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Terraces, uplift and climate in the Karakoram Mountains, Northern Pakistan: Karakoram intermontane basin evolution

by

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with 8 figures, 12 photos and 1 table

Abstract. The Karakoram mountains are one of the most dynamically-active tectonic and geomorphic areas in the world. The valleys hold great thicknesses of Quaternary and recent valley fill sediments comprising glacial, debris flow, fluvial and aeolian sediments. These have been eroded to form terraces. Their development was controlled by tectonic and climatic factors, as they record information about the last few million years of uplift and climatic changes. No simple relationship exists between terrace heights, degree of incision and terrace deformation, and the tectonic and climatic history of the area. Allocyclic processes further complicate the interpretation of terrace formation. Six main types of terraces can be recognised. These comprise:

1. Morainic terraces: The large glacial systems produce large deposits of till, dominantly of supraglacial meltout type. Three extensive glaciations have been recognised during Quaternary time and at least five minor advances during the Holocene. The morainic terraces have been used to reconstruct the extent and number of glaciations.

2. Glaciofluvial terraces: Considerable thicknesses of glaciofluvial deposits infill small palaeovalleys typically of ice-contact facies reflecting deposition by high-gradient streams.

3. Fluvial terraces: These form a minor component and are common near the present river level. They were produced mainly by allocyclic processes related to the highly variable discharges of the glacially-fed rivers.

4. Debris terraces: These widespread features were produced by failure of steep valley sides or by the resedimentation of debris, frequently till. Processes include debris flow, flowslide, rockslide, debris slide, rotational slide, creep, and slumps.

5. Lacustrine terraces: Great thicknesses of silt were deposited rapidly in short-lived lakes. Incision produced terraces after the lakes drained.

6. Fan terraces: These are polygenetic landforms comprising the sediments described above, but dominated by debris flow deposits of resedimented till. These formed early in the deglaciation of the area and represent a major phase of deposition which filled the valley bottoms. Fluvial aggradation and small mass movement processes have modified their surfaces to produce typical fan geometries with varying surface gradients. Fan-head entrenchment and fan-toe truncation indicates that these are relic features.

Tectonically deformed terraces are rare, but active faulting has been recognised near Rakhiot. Glaciotectonic processes, slope processes and dewatering may also deform terraces, and examples are described. Three planation surfaces were recognised and probably represent tectono-climatic cycles, puncuated by uplift and denudation in successive glaciations. A discordant drainage pattern indicates an early Karakoram structural grain modified by differential uplift of the Great Himalaya and the Nanga Parbat-Haramosh massif which produced the concordant drainage of the Indus River.

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Introduction

Impressive landforms are present within the valleys and intermontane basins of the Karakoram Mountains forming a gradational series ranging through scree cones, debris flow fans, moraines, glaciofluvial outwash terraces, alluvial fans, ice-contact fans and floodplains (Photo 1 and Fig. 1). Many of these have been eroded by fluvial incision, and their surfaces modified by debris flow and other slope processes. The term "terrace" has been loosely assigned to a complete spectrum of dissected landforms which comprise the valley fill sediments that have a gradient gentler than the valley side on which they are situated. A combination of these landforms superimposed on each other results in thick sedimentary deposits often exceeding several hundred metres in thickness. Many of the previous workers in the Karakoram Mountains have described these (DAINELLI 1922, 1934a & b, MISCH 1935, PAFFEN et al. 1956 and many others), but have payed little attention to their sedimentology

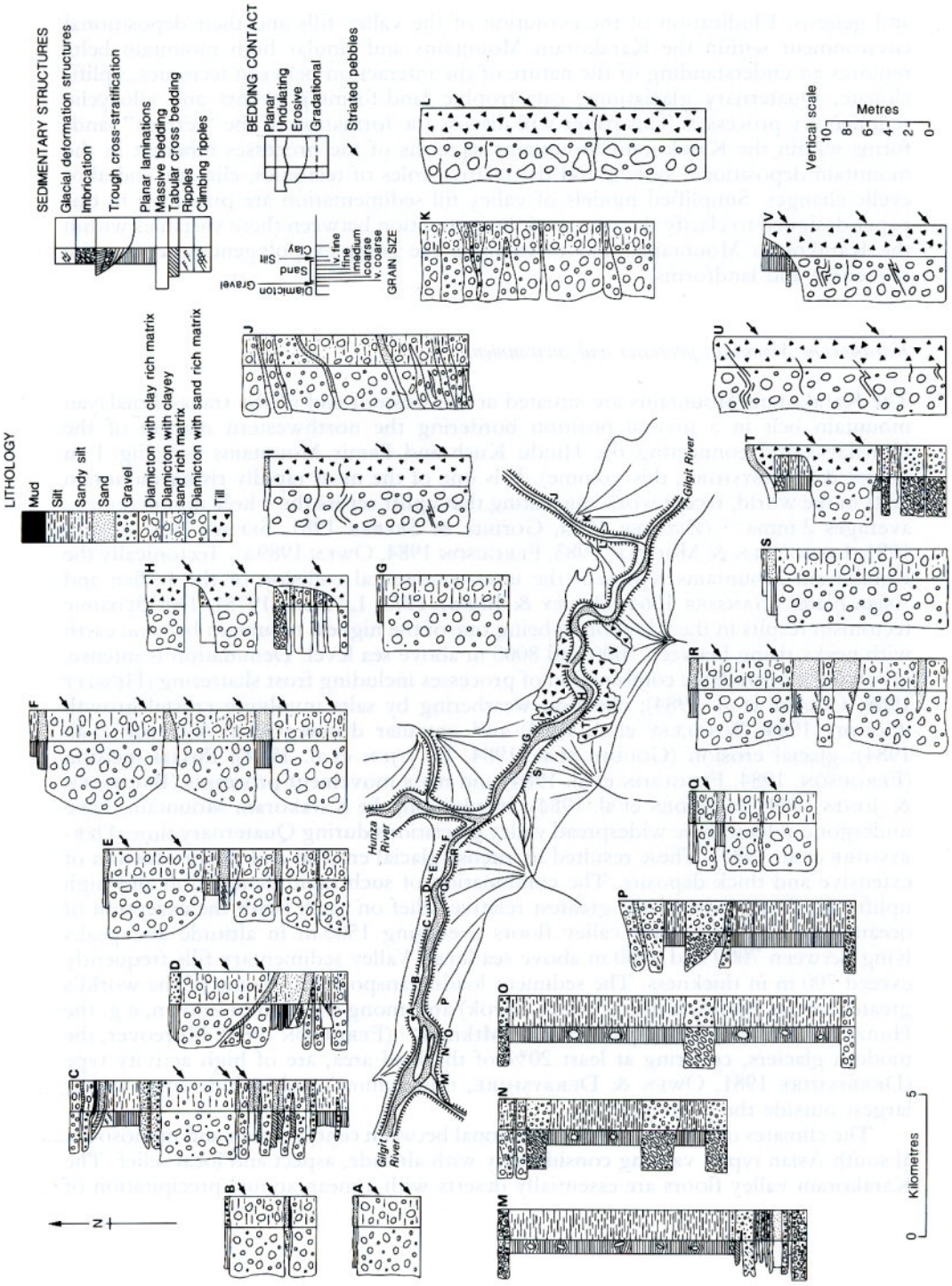
Photo 1. View looking south from Sost down the upper Hunza valley showing the large variety of landforms present within the valleys of the Karakoram Mountains. A fluvial terrace can be seen in the foreground while in the middle distance on the left two fan terraces can be seen, and a higher angled fan terrace is present in the middle of the plate. Impressive screes can be seen surmounting the western valley sides with those towards the middle of the photo having snow infilling the channels of debris flows that have modified the surface of the scree. Large thicknesses of highly dissected tills are also present on the western valley sides. The peaks in the distance exceed 6000 m in height.

and genesis. Eludication of the evolution of the valley fills and their depositional environment within the Karakoram Mountains and similar high mountain belts requires an understanding of the nature of the interaction between tectonics, uplift, climate, Quaternary glaciations, catastrophic land-forming events and allocyclic sedimentary processes. This paper will discuss the formation of the "terrace" landforms within the Karakoram Mountains in terms of the processes inherent in the mountain depositional system and the relative roles of tectonics, climatic and allocyclic changes. Simplified models of valley fill sedimentation are presented in this paper designed to clarify the nature of the interaction between these variables within the Karakoram Mountains, and to examine the complex polygenetic, composite sequences and landforms.

