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Geomorphology 22 (1998) 285–312

GEOMORPHOLOGY

The evolution of the great river systems of southern Asia during the Cenozoic India–Asia collision: rivers draining southwards

M.E. Brookfield *

Land Resource Science, Guelph University, Guelph, Ontario, Canada N1G 2W1

Received 24 June 1996; revised 4 December 1996; accepted 20 August 1997

Abstract

During uplift of the Tibetan plateau and surrounding ranges, tectonic processes have interacted with climatic change and with local random effects (such as landslides) to determine the development of the major river systems of Asia. Rivers draining southward have three distinctive patterns that are controlled by different tectonic and climatic regimes. In central and southern Afghanistan, the rivers have moderate gradients and fan out from northeastern sources to disappear into arid depressions. Anti-clockwise rotation of southern Afghanistan, caused by differential compression and right-lateral shear, cut the rivers on the north, while increasingly arid conditions developed on the south as arc accretion in the Makran separated sources from the coastal rains. In Tibet and southeast Asia, the rivers are widely separated and have low gradients on the Tibetan plateau, higher gradients as they turn southwards into close and parallel gorges, before they fan out southeast to enter different seas. Differential shear and clockwise rotation between the compressing Tibetan plateau and Southeast Asia determined the great sigmoidal bends of this river system which was accompanied by increasing aridity, with truncation of river systems in the north and river capture in the south. In the Himalaya and southern Tibet, the main rivers have steep gradients where they cut across the Himalayan range and occasionally truncate former rivers with low gradients on the Tibetan plateau to the north. Southward thrusting and massive frontal erosion of the Himalaya caused progressive truncation of longitudinal rivers on the plateau, accompanied by river capture, and glacial and landslide diversions on the south. The drainage history of southern Asia can be reconstructed by restoring the gross movements of the plates and the tectonic displacement, uplift, and erosion of individual tectonic units. Most important changes in drainage took place in Pliocene to Quaternary times. © 1998 Elsevier Science B.V.

Keywords: evolution; rivers; southern Asia; Cenozoic; collision

1. Introduction

During the Tertiary, India progressively collided with Asia, raising the Tibetan plateau and other areas, which caused enormous changes in climate and drainage (Fig. 1) (Burchfiel and Royden, 1991; Molnar et al., 1993). The heights of these plateaux and ranges are a balance between forces generated by plate convergence and forces caused by gravitational spreading (England and Houseman, 1988). The resulting lateral and vertical movements, modified by erosion at thrust fronts, climatic change and river capture (and occasionally important local effects such as blocking by landslides and glaciers),

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* Fax: +1 (519) 824 5730; E-mail: mbrookfi@lrs.uoguelph.ca

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PII S0169-555X(97)00082-2

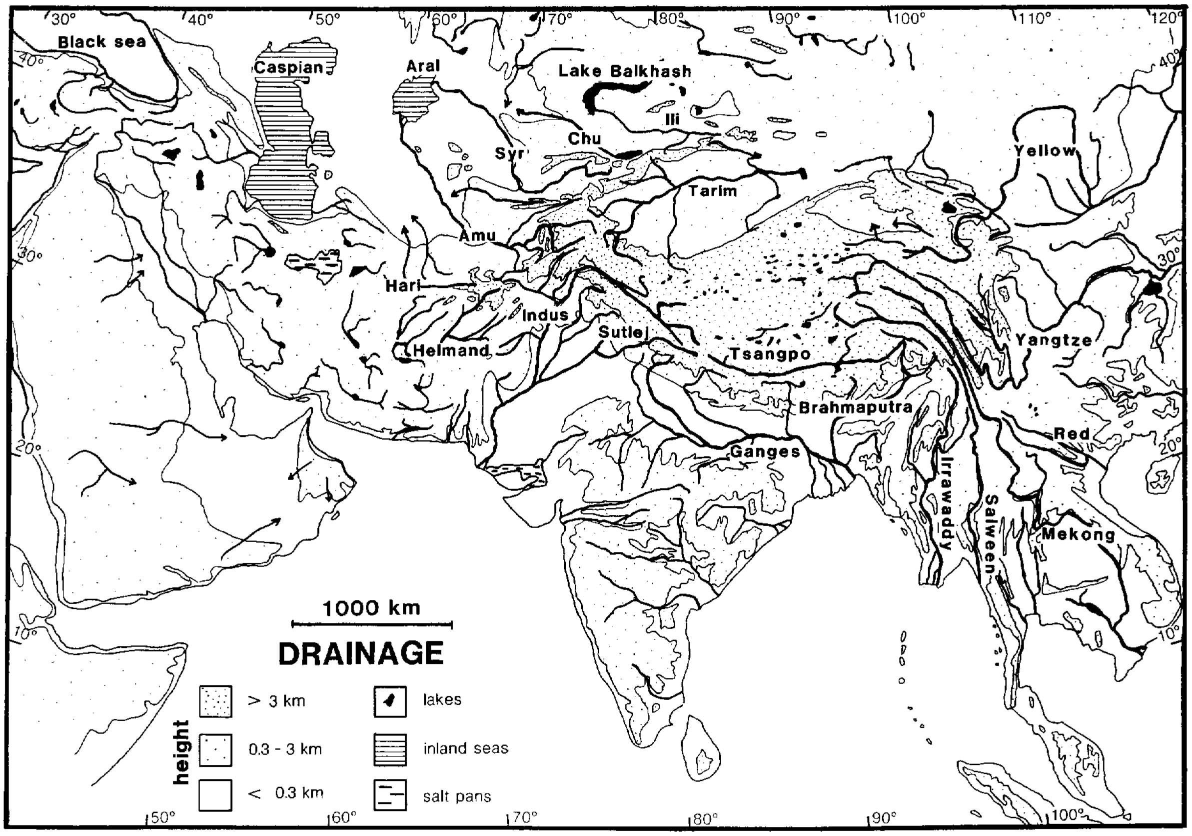

Fig. 1. Asia: major drainage systems related to topography. General topography from Canadian Oxford Atlas, 1957; 1:16 million; zenithal equidistant projection, origin 30°N and 75°E. In this projection elongation is greatest around the edges but tolerable (less than 10%) and distortion is less than in equal-area projections.

have determined the development of the drainage systems of these areas.

The drainage systems have also influenced the development of the plateaux and ranges by the effects of differential erosion and deposition on isostatic adjustment and stress distributions (e.g. Bishop and Brown, 1992; Koons, 1995). These drainage systems may also, by sediment loading and choking of subduction zones, have affected plate movements (Brookfield, 1993a). Geomorphic processes interact with tectonics and climate as an integrated system.

Until recently, geomorphology and tectonics were studied separately and drainage systems were analyzed in a fixed framework, with explanations involving only regional tectonics (e.g. Ahnert, 1970; Oberlander, 1985). Very few geomorphic studies related the evolution of large drainage systems to large-scale plate movements, and most of these studies were on the effects of rifting on stable supercontinent drainages (e.g. Potter, 1978; Cox, 1989; Summerfield, 1991; Ollier and Pain, 1997). Drainage controlled topographic feedbacks that affected large-scale tectonics were also ignored by structural geologists. As Koons (1995) noted, "In retrospect, it is difficult to understand how models of collision zones could be constructed without reference to the resulting topography, but somehow we managed."

The India–Asia collision belt is a good place to study the interactions among tectonics, climate, and drainage evolution. Mountain building is still forming the highest ranges and plateaux on Earth, and is clearly related in space and time to plate movements. The architecture of the belt is relatively simple, at least on a large scale. Because the basic plate motions are available from the magnetic anomalies, gross relationships are easy to determine (Mattauer, 1986; Dewey et al., 1989). But, paleoclimates are more difficult to determine and are based mostly on plants. Recent and Tertiary floras have been studied in most areas and allow the overall climatic history of each to be determined (Song et al., 1981; Wang, 1988).

Most studies of Asian river systems have emphasized control by vertical uplift and climatic change (e.g. Pilgrim, 1919; Barbour, 1936; Oberlander, 1985) or have been focused on small areas (e.g. Gornitz and Seeber, 1981; Burbank, 1992; Burbank et al., 1996). They have not included the effects of great lateral movements of huge crustal blocks during plate movements. Yet such large-scale movements (distributed movements on folds and localized movements on faults) seem, even at a cursory glance, to have determined the patterns of the great Asian river systems (Fig. 2).

The evolution of the great river systems of southern Asia can best be explained by plate tectonics, modified by the influence of climate and local, mainly tectonic, effects. Because many people consider that lithology is an important control of drainage, slope, and river gradients, I must emphasize (at length) that no evidence supports lithological control on the development of the drainage of southern Asian at the

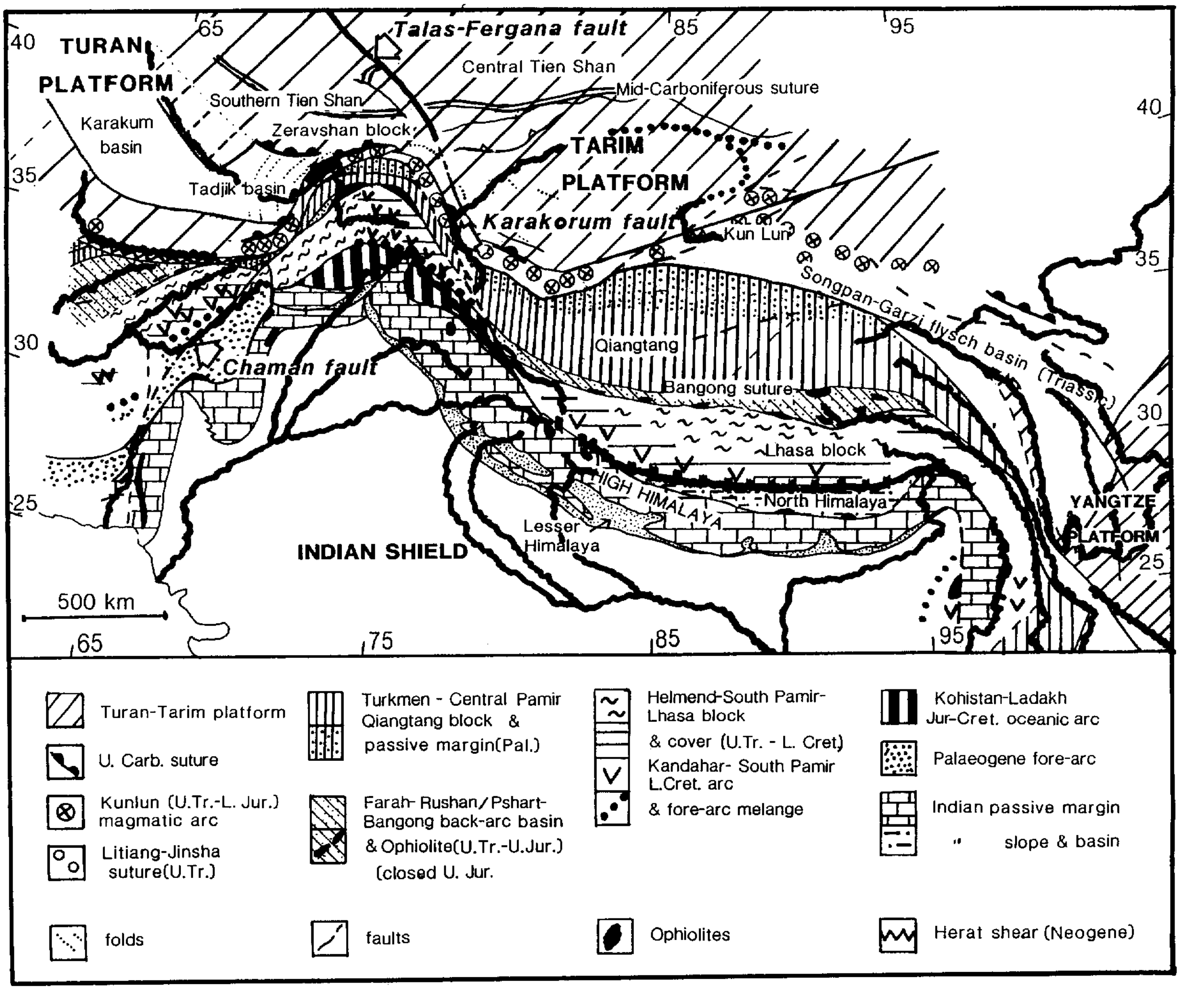

Fig. 2. Asia: major drainage systems related to gross structure (base map from Brookfield, 1993c).

large scale considered here. For example, the gradient changes of the rivers draining the Himalaya do not correspond with lithological changes but with structural changes. The gradients of the rivers of Afghanistan are independent of lithology even where they flow from crystalline to alluvial deposits. The major gradient changes of the Yangtze, Mekong, and Salween occur at cross-faults associated with river capture and not at lithological changes. Large drainage basins usually contain a variety of rocks whose resistance balances out and the effect of lithological differences upon the total sediment load is neutralized (Ahnert, 1970). Although lithology is locally important (e.g. in the Appalachians – Hack, 1973), lithological control is sometimes assumed where the data contradicts it. For example, Bishop et al. (1985) proposed lithological control on river gradients, whereas plotted profiles of gradients show no evidence for it (their figs. 5 and 7).

