression. These events may mark an important early transition in the Himalayan collision process. (This stage of the Himalayan collision is compared with continent–arc collision in New Guinea, see below).

The transition from the Subathu platform/distal/marine conditions to the Murrees–Dharmasala basin/proximal/fluvial conditions is gradational, time-transgressive, and completed by late Eocene (Karun Akaran and Ranga Rao, 1976; Johnson et al., 1979). Sedimentological studies suggest that even the initial Murree sediments were supplied primarily by a north–south drainage (Karun Akaran and Ranga Rao, 1976). Thus, the sedimentary record of the Himalayan foredeep is consistent with an antecedent drainage, preserved from the early stages of collision (Gill, 1951; Tandon, 1972; Parkash et al., 1974; Vissar and Johnson, 1978).

The Murree–Siwaliks contact is conformable, gradational, and time-transgressive (Karun Akaran and Ranga Rao, 1976). In general, the Murrees–Siwaliks transition represents only a minor change in facies and does not seem to require any drastic change in the drainage and in the tectonic regime.

The upward coarsening of the Siwalik “molasse” has been interpreted as indicating intensification of the Himalayan orogeny during the Plio-Pleistocene (Gansser, 1964, p. 245; Parkash et al., 1974, 1975; Parkash and Goel, 1977; Stöcklin, 1980). The appearance of conglomerates may either be interpreted as deposition at a constant distance from a growing mountain range, or as a time-transgressive facies change associated with the prograding alluvial fan sequence (Reynolds et al., 1980).

The coarser sediments near the mountain front are the first to be underthrust, whereas the more distal and finer portions of the older sediments are preferentially preserved in the accessible sedimentary record (Fig. 3C). In this way the tectonic process biases the sedimentary record tending to produce an increase in source distance with age at any outcrop. Thus, the decrease in coarseness with increasing age observed in the Sub-Himalayas does not necessarily require recent uplift of the Himalayas and may be consistent with a steady-state model.

The Himalayas vs. New Guinea

In the northward drift toward Asia, the Indo-Australian plate may have collided with a number of island arcs and related structures before interacting directly with continental Asia (Klootwijk, 1979; Tahirkheli et al., 1979). The Indian, or northwestern continental part of the Indo-Australian plate has already concluded the arc collision stage, whereas the Australian, or eastern continental part of this plate, is just beginning to interact with the southern boundary of the complex system of island arcs and microplates of Indonesia. Thus, the ongoing continent-arc collision between Australia and New Guinea may be similar to the collision that resulted in the formation of the Indus-Tsang-Po suture.

A mid-Tertiary collision suture in New Guinea separates the island arc terrains (north) from the north Australian passive margin (south) (Hamilton, 1979). The spatial distribution of sedimentary facies near the New Guinea suture (D'Addario et al., 1976) closely resembles that of the Indus-Tsang-Po suture (Gansser, 1964, plate II; Bally et al., 1980). In both cases, the suture zones are characterized by exotic blocks of deep-water sediments and fragments of oceanic crust in a flysch matrix (Figs. 6 and 7). North of the sutures, volcanoclastic sediments are intruded by granites, while south of the sutures, a suite of passive margin sediments grades progressively toward the foreland from deep water, to continental rise-slope, to outer shelf, and finally into inner shelf and platform sediments.

The recent pattern of sedimentation in New Guinea and northern Australia closely resembles that in northern India and in Southern Tibet during the Paleocene-Eocene. The shallow Arafura Sea covering a vast portion of the northern Australian continent is akin to the Subathu Sea transgressing over northern India. The gradual transition from platform to clastic sedimentation at the northern fringes of the Arafura Sea is reminiscent of the time-transgressive transition from Subathu to Murrees-Dharmasala. During Subathu time, the last phase of widespread sedimentation along the suture north of the Himalayas, is characterized by shallow marine and volcanoclastic sediments, very similar to the present or recent pattern of sedimentation north of the New Guinea suture.

In New Guinea, as in the Himalayas, the structures south of the suture display a strong southward vergence. Rocks of subduction complex are thrust southward over the formations of the outer passive margin. (Northward-verging discordant folds on

