

GEOMORPHOLOGICAL HAZARDS ALONG THE KARAKORAM HIGHWAY: KHUNJERAB PASS TO THE GILGIT RIVER, NORTHERNMOST PAKISTAN

With 19 figures, 3 tables and 14 photos (photos and table 3 as appendix)

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Zusammenfassung: Geomorphologische Hazards entlang des Karakorum Highway: Khunjerab Paß bis zum Gilgit River, nördlichstes Pakistan

Der Karakorum Highway quert einen der in raschster tektonischer Hebung begriffenen Gebirgszüge der Erde. Durch das Zusammentreffen von Erdbeben, Glazialerosion, Flußeintiefung, Periglazialwirkung und einer unvorhersehbaren Einwirkung der Monsunregen wird eine Region sehr hoher dynamischer Aktivität geschaffen. Seit seiner Fertigstellung unterlag der Karakorum Highway Störungen und Unterbrechungen durch Steinschlag, Fels- und Schuttrutschungen, Schutt- und Schlammströme, trockene Feinmaterialströme, plötzliche Überschwemmungen durch Wasser und Wildbachschotter sowie einer Untergrabung der Straßenbasis durch Materialfortführung, Einsinken und Frosthebung. Die Straßenoberfläche wird regelmäßig durch die Einwirkung von Steinschlag, Überschwemmungen und Frostsprengung beschädigt. Durch Kartierungen im Gelände und gravimetrische Verfahren wurden Rutschungen und Schuttströme erfaßt. Eine systematische Hazard-Untersuchung ist für den über 200 km langen Straßenabschnitt vom Khunjerab Paß (pakistanisch-chinesische Grenze) bis Gilgit fertiggestellt worden. Bedrohungen größeren Ausmaßes erwachsen durch fast beständige Massenbewegungen an übersteilten Böschungen aus unverfestigtem spätglazialen Moränenmaterial sowie durch die Schmelzwasserströme einiger großer Gletscher. Die häufigsten Hazards kommen durch das Wachstum von Schwemm- und Murfächern zustande, zusammen mit Abrutschungen von Sturzhalden.

Summary: The Karakoram Highway traverses one of the most rapidly rising mountain ranges on earth. A combination of earthquakes, glacial erosion, river incision, periglacial action and an unpredictable input of monsoonal rains make it a region of very high geodynamic activity. Since its completion, the Karakoram Highway has been subject to damage and disruption by rockfall, sliding of rock and debris, debris flow, mudflow, dry powder flow, flash flooding by water and torrent gravels, basement undermining by abstraction, subsidence and frost heaving. The road surface is regularly damaged by rockfall impact, floods and frost shattering. Landslides and debris flows have been evaluated using field mapping and gravimetric techniques, and a systematic hazard survey has been completed over a distance of more than 200 km from the Khunjerab Pass (Pakistan – China border) to Gilgit. The largest scale threats are semi-continuous mass movements on oversteepened cliffs of uncemented late-Pleistocene till, and the meltwater streams of some large glaciers. The highest frequency hazards are alluvial and mudflow fan progradation, together with talus fan sliding.

1 Introduction

The Karakoram mountain region of northernmost Pakistan is a harsh environment. It has some of the highest relative relief on earth sustained by the highest known rates of uplift, the very steep climatic gradients (from glacial to hyper-arid) resulting in an environment marked by extremes. The presence of the largest glaciers outside the polar regions, seasonally frequent hydraulic action by violent precipitation events and rapid snow and ice melting, and frequent earthquake shocks all play some part in destabilizing the long, steep slopes and the many thick accumulations of young, uncemented sediments. The landscape system is marked by very high rates of erosion regionally and locally. Many of these natural processes, including large rock avalanches (HEWITT 1998), result in localized, high magnitude – low frequency events that are difficult to anticipate and predict with any precision. Sites suitable for human settlement and livelihood are very restricted, so

that the region is quite sparsely populated. Even so, the history of the impact of such events on the human settlements, recorded from 1830 to the present (KREUTZMANN 1994), makes sober reading. The imposition, at the end of the 1970s, of a major engineering structure, the Karakoram Highway, on this dynamic terrain introduced into the Hunza valley for the first time a source of human-induced geological hazards of a much higher order than before. This study is the first to provide a detailed (1 km spacing) factual statement of the relationship between terrain type, operative surface processes and highway condition for the full length of the highway in the Hunza valley.