Karakoram Mountain processes and environment

The Karakoram Mountains are situated at the western end of the trans-Himalayan mountain belt in a pivotal position bordering the northwestern margin of the Himalayas and connecting the Hindu Kush and Pamir Mountains (see Fig. 1 in Owen & Derbyshire, this volume). It is one of the most rapidly rising mountain belts in the world, recent work suggesting that uplift across the whole mountain area averages 2 mma^{-1} (Zeitler 1985, Gornitz & Seeber 1981, Seeber & Gornitz 1981, Lyon-Caen & Molnar, 1983, Ferguson 1984, Owen 1989 a). Tectonically the Karakoram Mountains represent the inter-continental collision of the Indian and Asian plates (Gansser 1964, Dewey & Burke 1973, Le Fort 1975). This dynamic tectonism results in the Karakoram being one of the highest mountain belts on earth with peaks rising between 7000 and 8000 m above sea level. Denudation is intense, involving a formidable combination of processes including frost shattering (Hewitt 1968, Goudie et al. 1984); chemical weathering by salts involving crystal growth (Goudie 1984, Whalley et al. 1984) and granular disintegration (Goudie et al. 1984); glacial erosion (Goudie et al. 1984, Li Jijun et al. 1984); fluvial incision (Ferguson, 1984, Ferguson et al. 1984) and mass movement processes (Brunsden & Jones 1984, Brunsden et al. 1984). In addition, the Karakoram Mountains have undergone at least three widespread valley glaciations during Quaternary time (Derbyshire et al. 1984). These resulted in intense glacial erosion and the production of extensive and thick deposits. The combination of such rapid denudation and high uplift rates has produced the greatest relative relief on earth (with the exception of oceanic floor reliefs), with valley floors averaging 1500 m in altitude and peaks lying between 7000 and 8000 m above sea level. Valley sedimentary fills frequently exceed 700 m in thickness. The sediment loads transported by some of the world's greatest rivers (Indus, Gilgit, Hunza, Shyok) are among the highest known, e.g. the Hunza river has a sediment yield of 4800 $Mtkm^2a^{-1}$ (Ferguson 1984). Moreover, the modern glaciers, covering at least 20% of the land area, are of high activity type (Derbyshire 1981, Owen & Derbyshire, this volume) and include some of the largest outside the polar regions.

The climates of the region are transitional between central Asian and monosoonal south Asian types, varying considerably with altitude, aspect and local relief. The Karakoram valley floors are essentially deserts with a mean annual precipitation of


SEDIMENTARY STRUCTURES
Glacial deformation structures
Imbrication
Trough cross-stratification
Planar laminations
Massive bedding
Tabular cross bedding
Ripples
Climbing ripples
BEDDING CONTACT
Planar
Undulating
Erosive
Gradational
Striated pebbles
Vertical scale
Metres
10
8
6
4
2
0
LITHOLOGY
Mud
Silt
Sandy silt
Sand
Gravel
Diamicton with clay rich matrix
Diamicton with clayey sand rich matrix
Diamicton with sand rich matrix
Till
Gravel
Diamicton
Silt
Sand
Clay
v. fine
fine
medium
coarse
v. coarse
GRAIN SIZE
Gilgit River
Hunza River
Gilgit River
N
0
Kilometres
5

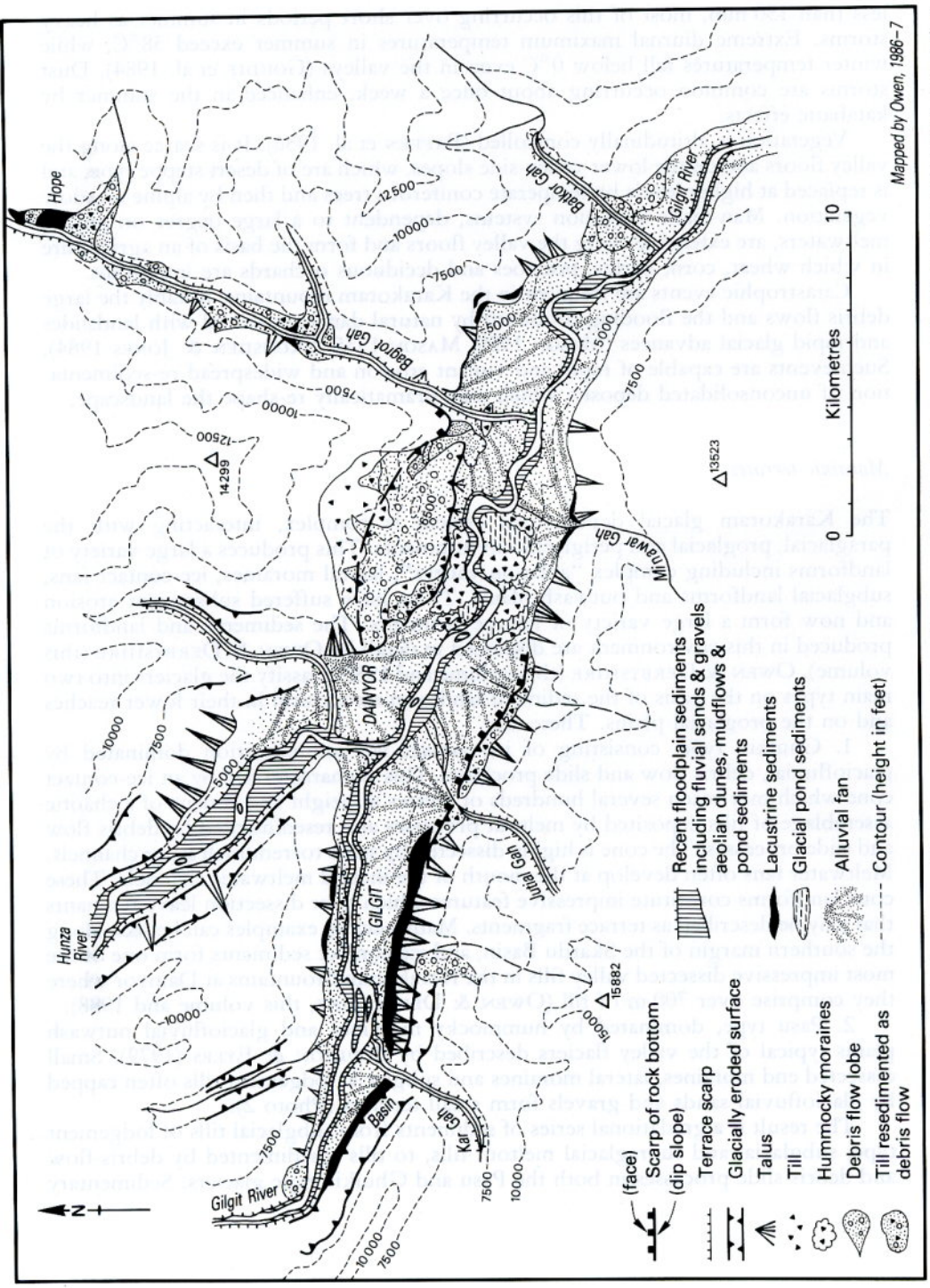


Fig. 1. Geomorphological and sedimentological map, and graphic sedimentary logs for the terraces and valley fills in the Gilgit area (after Derbyshire & Owen 1989).

less than 150 mm, most of this occurring over short periods in summer as heavy storms. Extreme diurnal maximum temperatures in summer exceed 38 °C, while winter temperatures fall below 0 °C even in the valleys (GOUDIE et al. 1984). Dust storms are common occurring about once a week, enhanced in the summer by katabatic effects.

Vegetation is altitudinally controlled (PAFFEN et al. 1956): It is scarce along the valley floors and on the lower valley-side slopes, which are of desert steppe type, and is replaced at higher levels by temperate coniferous trees and then by alpine meadow vegetation. Man-made irrigation systems, dependent to a large degree on glacier meltwaters, are extensive along the valley floors and form the basis of an agriculture in which wheat, corn, barley, potatoes and deciduous orchards are important.

Catastrophic events are frequent in the Karakoram mountains, notably the large debris flows and the flooding produced by natural dams associated with landslides and rapid glacial advances (MASON 1929, MASON 1935, BRUNSDEN & JONES 1984). Such events are capable of rapid and violent erosion and widespread re-sedimentation of unconsolidated deposits which may dramatically re-shape the landscape.

Morainic terraces

The Karakoram glacial depositional system is complex, interacting with the paraglacial, proglacial and periglacial environments. This produces a large variety of landforms including complex "ablation valleys", lateral moraines, ice-contact fans, subglacial landforms and outwash plains. These have suffered subsequent erosion and now form a large variety of terrace remnants. The sediments and landforms produced in this environment are discussed in detail by OWEN & DERBYSHIRE (this volume). OWEN & DERBYSHIRE (this volume and 1988) classify the glaciers into two main types on the basis of the sediment landform association in their lower reaches and on the proglacial plains. These are:

1. Ghulkin type, consisting of ice-contact fan sedimentation dominated by glaciofluvial, debris flow and slide processes. This is characterised by an ice-contact cone which may reach several hundreds of metres in height and consist of a chaotic assemblage of tills deposited by meltout processes and resedimented by debris flow and slide processes. The cone is highly dissected by steep torrent meltwater channels. Meltwater fans often develop at the mouth of the incised meltwater channels. These cone landforms constitute impressive features which after dissection leave remnants that may be described as terrace fragments. Many ancient examples can be seen along the southern margin of the Skardu Basin, and ice-contact sediments form one of the most impressive dissected valley fills in the Karakoram Mountains at Dainyor where they comprise over 700 m of fill (OWEN & DERBYSHIRE, this volume and 1988).