This paper describes the southward-draining systems of Afghanistan, of Tibet and southeast Asia, and of the Himalaya and southern Tibet, and concentrates on base levels of erosion, Recent river gradients and the response to tectonic, climatic, and local changes.

2. Base level of erosion and river gradients

The base level of erosion is the line or surface reached when water and sediment passes through the system with no net deposition or erosion. Such an ideal longitudinal profile under static equilibrium shows no degradation or aggradation and is impossible to attain because all streams erode and deposit and none are, by definition, in static equilibrium. Though no static equilibria profiles exist anywhere on Earth at present, dynamic stream equilibria can occur where downcutting or aggradation keeps pace with uplift or subsidence; these do occur at various times and places (Bull, 1991).

A river is graded when the gradient, width, and depth of its channel are in dynamic equilibrium with discharge and load (Mackin, 1948). But this rarely happens. Observations and theoretical analysis show that time-scales for river networks to reach equilibrium are very long (on the order of 1000 to 1,000,000 years) even under relatively stable conditions (Knox, 1976; Pizzuto, 1992). Thus, a river can never be entirely graded because of fluctuations in discharge and load, changes in rock type and climate, tectonic effects on its course, and isostatic responses to erosion and deposition. Nevertheless, rates of response increase exponentially from equilibrium, and gross deviations from grading must result from relatively recent events (Bull, 1991).

River gradients can be used to infer disequilibrium in drainage systems which can then be related to tectonic, climatic and other more local conditions (e.g. Merritts et al., 1994). Quantitative descriptions of stream gradients allow precise comparisons among streams (Hack, 1982). These descriptions can then be compared to idealized, quantitative models of stream responses to tectonics, climate, and other factors (e.g. Snow and Slingerland, 1990).

Most rivers increase in discharge downstream as groundwater and tributaries join. If the stream profile is plotted on semi-logarithmic paper, the effect of increasing discharge downstream is masked. An ideal graded river on uniform substrate plots as a straight line on a semi-logarithmic graph (Fig. 3). The effect of resistance in rivers is shown by the slope of the

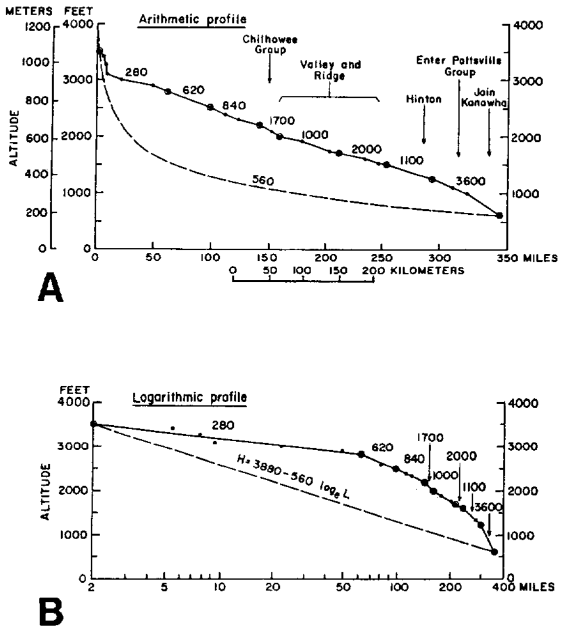

Fig. 3. New River, southern Appalachian, longitudinal profiles. (A) arithmetic; (B) logarithmic. Gradient indices for short lengths shown on profiles and for whole stream below (from Hack, 1973, Fig. 4).

line, which is roughly proportional to the size of the bed material. This slope can indicate the competence of the stream and channel slopes of streams of different sizes can be easily compared (Hack, 1973). At equilibrium, rivers adjusting to increasing resistance and/or decreasing discharge downstream have convex upwards profiles, whereas rivers adjusting to decreasing resistance and/or excessively increasing discharge downstream have concave upwards profiles.

The quantitative deviation of river channels, or segments of channels, from ideal equilibrium can be shown on such semi-logarithmic plots; the deviations of several streams can be compared, and the reasons for the variations evaluated (Hack, 1973, 1982).

Straight-line segments fit the relationship:

$$H = C - K \times \ln L \tag{1}$$

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

The stream gradient index (K) can characterize any stretch of the river or the entire profile. A stretch with anomalously high gradient indices has high stream energy and corresponds to; (a) a belt of resistant rocks, (b) a zone of differential uplift, or (c) erosional disequilibrium between two drainage systems. Conversely, a stretch of anomalously low gradient indices has low stream energy and corresponds to; (a) a belt of less resistant rocks, (b) a zone of differential subsidence, or (c) depositional disequilibrium between two drainage systems.

On the large scale studied here, relatively sudden changes of gradient (at major knickpoints) are caused by tectonics or by river capture. None of the major knickpoints correspond to lithological changes. For example, no major knickpoints occur where Himalayan rivers flow south from the resistant High Himalaya crystalline rocks onto the less resistant Lesser Himalaya sedimentary rocks. The sharpness of knickpoints measures, in a relative way, how recent the tectonic or river capture event was (Gardner, 1983). Fig. 4 shows asymptotic decay curves for re-establishment of graded equilibrium after fault displacement. Such curves need independent time calibration.

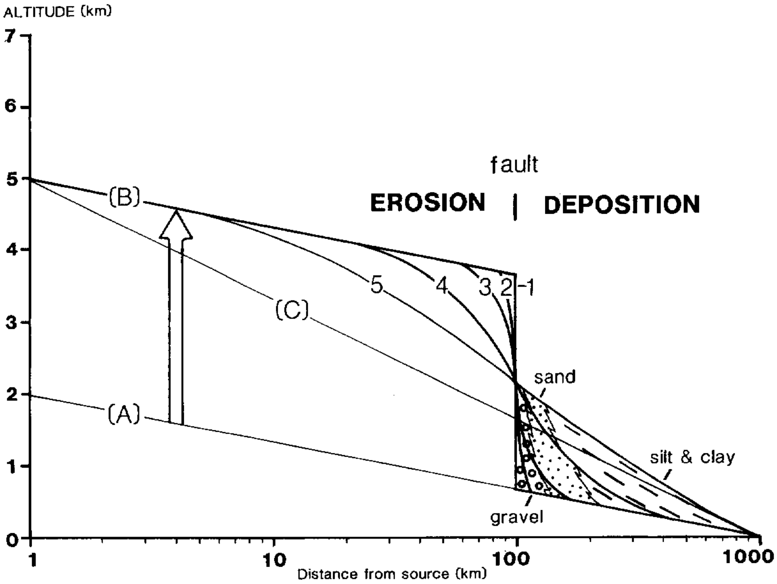

Fig. 4. Change in graded river profile by fault movement and the resulting adjustments. Graded river profile (A) is displaced to profile (B) by a sudden fault displacement (here 3 km analogous to Neogene uplift of Tibetan plateau) Erosion/deposition point is kept constant: in reality, it would migrate downwards and upstream, eroding earlier deposited sediment near the fault. Successive profiles 1 to 5 show a trend toward eventual new equilibrium profile (C). Reaction time is assumed to be instantaneous. Relaxation time to new dynamic equilibrium is unknown, but is exponential, with a half-life of probably millions of years for this size of river.

Small rivers in arid climates take a long time to adjust to disturbances, of the order of 10,000 to 1,000,000 years (Bull, 1991). The response times for the large Asian rivers should intuitively, be shorter. However, the large rivers that drain the steep southern slopes of the High Himalaya have still not attained dynamic equilibrium since the Main Central Thrust stopped moving during the Pliocene, about 5 million years ago (Macfarlane et al., 1992). Over a shorter time, the Pum–Arun knickpoint is still knife-sharp after 10,000 years since its late Quaternary formation (Wager, 1937).

Headward erosion of knickpoints from the margin of the Tibetan plateau has also been relatively small since the Miocene start of marginal thrusting and uplift of the entire system about 10 million years ago (Molnar et al., 1993). For example, the huge rivers of eastern Tibet, the Yangtze, Mekong, Salween, and Irrawaddy, are only at stage 3–4 (see Section 3.2).

3. Asian rivers

The study of river gradients is an old tradition in Asia as elsewhere (Burrard and Hayden, 1907). The existing great river systems of Asia transport vast amounts of solid and dissolved material to the ocean, where the sediments accumulate to form some of the largest submarine fans on Earth (Curray et al., 1982; Wang et al., 1986; Kolla and Coumes, 1987). River courses have also changed greatly and rapidly. In the last 4000 years the great Huangho (Yellow) river has switched its course eight times, sometimes by over 300 km, to opposite sides of the Shandong Peninsula (Wang, 1983). Such course changes greatly effect sedimentation and subsidence in the basins. And in turn, changing patterns of erosion in mountains and sedimentation in basins modify tectonic development (Beaumont et al., 1992).

In this paper, the drainage patterns and longitudinal profiles in three areas; (1) central and southern Afghanistan, (2) Tibet and southeast Asia, and (3) the Himalaya and southern Tibet, are described and related to the different large-scale deformations of the India–Asia collision.

Topography and drainage patterns are from the *Times Atlas of the World*, were checked with Landsat satellite images and the 1:500,000 *Tactical Pilotage Charts* of the U.S. Defense Mapping Agency, which are available for the whole of Asia. *Tactical Pilotage Charts* were also used to measure river gradients. On these maps the basic contour interval is usually 76.2 m, but can be 152.4 m in some poorly known areas like eastern Tibet. Surprisingly, I found no incompatible features, such as a river crossing the same contour twice, on these maps. When checked against satellite images, the maps seem to be very accurate.

Measurements of river profiles were made using Hack (1973) method. Heights were plotted on semilogarithmic paper against distances from sources. The highest contour that was crossed by the stream below its source was taken as the highest *i* point on the profile. The source was estimated from satellite photos and taken at the snout of any source glacier where present. Overall gradient indices of a river were computed from mouth to source, following the longest path. Tributaries were calculated separately, from the source to the confluence with the main river. Various gradients were calculated for different straight line segments of the streams and also for the entire profile.

Two main errors occurred in the profiles:

(a) Foreshortening of the length of the streams, especially in downstream areas, occurred because the maps used do not show the small sinuosities in the channels. The profiles were thus slightly steeper and more convex than they should have been, but plotting the Yangtze river profile in great detail showed that the effect was very small.

(b) Uncertainties in the actual heights and positions of the contours also affected the accuracy of the profiles in the first 100 km where the points plot far apart. These uncertainties had little effect because the first 100 km stretch is small compared to the scale of the entire river system.

Each of the generally southward-flowing systems, central and southern Afghanistan, Tibet and southeast Asia, and the Himalaya and southern Tibet, have different properties related to different tectonic situation, development, and climate. A discussion of each of these systems follows.

3.1. Central and southern Afghanistan

The main rivers of central and southern Afghanistan form the Helmand–Farah system (Fig.

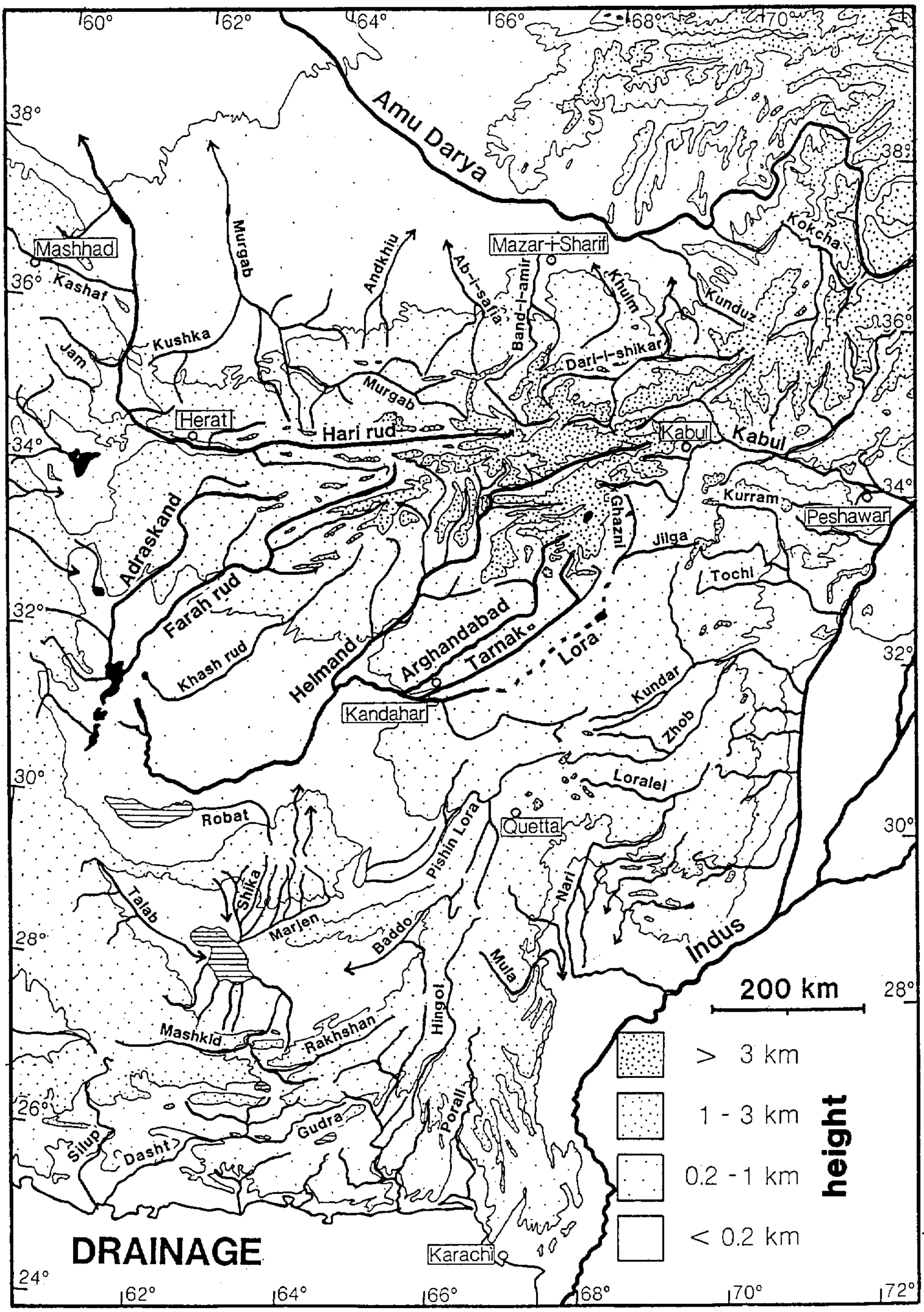

Fig. 5. Afghanistan and adjacent areas: drainage patterns in relation to topography. Names of major towns are in boxes; saline lakes are in black, and completely dried out lakes are horizontally ruled.

