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# GEOMORPHIC DEVELOPMENT OF THE WESTERN HIMALAYAS

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ABSTRACT

*Evolution of the drainage system of the western Himalayas was controlled by antecedance, superposition, capture, ponding, avulsion, and faulting following collision and suturing of the Kohistan-Ladakh island arc between the Indian and Eurasian Terranes. The Indus River arose sometime in the middle Tertiary from an area of eroded volcanics near Mt. Kailas in Tibet and established a course to an ancestral "Sindh estuarine" embayment about 300 km north of the present delta. Neither the old idea of a northwest-flowing "Indobrahm" river in the Himalayan foredeep, nor the newer postulate of an east-flowing ancestral Indus seem necessary to explain topographic or paleocurrent data that indicate diverse drainage directions. Instead the Indus River seems to have established itself along the axis of the island arc system, and in the Haramosh-Nanga Parbat area it was deflected south in an apparent sinistral sense along the Main Mantle Thrust. Subsequent reversal of motion produced a later dextral offset along the Raikot fault. The river was deflected similarly as it crosses the Kalabagh fault through the Salt Range.*

*Consideration of relations between uplift rates and erosion shows that the Himalayas are at least six times lower than the theoretical maximum, indicating that balance is achieved by discontinuous pulses of rapid uplift alternating with longer periods of quiescence, as well as by variable rates of channel incision and slope processes of erosion. Calculation of long-term sediment deposition in the Indian Ocean equates to a denudation rate of 0.2 mm/yr. Short-term present day rates are 1–1.8 mm/yr. Present uplift of Nanga Parbat is about 5 mm/yr and is nearly balanced by denudation at Raikot Glacier of 4 mm/yr.*

*In Pleistocene at least three episodes of glacial advance left thick valley-fill sections that allow definition of Quaternary events. The early stage is indurated lower Jalipur tillites that lack clasts from Nanga Parbat and show that uplift had not yet exposed the massif. Overlying heterogeneous upper Jalipur valley-fill sedimentary rock is younger than 1–2 m/yr and is overturned or overridden by basement faulting in places. The middle stage is two or more tills intercalated within variable sediments, including thick lacustrine deposits at Gilgit and Skardu. The last stage consists of three or more separate advances that retain moraine topogra-*

*phy. At Nanga Parbat and several other places, transverse glaciers at this time blocked the Indus to produce prominent lake deposits. Some of these ice dams failed and produced catastrophic floods and emplacement of the Punjab erratics at the mountain front. In Holocene time numerous glacial fluctuations and surges have occurred and are being monitored. Both glacial advances and major slope failures across rivers have occurred throughout the western Himalaya in historic time and have produced large impoundments, the dams of which failed subsequently and produced catastrophic floods.*

## INTRODUCTION

Sometime during the early part of June 1841, at two in the afternoon, a wall of water, mud and rocks roared out of the Tarbela gorge of the Indus River and overwhelmed a Sikh army encamped near the river. At least 500 soldiers perished immediately and the plain was "sown with barren sand" (Abbott, 1848, p. 231). That previous January, at the same time as a large British army was being shot down in nearby Afghanistan, an earthquake brought down the Hatu Pir spur of Nanga Parbat mountain into the gorge of the Indus River. The resulting dam backed water up over 150 m deep and as much as 30 km upstream to the confluence of the Hunza and Gilgit Rivers. Even though a note of warning on birch bark was sent downriver to warn of the rising hazard, no one at the mountain front seems to have understood the implications. The resulting flood devastation was but one more of a long line of outbreak floods that repeatedly sweep down the Indus from the high Himalayas. In the course of our recent search for the original rockslide dam (Shroder et al., in press), many additional large dams and other intriguing problems were discovered as well. This paper is about the general evolution of landforms in the western Himalayas, and particularly about the fluvial, glacial, and landslide events that have occurred there in the past few million years.

The catastrophic fluvial processes of the Indus gorge are the partial result of dams produced by large active glaciers and by rapid mass-wasting processes of several different types. These highly active geomorphic processes in the Himalayas are driven by an extraordinary rate of mountain uplift, itself produced by ongoing collision of the Indian and Eurasian crustal plates (Molnar, 1986). In the western part of the region, the Karakoram Himalayas have five peaks over 8000 m high and 36 over 7000 m. The collision that produced this great regional uplift also generated localized zones of intense diastrophism that result in such areas as the Nanga Parbat massif (8125 m), tenth highest mountain in the world. An understanding of the evolution of the general bedrock geology of these mountains is important to explain the genesis of their spectacular landforms.

The mountains of northern Pakistan and its border areas are a complex of large orogens — the Hindu Kush in Afghanistan to the west, the Pamirs to the north in Afghanistan and in the U.S.S.R. and China, the Karakoram Himalayas of Pakistan, and the Great Himalayan chain to the east in India (Figs. 1 & 2). The northern part of this complex is now referred to as the *Eurasian Terrane;* a part of the southern edge of the great Eurasian plate that here consists largely of metamorphosed sedimentary rock over several hundred million years old. The Eurasian Terrane was intruded later by the Karakoram batholith beginning about 100 million years ago and continuing for more than 50 million years. Silica-rich volcanics associated with these intrusions were later eroded and then redeposited from north to south as continental molasses (Gansser, 1980). The Eurasian Terrane was upthrust southward along the melange zone of the

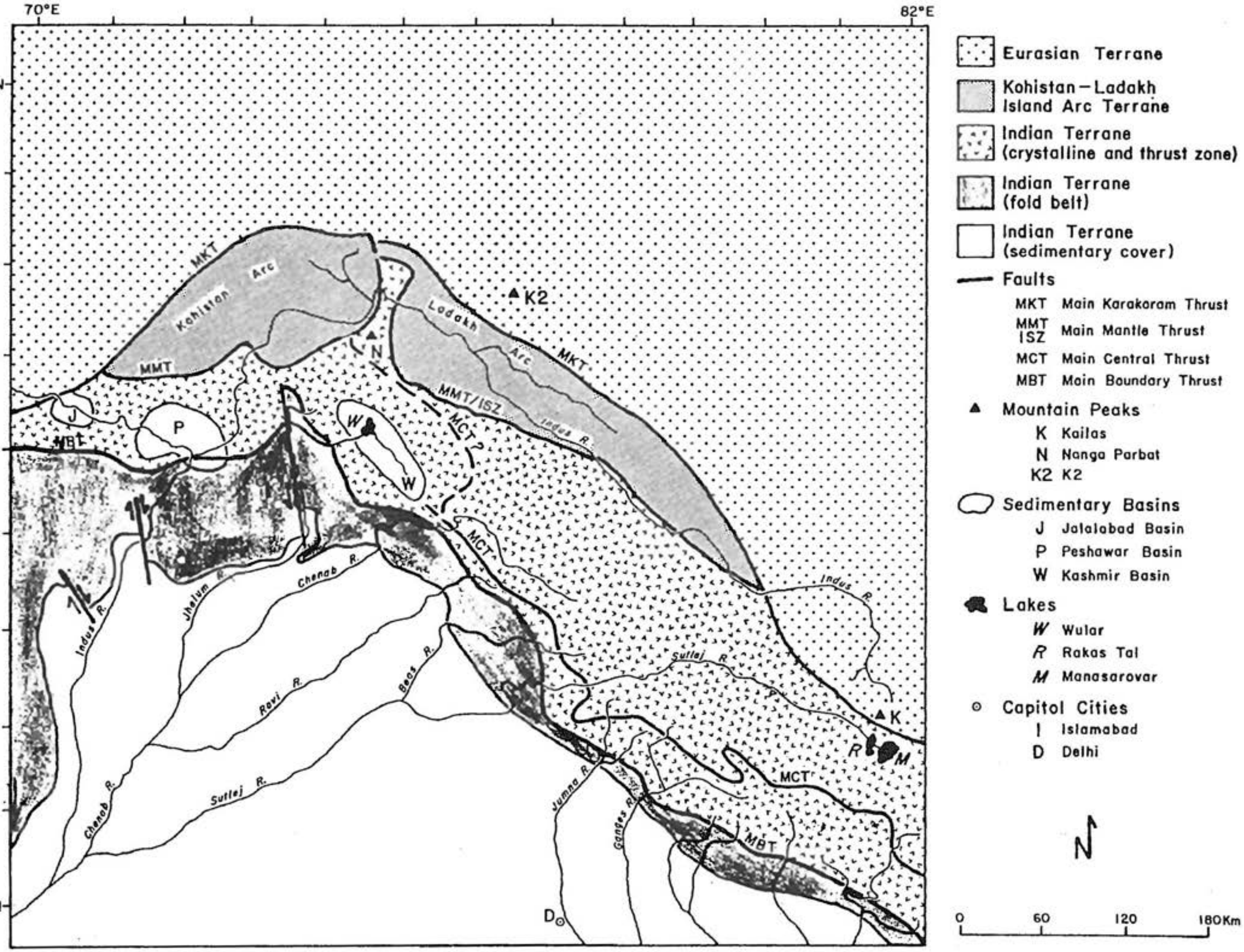


Fig. 1. Location map of western Himalayan and associated ranges with delineation of plate tectonic terranes, major faults and large rivers (adapted from Gansser, 1980; Kazmi and Rana, 1982; Yeats and Lawrence, 1984; Zeitler, 1985).