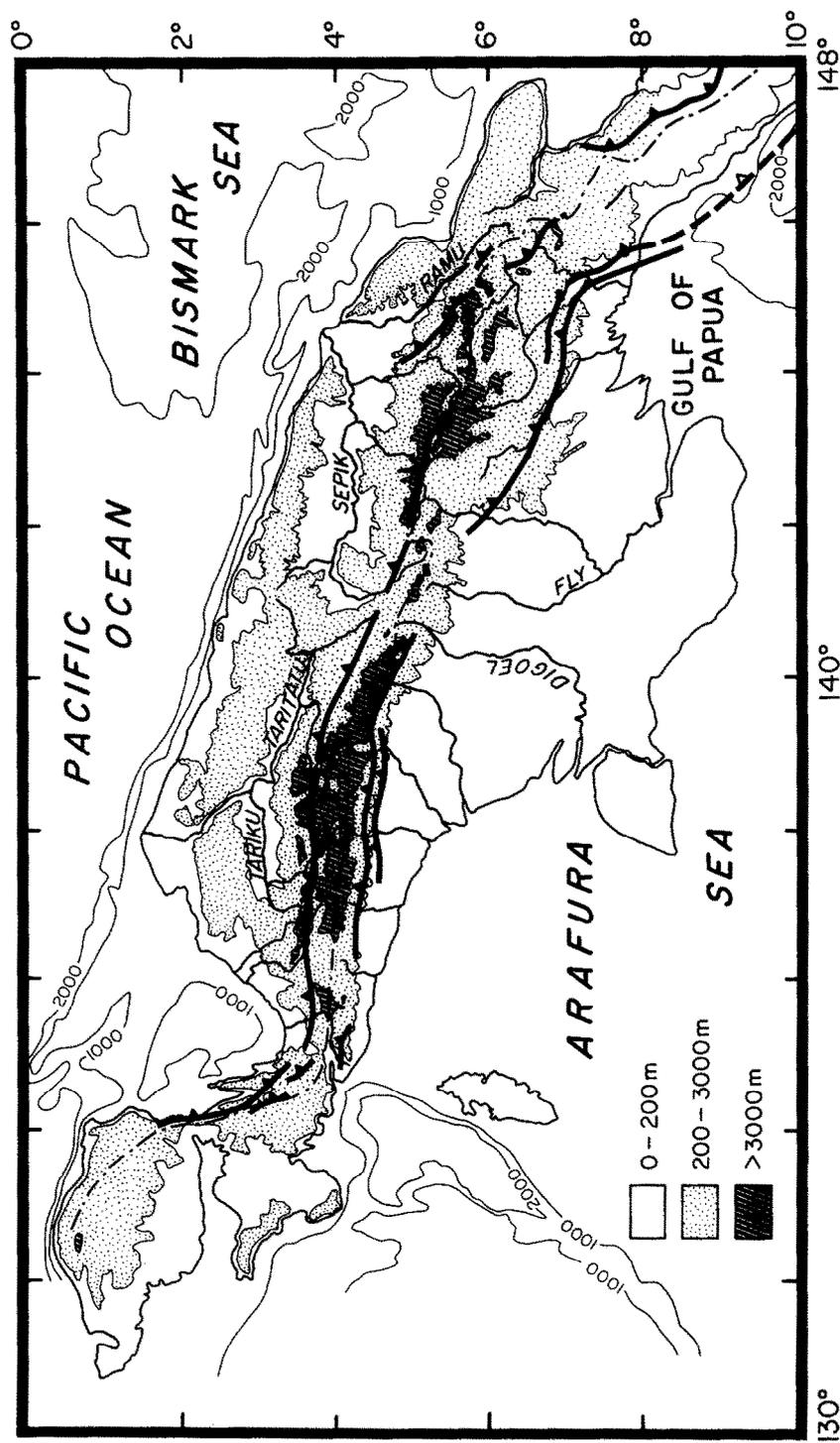


Fig. 6. Topography of New Guinea. The water divide (dashed line) coincides approximately with the highest topography. Major thrusts are indicated as in Fig. 7.