5). They fan out southwest from the high ground west of Kabul, following the structural grain of the land to meet and disappear in the salt flats along the Harirud fault zone separating Afghanistan from Iran (Fig. 6). To the north of the Herat shear, northward flowing ephemeral streams, like the Murgab and Hari, similarly disappear in the Karakum desert basin. To the south of the Helmand river system, and the Paleozoic–Mesozoic Helmand microcontinent, the mostly small and irregular ephemeral streams run parallel to and across the complex folds and faults in the Cenozoic sedimentary rocks.

These rivers all have similar and relatively low, for Asia, overall indices of gradient between 350 and 400. The profiles are only slightly convex; they are close to graded (Fig. 7). The Hari is an exception; its

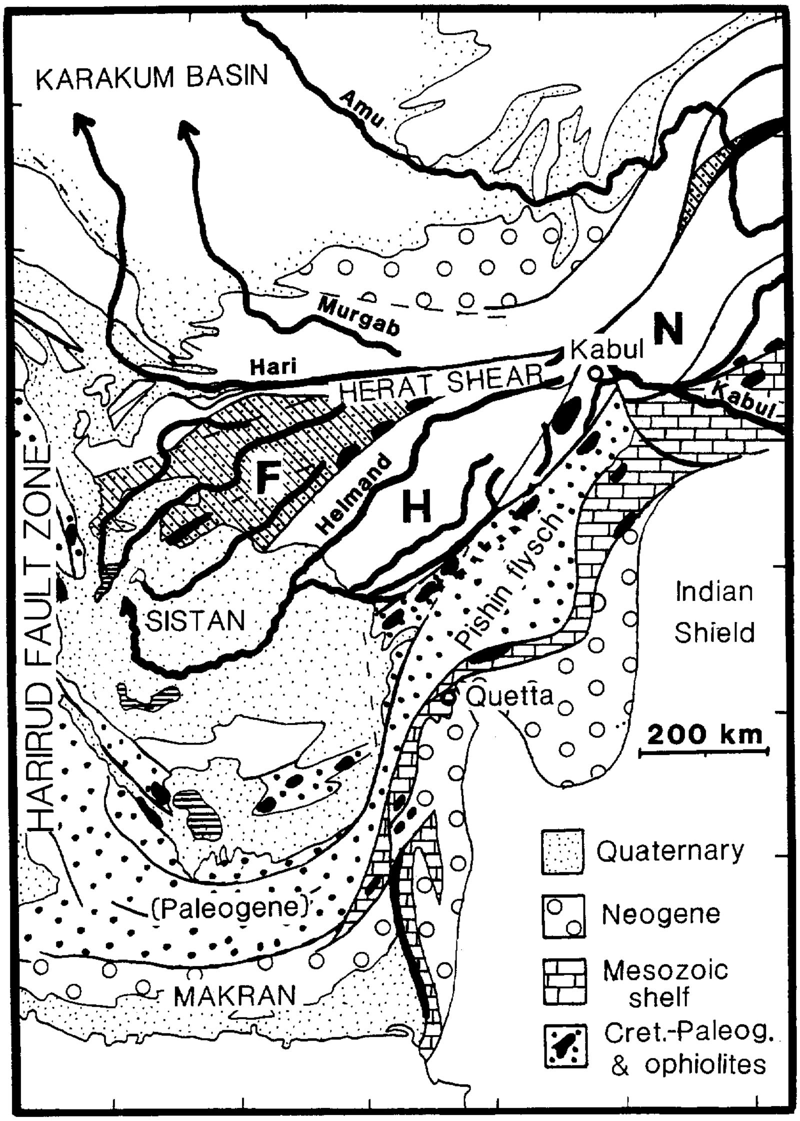

Fig. 6. Afghanistan: major rivers (heavy black lines) in relation to structure. Paleozoic Helmand microcontinent (*H*) with its extension into Nuristan (*N*) is flanked on the southeast by the Kandahar–Karakorum Upper Jurassic–Lower Cretaceous Andean magmatic arc, just north of ophiolite belt, and Farah back-arc basin on the northeast (*F*: obliterated along the Herat Shear).

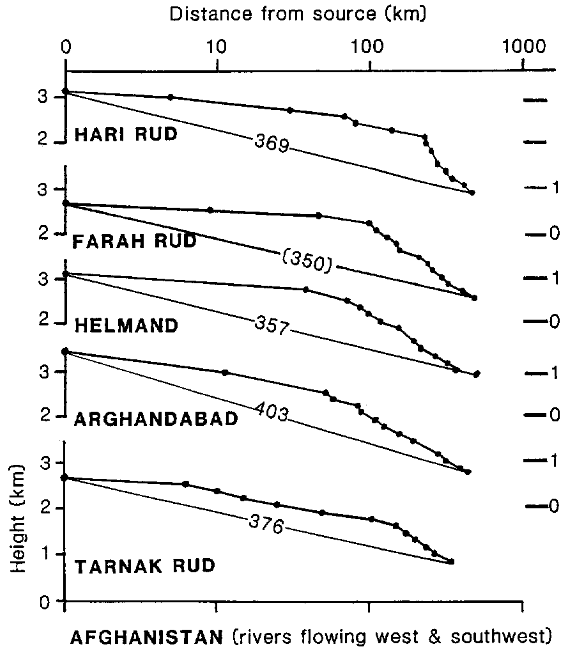

Fig. 7. Afghanistan: main westward and southwestward-flowing rivers, semi-logarithmic profiles and gradient indices.

relatively steep downstream stretch northwest of Herat is caused by river capture across the Herat Shear into the Karakum basin to the north (Fig. 5). In the other rivers, convexity increases progressively downstream from southeast to northwest, from the Tarnak to the Farah (Fig. 7). Increasing convexity indicates gradually increasing rock resistance downstream, or decreasing discharge, or differential uplift.

Increasing rock resistance is not a factor. The profiles are independent of the lithologies over which the rivers flow and in the most convex downstream sections the rivers flow over soft alluvium. The main breaks in slope take place at varying distances and heights from the sources but in the upper reaches. Below about 2 km in height all rivers, except the Hari, show straight graded profiles.

Decreasing discharge does occur. All streams flow into progressively drier regions, become smaller, and then die out in the salt flats of the Sistan desert. The most arid downstream reaches, however, do not show any marked convexity of profile. For this reason, tectonics is probably more important than climate in determining the gradients of the rivers. Climate may control (or have controlled) gradients within about 100 km of the headwaters of the rivers. The gentler upper reaches of the rivers were probably once filled by Quaternary glaciers and the rivers have not yet adjusted the profiles (Shroder, 1998).

Differential uplift has occurred. The Helmand microcontinent and Farah back-arc basin were progressively more compressed and uplifted from southwest to northeast during the Neogene to form the western end of the Hindu Kush (Boulin, 1981). This differential compression can explain the southwestward fanning of the major rivers, modified by river capture in the Kandahar and Kabul areas, (Fig. 5).

The short and jumbled drainages of southern Afghanistan and western Pakistan are a result of the dry climate and the rapid and active fore-arc folding and faulting that affects the soft Neogene clastic rocks. The belt of harder Mesozoic shelf deposits mostly controls the divide between streams that drain internally and directly into the Indian Ocean, and streams that drain eastward into the Indus. River capture into the Indus system increases northwards with progressive destruction of the Pishin Flysch belt (Fig. 6). Headward erosion of the Kabul, Kurram, and Tochi rivers has segmented a once continuous, southwestward-flowing river that probably formed part of the Helmand system (Fig. 5). Along the now narrow Cretaceous–Paleogene flysch belt, shearing, differential movement and uplift has caused drainage reversal and river capture west of the Mesozoic shelf (Fig. 6). A single river draining into the Indian Ocean probably once flowed southwest along the Pishin flysch belt, but is now broken into the Hingol, Pishin Lora and Zhob river systems draining, respectively, into the Indian Ocean, internally, and the Indus system (Fig. 5).

3.2. Tibet and southeast Asia

Three great rivers of southeast Asia, the Yangtze, Mekong and Salween rise on the Tibetan plateau, bend around the northeastern syntaxis of the Himalaya, run parallel in deeply incised gorges and then diverge into different seas (Figs. 1 and 8). Apparently a fourth, the ancestral Tsangpo–Irrawaddy, also once followed such a course, but it is now truncated by the Brahmaputra system. The great

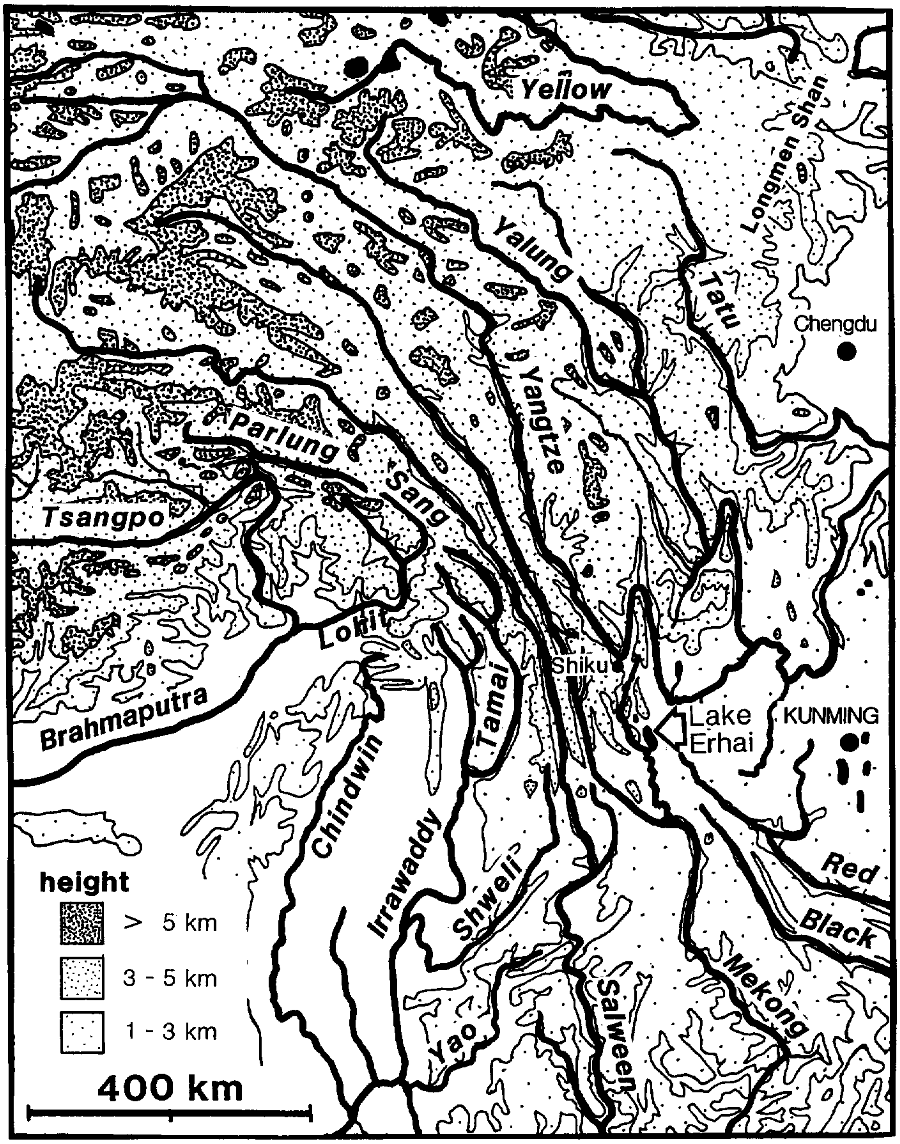

Fig. 8. Eastern Tibetan plateau and adjacent areas: drainage patterns in relation to topography. Major rivers are named, heavy lines.