2 Environmental Setting

The Karakoram Highway (KKH) was completed in 1979, forming the only overland route linking the Islamic Republic of Pakistan with the People's Republic of

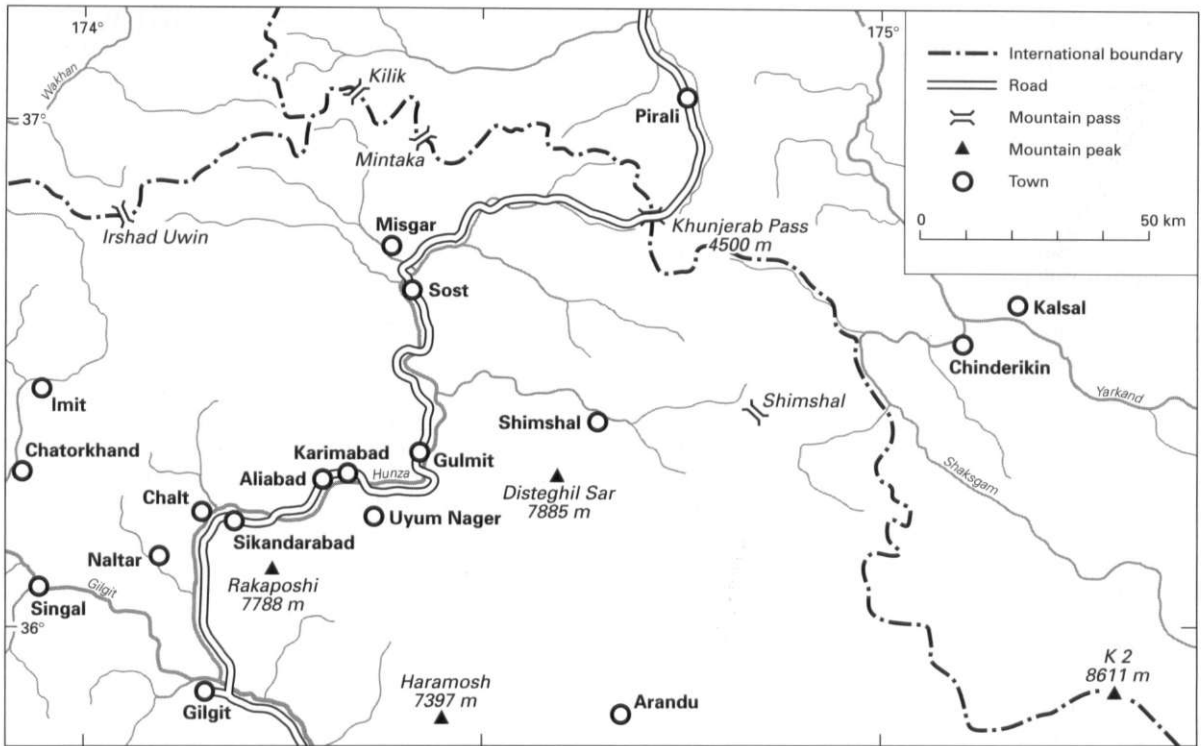


Fig. 1: Selected locations in relation to the Karakoram Highway, northern Pakistan
Ausgewählte Standorte in Bezug zum Karakorum Highway, Nord-Pakistan

China (Fig. 1). The original motives for this ambitious project were both strategic and economic. The route runs from the Pakistan lowlands, below 1000 m, into the Chinese Autonomous Region of Xinjiang by way of the Khunjerab Pass (ca. 4500 m). In following the valley of the Hunza and Khunjerab rivers, the upper part of the KKH cuts across one of the most geologically active mountain ranges on earth. It traverses a wide variety of morphoclimatic zones, ranging from extremely arid valley floors to glacial and periglacial conditions on the mountain peaks such as Rakaposhi (7821 m).