2. Pasu type, dominated by hummocky moraines and glaciofluvial outwash plains typical of the valley flaciers described by BOULTON & EYLES (1979). Small dissected end moraines, lateral moraines and subglacial lodgement tills often capped by glaciofluvial sands and gravels form small terraces (Photo 2).

The result is a gradational series of sediments from subglacial tills of lodgement type, subglacial and supraglacial meltout tills, to tills resedimented by debris-flow and debris slide processes in both the Pasu and Ghulkin type glaciers. Sedimentary

Photo 2. A terrace section near the Pasu Glacier formed of lodgement till which has been deposited against a glacially striated rock buttress (*roche moutonnée*). The imbricated cobbly gravels represent late fluvial/glaciofluvial sedimentation. The height of the terrace is approximately 3 m.

characteristics are broadly similar, all being very poorly to poorly sorted, positively skewed, depleted of fines (<10% clay), and having angular clasts. These properties result from a glacial system dominated by supraglacial deposits derived from rockfall and avalanche.

Three main glaciations during Pleistocene time and at least five minor advances can be recognised in the Karakoram and Nanga Parbat areas (DERBYSHIRE et al. 1984, OWEN 1988a). These helped to produce the impressive valley fills and tills of glacial origin. Using these deposits DERBYSHIRE et al. (1984) and OWEN (1988a) were also able to reconstruct the extents of the glaciations in this area (Table 1 and Fig. 2) and were able to show that all the glaciations were of valley glacier type.

Glaciofluvial and fluvial terraces

Glaciofluvial terraces encompass dissected ice-contact fans and outwash plains. The sediments consist of poorly to very poorly sorted sands, gravels and conglomerates. Terrace formation on the outwash plains may be related to the large fluctuations in

Table 1. Quaternary Glacial Stages in the Upper Hunza River Valley (after DERBYSHIRE et al. 1984).

Stage Name	Tentative Dates (yr. B.P)
Shanoz	
Yunz	139,000 ± 12,500 TL
Borit Jheel	65,000 ± 3,300 TL
	50,000 ± 2,500 TL
Ghulkin I	47,000 ± 2,350 TL
Ghulkin II	8,300 ^{14}C
Batura	
Pasu I	830 ± 80 ^{14}C
	325 ± 60 ^{14}C
Pasu II	"Historical"

Photo 3. Typical sheet of imbricated floodplain cobbles near Gilgit (note the river flows right to left).

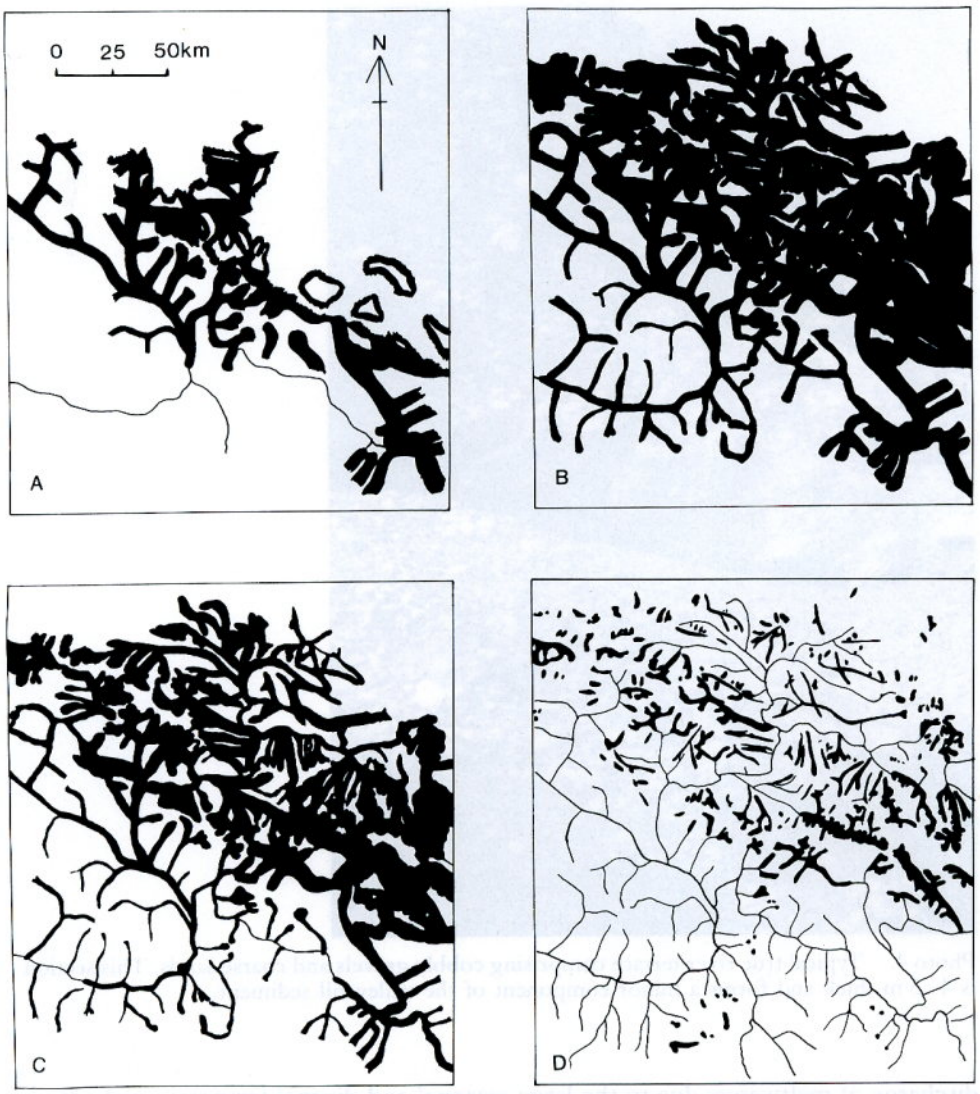


Fig. 2. Sequence and extents of the Quaternary glaciations in the Karakoram and the present day ice extent. A. Shanoz Glaciation; B. Yunz Glaciation; C. Borit Jheel Glaciation; and D. present.

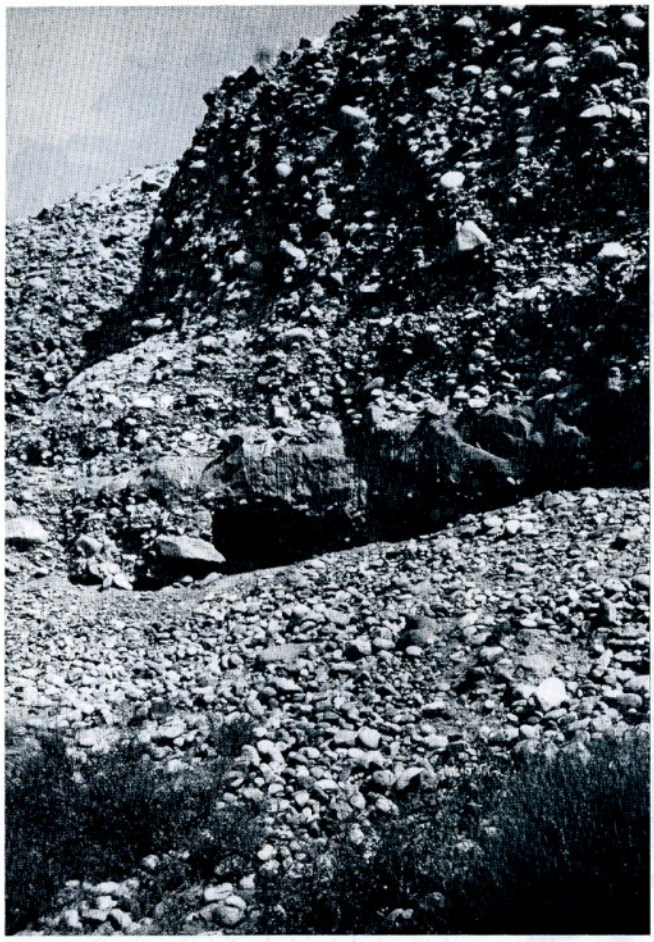


Photo 4. Typical true river terrace comprising cobbly gravels and coarse sands. This section is 4–5 m thick and forms a minor component of the valley fill sediment.

discharge of meltwaters due to the large seasonal and diurnal temperature changes. In the Indus catchment for example sediment output and river discharge may have increased from 500 to 1000 and 20 to 50 times respectively during the daytime in the summer because of the ablation of glacial ice (FERGUSON 1984 and FERGUSON et al. 1984): Similarly these changes influence river terrace formation and may lead to the development of ephemeral river terraces several metres in height along the main valleys many tens of kilometres away from the glaciers (Photo 1: OWEN 1988a, b). However, these river terrace sediments show a better degree of sorting than the glaciofluvial sediments and are characterised by sheets of sands and imbricated

cobbles (Photo 3). Changes in the position of meander belts in some of the basins e.g. Skardu help produce impressive terraces and/or chute cut-offs adding to the variety terrace types.

Glaciofluvial and fluvial terraces are produced both by allocyclic processes and climatic changes throughout Quaternary times. However though the terraces are widespread they only form a minor component of the valley fill sediments and landforms (Photo 4). They are often very subsidiary to terraces formed by other processes such as morainic terraces and debris terraces (Photo 2).