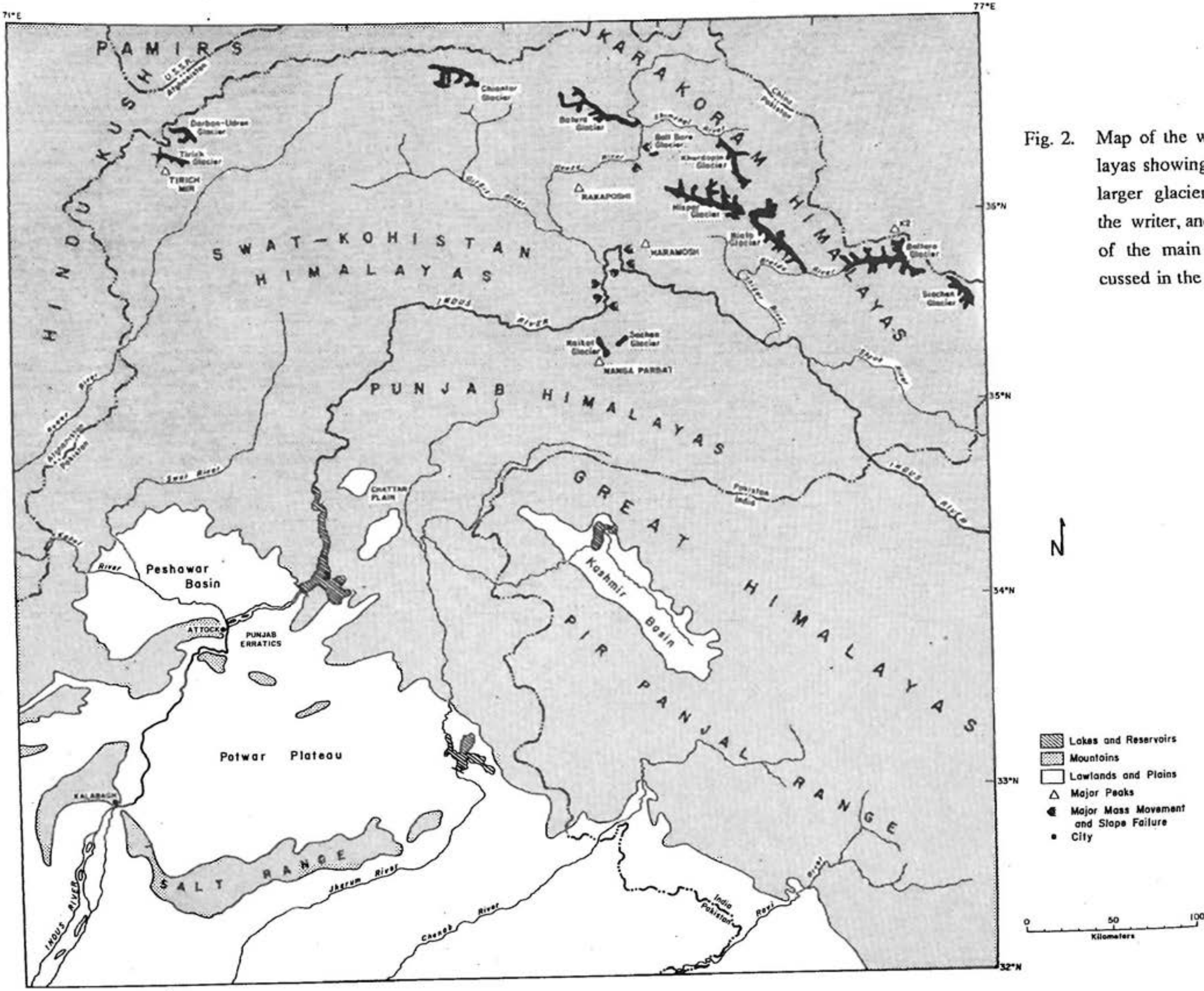


Fig. 2. Map of the western Himalayas showing a few of the larger glaciers studied by the writer, and the locations of the main features discussed in the text.

Main Karakoram Thrust (MKT) as the *Indian Terrane* was shoved northward beneath it. The MKT seems to connect southeastward with the Indus Suture Zone (ISZ) of the eastern Himalaya (Gansser, 1980; Zeitler, 1985). As with the Eurasian Terrane, the leading edge of the Indian plate also has a variety of older metasediments and intrusives of the deformed Indian continental margin and marine platform, as well as overlying thick continental molassic sediments shed from the rising Himalayas. The first major deposition of these sediments began perhaps 20 million years ago south of the main Himalayas as the Rawalpindi and Siwalik Groups (Meissner et al., 1974) were deposited on the leading edge of the Indian plate. Siwalik sedimentation continued up to less than one million years ago. The Indian Terrane is delineated on its north by faults known as the Main Mantle Thrust (MMT) which passes from Pakistan eastward in India into the ISZ.

Ancient volcanic island arcs formed in the Tethys ocean straits between the Eurasian and Indian plates prior to 65 million years ago. The Kohistan and Ladakh island arc terranes are mainly highly deformed mafic to silicic intrusives, volcanics and sedimentary debris shed from the mafic-rich source areas. The beginning of collision of the Indian and Eurasian plates began perhaps 50–60 million years go and the island arcs were thrust upward to be sandwiched between the two plates as they closed. The collision appears to have been most intense around 30 million years ago. Also at this time the rocks of the Nanga Parbat-Haramosh massif seem to have moved north, perhaps as the Kohistan and Ladakh arcs were thrust southwards along the MMT fault over the metasedimentary and other rocks of the northern margin of the Indian Terrane (Andrews-Speed and Brookfield, 1982). This fault has been locked since about 15 million years ago (Zeitler et al., 1982; Farah et al., 1984).

## EVOLUTION OF HIMALAYAN DRAINAGE SYSTEMS

Considerable discussion ensued in the older literature about the time of origin and the subsequent evolution of Himalayan rivers and their sediments (Oldham, 1896, 1907; Pilgrim, 1919; Pascoe, 1920; Mithal, 1968). Twin parallel rivers were hypothesized to have originated in the eastern highlands of Tibet and to have emptied into the "Sindh estuary," an arm of what remained of the Tethys Sea in the northwest, some time after about 60 million yeas ago when the first uplifts between northern India and Asia were forcing the seas out to east and west. An "Indobrahm" river, thought to have deposited the Siwaliks on the south, and an ancestral Tsangpo-Indus-Amu Darya on the north, were believed to have been partly captured and reversed to produce the present drainage configuration of the region. Commonly cited, for example, were the unusual "<-shapped" patterns of many tributaries that flow west or northwest out of the Himalayas, as though originally joining a west-flowing river at a slight angle and then later being forced to flow southeast in an apparent elbow of capture into the modern Ganges. Rivers eroding headward from the Bay of Bengal were presumed to have captured the northwest-flowing Indobrahm to become the presentday southeast-flowing Ganges, as well as capturing the Tsangpo–Brahmaputra that now joins the Ganges in the Bangladesh delta.

These speculations were adequate for the time but the paucity of either dates, sedimentologic data or of detailed information from the mountains allowed little additional progress. In the past two decades, extensive new explorations and discoveries have changed all this. Now it is known, for example, that the <-pattern of tributaries to the Ganges (Fig. 1) is an oversimplification because other deflection directions also occur and unusual flow directions or river diversions may result from aggradation upstream in valleys formed behind listric (downward rotating) fault blocks formed at the edges of the great boundary thrusts (Seeber and Gornitz, 1983).