The Karakoram Mountains lie immediately to the north of two major geological structures, the Indus (or Shyok) and northern sutures, that mark the closing of the Tethys and the collision of the Indian and Asian continental plates (Fig. 2). Since about 50 Ma ago to the present day, mountain building processes have continued to stimulate growth of the Himalaya to the south and the Karakoram Mountains to the north (SEARLE 1991). In the western Himalaya, the rate of uplift has been estimated to be about 1 cm/year (ZEITLER 1985), ten times the average rate for the Himalayan Range. This, together with rapid glacial and fluvial incision, has resulted in deeply incised valleys and some very

thick valley fills that are relatively easily examined in field sections.

In the Hunza and Khunjerab valleys, the main structural grain trends WNW-ESE with the major formations mimicking this trend (Fig. 3). For most of its length the KKH, therefore, runs approximately perpendicular to both the structural and lithological trends. The KKH crosses four major geological terrains (SEARLE 1991): the Karakoram Sedimentary Series (in the north), the Karakoram Batholith, the Karakoram Metamorphic Complex; and (in the south) the Chalt Green Schist Zone. The Karakoram Sedimentary Series comprises highly jointed and locally deeply weathered Palaeozoic and Mesozoic slates, limestones and dolomites. Cryogenic weathering dominates in these lithologies to produce steep cliffs that surmount by long scree slopes. The Karakoram Batholith (Tertiary in age) consists mainly of granodiorite but includes diorite and granite. The batholith is deeply incised to form steep cliffs that exhibit impressive cavernous weathering forms. Salt crystal growth and cryogenic processes dominate the weathering throughout this zone. The Karakoram Metamorphic Complex includes gneiss, schist marbles, phyllites, pelite and amphibolites, greenschist, agglomerates and tuffs. These

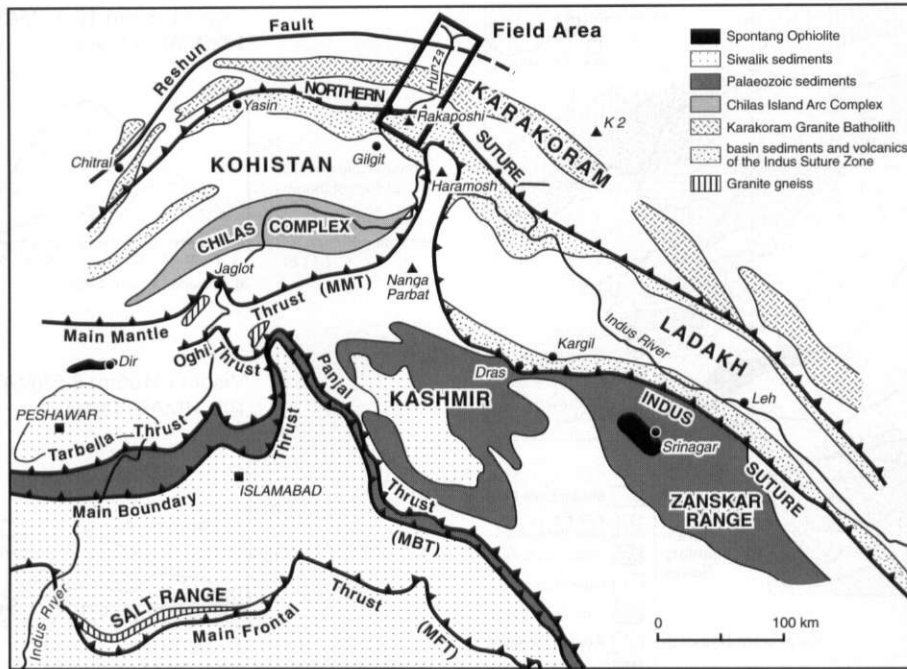


Fig. 2: Outline structural sketch-map of the Karakoram and the western Himalaya of northern Pakistan, showing the surveyed area

Übersichtsskizze der Struktur des Karakorum und West-Himalaya in Nord-Pakistan, mit Lage des Untersuchungsgebietes

show varying degrees of metamorphism, probably dating from the late Tertiary. The weathering characteristics of this zone are highly variable because of the large range of rock types. However, the highly foliated and fine-grained lithologies are extremely weathered and rarely support steep slopes. Low-grade metavolcanic and metasedimentary rocks make up the Chalt Greenschist Zone. Many are well weathered and supply abundant material to debris flows.