Debris terraces

Mass movement is a major process in the Karakoram Mountains. It results in varied diamictons many of which are resedimented deposits of till or previous mass movement deposits. Mass movement deposits range in scale from isolated small failures to extensive areas of complex movement. Nine main categories of mass movement have been recognised: rockfall, rockslides and debris slides, debris flows, mudslides, flowslides, rotional slips, slumps, creep and rock glaciers (Fig. 3: OWEN 1988a, 1989b). Large scale accumulation followed by fluvial incision and dissection produces the terraces; the surfaces of terraces of other origin may be modified by smaller mass movement processes.

Particularly important in the formation of terrace landforms in the Karakoram are large debris flows and flowslides. Photo 5 shows an example of a large debris deposit which was probably the result of large scaleresedimentation of till from an adjacent side valley by a combination of flowslide and debris flow processes (DER-

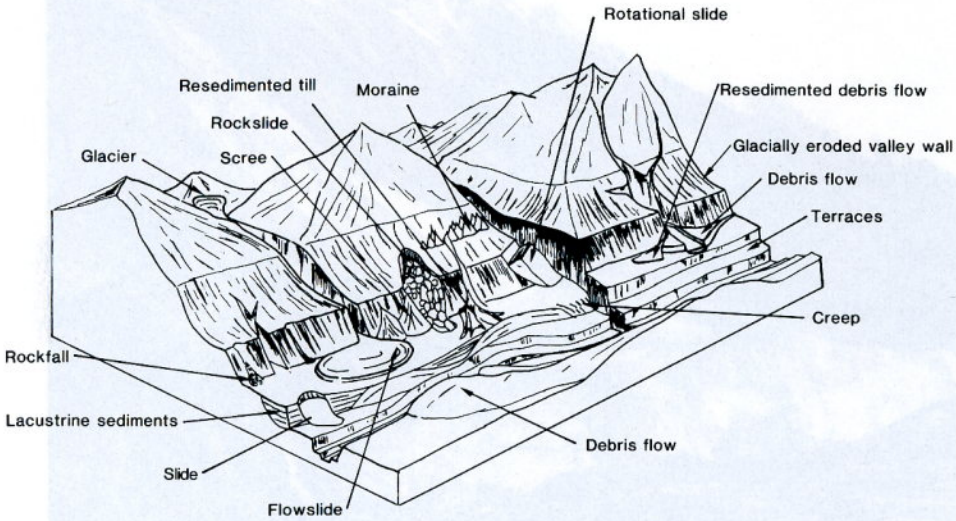


Fig. 3. Diagram summarising the variety of mass movement processes and landforms within the Karakoram valleys which contribute to the formation of the terraces and valley fills.

Photo 5. The Batkor debris flow terrace. Note the houses in the bottom foreground for scale.

Photo 6. Large debris flows at the southern end of the Bagrot valley. These blocked the valley and produced large lakes in which silts were deposited and onlap the debris flow deposits. One set of lacustrine silts can be seen in the centre foreground.

BYSHIRE & OWEN 1988, OWEN 1988a, 1989b). The 150 m thick bouldery diamicton forms an inlier within a fan, making an impressive terrace incised by the Batkor river.

Large-scale failure in the gorge sections of trunk valleys frequently results in the formation of steep (15–30°) cone-shaped fans (Photo 6). These may block the valley and thereby produce a lake. Upon breaching of the debris and draining of the lake the lacustrine silts are incised and the debris cone is incised at its toe to generate impressive terraces. Examples of these can be seen at Serat in the Hunza valley and at several points along the Bagrot valley (Photo 6: OWEN 1988a, 1989b).

Lacustrine terraces

Several different types of lakes are present and have existed during the past in the intermontane basins and valleys of the Karakoram Mountains. Formative processes include:

1. Damming of a tributary valley by glacial ice. Present day examples can be seen in the Shaksgam valley (DESIO 1980 and BURGISSER et al. 1982).
2. Lakes formed behind moraines or within moraine fields. Instances occur in association with many of the contemporary Karakoram glaciers.

Photo 7. A debris flood dammed lake on the Khunjerab river which formed in July, 1987. The bulldozers in the distance are constructing a channel to help release the water from this lake which has engulfed the highway.

3. Lakes formed within glacially eroded bedrock depressions. A good example is Borit Jheel in the upper Hunza valley.

4. Lakes resulting from blockage by debris flows, rockfalls and landslides. Many examples of these exist and range in size from several hundred metres (e.g. Khunjerab River, Summer 1987: Photo 7) to many tens of kilometres long (e.g. Yamzhou Yumco in Tibet, ZHANG MINGTAO et al. 1982).

The sediments deposited within all these lakes consist of fine grained clastic sediments, dominantly of silt size grade, containing quartz, feldspars, micas, chlorites and illite, but few other clay minerals. The sediments are planar bedded dm to metre thickness, planar laminated occasionally interbedded with cm beds of rippled sands. Upon infilling of the lakes or destruction of the dam rivers or streams may incise the deposits leaving them as terraces.

Many examples of ancient lake deposits falling into the above categories have been noted in the Karakoram Mountains. Of particular importance are terraces composed of glaciolacustrine silts. Examples can be seen south of Gilgit town stretching for 10 km (Photo and Fig. 1). These form two main terraces representing a glacial lake that formed during the Borit Jheel Glaciation when ice advanced down the Hunza valley and blocked the Gilgit valley. This allowed water to fill up behind the glacier and form a lake in which the silts accumulated (Fig. 4). The lake emptied and refilled with deposition of a second set of silts. These were later incised when

Photo 8. View of the southern slopes of the Gilgit valley near the town of Gilgit. The pale coloured terraces in the middle of the plate are the Basin lacustrine terraces. Note also the glacially eroded valley side with an absence of till.