sigmoidal curves of these four rivers, and tributaries, precisely outline the enormous right lateral shear and compression during the collision of northward moving India with Asia and the clockwise rotation of southern Asia behind the Indian indenter (Fig. 1) (Wang and Chu, 1988). Each river was, until recently, confined to a specific suture, marking the destruction of oceanic lithosphere between continental blocks (Fig. 9). Thus, the Yangtze runs behind a Triassic magmatic arc on the distorted marginal basin sediments of the Triassic Songpan–Garze area. The Mekong runs along the late Triassic Litian–Jinsha suture (though now diverted to the east in northern Thailand from its original southward course into the Yom). The Salween runs along the Bangong–Nujiang suture for most of its length before being diverted

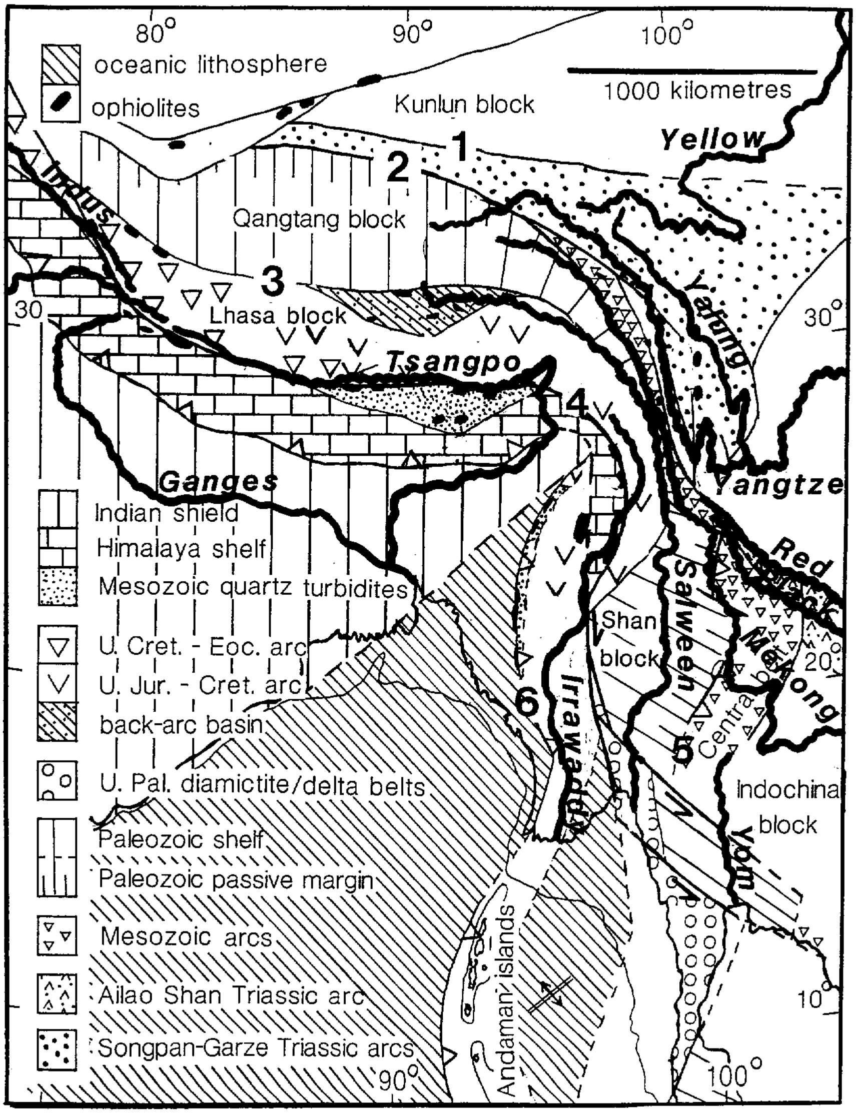

Fig. 9. Eastern Tibetan plateau and adjacent areas: major rivers (heavy black lines) related to structure. Major tectonic boundaries are: *1*, South Kunlun fault; *2*, Litian–Jinsha suture; *3*, Bangong–Nujiang suture; *4*, Indus suture; *5*, Uttradit–Nan suture; *6*, Burma suture (data and terminology after Brookfield, 1995; Chang et al., 1989; Metcalfe, 1990; Mitchell, 1993; Sengor et al., 1988; Chen et al., 1994).

across strike faults in Burma. And the Irrawaddy, and its original Tsangpo continuation, runs along the Cretaceous–Eocene Indus suture zone, marking the final destruction of the Tethyan ocean between India and Asia. All these rivers run parallel until the edge of the plateau at about 3 km. They then diverge along very complicated courses that are controlled by cross-faulting and river capture at the unstable triple junction between the Indian, South China, and Indochina blocks centred on Shiku (Fig. 8). The close approach of the Yangtze, Mekong and Salween in the three rivers area results from the almost complete shearing out of the microcontinent, which was once continuous between the Qangtang block of Tibet and the Shan block of Burma (Fig. 9). The minimum left-lateral displacement on the Red River fault zone in this area since the Eocene is 330 ± 60 km (Lacassin et al., 1993).

Profiles of the rivers draining the eastern part of the Tibetan plateau, with the exception of the now truncated Irrawaddy, show extremely marked convex profiles with average indices of gradient between 620 and 660 – much steeper than the Afghanistan rivers which have much lower average values (Fig. 10). The upper reaches, above 4 km, have indices of gradient of less than 350, which may, as in Afghanistan, be related to Quaternary glaciation or permafrost formation. Alternately, these gentler upper reaches may be tectonically related to extension and gravitational collapse. In the first case, either

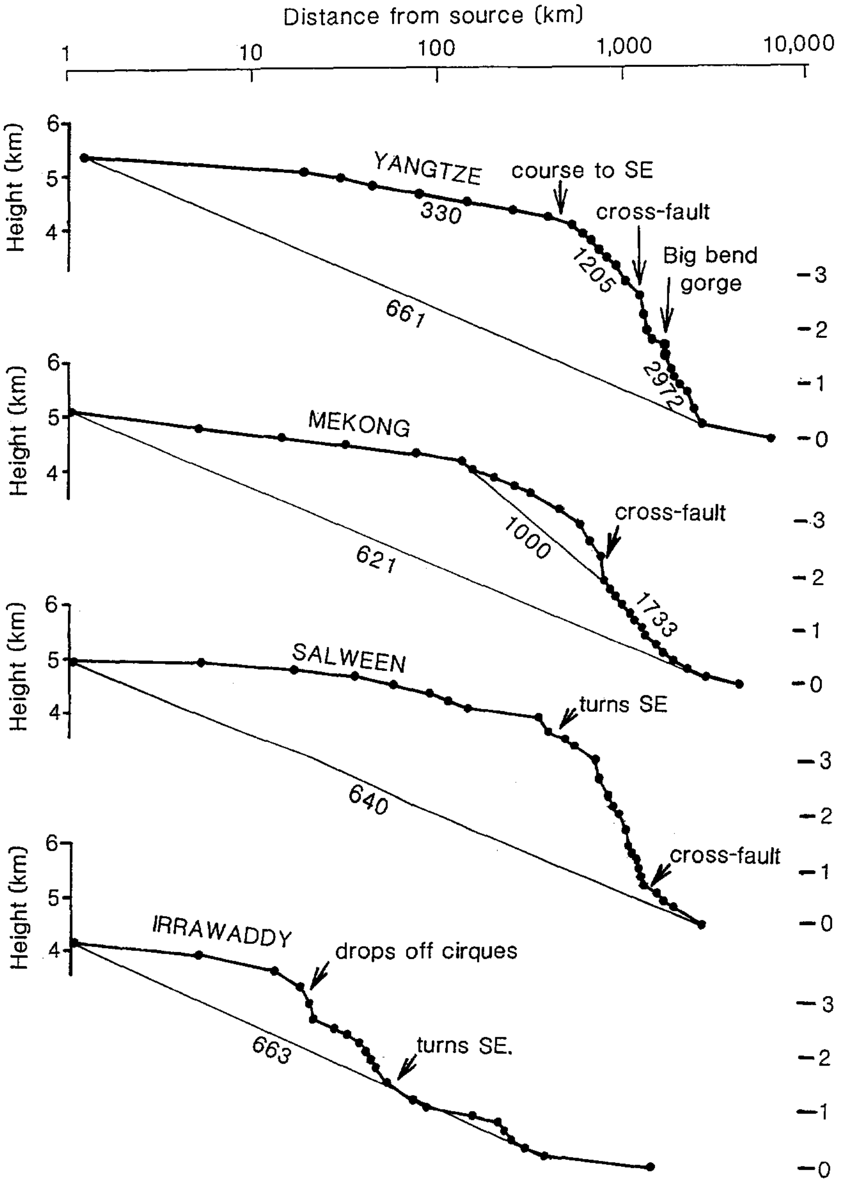

Fig. 10. Eastern Tibet, draining rivers: semi-logarithmic profiles and gradients.

Tibet had an ice cap in Quaternary times (Kuhle, 1986) or glaciers extending from the marginal mountains blocked outward flow and large lakes and permafrost occupied the plateau (Wang et al., 1981). In the second case, gravitational spreading with graben formation combined with increasing aridity is equally capable of disrupting the drainage (Burchfiel and Royden, 1985).

The asymptotically increasing gradients of the intermediate reaches, where indices of gradient increase to over 1000, mark the reaction to major uplift and shear of the Tibetan plateau relative to areas to the southeast. Indices of gradient rise to 1700 and more, across the Neogene Longmen Shan fault system where the Tibetan plateau obliquely overthrusts the Chengdu basin (Chen et al., 1994) (Fig. 8). In the Yangtze and the Mekong major cross-faults caused large dislocations and abrupt changes in the river gradients, with headward capture by southeasterly and southwesterly flowing streams, respectively. Changes are less abrupt in intermediate stretches of the Salween and Irrawaddy systems, which are now

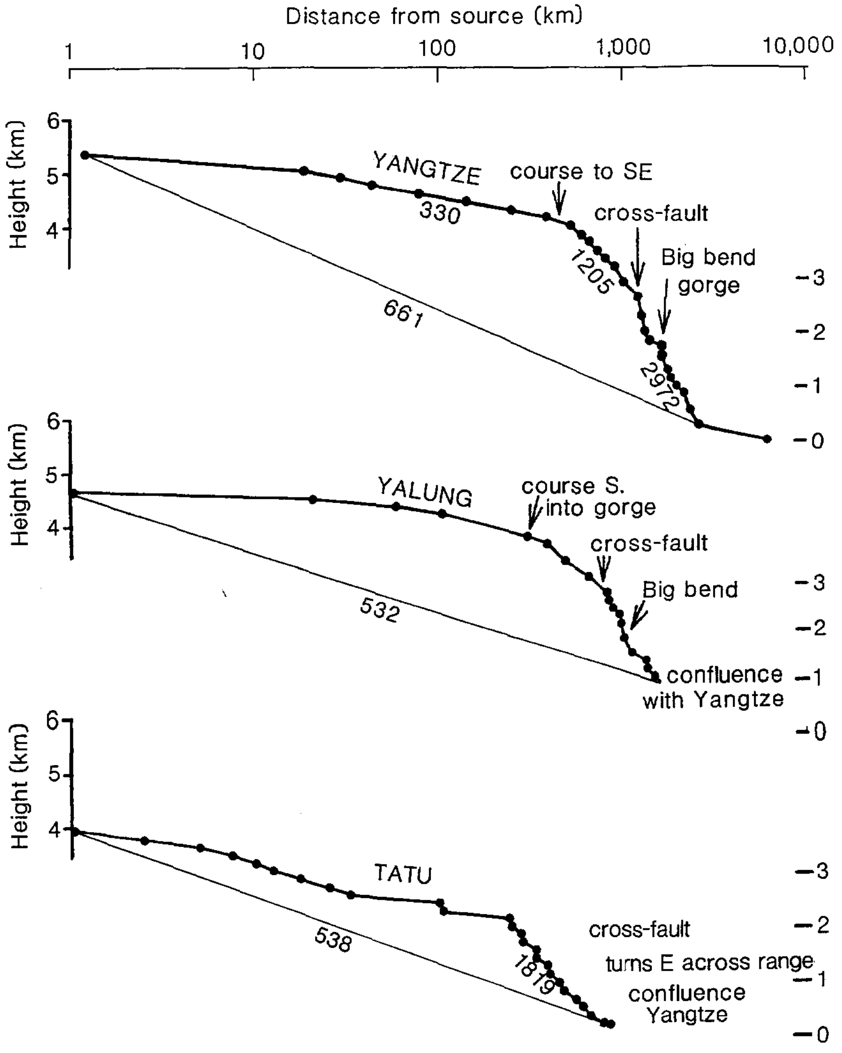

Fig. 11. Yangtze river and eastern tributaries: semi-logarithmic profiles and gradients, showing a general decrease in convexity but a consistency of average gradient.

removed from the actively compressing collision zone (Fig. 9).