These structural and lithological characteristics give rise to four main regions along the KKH, each having distinctive geomorphological characteristics. These include (Fig. 3)

- the Khunjerab-Gulmit region, dominated by the Karakoram Sedimentary Series, with the higher altitudes and steep slopes being dominated by cryogenic weathering;
- the Gulmit-Ayeenabad region, dominated by the Karakoram Batholith with its characteristic cavernous weathering and abundant rock stacks or *tors*;
- the Ayeenabad-Aliabad region, characterized by deeply weathered and highly variable metamorphic rocks; and
- the Aliabad-Gilgit region, distinguished by the Chalt Green Schist Zone and relatively heavy rainfall during the summer and, because of its relatively low altitude, high summer temperatures.

A major factor affecting the vulnerability of the slopes to rapid erosion and collapse is the long and complex Quaternary history of this region, including multiple glaciation (DERBYSHIRE et al. 1984; DERBYSHIRE 1996). Sediments of various origins (alluvial, morainic, debris-flow, lacustrine and aeolian) remain unequally distributed along the Hunza and its tributary valleys (OWEN 1988). Thick (often >100 m) deposits of Quaternary glacial, mass movement and lacustrine deposits unconformably overlie the bedrock throughout the whole of the Hunza and Khunjerab valleys. Most of these deposits are poorly consolidated and are rarely cemented. They are deeply incised to form impressive terraces with highly unstable cliffed frontal slopes (OWEN 1989), and represent essentially temporary sediment storages. Such loose materials are a ready prey to mass-wasting processes.

The climate in this region varies considerably with altitude, aspect and local relief (REIMERS 1992). The valley floors are essentially deserts with a mean annual precipitation of less than 150 mm, most of the rain falling over short periods in summer as heavy storms. Most precipitation at high levels is derived from westerly depressions in both winter and summer (GOUDIE et al. 1984; cf. WEIERS 1995). Irregular incursions of the South Asian Summer Monsoon into the higher valleys may greatly enhance total rainfall

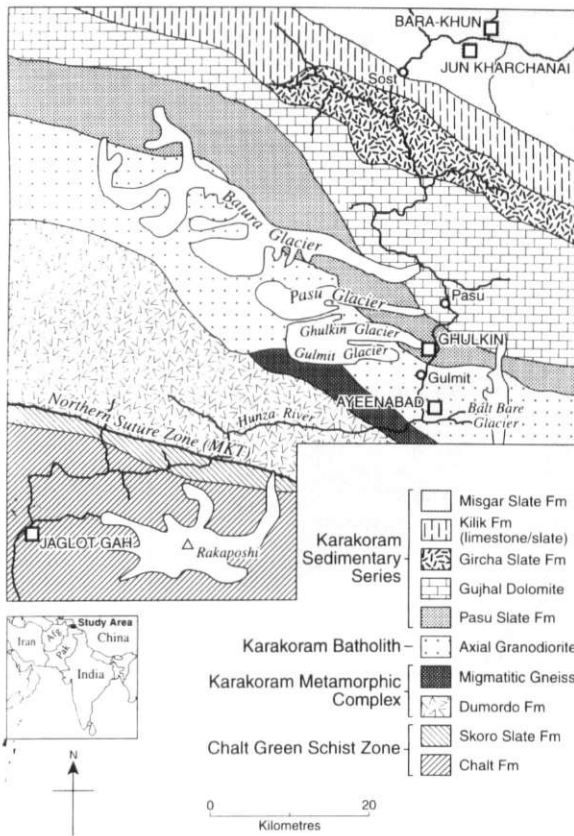


Fig. 3: Generalised geological map of the Karakoram between Rakaposhi and Bara-Khun. Sites of detailed topographical and gravimetric survey are shown by the open box symbols