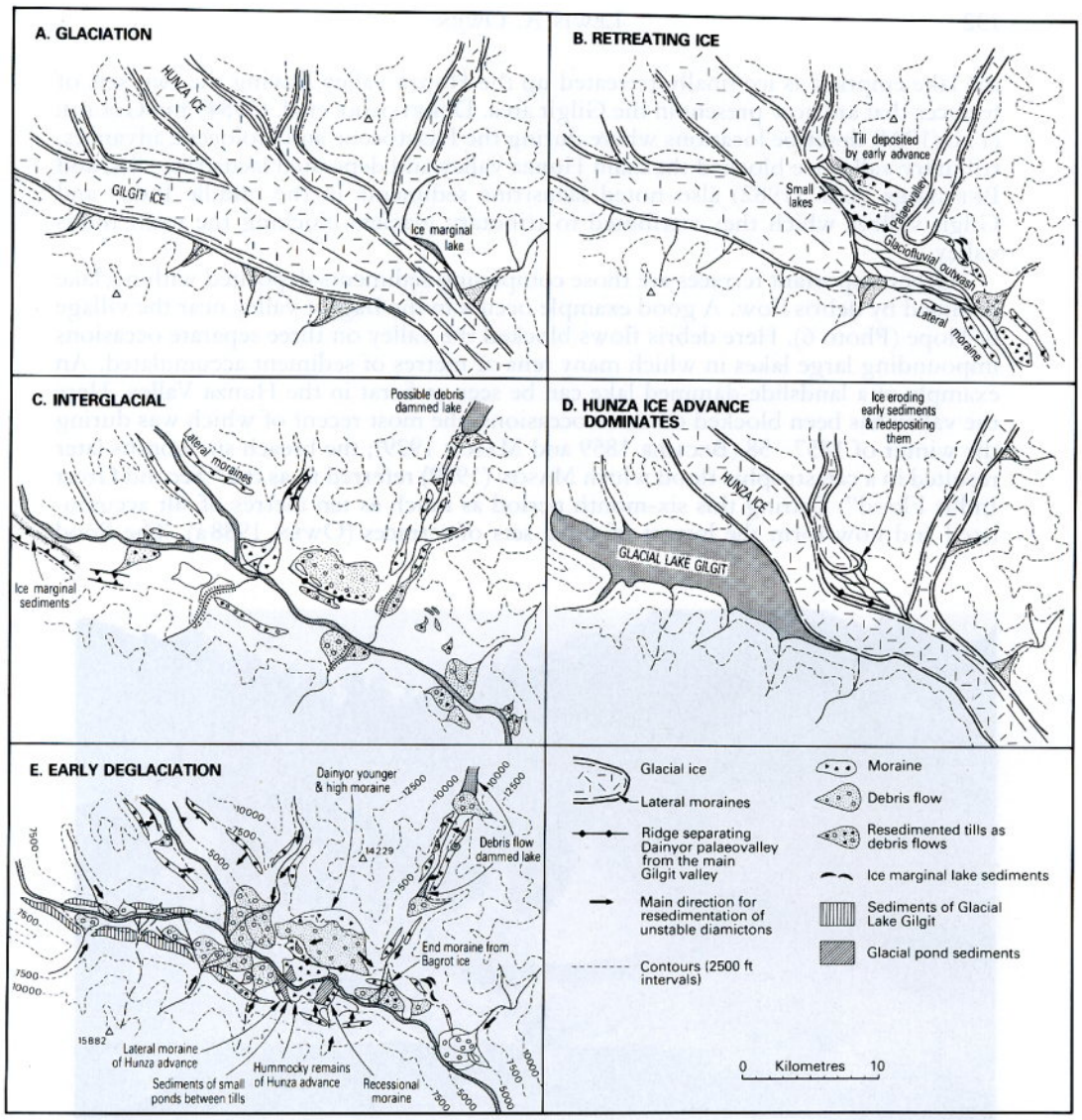


Fig. 4. Sequential development of the Gilgit area and its terraces and fans. A. Yunz Glaciation producing large valley glaciers; B. As ice retreated glaciofluvial sediments were deposited and many of the tills along the valley sides were resedimented by debris flow processes. Hummocky moraines and lodgement tills were deposited and left along the valley floors; C. During the interglacial the sediments were incised by the rivers helping to produce terrace geometries. D. Further Glaciation (Borit Jheel) produced a glacier only in the Hunza valley, destroying much of the evidence of the previous glaciation. The glacier also blocked the Gilgit valley allowing a large lake and associated sediment to form; E. As ice retreated tills were again resedimented from the steep valley sides to form large sediment fans; glaciofluvial channels incised the fills and deposited new sediments; the lacustrine sediments of Glacial lake Gilgit were dissected by the Gilgit river and small tributary streams to form impressive terraces.

the lake emptied as ice finally retreated up the Hunza valley leaving the two sets of terraces that are now present in the Gilgit area. DERBYSHIRE et al. (1984) and GOUDIE et al. (1984) describe locations where during the Pleistocene and Holocene advances, tributary valley ice blocked the main Hunza valley and deposited lacustrine silts, and BURGISSER et al. (1982) also noted lacustrine sediments in the middle Indus and Gilgit valleys which they attributed to tributary glaciers blocking the main Indus valley.

Other important terraces are those comprising sediments deposited within a lake dammed by debris flow. A good example occurs in the Bagrot valley near the village of Hope (Photo 6). Here debris flows blocked the valley on three separate occasions impounding large lakes in which many tens of metres of sediment accumulated. An example of a landslide-dammed lake can be seen at Serat in the Hunza Valley. Here the valley has been blocked on three occasions, the most recent of which was during the winter of 1857–58 (BECHER 1859 and MASON 1929); the breach six months later resulted in a catastrophic flood which MASON (1929) referred to as the "Second Great Indus Flood". During this six-month period as much as ten metres of silt accumulated and now form the lowest of three sets of terraces (OWEN 1988a). The flood

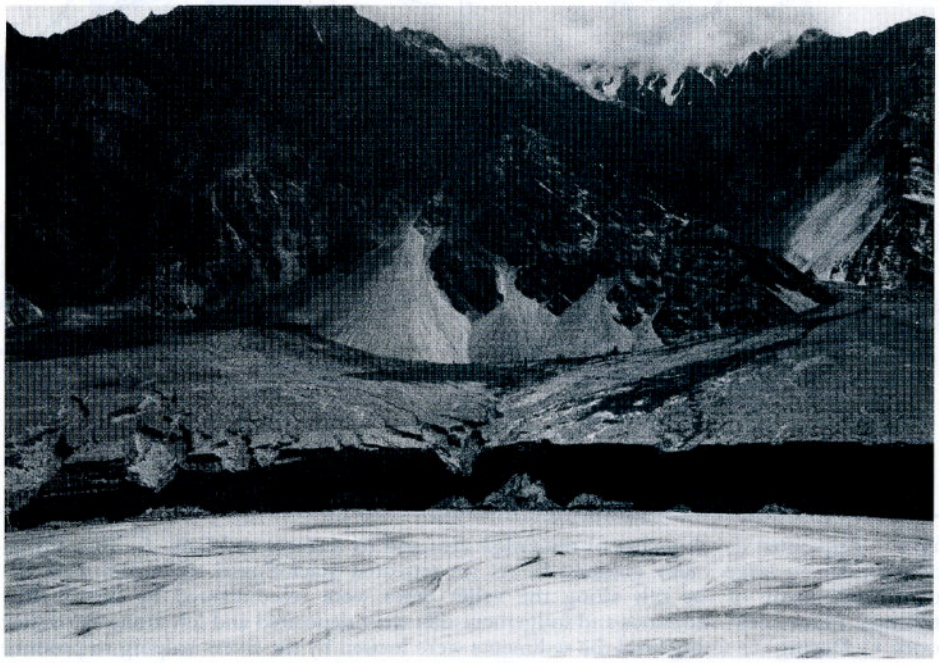


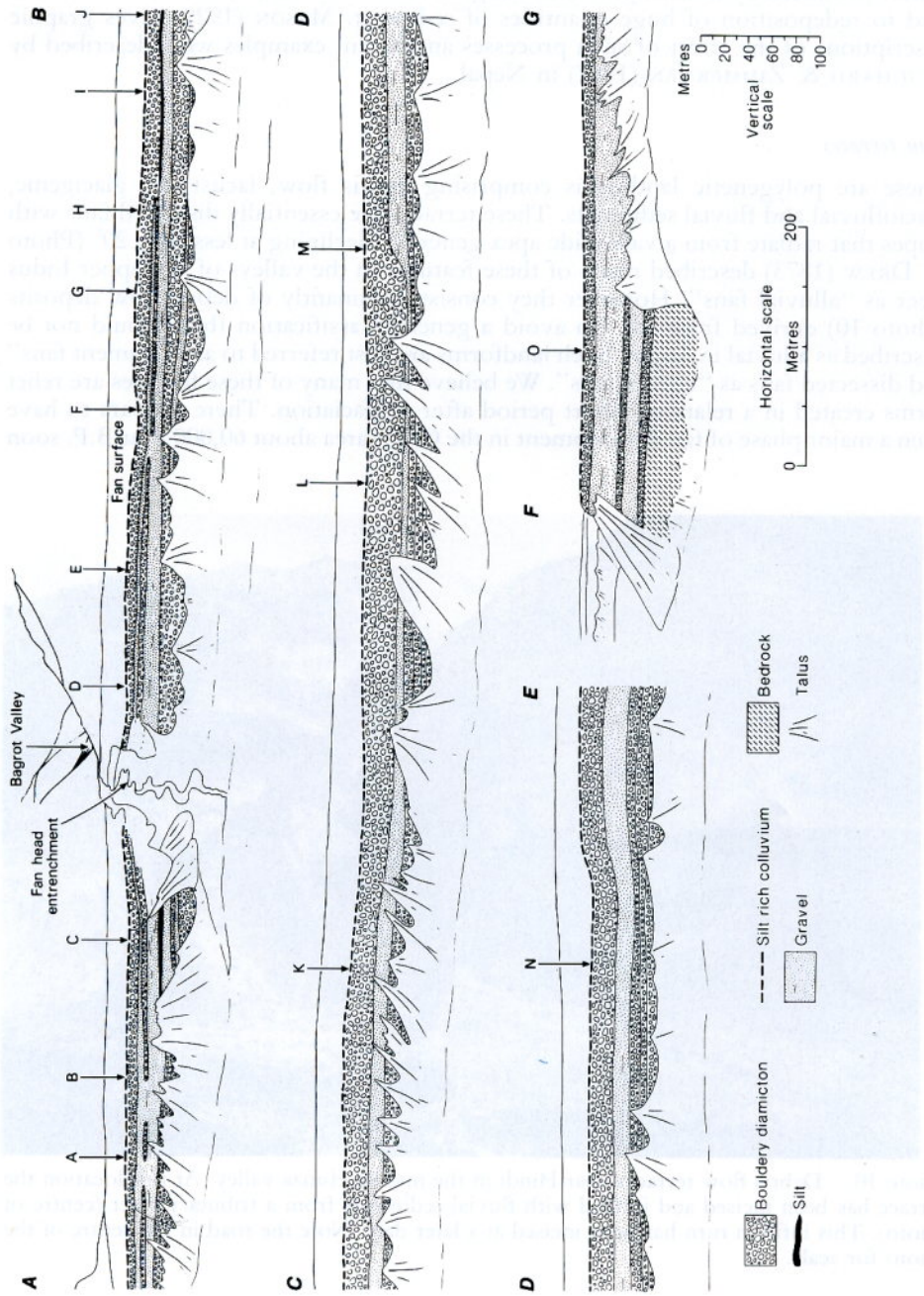
Photo 9. Sediment fans near Ghulkin village in the Hunza valley. Note the fan toe truncation and the initiation of fan head entrenchment by small ephemeral streams. The valley slopes are surmounted by scree fans which are between 600 and 700 m high and have angles between 20 and 30°. The Hunza river forms an impressive braid system along this part of the Hunza valley (part of this is seen in the foreground of the photo).

waters produced by catastrophic breaching of a dam may destroy earlier terraces and lead to redeposition of huge quantities of sediment. MASON (1929) gives graphic descriptions of the effect of such processes and recent examples were described by VUICHARD & ZIMMERMAN (1987) in Nepal.