Two other peculiar drainage features also caught the attention of observers from the outset. Most striking is the fact that both the Indus and Tsangpo-Brahmaputra rise near each other in Tibet 100–150 km north of the main Himalayan watershed, and after flowing parallel to the range along the rather straight watershed boundary for over a thousand kilometers, both turn abruptly to break through it and escape southwards. The other odd fact is that most of the remaining larger rivers of the Himalayas rise to the north of the highest peaks and cut deep and narrow transverse gorges south through the range. These rivers, however, do not cut into or bend the linear watershed boundary as they would if they had captured their headwaters from across the range.

The various ideas long used to explain the various drainage anomalies of the Himalayas have been that (1) the rivers predate or are antecedant to the rise of the mountains and have maintained their courses by active erosion across newly rising tectonic structures, (2) the rivers have cut down through an overlying cover of sediments to superimpose themselves across older mountain structures buried beneath, (3) the steep active headwaters of early rivers cut down and therefore pivoted backward through drainage divides to capture parts of other drainages, and (4) the rivers were periodically dammed by ice, landslides, or faulting that caused ponding and eventual overflow in different directions. Two other more minor drainage controls occur where rivers are deflected as they cross faults which have lateral offset, and through avulsion where rivers switch out of their channels through aggradation differences. All these drainage controls have operated in the Himalayas in the past.

Alhtough it would be unwise to read too much precise historical accounting of long-term geomorphic evolution from only a tectonic and sedimentation history of a region, still the structural control of an area as complex as the Himalayas is likely to override many of the climatic or process controls of landform development. The evolution of the major drainages of the Himalayas seems intimately tied, therefore, to long-term structural control although all the details of antecedance, superposition, capture, ponding, avulsion or fault deflection cannot be ascertained. The most striking factor is not that Himalayan rivers are so strongly associated with the structural and sedimentation history of the region that such long river histories can be deduced in some areas.

Thus the Indus River rises on the north slopes of Mt. Kailas (6714 m) in the Gangdise Range of Tibet (Allen, 1984) and flows northwest along the structural grain of the Himalayas (Fig. 1). Mt. Kailas, or Kangrinboqe Feng to the Tibetans, is sacred to both Hindus and Buddhists apparently because it is between the sources of the three great river systems of South Asia (Tsangpo-Brahmaputra, Ganges, and Indus). The mountain is an isolated remnant of debris eroded from the volcanos emplaced above the batholiths generated 40–60 million years ago by the plate collision. The Kailas deposits are likely to be some 20–40 million years old and are correlative with the Indus molasse that seems once to have covered the Ladakh arc intrusives to the west (Honegger et al., 1982; Sharma, 1983; Sharma and Gupta, 1983). Some of the sedimentation was in alluvial fans and plains; other sediment types were produced by drainage impedance due to mountain uplift across stream channels. As the Tethys seaway receded and an isthmus between the two plates grew in its place, at least part of the ancestral Indus appears to have come into existence near Mt. Kailas to drain the new highland. Similarly, the Tsangpo (Yarlung Zangbo) may have formed and flowed to the east to further erode the volcanic region (Seeber and Gornitz, 1983).

Subsequently the ancestral Indus seems to have cut down through the overlying sediments to superimpose itself upon the rocks of the Ladakh Terrane beneath, and the river also appears to have maintained erosion as an antecedant stream across other newly rising structures further downstream. Thus by about 20 million yeas ago, the ancestral Indus had established itself across the Ladakh arc. The relationship of the river to the Kohistan arc and its greater course to the Indian Ocean are less clear at this time, although Kazmi (1984) cited evidence that the marine delta of an ancestral Indus (or other large river) was some 300 km north of its present location. Near the Nanga Parbat-Haramosh massif, however where the Indus first strikes the rocks of the Kohistan arc and crosses the long-active Raikot fault, the drainage controls as a result of uplift and offset are striking.

At first glance at a small-scale map of the middle and upper Indus, the river seems deflected around the massif in an overall left-lateral sense, i.e. the Kohistan block on the west appears to have moved south as the Ladakh block moved north and twisted the river across them (Fig. 1). The collective apparent offset is about 30–40 km and might be the result of sinistral movement on the MMT prior to 15 million years ago in the waning phases of suturing of the island arc between the plates. Of course, it also may be possible that this bend in the river is a fortuitous relic of irregular superposition of the ancestral river across the structures. The likelihood of this is low, however; given the 1000 km of linear flow along the structural grain upstream and then the abrupt crossing of the regional structures coincident with a major fault system between the two arc terranes.

In addition to the above offset, close inspection of the large scale topographic and new geologic maps of the area reveals yet another picture of events in the last few million years as well. For example, the Indus river flows west-northwest from Skardu toward the Nanga Parbat-Haramosh massif and then is deflected first *north* along the Raikot fault zone before turning abruptly west again out of the fault zone and then finally south into the larger and older defelction mentioned above (Fig. 3). This younger deflection is obviously right lateral, and opposite in sense of motion to the original deflection; i.e. in the younger case the east block moved south relative to the west block moving north. Detailed new mapping of the Raikot fault (Madin, 1986) also has revealed various lineations in the rocks along the fault that confirm the change in directions of motion.

The nature and locations of all the fault sutures between the Eurasian, Indian and island arc terranes are controversial but the new ideas of a tear fault on the MCT which pushed up the Nanga Parbat- Haramosh massif better explain the younger deflections of the river than the old idea of the MMT fault plane that was later folded and exposed as the massif pushed up through it. In this latter case the Indus should be curved smoothly across the massif (Fig. 4), but it is not.

From Nanga Parbat down the Indus River to Tarbela at the mountain front, structural and other controls of the course of the Indus are known only poorly. The Tarbela Dam, largest such earth-filled structure in the world, is vulnerable to natural hazards of the Himalayas such as high siltation rates, catastrophic floods, and perhaps major seismic events. The west abutment of the dam unfortunately sits astride a thrust fault, that so far appears to be quite inactive.

In the Kohat-Potwar area south of Tarbela and Attock, Abbasi and Friend (1988) discovered in the Indus Conglomerate a blue-green hornblende characteristic of Kohistan island arc lithologies. About 15 million years ago, therefore, a paleo-Indus was depositing a thick section (~1500 m) in the area of the modern Indus.

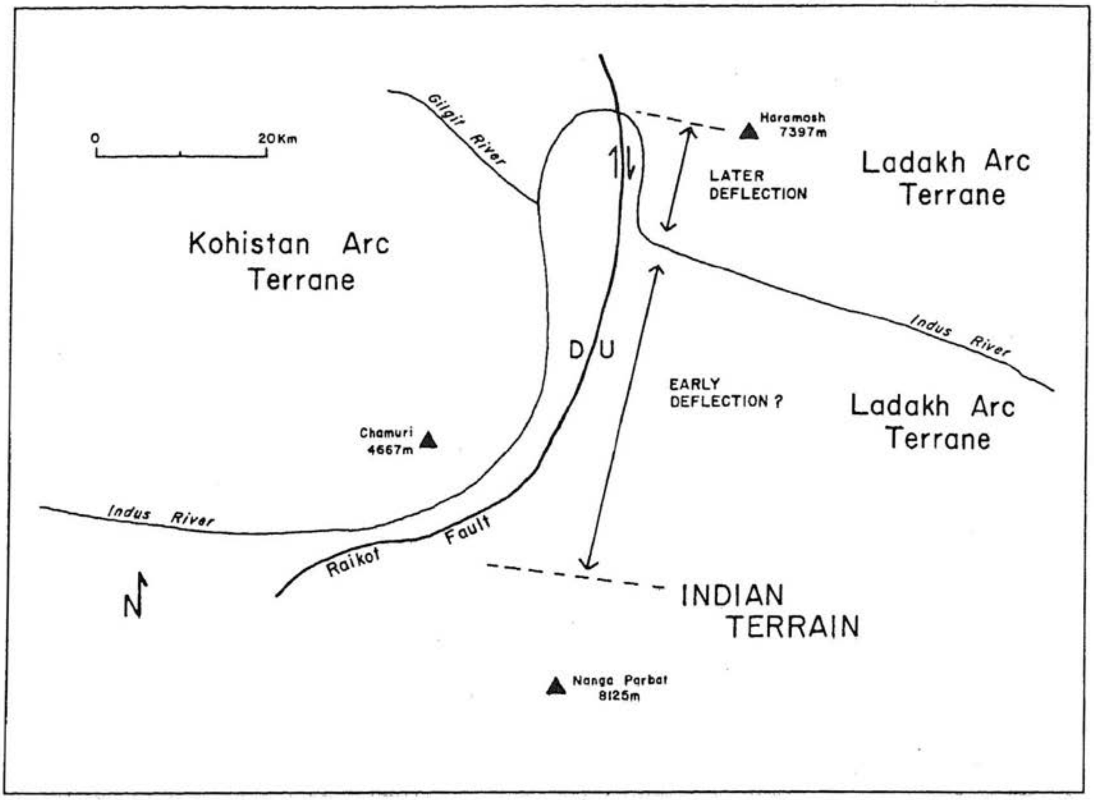


Fig. 3. Schematic diagram of the course of the Indus River between Haramosh and Nanga Parbat mountains and along the Raikot fault trace along which the river shows an apparent two generations of deflection.