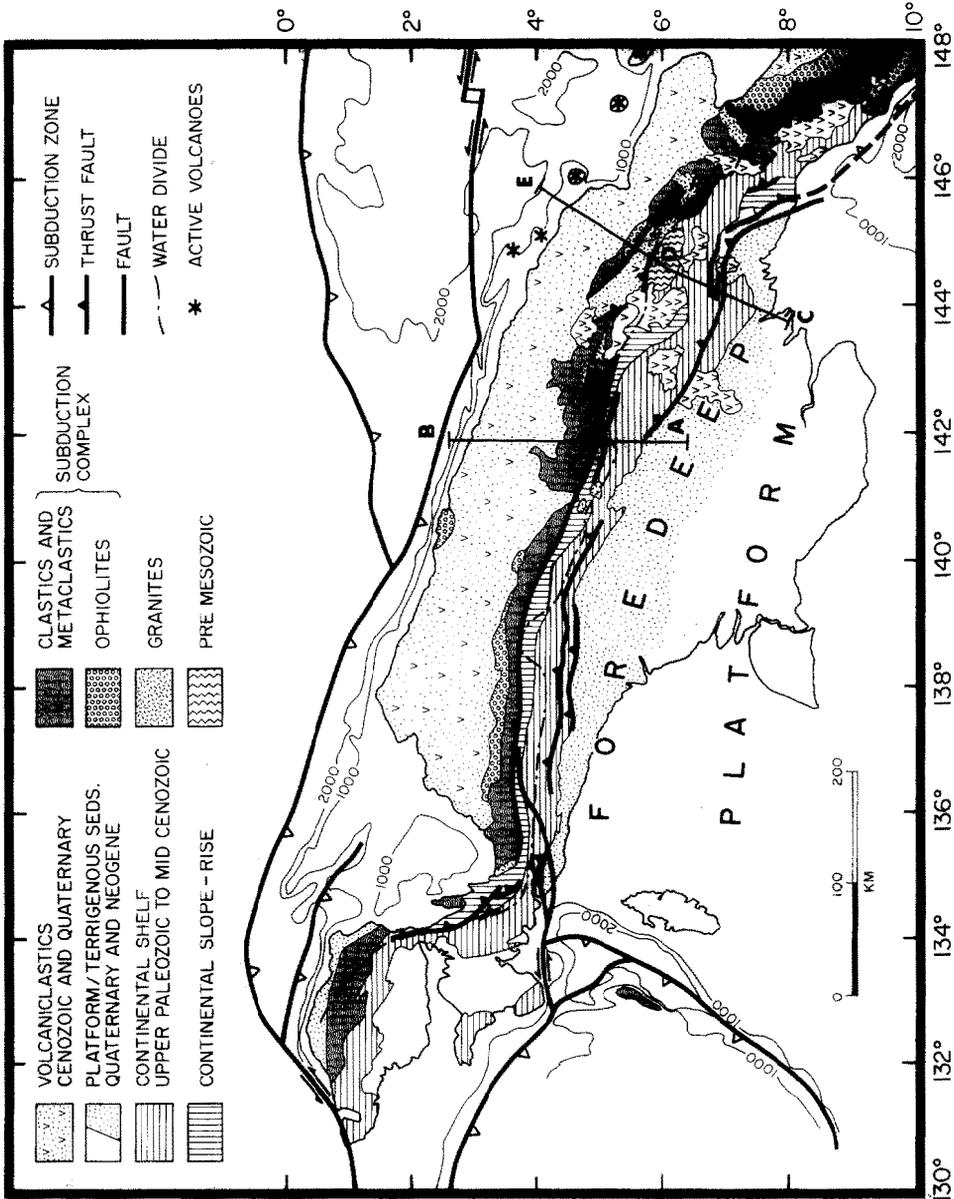


Fig. 7. Main features of the geology of New Guinea (from Hamilton, 1979).