The decreasing rate and effect of active compression to the northeast is shown by the decreasing convexity of the Yangtze and its two major parallel tributaries towards the north (Fig. 11). The similarity in average gradients of the Yalung and Tatu is puzzling, is unrelated to height or river length, and may be caused by regional rates of compression and uplift.

The southern end of the three rivers area is an exceptionally unstable area of jostling horsts and grabens between the rigid Yangtze, Indian and Indochina blocks (Figs. 2 and 9). Complicated and

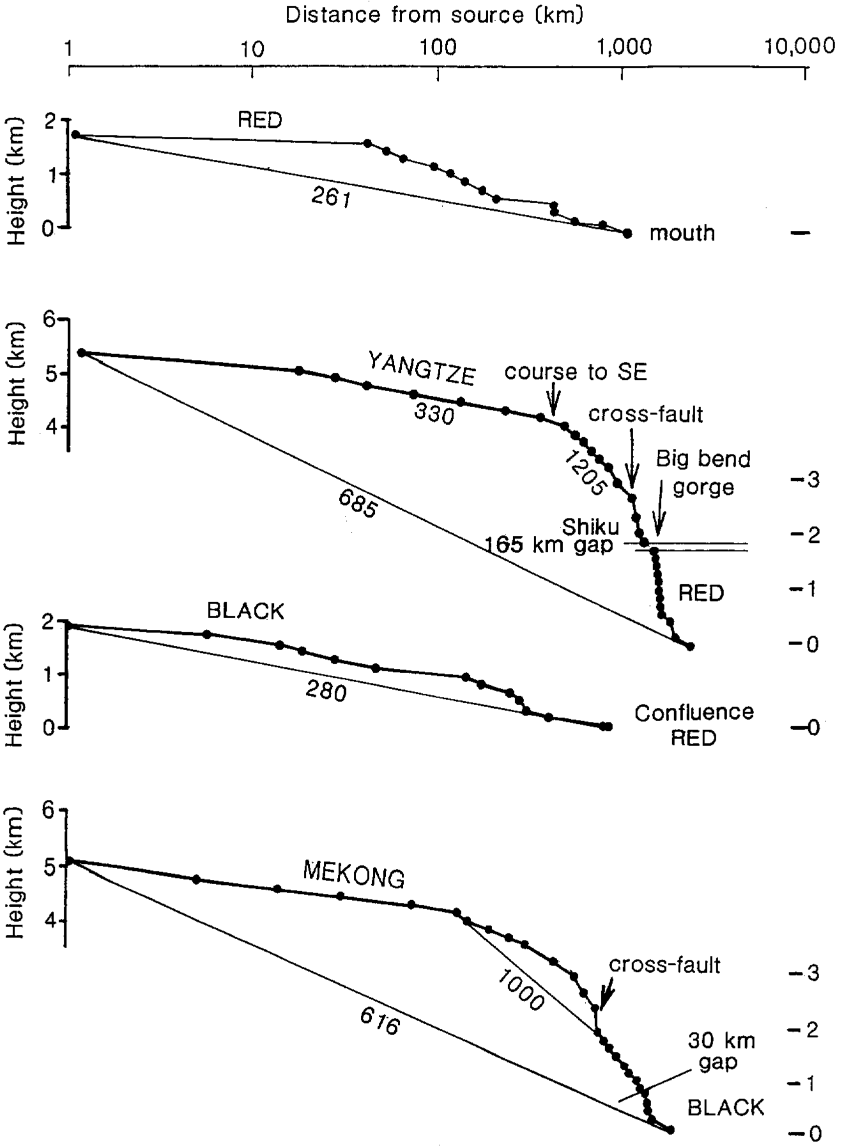

Fig. 12. Red and Black rivers of Vietnam and the Mekong and Yangtze (upper and intermediate stretches): semi-logarithmic profiles and gradients juxtaposed with their possible original lower courses in the Black and Red rivers of Vietnam, assuming original continuity before late Tertiary deformation.

changing strike-slip and oblique movements throughout the Neogene between these blocks occurred at the junction of northwesterly trending faults that are associated with the Red River fault zone and the northeasterly trending faults of the Longmen Shan zone (Scharer et al., 1994; Chen et al., 1994). These mixed vertical and lateral movements have controlled complex river-capture patterns to the south, and to a lesser extent in the mountains to the north (Lee, 1933).

The dramatic river captures in the intermediate stretches of the Yangtze and Mekong can be illustrated by comparing present upper and intermediate river profiles with possible original, but now truncated, lower river profiles in the Red and Black rivers of Vietnam. The Red and Black rivers are practically graded and of unbelievably low slope for this tectonically active area. But they fit very well as the original lower courses of the Yangtze and Mekong (Fig. 12). The lower Mekong river has also been diverted from its original course, by headward erosion and river capture from the Khorat plateau, into the Yom river of Thailand (Figs. 1 and 9). An even more outstanding example of river capture is the truncation by the Brahmaputra of the original Tsangpo–Parlung–Sang–Irrawaddy river. This truncation involves a further factor that is absent in southeast Asia, extensive lateral erosion at the front of thrusts during collision, and so is discussed in the Himalaya section.

The Tibetan plateau is a high (average 5 km) and flat (average slopes of less than 5°) area with up-

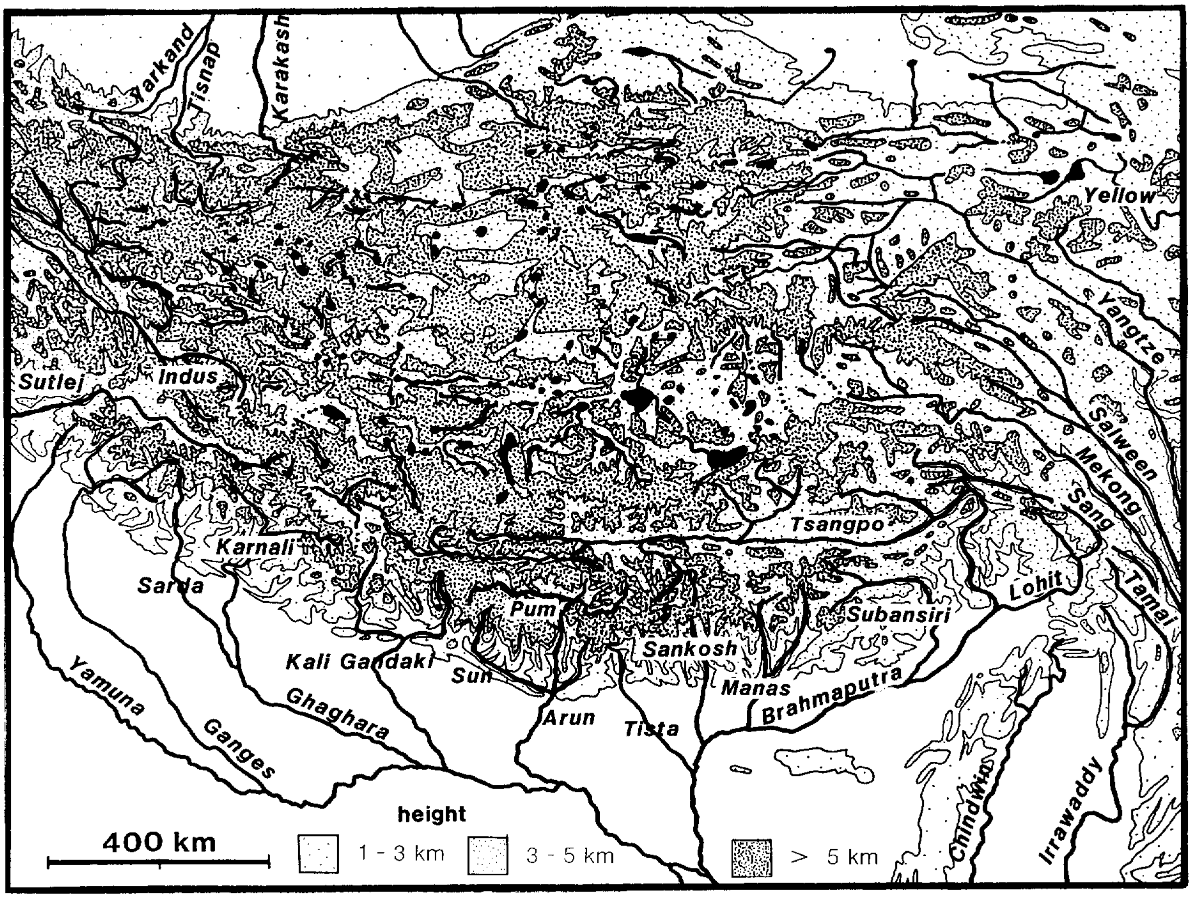

Fig. 13. Himalaya and Tibet: major rivers related to topography.

turned edges that are cut by roughly radially draining streams (Fig. 1). The tectonic compression, uplift, and northward displacement of the Tibetan plateau, together with related climatic changes, seem the main control on the rivers of Asia, as noted in the last section. The central and northern parts of the plateau, however, have low relief and are scarcely dissected at all (Fielding et al., 1994), implying that little crustal deformation or river erosion has occurred during the Neogene uplift, which is consistent with tectonic studies (Chang et al., 1989). Therefore, the landscape preserves earlier Neogene or even Paleogene features, including the earlier courses of the Yellow, Yangtze, Salween and Mekong rivers.

In the central and northern plateau, lines of lakes and dry valleys outline the west–east dry courses of streams, which once flowed into the headwaters of the Yangtze and other southeast Asian rivers (Fig. 13). These courses are emphasized by the trends and locations of Quaternary sediments (Fig. 14). I attribute the drying up and destruction of these rivers to uplift, increasing aridity, and permafrost formation. The age of most of the northern lakes and Tertiary sediments are poorly known, and the time when the main changes occurred are uncertain. The main changes probably took place in Quaternary times, with the formation of year-round frozen ground (Wang and French, 1995) or even an ice cap (Kuhle, 1986).

3.3. Himalaya and southern Tibet

The southern part of the Tibetan plateau has significant relief and is partially dissected by rivers

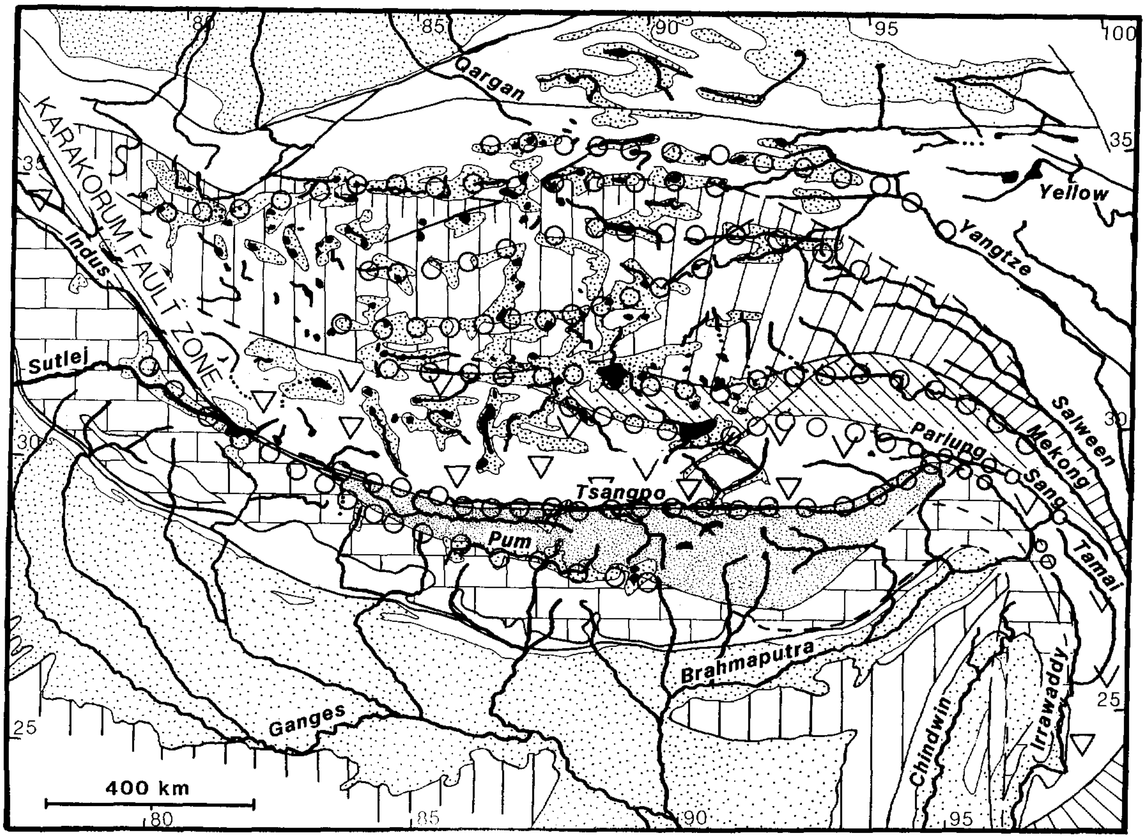

Fig. 14. Himalaya and Tibet: major rivers related to Quaternary basins and structural units (data from Brookfield, 1993c; Institute of Geological Sciences Xizang, 1984). Structural units as for Fig. 9. Open circles are inferred former extensions of the Yellow, Yangtze, Salween, and Mekong rivers and tributaries. Medium stipple marks, Neogene clastic sediments.

that flow behind and across the Himalaya (Oberlander, 1985). The Tsangpo, Indus, and Sutlej rise near each other and then diverge (Fig. 13). The Tsangpo and Indus flow east and west, respectively, for hundreds of kilometres, then turn abruptly south to cut right across the main Himalaya and its structural grain (Fig. 14). The Sutlej cuts obliquely across the range. These rivers all have impressive gorges where they cut the High Himalaya and may have once flowed latitudinally behind the Himalaya (the Sutlej along the present Spiti and Chenab rivers)(Brookfield, 1993b). But all these rivers have now been truncated by headward erosion from rivers draining and eroding the front of the High Himalaya (Burrard and Hayden, 1907; Seeber and Gornitz, 1983; Oberlander, 1985). Because of tilting of the southern edge of the plateau as a result of isostatic uplift of the dissected Himalayan edge, these rivers have, in places, also been diverted northward (for example, the western end of the Tsangpo in Fig. 13).