South and east of Tarbela in the Jhelum area (Fig. 2), molasse sediments of the upper Siwalik Group have a lower unit of clast assemblages and paleocurrent structures that suggest a river which flowed east-northeast there just prior to about 5 million years ago (Raynolds, 1981). Whether this was an ancestral Indus seems unlikely, but in any case it was replaced by a southward flowing ancestral Jhelum River after about 4.5 million years ago. This river was responding to migration of the Himalayan foredeep south at about 2 cm/yr. From about 2.4–0.7 million years ago the molasse coarsens upwards into conglomerates that advanced south at about 3 cm/yr as a time-transgressive phenomenon in response to outward displacement of the Pir Panjal orogenic front (Raynolds and Johnson, 1985). This progradation of the ancestral Jhelum fan gravels likely would have included lateral migrations as well. Lateral movement of Himalayan rivers through avulsion across their fans is not unusual, as for example the Arun-Kosi River in eastern India that shifted laterally over 100 km and through as much as 75° in overall flow direction in only two centuries (Gole and Chitale, 1966). Such extreme lateral movement, over 15,000 times more rapid than the Jhelum progradation, could be involved in the apparent shift from an east-northeast flow to a later southerly direciton. Certainly having a

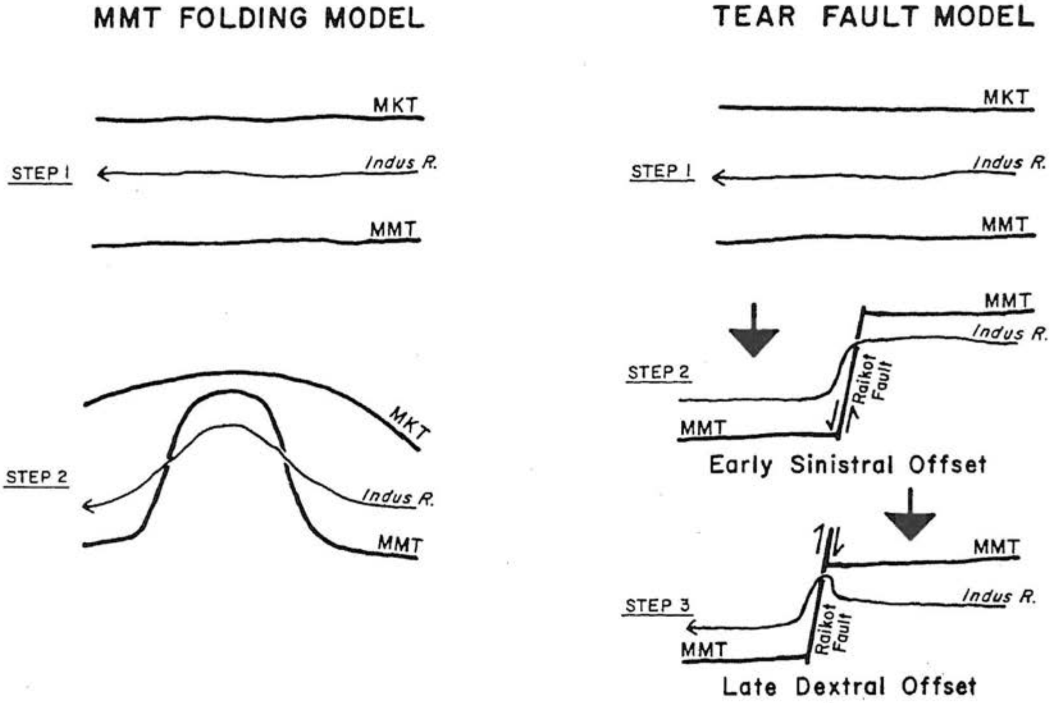


Fig. 4. Schematic diagram of two possible hypotheses for deflection of Indus River across the Nanga Parbat syntaxial bending of faults. In the MMT Model, the MMT thrust sheet is supposedly folded into the syntaxial bend to produce apparent strike–slip fault offsets that would provide roughly equivalent offsets of the river. In the tear fault model, on the other hand, the two generations of movements on the Raikot fault produce the offset observed at present.

paleo-Indus in approximately its present position 15 million years ago (Abassi and Friend, 1988), shifting it to drain into the Ganges ~5 million years ago (Burbank and Raynolds, 1984), and then back again to the modern location seems unlikely. The principle of parsimony in construction of hyptheses would indicate a greater likelihood that the evidence for an east-flowing river in the Jhelum area might be better explained by reworking of Indus sediments and later shifting of the Jhelum fan. In addition, deflection into the S-shaped bend of the modern Jhelum River (Fig. 1) could have been facilitated by the ongoing thrust-driven counterclockwise rotation of over 20° of part of the Potwar Plateau and Salt Range that occurred between 1.8 million years ago and the present (Burbank and Raynolds, 1984; Yeats et al., 1984).

Four major sedimentary basins were produced in the last few million years in the front of the western Himalayas. From west to east across this region, the basins of Kabul, Jalalabad, Peshawar with its Campbellpore extension to the southeast, and Kashmir reflect the transfer of the locus of thrusting and uplift from the north to the southern margins of the basins (Burbank, 1983). The Peshawar Basin, through which the Indus River flows, began by about 3 million years ago through differential uplift of the Attock Range and ponding of the pre-existing fluvial system (Burbank and Tahirkheli, 1985). Widespread intermontane deposition was terminated about 600,000 years ago about the same time that the Attock Range uplift accelerated (Fig. 2), after which catastrophic floods periodically inundated the basin.

In its course south-southwest from Attock, the Indus passes through the south end of the Campbellpore basin, skirting to the west of the Potwar Plateau. The river there turns at nearly a right angle to pass west through the Salt Range and across the Kalabagh tear fault along which the west edge of the Salt Range is being thrust to the southeast (Yeats et al., 1984; Yeats and Lawrence, 1984). From there the Indus turns south again and spreads into a broad braid plane for its remaining 1150 km course to the sea. The Kalabagh fault has 12–14 km of right lateral offset (McDougall, 1987 and pers. commun.), which also accords with paleomagnetic studies of the Middle Siwaliks that indicate a small counterclockwise rotation of the region (Opdyke et al., 1982). Deflection of the south-flowing Indus west across the Kalabagh fault and then south again is supported also by new discovery of extensive high-level gravels characteristic of a Himalayan source. The river apparently was pulled south and west away from the gravels as fault movement progressed.

Thus the above evidence seems to indicate formation of an Indus River at least 20 million years ago, with the upper Indus from Kailas to Tarbela, and the Kabul River from the Hindu Kush to Peshawar, connected somewhere through the Attock and Salt Ranges to the delta. On the other hand, some of the other rivers of the Kashmir and Punjab that are now southwest-flowing tributaries to the Indus, seem once to have flowed east (Raynolds and Johnson, 1985). Further work on this probelm is in progress in light of the conflicting evidence of multiple flow directions, the similar river faunas between the Indus and Ganges (Pascoe, 1920), the presumed captures and the cross divide relations, and the more than 10 km thickness of alluvial sediments deposited in that reigon over the last 20 million years (Khan et al., 1986).

## OROGENY AND DENUDATION

Relationships between uplift and erosion in the western Himalaya are important to understanding the great relief and the highly dynamic geomorphic processes there. Variations in mountain landforms commonly reflect differences between channel incision and slope processes, rather than between rates of uplift and erosion. Nevertheless, consideration of overall regional effects produces interesting questions about local relief characteristics.