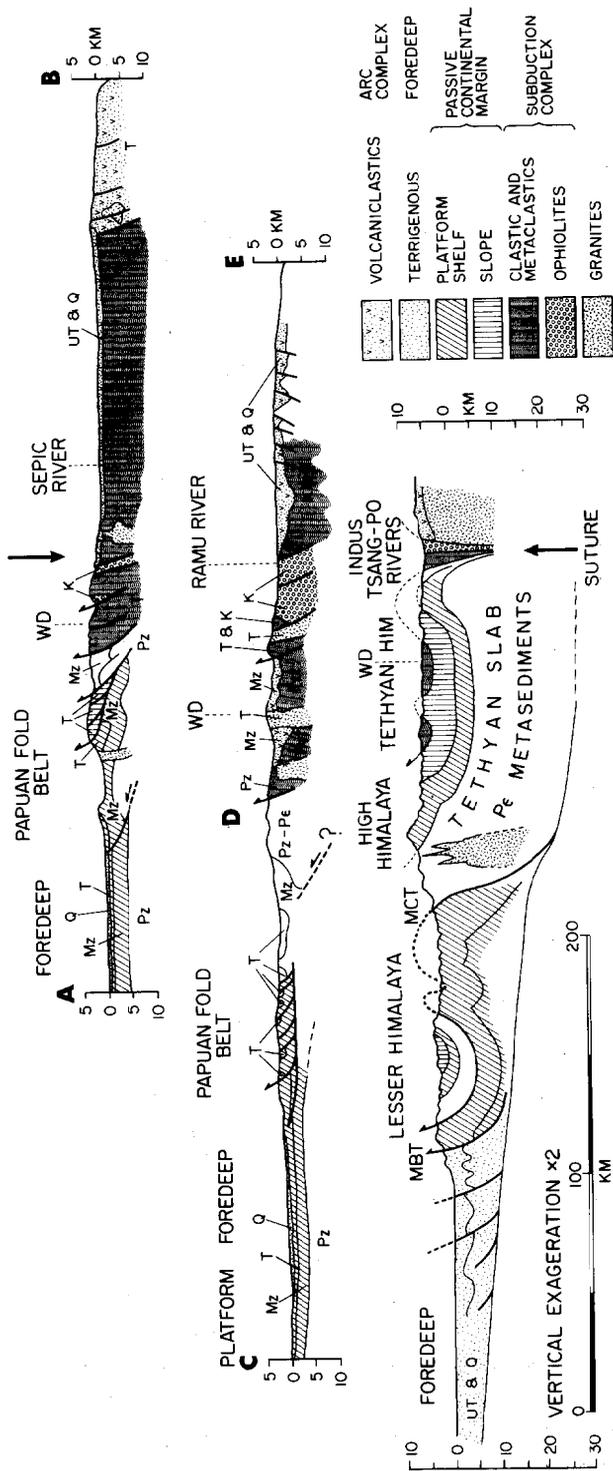


Fig. 8. Two sections across New Guinea (AB and CDE, located in Fig. 7; from D'Addario et al., 1976) compared to a section across the central Himalayas (from Gansser, 1964, plate II and Seeber et al., 1981; also Figs. 1 and 3). Sections are aligned at the suture zones. Note location of water divide (WD). Q = Quaternary, U = Upper, T = Tertiary, K = Cretaceous, Mz = Mesozoic, Pz = Paleozoic, PC = Precambrian. The present stage of development in New Guinea resembles the Subahtu (Late Eocene) stage in the development of the Himalayas.

the northward slope of the High Himalayas probably developed later; see above.) In both regions, the dominant southward vergence is attributed to the northward polarity of subduction (Klootwijk, 1979; Hamilton, 1979).

In New Guinea, continental collision has not yet occurred; however, a deeply rooted thrust, reminiscent of the MCT, may be already active south of the suture, below the uplifted block of Paleozoic rocks in section CDE (Fig. 8). Further south, a listric set of shallow thrusts in the Papuan fold belt may be the counterparts of an incipient "MBT".

The water divides along both the Himalayas and New Guinea lie close and south (towards the foreland) of the sutures (Figs. 2 and 7). South of the divides, the rivers flow radially across the arcs. North of the divides, instead, the rivers flow along the suture. In New Guinea the drainage conforms to the present topography. A narrow high range (3–5 km) is parallel and near to the suture and coincides approximately with the water divide. The longitudinal drainage north of the suture is parallel to ridges which are probably structurally controlled. On the other hand, the present Himalayan drainage does not conform to the topographic profile. The high ridge of the Himalayas lies consistently 100–150 km south of the water divide (Figs. 2 and 8). Moreover, this ridge is asymmetrical, rising sharply from the Lesser Himalayas on the south, and merging gradually into the Tibetan Plateau on the north. The characteristic features of Himalayan topography are probably the result of continental subduction (Fig. 3), which has not yet occurred in New Guinea.

Thus, New Guinea and the Himalayas appear as similar structures at different stages of evolution. The drainage pattern probably originates during the early tectonic phase (continent–arc collision) in both cases, and is now antecedent in the Himalaya, but still consequent in New Guinea.

SUMMARY AND CONCLUSIONS

Most major transverse Himalayan rivers originate south of the Indus–Tsang–Po suture and flow southward through the axis of highest topography (trans-Himalayan). All of the trans-Himalayan rivers examined here show profiles quite different from the ideal graded case (Fig. 4). These rivers are characterized by relatively steep gradients through the High Himalayas, and by relatively low gradients, downstream, in the Lesser Himalayas, the Sub-Himalayas and the alluvial plain, and also upstream, in the high plateau (Tethyan Himalayas) north of the High Himalayas.

The downstream edge of the zone of increased gradient correlates with the topographic front between the High and the Lesser Himalayas and with the belt of thrust earthquakes. In the steady state model, these features are the expressions of the basement thrust front (BTF), a fundamental transition in the behavior of the elements overriding the subducting Indian shield: the more rigid Tethyan slab and the more ductile sedimentary wedge. The overthrusting of the sedimentary wedge (Lesser Himalayas) by the Tethyan slab (High Himalayas) produces the topographic, structural and seismic expressions of the BTF.