Source: Re-drawn after GOUDIE et al. 1984

Generalisierte geologische Karte des Karakorum zwischen Rakaposhi und Bara-Khun. Die Stellen eingehender topographischer und gravimetrischer Untersuchungen werden durch die Quadrat-Symbole bezeichnet

amounts, a fact reflected in the broad south to north aridity gradient. Appreciable winter precipitation amounts fall only at the higher altitudes, inducing significantly more humid conditions (Fig. 4). Extreme diurnal maximum temperatures in summer exceed 38°C, while mean monthly winter temperatures fall below 0°C in the valleys above 2300 m (Fig. 5). Such extremes of temperature may cause abnormal glacier melting with severe and often rapid increases in river discharge. This effect is enhanced by the great relative relief (>4000 m in many parts of the Hunza Karakoram), the steep slopes, and the broad geo-environmental range. The rivers tend to be very 'flashy', with very low levels in winter and a pronounced peak-flow

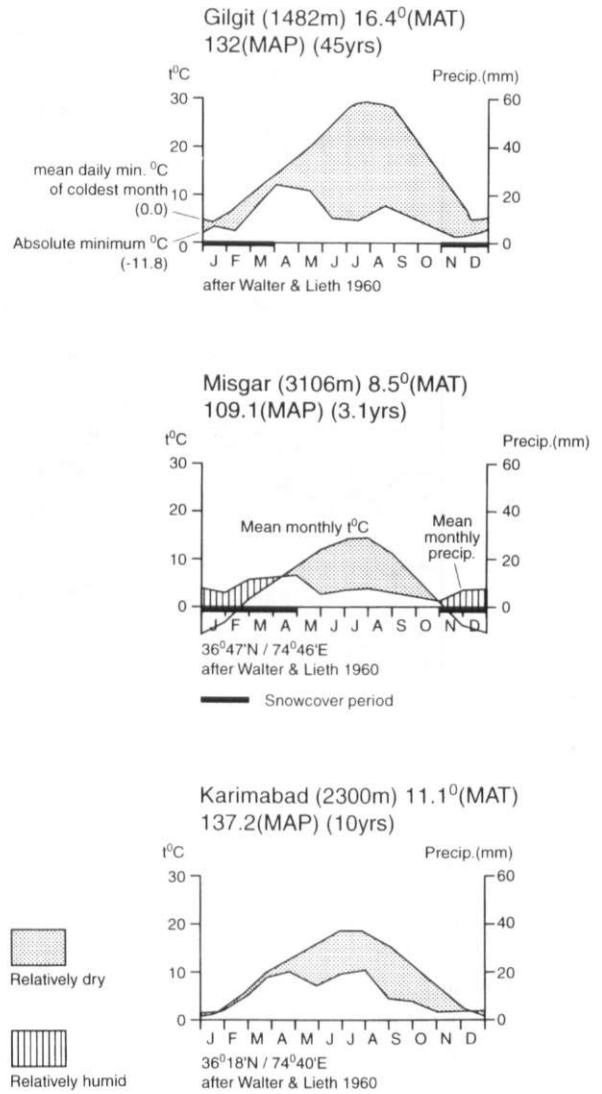


Fig. 4: Graphs of selected climatic data for Gilgit, Karimabad and Misgar

Source: after WINIGER et al. 1995

Klimadiagramme von Gilgit, Karimabad und Misgar

period from late spring and throughout the summer (see below).

The vegetation cover (BRAUN 1996) varies from dry, steppic associations at lower altitudes through an irregular double tree-line to alpine periglacial tundra and glaciers at the highest levels. Several geoecological zones have been recognized. The Hunza valley lies at the aridity margin of forest, the dominantly spruce and pine woodland petering out on the north side of Rakaposhi (PAFFEN et al. 1956). Fir and *Quercus ilex* reach only as far as the southern slopes of Rakaposhi, and *Pinus gerardiana* is found only to the south of the Chalt