Theoretical considerations (Ahnert, 1970) show that in order to have a balance between rate of erosion and a "typical" rate of mountain uplift (1 cm/yr) a relief of over 50 km would be necessary. Of course the rates of erosion probably increase exponentially with altitude but the fact that the Himalayas are at least six times lower than the theoretical maximum are an indication that balance is likely achieved by discontinuous pulses of rapid uplift, alternating with longer periods of quiescence or slow uplift. Numerous measurements made at various places have shown this disparity between present rates of denudation and orogeny (Schumm, 1963), but only a portion of this difference can be attributed to the fact that process rates are partly a function of measured time interval (Gardner et al., 1987). In general, the modern rates of uplift (~7-8 mm/yr) are about eight times greater than average maximum denudation. But differences in the form of mountain slopes seem not to be the result of this disparity anyway, rather the differences between rates of channel incision and slope processes are the controlling factors. Thus where rocks are very resistant, channel incision will be relatively much greater than the slope erosion and a narrow canyon will be formed. Furthermore, rates of erosion vary greatly between different mountain processes. For example, the highest rates of any erosion processes occur in glacial and periglacial regions. Glacierized areas generally have average erosion rates of about 2 mm/yr, whereas rivers have rates about four times less (Corbel, 1959).

The total volume of sediments from the Himalayan source regions that have been deposited on the land and in the Indian Ocean basin over the last 40 million years is about $8.5x10^6$ $km^3$ (Menard, 1961). This is equivalent to a regional long-term denudation rate of about 0.2 mm/yr. The short-term present-day erosion rate, however, seems to be at least 1 mm/yr; five times greater than the long-term rate. The Arun-Kosi River system that drains the Everest and Kangchenjunga areas has filled in reservoirs at a 1 mm/yr denudation equivalent (Khosla, 1953), and the Hunza River tributary to the Indus carries about a 1.8 mm/yr denudation equivalent (Ferguson, 1984).

Zeitler (1985) has shown that in the last 10 million years in the western Himalayas, fission tracks have accumulated as a function of time in mineral structures being uplifted through the crust, which allows analysis of uplift and erosion rates. During this period the western Himalayas were uplifted regionally some 3–6 km and locally over 10 km. Nanga Parbat (8125 m) (Fig. 5), Haramosh (7397 m), and Rakaposhi (7790 m) have experienced accelerating uplift and erosion during the past 7 million years at rates increasing from less than 0.5 mm/yr to over several mm/yr. In the past 2 million years alone, the Nanga Parbat-Haramosh massif, across which the Indus maintains a great trench, has increased its uplift rate from 2.5 mm/yr to 5 mm/yr. These immense mountains thus were produced essentially in only the last few million years, and surprisingly enough, at rates sufficient to affect growth of glaciers on their flanks.

The Jalipur tillite, a glacial remnant preserved beneath the Raikot overthrust fault in the Inuds valley yet contains almost no rock types from the mountain itself. Apparently during Jalipur time the mountain was not high enough to generate glaciers, although glacial ice from further upstream was moving past the locality. Overlying and slightly younger tills nearby are replete with Nanga Parbat lithologies, which shows that only a short time after the Jalipur the mountain had become uplifted sufficiently to affect local glaciers.

Vertical relief between the Indus gorge and the top of Nanga Parbat is nearly 7000 m in 21 km horizontally. On this immense mountain face the Raikot Glacier descends as a block or plug of tumbled ice seracs at an angle of about 51° to an altitude of 5000 m. From there it moves on a more gentle slope of about 7° to its terminus at 4250 m altitude. The glacier was discovered recently (Gardner, 1987 and written commun.) to be eroding the area at a rate of about 4 mm/yr, which nearly balances with the fission-track uplift rate of 5 mm/yr (Zeitler, 1985).

Near equilibrium conditions between uplift and erosion therefore seem to occur at the lower part of the Raikot Glacier, and perhaps in the nearby Indus River gorge as well. A steadystate condition is obviously not widespread, however, because the Nanga Parbat and Haramosh summits loom far above both glacier and gorge. Although the mountains are deeply incised by many other glacier and river systems as well, these processes do not cover the entire ground surface, and the fact that such major relief still stands shows that great rock strength

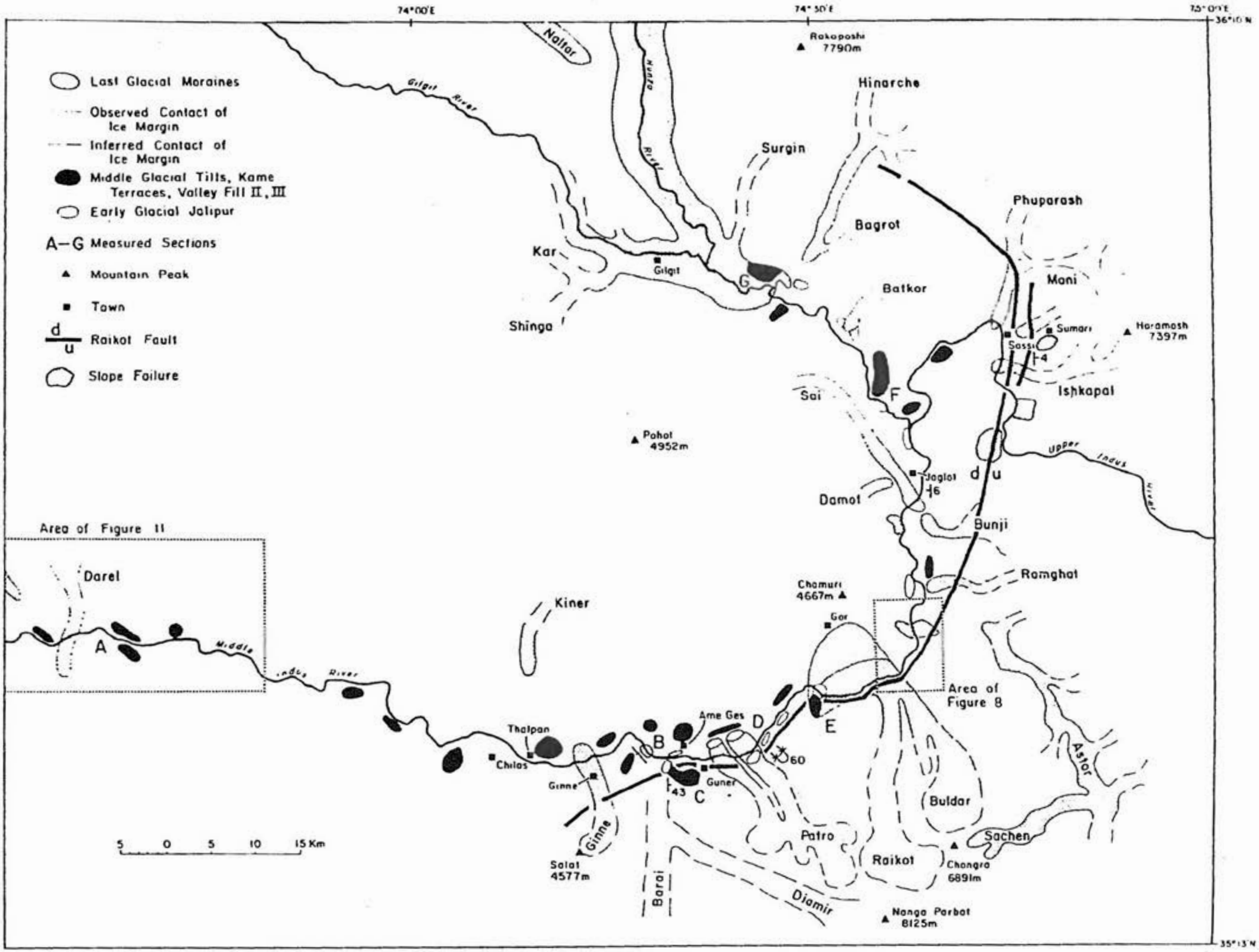


Fig. 5. Location map of the ice-related and slope failure deposits in the Indus Valley and its tributaries.

allows maintenance of steep slopes even in such high seismic areas.

Apparently only major slope failures could reduce such mountains in this climate regime, and even then only rarely when incision and slope angle are much greater than now. At what elevation the processes of slope failure coupled with glaciers and river erosion would be great enough to achieve more widespread equilibrium with uplift is as yet unknown.