Fan terraces

These are polygenetic landforms comprising debris flow, lacustrine, glacigenic, glaciofluvial and fluvial sediments. These terraces are essentially dissected fans with slopes that radiate from a valleyside apex generally declining at less than 20° (Photo 9). DREW (1873) described many of these features in the valleys of the upper Indus river as "alluvial fans". However they consist dominantly of debris flow deposits (Photo 10) derived from till. To avoid a genetic classification they should not be described as alluvial in origin. Such landforms are best referred to as "sediment fans" and dissected fans as "terrace fans". We believe that many of these features are relict forms created in a relatively short period after deglaciation. There appears to have been a major phase of fan development in the Gilgit area about 60,000 year B.P. soon

Photo 10. Debris flow terraces near Hindi in the middle Hunza valley. At this location the terrace has been incised and infilled with fluvial sediments from a tributary river (centre of photo). This infill in turn has been incised at a later date. Note the road in the centre of the photo for scale.


A
B
C
D
E
F
G
Bagrot Valley
Fan head entrenchment
Fan surface
Bouldery diamicton
Silt
Silt rich colluvium
Gravel
Bedrock
Talus
Horizontal scale
Metres
0
200
Vertical scale
Metres
0
20
40
60
80
100

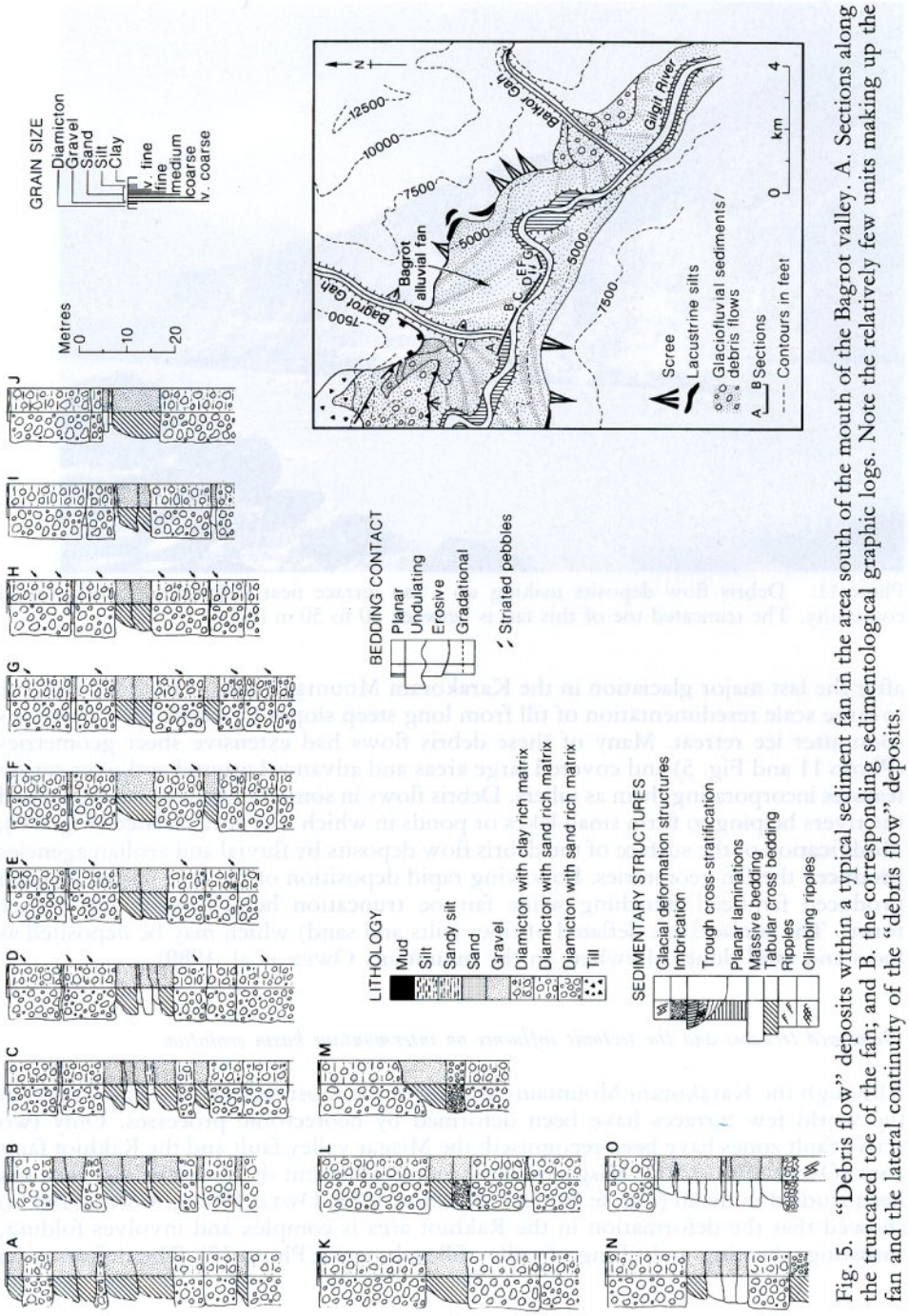


Fig. 5. "Debris flow" deposits within a typical sediment fan in the area south of the mouth of the Bagrot valley. A. Sections along the truncated toe of the fan; and B. the corresponding sedimentological graphic logs. Note the relatively few units making up the fan and the lateral continuity of the "debris flow" deposits.

Photo 11. Debris flow deposits making up a fan terrace near Gilgit. Note their lateral continuity. The truncated toe of this fan is between 40 to 50 m high.

after the last major glaciation in the Karakoram Mountains (Fig. 4 E). This was due to large scale resedimentation of till from long steep slopes by debris flow processes soon after ice retreat. Many of these debris flows had extensive sheet geometries (Photo 11 and Fig. 5) and covered large areas and advanced around and over earlier features incorporating them as inliers. Debris flows in some valleys may have dammed the rivers helping to form small lakes or ponds in which silts accumulated (Fig. 4 C). Modification of the surface of the debris flow deposits by fluvial and aeolian agencies produced the fan geometries. Following rapid deposition of the fans fluvial incision produced fan-head trenching while fan-toe truncation helped create the terrace forms. The surfaces are deflated of fines (silts and sand) which may be deposited as loess and sand dunes elsewhere in the mountains OWEN et al. 1989).

Deformed terraces and the tectonic influence on intermontane basin evolution

Although the Karakoram Mountains are one of the most tectonically active areas in the world few terraces have been deformed by neotectonic processes. Only two active fault zones have been recognised: the Misgar valley fault and the Rakhiot fault zone (OWEN 1989 a). The Misgar valley is inaccessible, but the Rakhiot fault zone has been studied in detail (Fig. 6: BUTLER & PRIOR 1988, OWEN 1989 a). OWEN (1989 a) showed that the deformation in the Rakhiot area is complex and involves folding, thrusting, shearing and tilting of valley fill sediments (Photo 12). The deformation

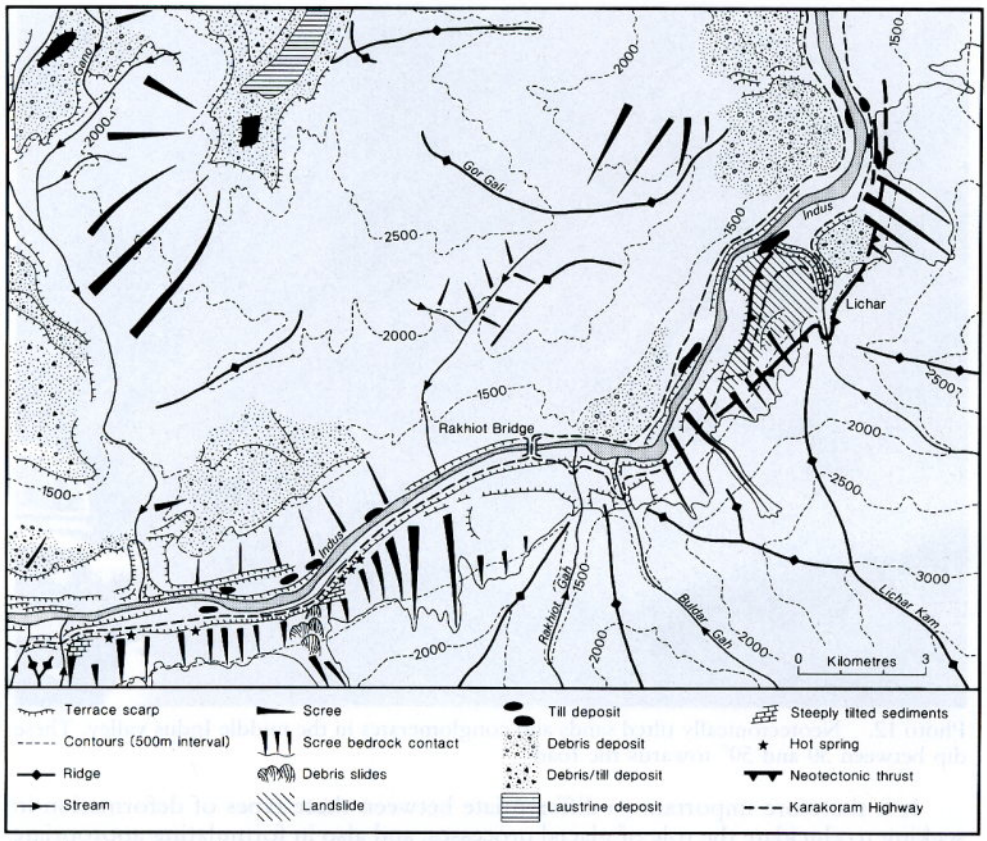


Fig. 6. Neotectonic and geomorphic map of part of the middle Indus river.