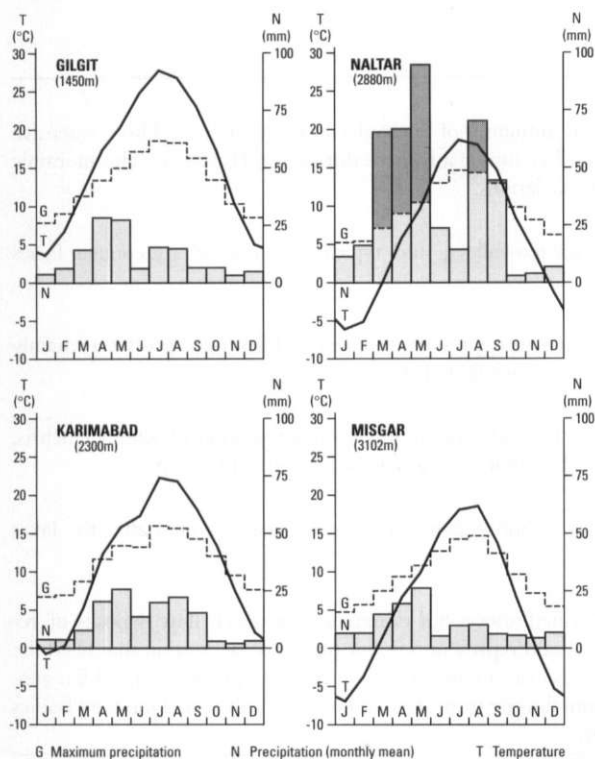


Fig. 5: Climatic means for selected stations in the Hunza valley
Source: after KREUTZMANN 1989

Klima-Mittelwerte ausgewählter Stationen im Hunza-Tal

area. In the Hunza valley, desert steppe (*Artemisia* spp.) is widespread below 2700 m, making only a discontinuous ground cover above that altitude that contains some juniper. Some temperate coniferous forest (spruce, mesic pine and juniper) occurs between 3300 and 3400 m, but this is confined to slopes south of the Ghulkin Glacier. It is replaced up to 3600 m by a sub-alpine birch-willow-mountain ash association that gives way to alpine zone associations above 3800 m. The vegetation cover is more open with passage up-valley, although this may also reflect human settlement and interference in the form of wood gathering and domestic animal grazing (Goudie et al. 1984).

The high level of tectonic activity in the Himalayan tract has two important consequences for the human population and the hazard regime. First, the whole region is subject to frequent and severe earthquakes. The local village communities are well aware of this threat and have adapted to it in their traditional building techniques, using the "kutchra", a mixture of mud, wattle, timber and boulder (COBURN et al. 1984). A second important consequence of the actively tectonic regime is that rocks of different composition and contrasting mechanical properties are frequently juxtaposed, making them unequally resistant to erosion and mass wasting.

posed, making them unequally resistant to erosion and mass wasting.

Human settlement in the Hunza valley is largely in the form of numerous but sporadic villages, all of which depend upon irrigation for crop production. Widespread slope instability renders maintenance of the KKH a difficult task, but further complications have arisen from the economic developments induced by the road itself (KREUTZMANN 1989; 1993; 1994), with a notable effect upon the ecology of the high altitude forests (SCHICKHOFF 1997).

3 Aims

The main objectives of the 1988 survey of the highway included

- (1) evaluation of the condition of the road ten years after its completion;
- (2) description of the complex of processes involved in the degradation of the road;
- (3) recognition of the potential hazards threatening the road and likely to hamper its strategic and economic functions over the short and middle term; and
- (4) provision of data suitable for an assessment of the changes that have taken place since the 1980 survey undertaken by the International Karakoram Project (JONES et al. 1983) for that part of the road between Gulmit and Gilgit.

Evaluation of natural hazards in a region as extensive and rugged as the Karakoram Mountains is a demanding task. The difficulties posed by the terrain, and the strategic location of the region adjacent to Afghanistan, the Russian Federation, China and the disputed territory of Kashmir, has been compounded by a map coverage that is poor, the largest scale full coverage available being the 1:250,000 U502 series. Moreover, although complete stereoscopic aerial photographic cover exists for the region, access to this material is restricted on grounds of national security. The remotely-sensed imagery derived from orbiting satellites provides complete cover, but the resolution necessary for appropriate-scale geomorphological and sedimentological mapping is not uniformly provided by LANDSAT, and uncertainties of cover and delivery rendered the use of SPOT imagery impractical. The approach adopted here involved initial reconnaissance field techniques to establish the main geomorphological units and sedimentary assemblages, followed by detailed site-specific mapping and recording with at regular spacing along the highway.