Many transverse southward-draining Himalayan rivers rise north of the high peaks and cut deep gorges through them. Yet these transverse rivers do not deflect the linear watershed boundary along the

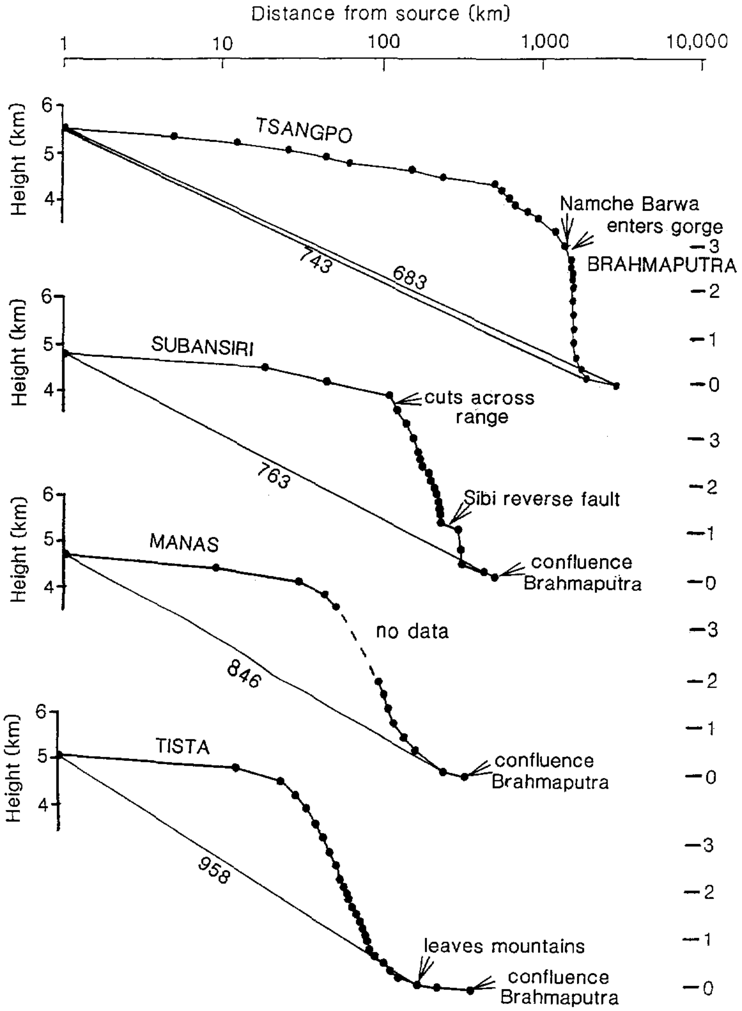

Fig. 15. Tsangpo–Brahmaputra and its Himalayan tributaries: semi-logarithmic profiles and gradients showing increasing gradients from flank to centre of the Himalayan arc.

High Himalaya, which they should do if they had simply captured other rivers from across the range by headward erosion (Shroder, 1993). Simple vertical uplift can not explain this striking peculiarity and it remained unexplained until the idea of massive frontal as well as vertical erosion of southward-moving thrust sheets was developed (Brookfield, 1989). The southwardly thrusting Himalaya are being continually eroded by rapidly incising and back-cutting streams. The consequent isostatic uplift, with the development of glaciers on the interfluves, is forming the highest mountain range and the steepest river gradients on Earth (Figs. 15–17). A dynamic balance exists between the headward erosion of rivers and the northward diversion of originally longitudinal rivers behind the rising Himalaya.

If frontal thrusting and isostatic uplift are faster than headward erosion, then drainage divides rise faster than they can be cut back by headward erosion, and Himalayan rivers have relatively short courses that end within the mountains. Thus, rivers at the center of the Himalayan arc, from the Manas to the Kali Gandak, have steep gradients (Figs. 15 and 16). Latitudinal rivers behind the range tend to get uplifted on the south, and the drainages become tilted to the north. Therefore, they tend to become dissected into northerly flowing tributaries of the Tsangpo (Figs. 13 and 14).

If, however, frontal thrusting and isostatic uplift are slower than headward erosion, headward erosion overtakes rising divides, and the Himalayan rivers extend behind the range to capture originally latitudi-

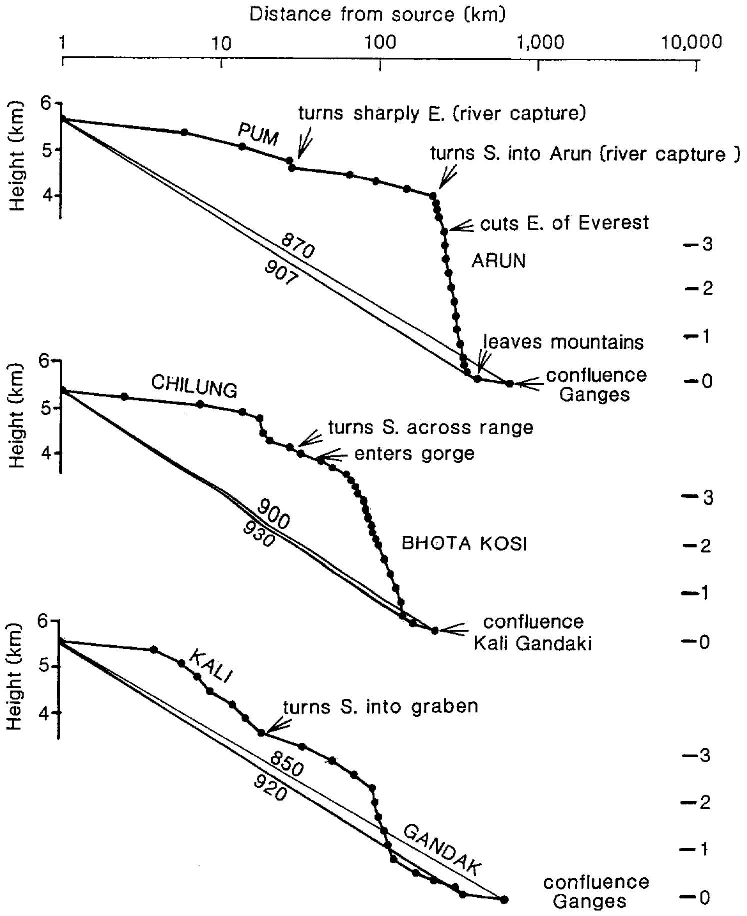

Fig. 16. Himalayan rivers of Nepal that drain into the Ganges: semi-logarithmic profiles and gradients.

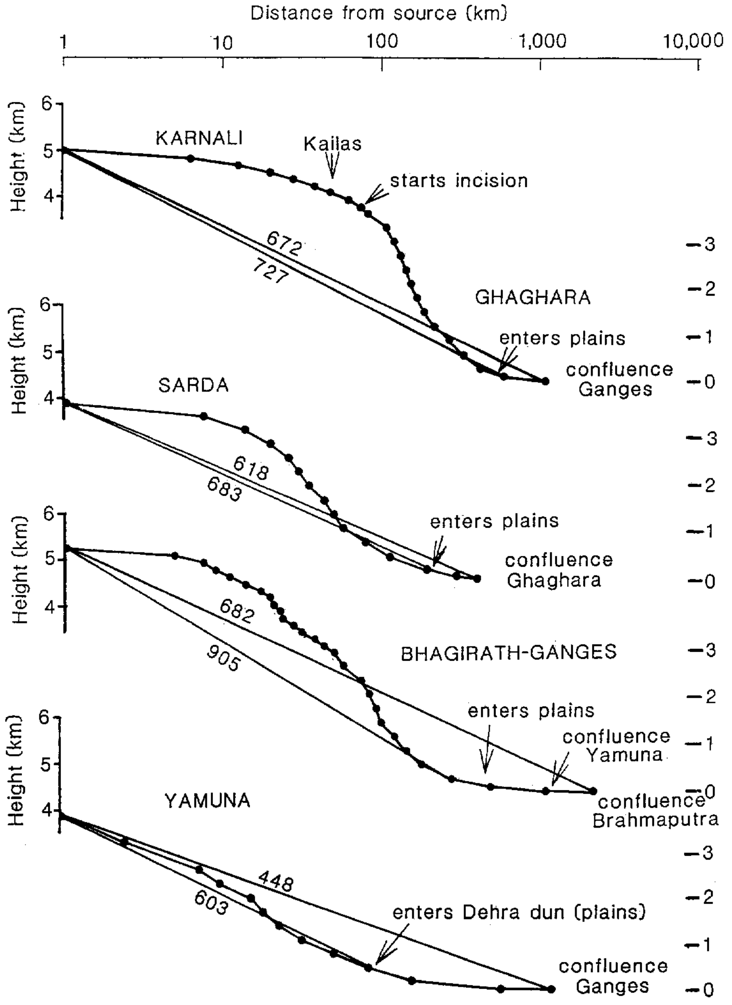

Fig. 17. Himalayan rivers in India: semi-logarithmic profiles and gradients of the Ganges drainage.

nal rivers, and northward flowing tributaries, on the plateau behind. This occurs mostly towards the flanks of the Himalayan arc, where frontal thrusting and uplift declines with progressively more motion translated into strike-slip components. Thus, rivers like the Subansiri and Karnali–Ghaghara extend back onto the plateau with gentler overall gradients (Figs. 15 and 17). Further east and west, headward erosion extends even further back onto the plateau to capture major originally latitudinal drainages, as in the case of the Tsangpo–Brahmaputra on the east and the Sutlej and Indus on the west (Fig. 13). The Pum–Arun is an exception, but this drains an old, deep latitudinal valley that is filled with Neogene sediments (Fig. 14).

The Karnali–Ghaghara river marks the transition from the southwardly moving frontal Himalayan arc system of India and Nepal into the clockwise rotating system of the Kashmir Himalaya. This transition reflects the change from the Himalayan to the Pamir system along the transpressional Karakorum fault zone (Fig. 14). Thus, west of the Karnali–Ghaghara, the rivers have generally similar gradients (Fig. 17). Recent fault movements are locally important. The kink in the profile of the Subansiri river as it crosses the Himalaya (Fig. 15) is directly related to the active Sibi fault, which has an almost vertical reverse fault focal mechanism (Holt et al., 1991).

The drainage into the Ganges system shows average indices of gradient of around 600–700. Those rivers that extend back onto the Tibetan plateau, with the exception of the Pum–Arun, show mostly rounded profiles and knickpoints indicative of fairly old river capture (Figs. 16 and 17). The Yamuna is the only tributary to show a completely concave low-gradient profile and has probably been beheaded by the Sutlej (Fig. 17).