## SLOPE FAILURE IN THE WESTERN HIMALAYAS

Since the collision of the Indian and Asian plates produced such intense igneous and metamorphic activity, the resulting massive crystalline rocks are resistant to slope failure. Still, the immense relief, strong fracturing, and high seismicity guarantee major failure in some places. Where slopes are undercut by the strongly erosive rivers and where pressure release occurs in over-steepened rockslopes following retreat of glacial ice, large falls are pronounced. Even at the bottom of deep mountain valleys and in the foothills, failure of residual soils, valley-fill gravels, and deeply weathered saprolites is common wherever gradients are sufficient. The impressive Karakoram Highway, forced through the heart of the Himalayas to China, is constantly cut by large and small landslips. In fact, as the exponentially increasing population pressure pushes into this fragile environment, the deforestation, overgrazing and construction contribute significantly to further slope-failure hazards.

Many large slope failures have been recognized in the middle and upper Indus, Gilgit and Hunza River valleys (Burgisser et al., 1982; Goudie et al., 1984), but only a few examples are mentioned here (Fig. 5). Along the Raikot fault zone 10 km south of Sassi village, steep dips on foliation planes into the Indus gorge have produced a massive block glide and rock slide over 1.5 km wide. Sumari village sits in a till-filled graben on another large slide above Sassi. Across the gorge on the ridge cut by the Raikot fault between Haramosh and Nanga Parbat, a large number of antislope scarps show characteristics of massive failure. Directly on top of the narrow ridge, 1600 m above the Indus River, Sarkun Lake shows the *sackung* (literally "sagging") style of failure in which a mountain fractures and moves down (Bovis, 1982).

Two major rock slides blocked rivers in the Western Himalaya in the 19th century. A slide in 1858 at Pungurh in the Hunza River gorge caused significant flooding downstream when the dam broke. Large scale failures have continued on both sides of the valley there ever since because of the steeply dipping bedding planes (Goudie et al., 1984). The most famous slope failure, however, was that which generated the 1841 flood at Attock; mentioned at the outset of this paper and relocated and mapped as a part of this study (Fig. 6). The vertical drop of the rock slide was about 1900 m and the horizontal distance of transport was about 4 km. As the impounded Indus backed up to its full height on the terrace plateau by Bunji fort, the opposite rock slope failed as well and made a giant wave in the lake (Drew, 1875). When the lower landslide dam ultimately failed, the floodwaters produced scour marks and megaripples in the vicinity. Subsequently the Indus was diverted around the Bunji rock slide, undercut the plateau, and part of it failed as well.

The uplifted foothill regions of the Himalayas have other kinds of failure. On the Chattar Plain, for example, deep weathered, clay-rich saprolites slide and flow slowly downhill (Lawrence and Shroder, 1985). Large and small debris falls and slides occur in the valleys where the thick valley-fill gravels are undercut by rivers and fault scarps. Talus slopes how-

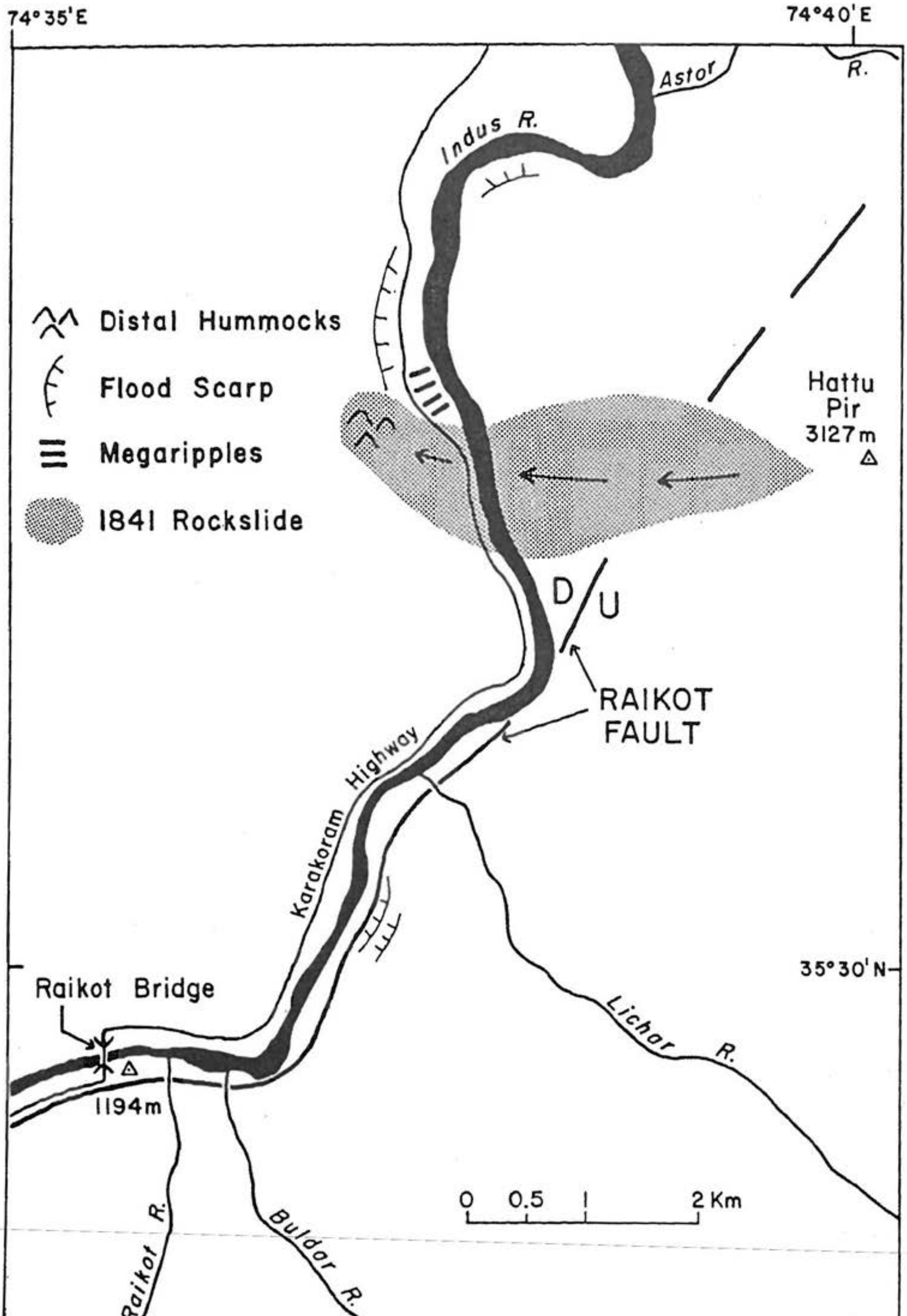


Fig. 6. Sketch map of the rockslide that blocked the Indus River in 1841. The massive slope failure from Hattu Pir was produced by an earthquake, presumably from movement on the Raikot fault that crosses beneath the slide.

Fig. 7. Sachen Glacier on the east side of Nanga Parbat.

ever, are probably the most conspicuous and dramatic element in the mountain landscape. They are formed by the constant rock falls, dry grain flows and wet debris flows that form simple small cones up to huge compound accumulations kilometers wide and up to a kilometer long (Brundsen et al., 1984).

Porbably the most common catastrophic mass-movement mechanism in the Himalayas is the debris flow in which surface debris is mobilized by rain or snowmelt. Waves or walls of this slurry rush down gullies, cross fans, and devastate bridges and fields. Small storms on the peaks can generate many flows that rush in the arid lower valleys in the mountain rainshadows. Larger more destructive debris flows have blocked some of the larger rivers and overwhelmed major structures as a result of intense storms or breakout floods from ice-blocked water bodies in ice and rock glaciers (Goudie et al., 1984).