This paper first describes in some detail the sediment-landform associations along the KKH. This is

Table 1: Classification of terrace types (after OWEN 1989)

Klassifikation der Terrassen-Typen (nach OWEN 1989)

1. Morainic terraces

The extensive glacial systems produce voluminous till deposits, dominantly of supraglacial meltout type. Three extensive glaciations have been recognised for the Quaternary, 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 palaeo-valleys, and typically consist of ice-contact facies reflecting deposition by high-gradient streams.

3. Fluvial terraces

These form a minor component of the landscape and are common near present river levels. 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 re-sedimentation of diamict 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. Subsequent 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 re-sedimented till. These formed early in the deglaciation of the area and represent 5 major phases of deposition that filled the valley bottoms. Fluvial aggradation and minor mass movement processes modified their surfaces to produce typical fan geometries with varying surface gradients. Fan-head entrenchment and fan-toe truncation indicates that these sedimentary bodies are not in equilibrium with the current geomorphological system.

followed by a brief account of the method of data collection in the field. The results are then presented and discussed.

4 Sediment-landform associations

Although some emphasis has been placed on the bedrock geology in the introduction, the dynamic interplay of surface processes, sedimentary accumulations, and particularly susceptible bedrock types lies at the heart of the geohazard problem in this region. The valleys and intermontane basins of the Hunza Karakoram contain substantial accumulations of sediments of glacial, glaciofluvial, mass-wasting, fluvial, lacustrine and aeolian origin. These make up a range of youthful landforms that are in various stages of modification by the processes of erosion and re-deposition (Photo 1). Such valley fills frequently exceed tens of metres in thickness, exceptional examples occurring at Gilgit (Dainyor) and Skardu (Bunthang) where thicknesses exceed 1000 m. The variously dissected valley fills form a gradational series, the most frequent components being scree cones, debris flow fans, ice-contact fans, outwash terraces, moraines, and floodplains. OWEN (1989) referred loosely to these dissected landforms as terrace-like features, and recognized six main types (Tab. 1). These were classified on the dual basis of the

dominant sediment type present, and the mode of formation. However, it was emphasised that most terrace-like accumulations consist of several types of sediment and that they are frequently polygenetic in origin (DERBYSHIRE a. OWEN 1990; OWEN 1993). The sedimentological and related properties of a variety of valley fill deposits in the Hunza valley have been considered by LI et al. (1984), BRUNSDEN et al. (1984), Owen (1988), OWEN a. DERBYSHIRE (1988; 1989), and DERBYSHIRE a. OWEN (1990) (Tab. 2). It is evident from these data that there exists a considerable degree of overlap in the material properties and bulk behavioural characteristics of the different sediment types. This makes it difficult to predict the geotechnical properties of the sediments based on their field characteristics alone.

The sedimentary environment within these mountains is dominated by the glacial depositional system (LI et al. 1984; OWEN a. DERBYSHIRE 1989; HEWITT 1989). The glaciers are of the valley type and include some that are the longest glaciers outside the polar regions. These thick and steep ice bodies are glaciologically complex, i.e. they contain both isothermal and colder ice. They have high rates of movement, with a high mass-throughput, i.e. high activity indices. Rates of movement are typically $>400 \text{ ma}^{-1}$ for glaciers ca. 20 km long (GOUDIE et al. 1984; GARDNER a. JONES 1993). Large diurnal and seasonal changes in tempera-

Table 2: Selected properties of various types of Quaternary sediments along the Karakoram Highway

Ausgewählte Charakteristika verschiedener Typen von Quartär-Ablagerungen entlang des Karakorum Highway

a) – bulk density –
Lagerungsdichte

Sediment type	bulk density (g/cc)
Lodgement till	2.45
Lodgement till	2.41
Debris slide	2.39
Debris slide	2.38
Lateral moraine	2.22
Lodgement till	2.17
Debris flow	2.17
Debris flow	2.08
Hummocky moraine	2.08
Debris flow	2.04
Hummocky moraine	1.97

b) – clay mineralogy (based on X-ray diffractometry) –
Ton-Mineralogie (röntgen-diffraktometrische Bestimmung)