The MCT, as the surface trace of the inactive ductile shear zone at the base of the Tethyan slab, follows the BTF along part of the Himalayas, primarily in the central portion of the arc. Locally, this and other recognized faults are associated with very steep river gradients (knickpoints). In general, tectonic movement rather than differential erosion seems to play the main role in shaping the large-scale features of Himalayan river profiles, since steep gradients are associated with the MCT only where the trace of this fault falls along the BTF. Further downstream, where the MCT and related litho-stratigraphic units (Lesser Himalayas crystallines) reappear at the base of Klippen, steep river gradients are not associated with this fault. The MBT is not associated with steep gradients, except in the Kashmir Himalayas where this thrust lies close to the thrust-earthquake belt. This seems to preclude a major tectonic role for this thrust. Elsewhere, the transverse rivers tend to be diverted laterally at or near the MBT. River diversions may result from aggradation upstream of the listric MBT during periods of backward tilting of the upthrust block (Mahabharat).

Several lines of evidence suggest that arc-continent collision in New Guinea is a good representation of the early stages (Subathu) of Himalayan evolution. Less developed counterparts to the major Himalayan structures are recognized in New Guinea. Moreover, the drainage patterns in these two orogens are remarkably similar in their relation to these structures. This suggests that the main features of the Himalayan drainage pattern was formed in the early stages of collision when Himalayan topography presumably resembled the present topography in New Guinea, and before the rise of the High Himalayan. Thus, Himalayas drainage is probably antecedent, for the most part.

Capture of relatively weak drainage on the north side of the High Himalayas by more energetic drainage on the south side is locally possible, but it does not seem adequate to form the main features of the drainage pattern.

The combined evidence presented here is consistent with a steady-state model in which the MCT and the MBT are both active, have evolved simultaneously, but play different roles. In this steady-state process, uplift balances erosion, and topography is invariant in the dynamic equilibrium. The sedimentary record of the foredeep does not require changes in the nature or rate of the tectonic regime during post-Eocene times.

ACKNOWLEDGMENTS

John Armbruster and Klaus Jacob gave us valuable suggestions and ideas in many stimulating discussions through the development of this paper. Gerard Bond pointed out the similarity between the drainages of New Guinea and the Himalayas. John Hack, Klaus Jacob, and David Simpson read the manuscript critically and offered helpful suggestions. We thank M. Fort, A. Pecher and M. Brunel for their helpful reprints. Lynn Zappa typed the manuscript and Kazuko Nagao drafted the figures. This work was supported by the following grants: NSF 19995; USGS 19123; USGS 19749; NASA Cooperative Agreement NCC 5-16.