## GLACIAL GEOMORPHOLOGY

Rock glaciers, a polygenetic landform involving mostly slow movement of ice and rock fragments, as well as water under pressure in some cases, abound in the Himalayas and Hindu Kush. Sachen Glacier on the east slopes of Nanga Parbat has several enigmatic ice-cored examples that broke out through the lateral moraines (Fig. 7). This glacier, like many others in the Himalayas, is fed largely by ice and snow avalanches from the cliffs on the mountain above. This produces an unusual configuration of a glacier at about 3500–4000 m altitude with no obvious connection to its source area 2000 m above on the mountain where the snow and

TABLE I. CRITERIA USED ON SATELLITE IMAGERY OF THE WESTERN HIMALAYAS FOR RECOGNITION OF RESOLVABLE TYPES OF UNUSUAL DIFFERENTIAL OR RAPID GLACIER MOVEMENT FOLLOWED BY LESS RAPID MOVEMENT OR RETREAT.

| | |
|---|---|
| 1. | Strongly convoluted medial or lateral moraines (5 glaciers; including Hispar Glacier and 2 in Shimshal valley). |
| 2. | Medial or lateral moraines convoluted or offset by extensive crevasses or ogives (13 glaciers). |
| 3. | Tributary ice overriding or displacing main glacier ice (7 glaciers). |
| 4. | Marked depression of ice surface below lateral moraines or tributary glaciers (14 glaciers). |
| 5. | Lateral and medial moraines slightly sinuous, or lobate, or offset by crevasses or ogives (76 glaciers). |
| 6. | Recent major melting or retreat of ice front leaving light-coloured scars behind (9 glaciers). |
| 7: | Extensive area of debris-covered downwasting ice or stagnant ice (106 glaciers). |
| 8. | Linear moraines and accordant tributaries (47 glaciers). |

icefields accumulate at an elevation of about 6000 m. Nevertheless, this source of nourishment is sufficient to maintain the glacier with remarkably little change over the last 50 years since its first survey in 1934 (Finsterwalder, 1937), although our recent rephotography and tree-ring dating do show some downwasting at the terminus.

The tremendous accumulations of mass-movement debris and snow avalanche debris, coupled with the intense summer heat that melts the ice rapidly in the deep arid vallleys, produce great thicknesses of tills on glacier surfaces, as well as massive moraines down valley. Outside of the well-studied glaciers of Alaska and the Yukon, the western Himalayas have more glacier surges than anywhere else. Over 12 documented cases of rapid glacier advance are known from there (Hewitt, 1969; Wang et al., 1984), and plentiful twisted moraine loops show other examples (Shroder, in press). Recent observation in Alaska of subglacial tunnel collapse leading to hydrostatic "floating" and rapid surges (Kamb et al., 1985) suggest that plentiful meltwater in the hot mountain valleys may be a cause of many surges in the western Himalayas.

With so many glaciers in the world in retreat, fresh water in increasingly short supply, and in part because of need to gather greater data pertinent to suspected world climatic warming, the U.S. Geological Survey has sought to use satellite imagery to assess the world glacier ice mass. To this end, many (168) of the glaciers of the western Himalaya were analyzed in the field and from the imagery and maps to gain increased understanding of these remote and difficult areas (Shroder, in press). Emphasis was directed towards glaciers with unusual advance, retreat, or surge histories (Table 1). The largest and most prominent examples of glaciers with strongly convoluted moraines indicative of surge behaviour are in the valleys of Shimshal, Hispar and Braldu, although several also occur in directly adjacent China north of K2 mountain. The Shimshal valley is notorious for having glaciers that dam the main river periodically and cause floods.

The Batura Glacier in Hunza is about 59 km long, making it one of the eight largest glaciers in the middle and low latitudes. Although it is not a hazardous surging type of glacier, it has received special study in the past decade (Batura Glacier Investigation Group, 1980; Shroder, 1984) because of some unusual characteristics and its close proximity to the Karakoram Highway between Pakistan and China. The climate of the deep valleys of the Karakoram near Batura is dry, with only about 10 cm of precipitation on average. Annual snowfall on the upper reaches of the Batura is greater, but still only 100–130 cm. The annual 0° C isotherm is near 4200 m and the equilibrium line occurs at about 5000 m. The glacier is therefore cold in its upper reaches, and temperate or warm based in its middle and lower parts where two-thirds of the glacier is covered with debris except for a thin (ca. 700 m wide) strip of white ice that extends to within about 4 km of the terminus. The terminus itself extends to less than a third of a mile of the vital Karakoram Highway.

Desire by engineers to know more about the potential threat to the highway by the glacier led to a series of studies about 15 years ago of climate, tree rings, ice flux, ablation and velocity. Results indicated that the glacier would advance quite close to the highway into the 1990s and then decline thereafter for 20–30 years. Recent resurvey has shown that the predicted advance has not yet begun and instead the frontal ice cliff has downwasted and the cliff above the main meltwater channel has backwasted (Shroder, 1984). No further hazard is anticipated but monitoring continues.

Early explorers and scientists of the Himalayas were rightly impressed with the plentiful evidence of widespread former glacial advances in the Himalayas but most of their studies were flawed by unwarranted correlations to European and American glacial stages, themselves all too imprecisely defined or temporally controlled. Recent work in the western Himalayas still has resulted in far too few age dates but considerable progress has been made on the stratigraphy and geomorphology (Burbank and Fort, 1985; Derbyshire et al., 1984; Johnson, 1986; Porter, 1970; Rothlisberger and Geyh, 1985). As would be expected in an area as large, complex and dynamic as the Himalayas, however, a divergence of views has emerged concerning both the evidence for, and the extent of former glaciations. The problem of diamicton differentiation in this context is further compounded by the fact that debris flows can remobilize older tills and thus produce a deposit with a misleading apparent glaciogenic character. Thus the various opinions about former glacier extent in the Himalayas can be divided into maximalist and minimalist approaches, with various intermediate interpretations as well.

The maximalist ideas about glaciation were represented first by the now outmoded approach of Dainelli (1922, 1934a, 1934b) who mapped glacier ice extending down the middle Indus to the Peshawar Basin, although he did not travel through this area. More recently Kuhle (1985) has presented evidence of a Pleistocene depression of the equilibrium lines of Himalayan glaciers below much of the Tibetan landscape, with the resulting formation of a massive ice cap of 2–2.4 million $km^2$. Such a large glacier would have had widespread and lengthy outlet glaciers in the lower valleys of the Himalayas. The minimalist ideas of glaciation in the western Himalayas may be exemplified by the recent work of Owen and Derbyshire (in press), who have tended to discount some diamictons as non-glaciogenic and to de-emphasize the extent of ice in the Indus valley downstream from Skardu and the Nanga Parbat area. An intermediate approach to the former extent of glaciers in the western Himalayas is represented by the work of Shroder et al., (in press) that is presented below.

Fig. 8. Grooved and striated boulder in Jalipur tillite at Buner Bridge.

Three to four major separate episodes of glaciation now have been recognized from tillites, stacked tills, and moraine landforms that are separated by proglacial and nonglacial valleyfill deposits (Shroder et al., in press) (Fig. 5). Inasmuch as 15 — 20 glaciations occurred elsewhere in the world in the last 2 million years or so, it is clear that the sediment record has major unconformities.

Scanning electron microscopy showing characteristic glacially affected sand grains, together with striated clasts, iceberg dropstones in lake beds, and other structural evidence have proved the problematic Jalipur tillite to be evidence of an early glacial episode in the western Himalaya (Fig. 8). Jalipur ice extended at least 25 km down the Indus valley past Nanga Parbat and the strongly indurated remnants were preserved fortuitously beneath the upthrown edge of the Raikot fault along which the mountain has been uplifted recently so rapidly. The glaciation probably correlates with the high-level Shanoz glaciated surface in Hunza (Batura Glacier Investigation Group, 1979), but whether ice also came down the upper Indus from areas of the K2 massif and the Skardu region is as yet unresolved.

The middle glacial interval is represented in the Gilgit and Indus valleys by at least two tills that are separated by valleyfill sections and that overlie the Jalipur tillite and its associated non-glacial valley fills. The first glacier of this middle group extended down the Indus valley over 100 km downstream from Nanga Parbat, farther than any other advance, and left a prominent wide valley with massive remnants of a single till partly covered by a thick valley fill (Fig. 9). Upstream from Chilas numerous localities have two thick tills as well as numerous