is related to reactivation of the Main Mantle Thrust, a fault zone that separates the high grade metamorphic rocks of the Indian Plate from those of the Kohistan Island Arc complex (Butler & Prior 1988). However, many of the terraces which comprise tills and glaciofluvial sands and gravels have deformation structures which verged down valley discordant to the neotectonic structural grain and can not be explained by any neotectonic model. They are the result of deformation produced by the movement of a large glacier down the Indus Valley. Owen (1989a) showed that it was important to distinguish between neotectonic deformation and deformation produced by glacial processes. Similar glacially deformed terraces can be recognised throughout the Karakoram Mountains. Impressive examples can be seen in the Skardu basin including in particular the terraces on which the town of Skardu is built. These relate to ice advancing northward from the Deosai Plateau into the Skardu Basin, overriding and pushing terraces composed of floodplain sediments to form complex structures (Owen 1988b).

Photo 12. Neotectonically tilted sands and conglomerates in the middle Indus valley. These dip between 30 and 50° towards the road.

It is therefore important to differentiate between these types of deformation in seeking to elucidate the role of glacial processes, and also in formulating appropriate glacial histories and neotectonic models for the Karakoram Mountains.

Additional information regarding the neotectonic and the Quaternary history of the Karakoram intermontane basins can be gained from an examination of satellite imagery. OWEN (1989 a) showed that two systematic sets of lineaments (comprising valley lineations, bedrock lineations and very long linear glaciers) can be recognised throughout the region, comprising a NNW-SSE set and a SW-NE set. Also particularly apparent is the deflection of the Indus River around the Nanga Parbat massif and its east-west trend parallel to the Great Himalaya for several hundred miles. OWEN (1989 a) suggested that these lineations plus the discordant drainage were controlled by an old structure which developed early in the history of the Karakoram Mountains and that this indicates that the Indus River course is younger than the uplift of the Great Himalaya. This implies/suggests that the differential uplift of the Nanga Parbat massif and the Great Himalaya modified the Indus drainage which now flows parallel to the trend of the Great Himalaya and its drainage is deflected around the Nanga Parbat Massif (OWEN 1989 a).

Throughout the Karakoram Mountains a series of planation surfaces or rounded ice-smoothed slopes can be recognised. The highest surface is above 5200 m and

probably represents a palaeo-relief. This is younger than the age of the granodiorites (8.6 Ma B.P.) near Karimabad (DERBYSHIRE et al. 1984) into which the surface has been eroded. A lower surface at a height of 4100–4200 m was recognised by PAFFEN et al. (1956) in the middle Hunza valley and was considered to represent a "pre-Pleistocene relief". DERBYSHIRE et al. (1984) recognised a similar surface in the upper Hunza valley at a similar height but renamed it the "Patundas surface" and assigned its formation to the Shanoz Glaciation. Two lower surfaces can be recognised at heights of approximately 3000 m and 2700 m and were probably formed by the Yunz and Borit Jheel Glaciations respectively (DERBYSHIRE et al. 1984 and OWEN 1989 a). Fig. 7 summarises the surfaces that have been recognised throughout the Karakoram Mountains and Tibet. Although these surfaces have clearly been eroded by ice and have scattered erratics and tills on them the large altitudinal range in heights and the continuity of the surfaces suggests that tectonic uplift may have been important in their formation. Chinese workers recognise similar surfaces in Tibet (LI JIJUN et al. 1979, SUN & WU 1987) and attribute them to a combination of changes in the Quaternary climate and punctuated tectonic uplift which SUN & WU (1987) call tectono-climatic events. OWEN (1989 a) indicated that a broad correlation may be made between Tibet and the Karakoram on the basis of these planation surfaces (Fig. 7). These large surfaces indicate that long wave, long term regional warping is important in the formation of the Karakoram Mountains and that discrete movements along fault zones has only a localised effect. This is a similar conclusion to that reached by IWATA (1987) in his work in the Nepalese Himalayas.

Conclusion: A model for Karakoram intermontane basin evolution and terrace formation

The types of terrace and their modes of formation are complex. The sediments and facies associations that comprise the terrace successions are controlled by allocyclic, glacial, fluvial, slope, lacustrine and aeolian processes. The glacial system dominates, though high magnitude-low frequency and catastrophic events also produce major landform modifications by erosion and resedimentation. They may, for example, initiate sites for renewed sedimentation as when a landslide dams the river and impounds a lake in which lacustrine materials accumulate. Intense incision stimulated by rapid tectonic uplift results in highly dissected landforms which are loosely referred to as terraces. These terrace remnants may be recognised throughout the valley floors and along the valley sides to altitudes several thousand metres above the present river level. They comprise glacial, glaciofluvial, debris flow, fluvial, lacustrine and aeolian sediments. The resultant landforms are composite and polygenetic.

Four main factors control the evolution of the Karakoram basins, their sediment fills and terraces. They are:

i) tectonics;
ii) climatic changes;
iii) allocyclic processes; and
iv) catastrophic or high magnitude-low frequency events.

The flow diagram in Fig. 8 shows the relationship between tectonics, catastrophic or high magnitude-low frequency events and climatic changes responsible for the present geometries of the basins and their terrace successions.

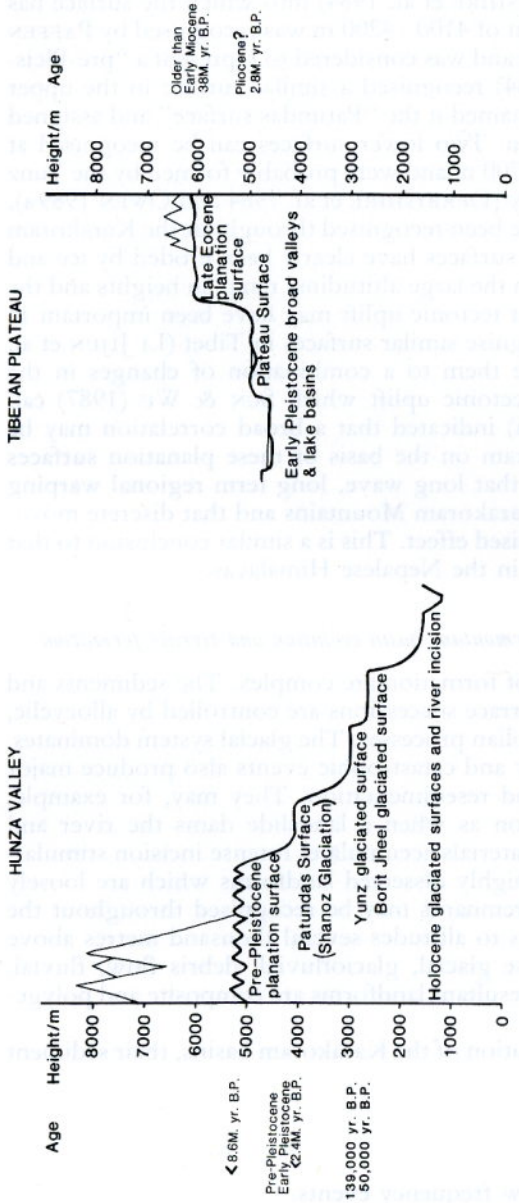


Fig. 7. Diagram summarising the planation and glacial surfaces in the Hunza area and Tibetan Plateau (after OWEN 1989a).

Textonics were primarily responsible for the creation of the positive relief of the Karakoram Mountains due to the collision of the Indian and Asian continental plates and the incorporation of the Kohistan Island Arc. Uplift of the region probably occurred during Eocene time creating an upper planation surface at an altitude of about 5200 m. A similar surface was created in Tibet at a height of about 6000 m but it is time transgressive.

With progressive uplift of the Karakoram region a primeval drainage system developed draining the mountains in a SSE and WSW direction. This may have been superimposed on an early joint system related to the gross tectonic structure of the area. With increasing uplift the rivers became incised and and the Karakoram area reached sufficient altitude for the development of firn and consequently the formation of glaciers. Glacial processes further increased denudation producing a pre-Pleistocene planation surface (<8.6 Ma B.P.) in the Hunza valley and Baltistan, which is now at a height of between 4100–4200 m. This possibly provides evidence for the first glaciation of the region.