The Himalayan rivers of the Indus system, the Indus, Jhelum, Chenab, Ravi, Beas, and Sutlej, resemble those of the Ganges system in that they vary from rivers rising within the High Himalaya to rivers cutting across the High Himalaya (Fig. 18). The Indus tributaries also traverse similar geological units (Fig. 19). The Indus and its Himalayan tributaries have, with the exception of the Jhelum, slightly higher average indices of gradient than those of the Ganges system, over 700 (Figs. 20 and 21). The main Indus and those of its tributaries that cut the High Himalaya have more kinked profiles indicative of more recent river capture of headwaters than the Ganges system (Fig. 20). By contrast, the major tributaries of the Indus that rise within the High Himalaya have almost graded profiles (Fig. 21). Deviations are of interest. For example, the short gentle stretch of the Jhelum within the Kashmir valley (Fig. 21) can be related to the rapid uplift of this valley and the formation of the Pir Panjal to the south within the last 1.7 million years (Burbank and

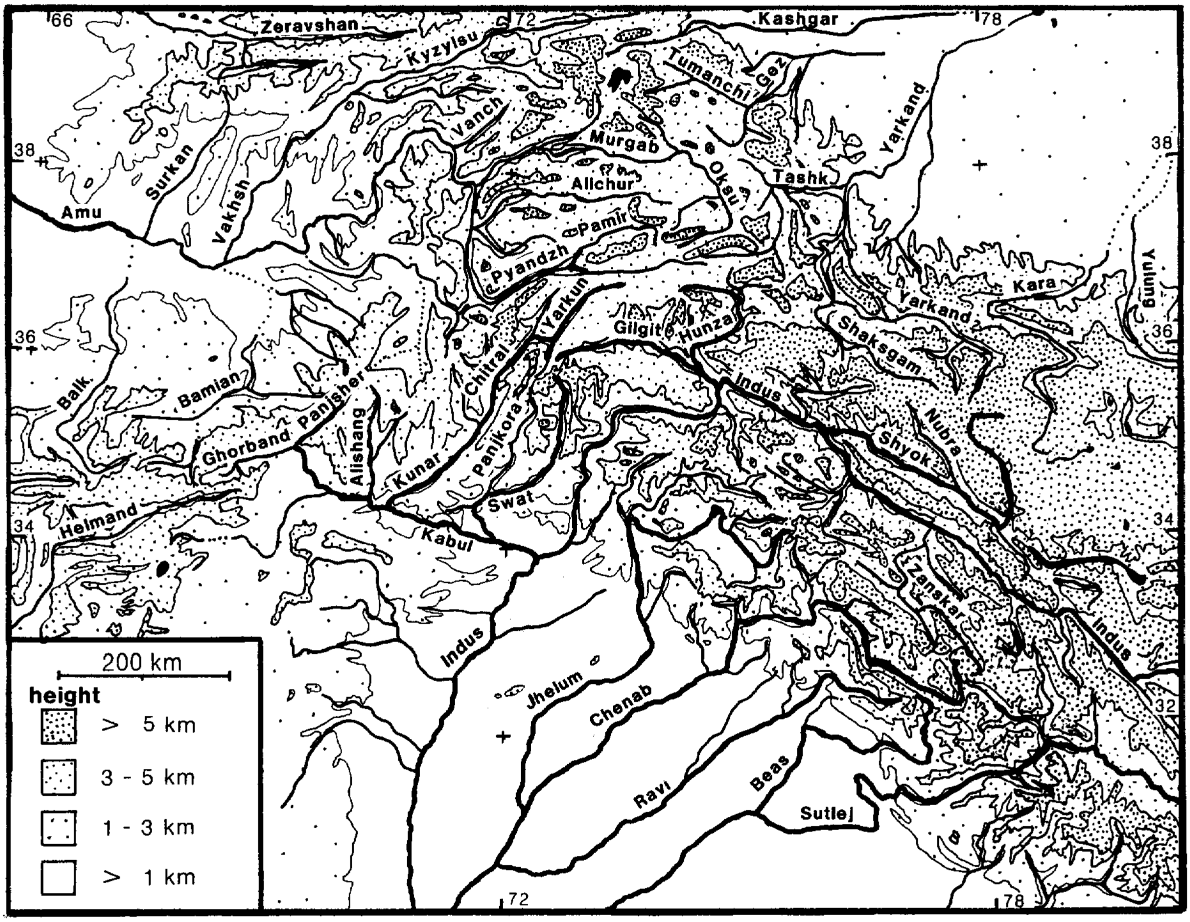

Fig. 18. Northwestern syntaxis: major rivers related to topography.

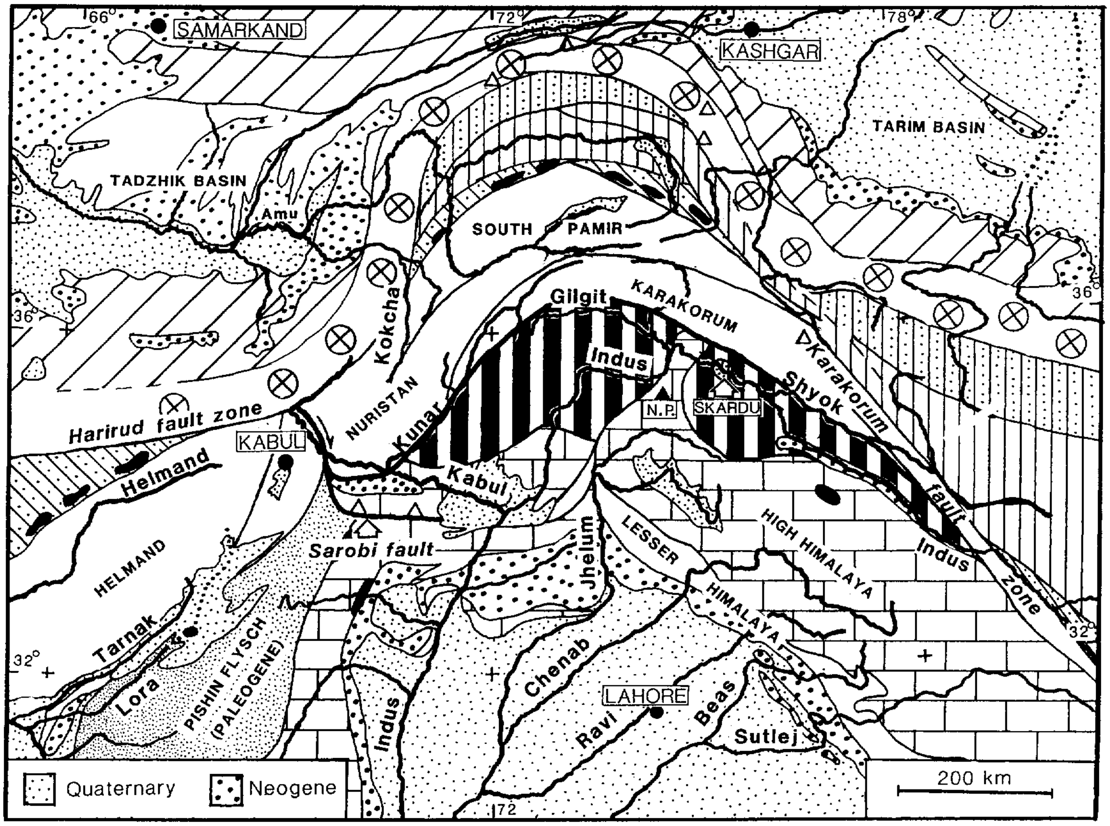

Fig. 19. Northwestern syntaxis: major rivers related to structure (data base from Brookfield, 1993a).

Johnson, 1983). The strong deviations of the Indus in its steepest graded stretch, from gentle above Skardu to very steep from Skardu around Nanga Parbat, is related to extremely rapid uplift, and the consequently extreme rate of erosion of 5 mm/year, of that massif and areas to the northeast (Zeitler et al., 1993).

The amount eroded from the front of the High Himalaya nappes can be roughly calculated from sediment budgets (Brookfield, 1989). An average width of at least 150 km has been eroded from the nappe fronts since the start of thrusting and rapid uplift in the late Miocene. The width removed is compatible with the absence of Mesozoic inner shelf facies between the Lesser and High Himalaya (Brookfield, 1993c). Massive horizontal erosion may have removed one latitudinal drainage system that once flowed within the High Himalaya. Vestiges of this system can be recognized only in the northwestern Himalaya, where frontal thrusting and erosion is less and almost the entire width of the Tethyan sedimentary rocks are preserved. Here, the alignment of the upper reaches of the Chenab and Sutlej rivers, and possibly the present Kashmir valley, with their Neogene sedimentary fills is suggestive of an ancestral latitudinal river course (Fig. 19) (Brookfield, 1993b). The Neogene basins along the Pum may also have once been part of this system (Fig. 14).

3.4. River capture in the syntaxes

In the northeastern and northwestern syntaxes, the enormous bending of structural units and originally latitudinal river systems have interacted with extreme uplift and erosion along transverse anticlinal axes to completely change drainage patterns.

In the northeastern syntaxis, a river that once flowed eastward and was bent around the developing

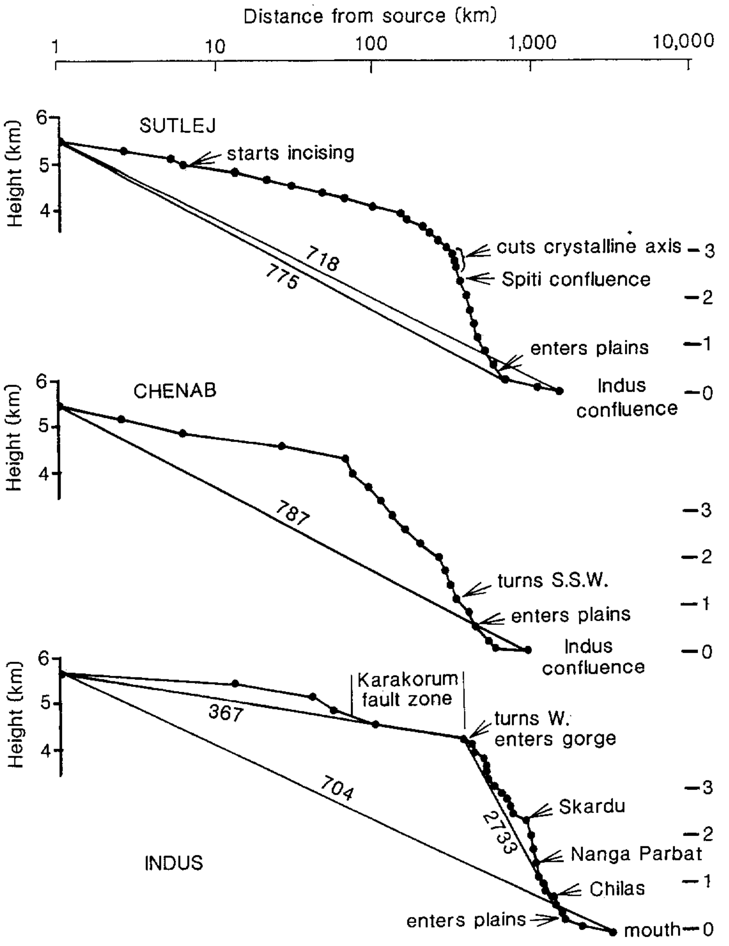

Fig. 20. Indus drainage, the main trunk rivers, the Sutlej, Chenab, and Indus: semi-logarithmic profiles and gradients.

syntaxis has been truncated by headward erosion from the Brahmaputra and Lohit rivers. All of the Indus–Tsangpo suture and most of the Himalaya structural units have been removed in this area (No. 4 on Fig. 9). In particular, the Mesozoic flysch of the North Himalayan unit disappears. The river patterns show that an earlier distinct river, which is separate from the Tsangpo, possibly flowed along the present Parlung, Sang and Tamai courses into the upper Irrawaddy (Fig. 8). In any case, the ancestral Tsangpo, which once flowed through the Sang, Tamai, and eventually into the Irrawaddy, is completely gone (Fig. 13). The capture possibly took place possibly several million years ago, as incision has now increased the gradient several hundred kilometres above the capture point (Fig. 15). Furthermore, the area between the present Tsangpo and Irrawaddy has only high passes with no obvious wind gaps. The capture by the Subansiri, on the other hand, took place very recently, as shown by the sharp angular join in gradients (Fig. 15).