REFERENCES

- Akiba, C, Amma, S. and Ohta, Y., 1973. Arun River Region. In: S. Hashimoto, Y. Ohta and Ch. Akiba (Editors), *Geology of the Nepal Himalaya*. Saikon, Jpn., Ch. 1, pp. 13–33.
- Andrieux, J., Brunel, M. and Hamet, J., 1977. Metamorphism, granitization and relations with the Main Central Thrust in Central Nepal: $^{87}\text{Rb}/^{87}\text{Sr}$ age determinations and discussion. *Écologie et Géologie de l'Himalaya—Colloq. Int. C.N.R.S.*, 268: 31–40.
- Armbruster, J.G., Seeber, L. and Jacob, K.H., 1978. The northern termination of the Himalayan mountain front: active tectonics from microearthquakes. *J. Geophys. Res.*, 83 (B1): 269–282.
- Bally, Allen, C.R., Geyer, R.B., Hamilton, N.B., Hopson, C.A., Molnar, P., Oliver, J.R., Opdyke, N.D., Plafker, G. and Nu, F.T., 1980. Notes on the geology of Tibet and adjacent areas—report of the American plate tectonics delegation to the People's Republic of China. *U.S. Geol. Surv., Open-File Rep.*, 80-501.
- Barazangi, M. and Ni, J., 1982. Velocities and propagation characteristics of Pn and Sn beneath the Himalayan arc and Tibetan Plateau: possible evidence for underthrusting of Indian continental lithosphere beneath Tibet. *Geology*, 10: 179–185.
- Bird, P., 1978. Initiation of intracontinental subduction in the Himalaya. *J. Geophys. Res.*, 83: 4975–4987.
- Bordet, P., 1961. *Recherches géologiques dans l'Himalaya du Népal, Région du Makalu*. C.N.R.S., Paris.
- Bordet, P., 1973. On the position of the Himalayan Main Central Thrust within Nepal, Himalaya. *Seminar on the Geodynamics of the Himalayan Region, Hyderabad, March 5–8, 1973*, pp. 48–55.
- Bordet, P., Colchen, M., Krummenacher, D., LeFort, P., Mouterde, R. and Remy, M., 1971. *Recherches géologiques dans l'Himalaya du Nepal, région de la Thakkola*. C.N.R.S., Paris.
- Brunel, M. and Andrieux, J., 1977. Déformations superposées et mécanismes associés au chevauchement central Himalayen MCT: Nepal oriental. *Ecologie et Géologie de l'Himalaya—Colloq. Int. C.N.R.S.*, 268: 69–83.
- Calkins, J.A., Offield, T.W., Abdullah, S.K.M. and Ali, S.T., 1975. *Geology of the southern Himalaya in Hazara, Pakistan and adjacent areas*. U.S. Geol. Surv., Prof. Pap., 716-C.
- Chapple, W.M., 1978. Mechanics of thin-skinned fold-and-thrust belts. *Geol. Soc. Am. Bull.*, 89: 1189–1198.
- Colchen, M., Fort, M. and Freydet, P., 1980. Évolution paléo-géographique et structurale du fossé de la Thakkola–Mustang (Himalaya du Nepal), implications sur l'histoire récente de la chaîne himalayenne. *C.R. Acad. Sci., Sér. D*, 290: 311–314.
- Curry, J.R. and Moore, D.G., 1971. Growth of the Bengal deep-sea fan and denudation of the Himalayas. *Geol. Soc. Am. Bull.*, 82: 563–572.
- D'Addario, G.W., Dow, D.G. and Swoboda, R., 1976. *Geology of Papua New Guinea*. Australia Bureau of Mineral Resources, Geology and Geophysics, Map scale 1:2,500,000.
- Defense Mapping Agency (U.S.), *Operational Navigation Charts (ONC)*, 1:1,000,000, H9 (1973), H10 (1973), G6 (1977), G7 (1974).
- Department of Defense (U.S.), *Joint Operation Graphic (1954)*. Topographic Maps 1:250,000, Ser. 1501, Sheets NI—42-8, 42-4, 43-1, 43-2, 43-5, 43-6, 43-9.
- Elliott, D., 1976. The motion of thrust sheets. *J. Geophys. Res.*, 81: 949–963.
- Fort, M., Bassoulet, J.P., Colchen, M. and Freydet, P., 1980. Sedimentological and structural evolution of the Thakkhola Mustang graben (Nepal Himalayas) during late Neogene and Quaternary. *26 Int. Geol. Congr., Paris, Abstr.*, p. 652.
- Fuchs, G. and Frank, W., 1970. The geology of West Nepal between the rivers Kali Gandaki and Thulo, Bheri. *Jahrb. Geol. Bundesanst.*, 18: 103 pp.
- Gill, W.D., 1951. The stratigraphy of the Siwalik series in the northern Potwar, Punjab, Pakistan. *Q. J. Soc. London*, 107: 375–394.
- Gansser, A., 1964. *Geology of the Himalayas*. Interscience–Wiley, New York, 289 pp.