Evidence for Quaternary and recent faulting is sparse and only two areas of recent displacement (Misgar valley and the Rakhiot area) have been recognised. This suggests that regional warping was the main mode of uplift. A series of planation and glaciated surfaces throughout the region implies that the uplift was sporadic. The relative importance of tectonics and climate (i.e. glaciation) in the formation of these surfaces is difficult to determine. The dynamic tectonism helped intensify the role of denudation conforming to the "Principle of Antagonism" (SCHEIDEGGER 1979) There is no apparent structural control on the basins and embayments and their formation was probably a consequence of localised intense glacial and fluvial erosion.

Differential uplift of the Great Himalaya and the Nanga Parbat-Haramosh massif along the southern edge of the study region modified the drainage systems, creating the east-west drainage of the Indus and its constriction through an area of differential uplift, the Nanga Parbat-Haramosh massif. Progressive uplift restricted the southern Asian monsoon from penetrating into the Karakoram Mountains. This resulted in an increasing aridity within the Karakoram Mountains. It would also have had profound effects on global circulation and climatic changes through most of High Asia. However, from this preliminary study it has not been possible to assess the influence of this change of climate on the glaciations within the Karakoram Mountains.

Climatic changes throughout the Quaternary resulted in three major glaciations and at least five minor advances. During the three major glaciations (in the Pleistocene) extensive glaciers flowed down the valleys of the Karakoram. These eroded the valleys, deepening and widening them. At the confluence of the two main arteries large basins were produced by intense erosion e.g. Skardu and Gilgit Basins. Where tributaries entered the trunk valleys, the advancing glaciers may have crossed the main valley and consequently widened it by erosion helping to produce an embayment.

The glacial system produced thick deposits of till, both on the valley sides and on the valley floors. Upon deglaciation much of the valley side till was resedimented by debris flow processes en masse to form extensive fans. Meltwater from the

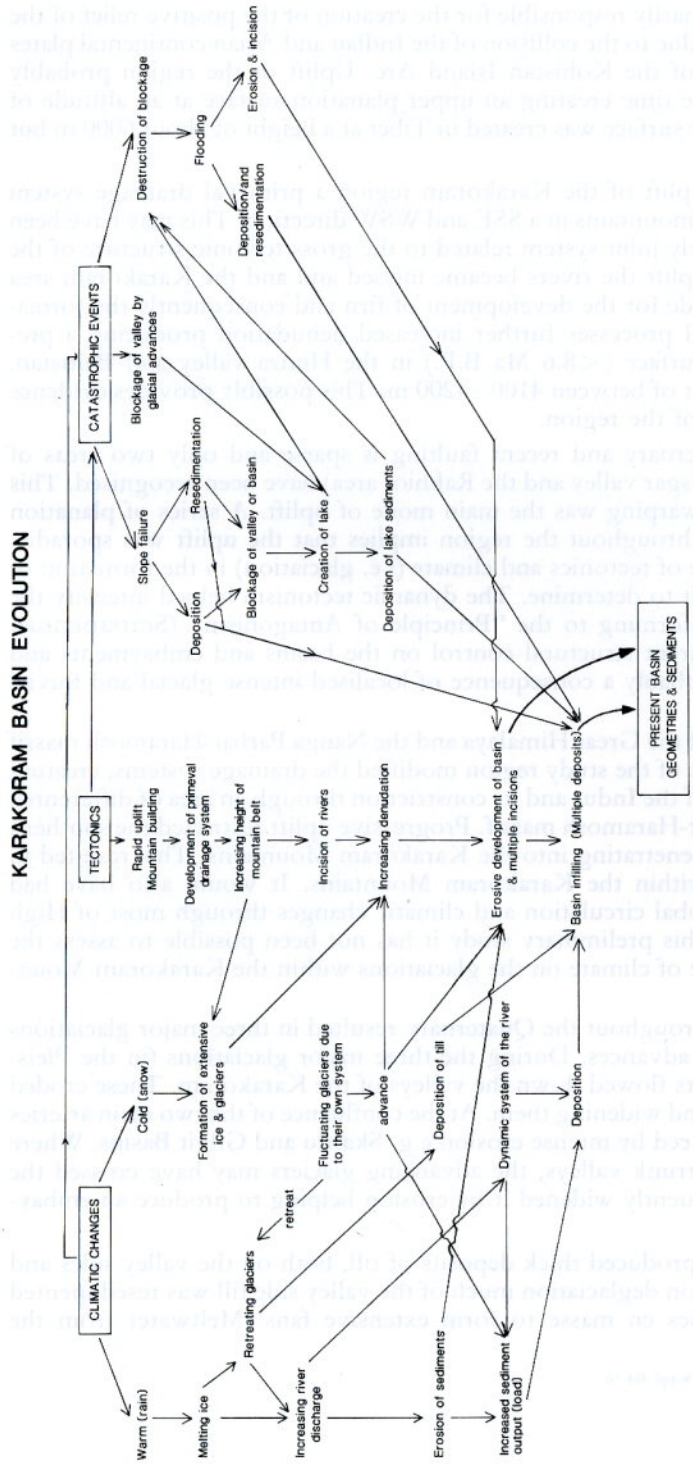


Fig. 8. Flow diagram showing the development of the Karakoram intermontane basins, and their sediment fills and terraces.

retreating ice also deposited glaciofluvial sediments. Further glaciations or advances of a fluctuating snout may have eroded previously deposited sediments or deformed them by glaciotectonic processes. Climatic changes may have been responsible for terrace formation comprising dominantly glaciofluvial sediments during interglacials (cf. CLAYTON 1977) or in late glacial/early interglacial or interstadial phases (cf. BRIGGS 1973) when discharges were greater, allowing large quantities of sediment to be deposited and subsequently eroded into terraces.

Glacial advances also blocked tributary valleys impounding glacial lakes. Ice-contact fan sediments constituted another important landform feature and a major sedimentary component within the valleys. These valley infills were frequently reworked by mass-movement, glacial, fluvial and aeolian processes, creating multiple sediment deposits. Fluvial erosion produced incision and consequent terrace formation.

Low frequency-high magnitude and catastrophic events had a profound influence on valley sedimentation. Debris flows and landslide failures temporarily blocked some of the valleys and rivers, and produced lakes. These became infilled with sediment and, upon destruction of the dam, were incised to form lacustrine terraces. The floodwaters eroded and resedimented large quantities of material.

Allocyclic processes also produced terrace successions. SCHICK (1974) showed that both aggradation and degradation can occur within a desert stream along different stretches which vary in their position with time. This would allow sediments to be deposited along one stretch while simultaneous erosion along another would incise previously deposited sediment to form terraces. LEWIS (1944) also showed that terraces are rarely in equilibrium and may develop and be subsequently obliterated due to changes in discharge controlled by climate. They may also be produced by subtle changes in sediment load or channel bed friction. Deposition of the river load effectively increases stream power enabling it to erode previously deposited sediments to form terraces. Fluvial and glaciofluvial terraces along the floors of the Karakoram valleys are readily formed due to the large variability of river discharge as it fluctuates seasonally and diurnally. The extreme changes in discharge and sediment load produce numerous ephemeral terraces which may last only a few hours or days but may be several metres high.

Similar cyclic processes have been envisaged for fan head entrenchment (HOOKE 1968). However, most sediment fans exhibit only one phase of fan head entrenchment and associated fan toe truncation. This phase of fan dissection represents rapid degradation of the fan soon after its growth following deglaciation.

The present Karakoram intermontane basins are dominated by the glacial and fluvial systems, and the processes of mass movement. The sediments produced by these various processes include subglacial tills of lodgement and meltout type, supraglacial tills, resedimented till, debris flows, glaciofluvial, lacustrine, fluvial and aeolian sediments. The sedimentary characteristcs of these deposits including particle size distribution, pebble fabric, microfabric, structure, facies associations and morphological characteristics, are all a function of the sedimentary environment, the mode of deposition and the lithology of the source rock. Careful comparative analysis of these properties facilitates differentiation between sediments with broadly similar characteristics e.g. debris flows and supraglacial tills. Such distinctions are essential aids in the interpretation of ancient sedimentary sequences.

Although the fluvial system is a dominant feature within the valleys it contributes little to the valley fill sedimentation and terrace succession. Rather it acts as a transporting system essentially carrying sediment through the mountains out to the foothills and foreland basins. Silts are carried out of the mountains by these processes and may be deposited as alluvial fan sediments. These are subsequently reworked by deflation and may contribute to the formation of thick loess terraces such as those on the Potwar Plateau. COLLINS (1988) has shown that the sediment loads in the main trunk rivers are considerably higher than sediment loads produced by the glacial systems suggesting that the rivers are actively eroding previously deposited valley fill sediments and bedrock within the gorge sections. This suggests that the rivers are degrading the landscape to a considerable degree, no doubt mainly as a result of rapid uplift. However, it must be emphasised that the rivers do produce extensive floodplains within some of the basins, e.g. Skardu, and within large entrenched meanders.

Although this study was primarily concerned with the intermontane basins and embayments and their sediment terraces, they form only about 15% of the total area of the Karakoram Mountains. The majority of the landscape is one of glaciated terrain with areas of permafrost and bare rock subject to dynamic nivation processes. These have obvious importance for the further development of landscape within the Karakoram Mountains. However, it is in the small intermontane basins and their terrace successions that the majority of the information on the Quaternary history of these mountains is to be found.

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