In the northwestern syntaxis, because of more complicated tectonics, river patterns are much more complex than in the eastern syntaxis (Figs. 18 and 19). Southern Afghanistan was rotated and displaced to the west, which meant that vertical uplift was not as great there as in the eastern syntaxis, and complex thrust sheets and blocks are bounded by strike-slip faults with large displacements (Tapponnier et al., 1981). These faults cut across the syntaxis and rivers

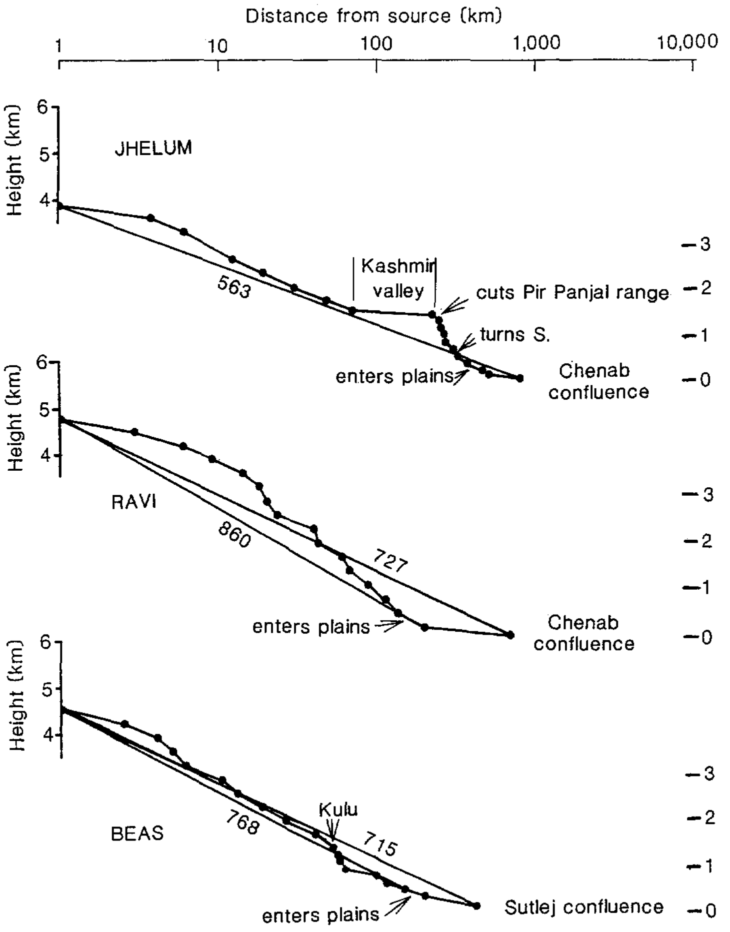

Fig. 21. Indus drainage, the major eastern tributaries, the Beas, Ravi, and Jhelum: semi-logarithmic profiles and gradients.

like the Indus and Kabul rapidly cut far back to truncate the original west to southwesterly drainage (Figs. 18 and 19). The incision of the Kabul river has taken place gradually over a long time. Its course is essentially graded despite the contrast between alternating stretches of metamorphic, igneous and sedimentary rocks, and sediments (Fig. 22). The development of the Indus river system is related to the river capture of deformed, originally latitudinal, westward-flowing streams, whose truncated remains now lie in Afghanistan (Fig. 5). This obvious idea, proposed in the earliest days of pilgrimage and exploration, can now be developed more coherently with better maps; satellite images; and modern concepts of isostasy, plate tectonics, and climatic change (Shroder, 1993).

Compressional and extensional stresses generated by the India–Asia collision have also affected the drainage systems of the Indian Shield. Since the Miocene, the southward-moving Himalaya forced the Ganges system to progressively move south. Before then, the tributaries of the Narmada and other westward-flowing shield rivers had much larger catchment areas, which extended further northwards (Sant and Karanth, 1993) (Fig. 1).

4. Relation of river patterns to plate movements

Four main stages in the collision of India with Asia can be recognized (Burchfiel and Royden, 1991; Dewey et al., 1989). The first stage, from about 80 to

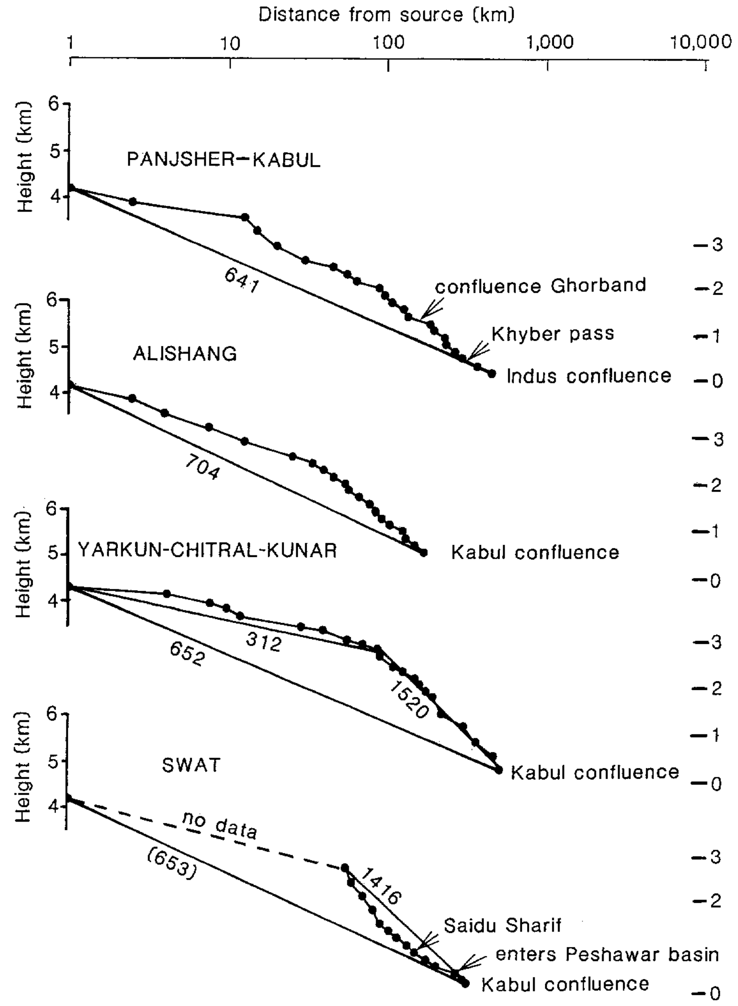

Fig. 22. Indus drainage, the major western tributaries: semi-logarithmic profiles and gradients.

50 Ma, involves the accretion of oceanic arcs onto the northern Indian margin, and ended with the final closure of the main Tethys ocean as India collided with a marginal Asian–Andean arc. The second stage, from about 50 to 25 Ma, involves lithospheric shortening, by up to 1000 km, of the future Tibetan plateau, as convergent deformation progressed from the initial southern collision site to the northern edge of the Tibetan plateau against the rigid Tarim block. This phase was probably accompanied by eastward lateral extrusion of southeastern Asia (Tapponnier et al., 1986). The third stage, from about 25 to 5 Ma, involves conjugate strike-slip faulting within the Tibetan plateau and transfer of the main shortening to areas south (Himalaya) and north (Tien Shan) of the plateau, with deformation of older Asian and Indian continental lithosphere. This phase was accompanied by northeastward motion of the entire collision zone between the left lateral Altyn Tag fault on the north and the Sagaing and related faults on the east. It probably also involved the lateral extrusion of the whole of eastern Asia. This stage is characterized by rapid uplift with some extension of the Tibetan plateau, the exact mechanisms and timing of which are controversial (Molnar et al., 1993). The fourth stage, from about 5 Ma to the present, involves the

gravitational spreading of the uplifted mass, consequent on changing plate motions in the Indian Ocean (Royer and Sandwell, 1989).

Reversing the motion of India with respect to Asia and restoring the probable distortions and erosional and subduction losses of the areas in between gives the cartoons shown in Fig. 22 (Brookfield, 1995). If the major rivers are plotted on these cartoons, then the evolution of the main drainage systems during the collision of India with Asia can be inferred. Though the cartoons should not be taken too seriously until they are tested against the stratigraphy and sedimentology of the various Neogene basins of southern Asia (a project yet to be done), the cartoons do show the importance of drainage studies to understanding the sedimentary history of the collision zone and have some interesting implications.

For example, the late Miocene (Tortonian) reconstruction shows three important changes from the present (Fig. 23):

(a) In the northwestern syntaxis, the absence of the Pamir indent, Karakorum fault and Nanga Parbat uplift, all of which control headward erosion of the

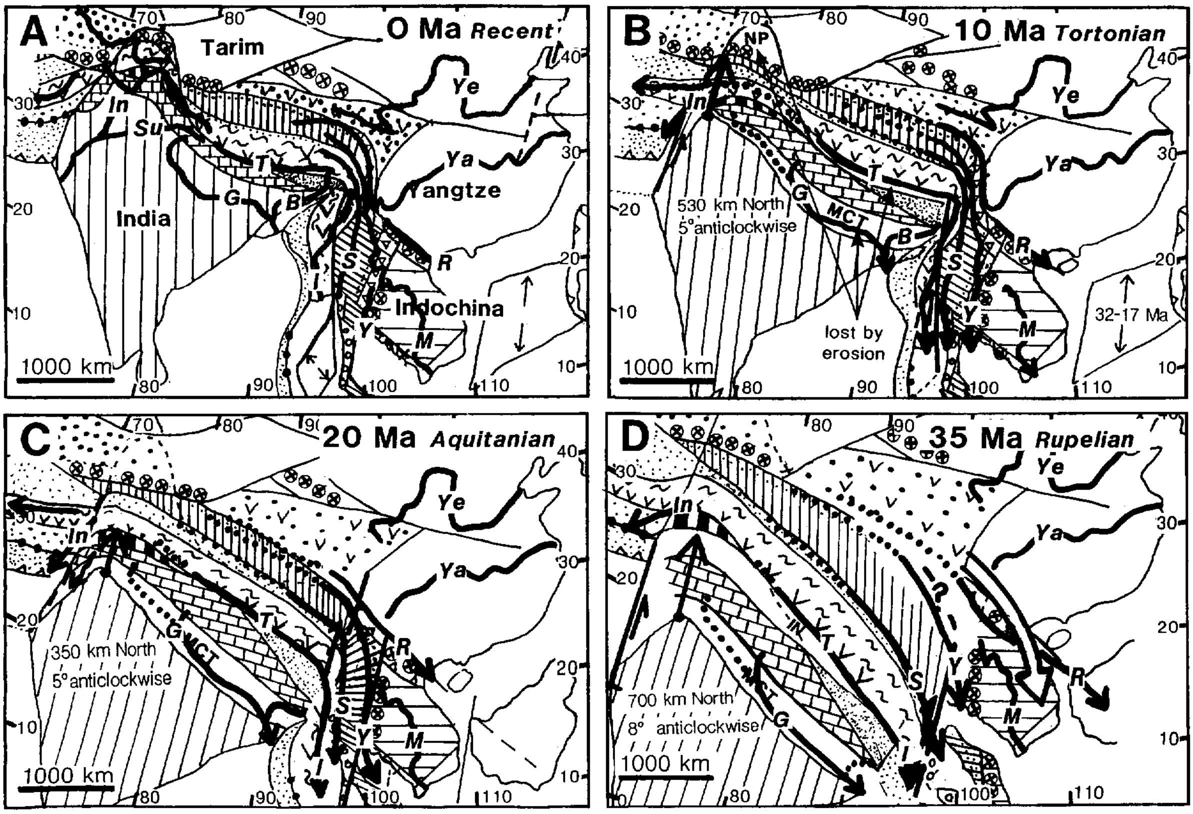

Fig. 23. Evolution of Asian river systems: position of structural units and main rivers (see Fig. 2). *In*, Indus; *Su*, Sutlej; *G*, Ganges; *B*, Brahmaputra; *I*, Irrawaddy; *S*, Salween; *Y*, Yom; *M*, Mekong; *R*, Red; *Ya*, Yangtze; *Ye*, Yellow. Late Miocene (Tortonian, 10 Ma), based on removing 530 km northward motion at northwestern syntaxis (shown by heavy black arrow) and 5° anticlockwise rotation of India between 10 and 0 Ma (Dewey et al., 1989). Note restoration of eroded parts of Lesser and High Himalaya (*MCT*), North Pamir (*NP*), and Indus Suture Zone. Possible river courses are shown with dotted lines. Early Miocene (Aquitanian, 20 Ma), based on removing 350 km northward motion (black arrow) and 5° anticlockwise rotation of India between 20 and 10 Ma (Dewey et al., 1989). Early Oligocene (Rupelian, 35 Ma), based on removing 700 km northward motion (black arrow) and 8° anticlockwise rotation of India between 35 and 20 Ma (Dewey et al., 1989). *IN* is restored crust that was lost by erosion and shortening along the Indus Suture Zone. The large double arrow is possible extrusion and rotation of southeast Asia (not restored).

present plains Indus, means that the mountain Indus probably then flowed into the Makran via the Kunar and Lora rivers (Fig. 6).

(b) In the northeastern syntaxis, the presence of an easily eroded flysch belt (cf. Oberlander, 1985) and the wide extent of the High Himalaya probably means that river capture had not yet truncated the Tsangpo–Irrawaddy river. Before truncation, this river would have been rapidly building out a delta through Myanmar into the developing Andaman back-arc basin.

(c) In southeast Asia, the mountain Mekong probably flowed into the Yom river, and the mountain Yangtze probably flowed into the Red river. The captures that diverted the Mekong into Cambodia and the Yangtze into China are almost certainly late Quaternary or younger, since geomorphic features like wind gaps are still preserved in these upland areas. But, only the Mekong is shown in its pre-diversion course into the Yom in Fig. 23.

Only 10 million years ago drainages were completely unlike those of today. In southern Asia, most of the important river changes have taken place since the late Miocene.

The early Miocene (Aquitanian) and early Oligocene (Rupelian) reconstructions have few major differences in river patterns compared with the late Miocene, except that the rivers flow in straighter structural belts (Fig. 23). Until the late Miocene, all the major rivers flowed in parallel structural belts that were inherited from the initial collision and uplift in the northwestern syntaxis. Deposits of these ancestral rivers are now only preserved locally beneath backthrusts along the Indus Suture Zone (Brookfield and Andrews-Speed, 1984).

Acknowledgements

My work in central and southeast Asia is funded by N.S.E.R.C. (Canada) and by the National Geographic Society. I appreciate the criticism of several anonymous reviewers.

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