- Gansser, A., 1977. Structural map of the Himalaya and South Tibet, 1 : 3,500,000. *Ecologie et Géologie de l'Himalaya—Colloq. Int., C.N.R.S.* 268.
- Gansser, A., 1980. The significance of the Himalayan suture zone. *Tectonophysics*, 62: 37–52.
- Gornitz, V. and Seeber, L., 1981. Morphotectonic analysis of the Hazara arc region of the Himalayas, North Pakistan and northeast India. *Tectonophysics*, 74: 263–282.
- Hack, J.T., 1973a. Drainage adjustments in the Appalachians. In: M. Marisawa (Editor), *Fluvial Geomorphology*. State University of New York, Binghamton, N.Y., 51–69.
- Hack, J.T., 1973b. Stream profile analysis and stream-gradient index. *J. Res. U.S. Geol. Surv.*, 1 (4): 421–429.
- Hack, J.T., 1979. Rock control and tectonism—their importance in shaping the Appalachian highlands. *U.S. Geol. Surv., Prof. Pap.*, 1126-B.
- Hamilton, W., 1979. Tectonics of the Indonesian region. *U.S. Geol. Surv., Prof. Pap.*, 1078.
- Hashimoto, S., Ohta, Y. and Akiba, C., 1973. *Geology of the Nepal Himalaya*. Saikon, Sapporo., 286 pp.
- Hayden, M.M., 1907. The geology of the provinces of Tsang and U in central Tibet. *Mem. Geol. Surv. India*, 36, pt. 2: 122–201.
- Heim, A. and Gansser, A., 1939. Central Himalaya. Geological observations of the Swiss expedition, 1936. *Denkschr. Schweiz. Naturforsch. Ges.*, 73 (1): 245 pp; Hindustan Publ. Co., New Delhi, 1975 (reprint), 245 pp.
- Heron, A.M., 1922. Geological results of the Mt. Everest reconnaissance expedition. *Mem. Geol. Surv. India*, 54, pt. 2: 215–234; and *Geogr. J.*, 59: 418–432.
- Holmes, A., 1945. *Principles of Physical Geology*. Nelson, London, 1288 pp.
- Hsu, J., 1976. On the paleobotanical evidence for continental drift and Himalayan uplift. *The Paleobotanist*, 25: 131–144.
- Jain, A.K., Thakur, V.C. and Tandon, S.K., 1974. Stratigraphy and structure of the Siang district, Arunachal (Nepa) Himalaya. *Himalayan Geol.*, 4: 28–60.
- Jaros, J. and Jalvoda, J., 1978. Quaternary relief thrusts in the Himalaya, East Nepal. In: P.S. Saklani (Editor), *Tectonic Geology of the Himalaya*. Today and Tomorrow's Printers and Publishers, New Delhi, pp. 167–220.
- Johnson, G.D., Johnson, N.M., Opdyke, N.D. and Tahirkheli, R.A.K., 1979. Magnetic reversal stratigraphy and sedimentary tectonic history of the upper Siwalik group, Eastern Salt Range and Southwestern Kashmir. In: A. Farah and K. DeJong (Editors), *Geodynamics of Pakistan*. *Geol. Surv. of Pakistan, Quetta.*, pp. 111–124.
- Karig, D.E., 1977. Growth patterns on the upper trench slope. In: M. Talwani and W. Pitmann (Editors), *Island Arcs, Deep Sea Trenches and Back-Arc Basins*. *Am. Geophys. Union, Washington, D.C.*, p. 175.
- Karun Akaran, M.B. and Ranga Rao, 1976. Status of Exploration for hydrocarbons in the Himalayan region. *Contributions to stratigraphy and structure*, New Delhi; *Spec. Publ. O.N.G.C., Dehradun*, 72 pp.
- Klootwyk, C.T., 1979. A review of paleomagnetic data from the Indo-Pakistan fragment of Gondwanaland. In: A. Farah and K. De Jong (Editors), *Geodynamics of Pakistan*. *Geol. Surv. of Pakistan, Quetta.*, pp. 41–80.
- Krishnaswamy, V.S., Jalote, S.P. and Shome, S.K., 1970. Recent crustal movements in northwestern Himalaya and the Gangetic foredeep and related patterns of seismicity. *Proc. 4th Symp. on Earthquake Engineering*. University of Roorkee.
- LeFort, P., 1975. Himalayas: The collided range. Present knowledge of the continental arc. *Am. J. Sci.*, 275-A: 1–44.
- Mackin, J.H., 1948. The concept of a graded river. *Geol. Soc. Am. Bull.*, 59: 463–512.
- Mattauer, M., 1975. Sur le mécanisme de formation de la schistosité dans l'Himalaya. *Earth Planet. Sci. Lett.*, 28: 144.
- Medlicott, H.B., 1868. The Alps and the Himalaya, a geological comparison. *Q. J. Geol. Soc. London*, 24: 34–52.