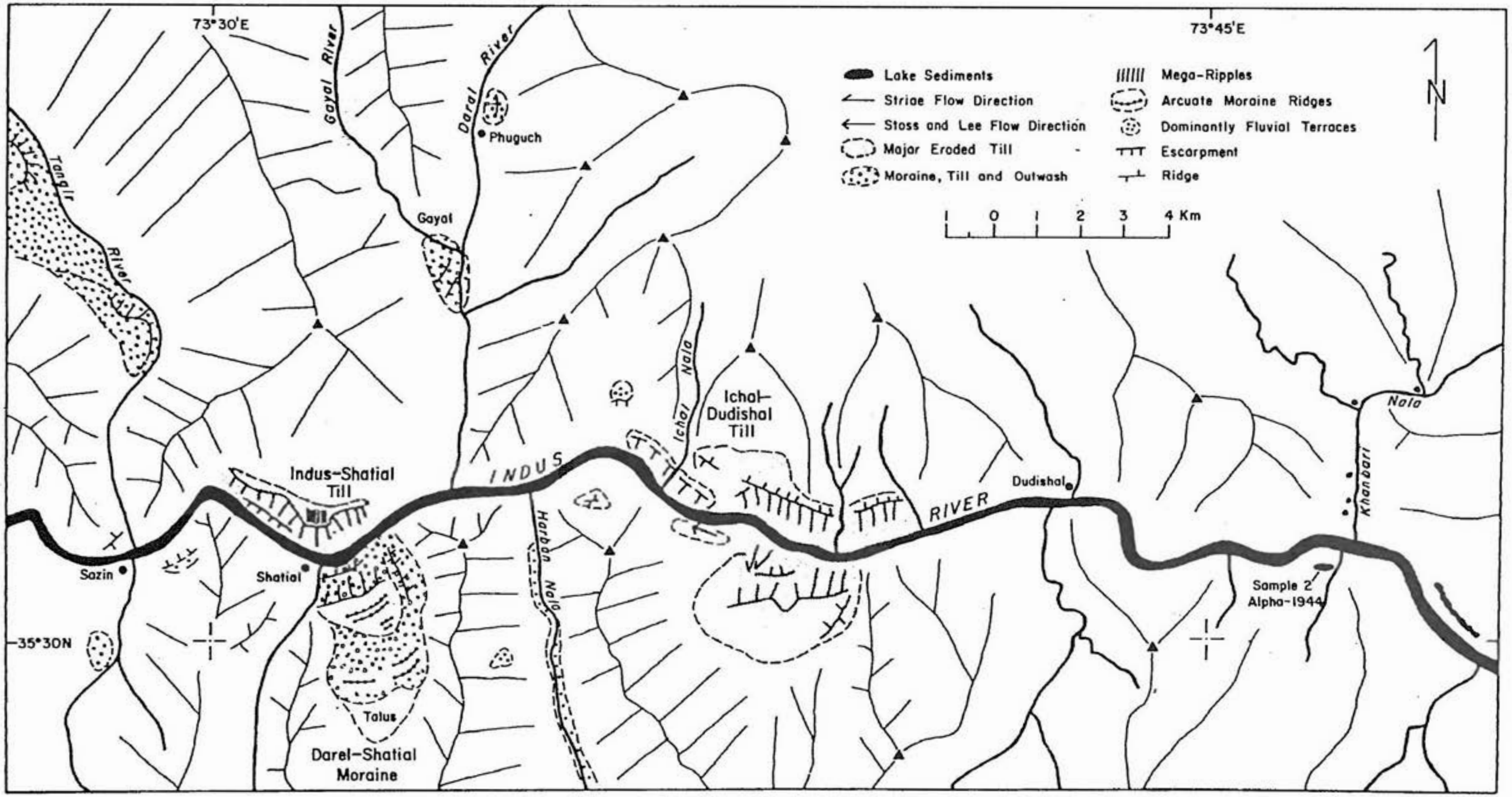


Fig. 9. Sketch map of the Indus valley and terminus of longitudinal ice of the middle glaciation at Shatial. In the late Pleistocene, ice from the Darel valley apparently emplaced the young moraine across on the south side of the Indus and dammed the river to produce the extensive lake sediments upstream.

Fig. 10. Moraines at Gor below Chamuri Peak that were produced by Raikot and Bouldar Glaciers from Nanga Parbat.

lake beds with dropstones. These middle glaciations probably correlate with the Yunz high-level tills in Hunza and the Bunthang till in Skardu which was deposited prior to about 730,000 years ago (Johnson, 1986).

The last major phase of glaciation in the western Himalayas seems to have occurred from at least 140,000 to about 10,000 years ago, and included four or five separate advances. Ice from Hunza deposited the 750 m-thick Dianyor moraine on the south slopes of Rakaposhi Peak (7790 m) and across the valley just east of Gilgit. Elsewhere in the area most glaciers descended from the peaks and expanded only into the adjacent valleys. Over seven of these advances in the Indus valley around Haramosh and Nanga Parbat dammed the river and produced large lakes. The fine-grained sediments deposited in these bodies of water stand in stark contrast to the thick gravels and great boulders scattered throughout the region from the high magnitude floods, landslides and glacier advances. Many other ice dams occurred elsewhere in the western Himalayas at that time as well, and some even produced threatening floods up into the early 20th century (Mason, 1929).

Moraine surfaces at Gor north across the Indus gorge from Nanga Parbat show that the ice dams from the Raikot and Buldar Glaciers were 1—1.8 km thick at different times (Fig. 10). Glaciers from the Patro cirque on Nanga Parbat and from the Darel valley in Kohistan produced thick lake beds behind them as well. The Punjab erratics, large blocks of exotic crystalline rock on the plains of Attock, were cited over a century ago as evidence of lowland glaciation, later


Fig. 11. One of the Punjab erratics near the Haro River Bridge on the Grand Trunk Road.

as products of catastrophic floods (Fig. 11). Two of the hundreds of blocks recently have been traced back to their sources in the Patro and Raikot glaciers, showing their probable emplacement downstream in iceberg rafts as the dams broke. Of the seventeen known major historic floods on the Indus (Table II), all were from breaking of ice and landslip dams, but none rose over 100 feet at Attock. We must seek further, therefore, to understand the great flood magnitudes associated with emplacement of the Punjab erratics. Observation of rhythmic bedding characteristic of repetitive major flooding (Burbank, 1983), and new recognition of large pendant bars, giant current ripples, and other evidence of prehistoric catastrophic flooding in the Indus valley show the nature of an uncommon hazard, but one that has not entirely disappeared from these mountains.

Improved assessment of natural hazards such as these floods, glacier advances and various forms of slope failure will greatly benefit development in Pakistan as the population continues to expand into this already sorely-stressed environment. Highways, settlements and water works in the Himalayas are of much importance, yet the vital Karakoram Highway and the massive Tarbela Dam are much threatened. Continued study of landform-generating processes in the western Himalayas will provide baseline data for retrodictive, predictive, protective and remedial measures in hazard mitigation; a vital necessity according to the recent call from the United States National Research Council for an International Decade of Hazard Reduction.

TABLE 2: HISTORIC FLOODS CAUSED BY GLACIER AND SLOPE-FAILURE DAMS RECORDED IN THE MIDDLE INDUS, GILGIT AND HUNZA RIVER VALLEYS (AFTER MASON, 1929; AND GOUDIE ET AL., 1984). ALTHOUGH MANY OF THESE FLOODS WERE IMPRESSIVE OR CATASTROPHIC AT THE TIME, NONE IS KNOWN TO HAVE PRODUCED MORE THAN LOCAL EROSION AND DEPOSITION EFFECTS. THE "MAJOR" EFFECTS AT ATTOCK NEAR THE PUNJAB ERRATICS INDICATE MAINLY DEEP WATER, LOSS OF LIFE, AND DEPOSITION OF SAND AND GRAVEL ONLY.

| Date | Flood | Effects & Depth at Attock |
|---|---|---|
| 1780? | Shyok Glacier Flood? | ? |
| 1826? | Origin unknown | ? |
| 1835 | Shyok Glacier Flood | Nil |
| 1839 | Shyok Glacier Flood | Nil |
| 1841 | Lichar (Hatu Pir) Rockslide | Major ~ 28 m |
| 1842 | Shyok Glacier Flood | Nil |
| 1844 | Gilgit River Flood (Ishkuman Valley) | Nil |
| 1855 | Middle Indus Flood (Shyok area) | Nil |
| 1858 | Phungurh, Hunza Rockslide | Major ~ 24 m |
| 1865 | Gilgit River Flood (Ishkuman Valley) | Nil |
| 1873? | Hunza River Flood (Batura Glacier?) | Nil |
| 1884 | Shimshal Valley Flood | Nil |
| 1893 | Shimshal Valley Flood | Nil |
| 1903 | Upper Shyok Valley Flood | Nil |
| 1905 | Shimshal Valley Flood | Nil |
| 1906 | Shimshal Valley Flood | Nil |
| 1926 | Upper Shyok Valley Flood | Nil |
| 1927 | Shimshal Valley Flood (Khurdopin Glacier) | Nil |
| 1929 | Upper Shyok Valley Flood | Major 15+ m |
| 1959 | Shimshal Valley Flood | Nil |
| 1974 | Hunza Valley Flood (Balt Bare Glacier) | Nil |

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