- Mehta, P.K., 1980. Tectonic significance of the young mineral dates and the rates of cooling and uplift in the Himalaya. *Tectonophysics*, 62: 205–217.
- Molnar, P., Chen, W.P., Fitch, T.J., Tapponnier, P., Warsi, W.E.K. and Wu, F.-T., 1977. Structure and tectonic of the Himalaya: a brief summary of relevant geophysical observations. *Écologie et Géologie de l'Himalaya—Colloq. Int. C.N.R.S.*, 268: 269–294.
- Parkash, B. and Goel, R.K., 1977. Paleogeographic evolution of a part of the Indo-Gangetic trough from the late Tertiary to recent. *J. Geol. Soc. India*, 18: 288–294.
- Parkash, B., Bajpai, I.P. and Saxena, H.P., 1974. Sedimentary structures and paleocurrents of the Siwaliks exposed between the Yamuna and Gola Rivers, U.P. (India). *Geol. Mag.*, 111: 1–96.
- Parkash, B., Goel, R.K. and Sinha, P., 1975. Paleocurrent analysis of the Siwaliks of Panjab, Haryana and Himachal Pradesh. *J. Geol. Soc. India*, 16: 337–348.
- Pecher, A., 1977. Geology of the Nepal Himalaya: Deformation and petrography in the Main Central Thrust zone. *Écologie et Géologie de l'Himalaya—Colloq. Int. C.N.R.S.*, 268: 301–318.
- Pecher, A., 1978. Déformations et Métamorphisms associés à une Zone de Cisaillement. Thesis, Univ. of Grenoble, 354 pp.
- Pecher, A., 1979. Les inclusions fluides des quartes d'exudation de la zone du M.C.T. himalayen au Nepal central: données sur la phase fluide dans une grande zone de cisaillement crustal. *Bull. Mineral*, 102: 537–554.
- Plafker, G. and Rubin, M., 1978. Uplift history and earthquake recurrence as deduced from marine terraces on Middleton Island, Alaska. *U.S. Geol. Surv., Open-File Rep.*, 78-943: 687–721.
- Powell, C.McA., 1979. A speculative tectonic history of Pakistan and surroundings: some constraints from the Indian Ocean. In: A. Farah and K. DeJong (Editors), *Geodynamics of Pakistan*. *Geol. Surv. of Pakistan*, Quetta, pp. 5–24.
- Powell, C.McA. and Conaghan, P.J., 1973. Plate tectonics and the Himalayas. *Earth Planet Sci. Lett.*, 20: 1–12.
- Reynolds, R.G.H., Johnson, G.D., Johnson, N.M. and Opdyke, N.D., 1980. The Siwalik molasse: a sedimentary record of orogeny. *Proc. Int. Comm. Geodynamics*, Peshawar, 1979, pp. 47–50.
- Seeber, L. and Armbruster, J., 1979. Seismicity of the Hazara arc in northern Pakistan: décollement versus basement faulting. In: A. Farah and K. DeJong (Editors), *Geodynamics of Pakistan*. *Geol. Surv. of Pakistan*, Quetta, pp. 131–142.
- Seeber, L. and Armbruster, J.G., 1981. Great detachment earthquakes along the Himalayan arc and long-term forecasting. *Maurice Ewing Ser., Am. Geophys. Union*, 4.
- Seeber, L. and Jacob, K.H., 1977. Microearthquake survey of northern Pakistan: preliminary results and tectonic implications. *Écologie et Géologie de l'Himalaya—Colloq. Int. C.N.R.S.*, 268: 347–360.
- Seeber, L., Armbruster, J.G. and Quittmeyer, R.C., 1981. Seismicity and continental subduction in the Himalayan arc. *Am. Geophys. Union, Geodynamics Ser.*, 5, Washington, D.C.
- Sharma, T., Upreti, B.N. and Vashi, N.M., 1980. Kali Gandaki gravel deposits of central west Nepal—their neotectonic significance. *Tectonophysics*, 62: 127–139.
- Sinval, H., Agrawal, P.N., King, G.C.P. and Gaur, V.K., 1973. Interpretation of measured movement at a Himalayan (Nahan) thrust. *Geophys. J. R. Astron. Soc.*, 34: 203–210.
- Stöcklin, J., 1980. Geology of Nepal and its regional frame. *J. Geol. Soc. London*, 137: 1–34.
- Tahirkheli, R.A.K., 1980. Major tectonic scars of Peshawar Vale and adjoining areas and associated magmatism. *Proc. Int. Comm. Geodynamics*, Peshawar, 1979, pp. 39–47.
- Tahirkheli, R.A.K., Mattauer, M., Proust, F. and Tapponnier, P., 1979. The India–Eurasia suture zone in northern Pakistan: synthesis and interpretation of recent data at plate scale. In: A. Farah and K. DeJong (Editors), *Geodynamics of Pakistan*. *Geol. Surv. of Pakistan*, Quetta, pp. 125–130.
- Tandon, S.K., 1972. Heavy minerals and quartz axial ratios as provenance indicators in Siwalik sediments around Ramangar, Kumaun Himalaya. *Himalayan Geol.*, 2: 206–221.
- Valdiya, K.S., 1980. The two intracrustal boundary thrusts of the Himalaya. *Tectonophysics*, 66: 323–348.

- Visser, C.F. and Johnson, G.D., 1978. Tectonic control of late Pliocene molasse sedimentation in a portion of the Jhelum re-entrant, Pakistan. *Geol. Rundsch.*, 67: 15–37.
- Wadia, D.N., 1931. The syntaxis of the northwest Himalaya—its rocks, tectonics, and orogeny. *India Geol. Surv. Rec.*, 65, pt. 2: 189–220.
- Wadia, D.N., 1961. *The Geology of India*, 3rd ed. MacMillan, London, 536 pp.
- Wager, L.R., 1937. The Arun river drainage pattern and the rise of the Himalaya. *Geogr. J.*, 89: 239–250.
- Zeitler, P., Tahirkheli, R.A.K., Naeser, C., Johnson, N. and Lyons, J., 1980. Preliminary fission track ages from the Swat valley, Northern Pakistan. *Proc. Int. Comm. Geodynamics*, Peshawar, 1979.
- Zeitler, P., Johnson, N.M., Naeser, C.W. and Tahirkheli, R.A.K., 1982. Fission-track evidence for the Quaternary uplift of the Nanga Parbat region. *Pakistan. Nature*, 298: 255–257.