Sediment type	Mica	Chlorite-Vermiculite	Kaolinite	Illite	Chlorite	Smectite	Dickite
Till	1	–	3	5	4	–	–
	1	3	2	4	2	–	–
	1	5	3	–	–	–	–
	1	5	2	2	4	–	–
Lacustrine sediments	1	4	3	2	4	–	–
	1	4	3	3	4	–	–
	1	4	3	3	4	–	–
	1	3	2	2	3	–	–
Debris flows	1	4	4	2	4	–	–
	1	4	4	2	5	–	–
	1	5	5	3	–	–	–
	1	3	2	3	4	–	–
	1	4	3	2	5	–	–

c) – liquid limits (percentage moisture) –
Fließgrenzen (Feuchtigkeit in %)

Sediment type	liquid limit (% moisture)
Debris slide	20
Debris flow	15
Debris flow	15
Debris flow	12
Debris flow	12
Hummocky moraine	14
Hummocky moraine	14
Lodgement till	14
Lodgement till	14

ture induce considerable variations in ice melting rates and hence large fluctuations in meltwater discharge volumes. This peak period is subject to wide intra-annual and inter-annual variations (Batura Glacier Investigation Group 1976; 1979; 1980; GOUDIE et al. 1984; GARDNER 1986; GARDNER a. JONES 1993).

FERGUSON (1984) and FERGUSON et al. (1984) measured increases in discharge of between 20 and 30 times in a single day in the summer with an increased output of sediment load of the order of 500 to 1000 times. Similarly large changes in discharge occur seasonally, the annual peaks occurring between June and Septem-

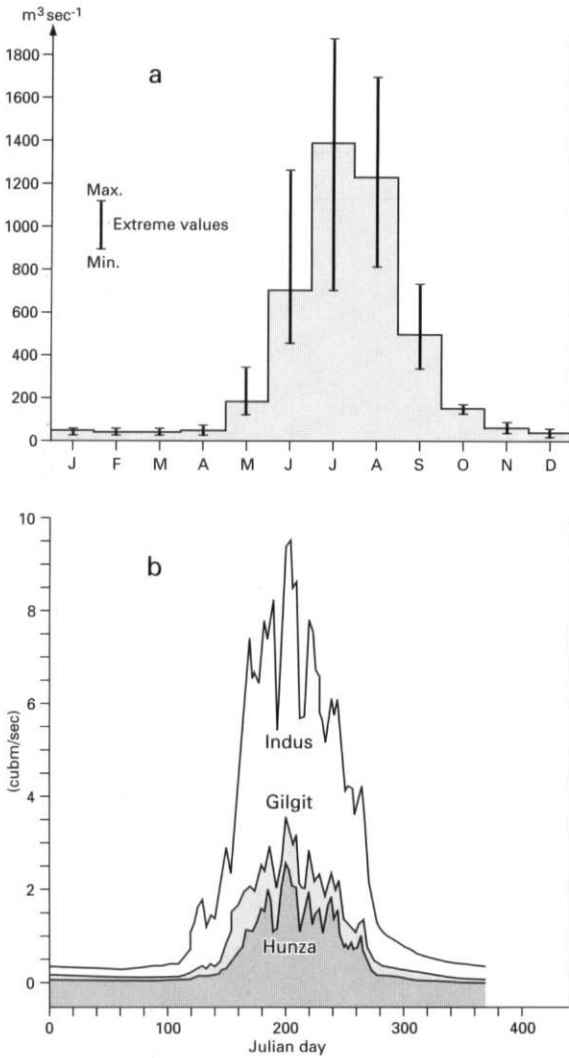


Fig. 6: A: Monthly average and extreme discharge values for Dainyor, 1971–1981

B: Daily runoff means 1973 for the Indus, Gilgit and Hunza rivers

Source: after KREUTZMANN 1995

A: Monatsmittel und extreme Abflußwerte für Dainyor, 1971–1981

B: Abfluß-Tagesmittel 1973 für die Flüsse Indus, Gilgit und Hunza

ber (Fig. 6). These meltwater streams feed the main valley rivers that include the Indus, Hunza and Gilgit. Thus, meltwater inputs dominate the discharge and sediment load characteristics of the trunk rivers draining the Karakoram Mountains and the Greater Himalaya.

The glacially-derived sediment store is complex, three extensive valley glaciations having been recognized in the Quaternary record of the Karakoram

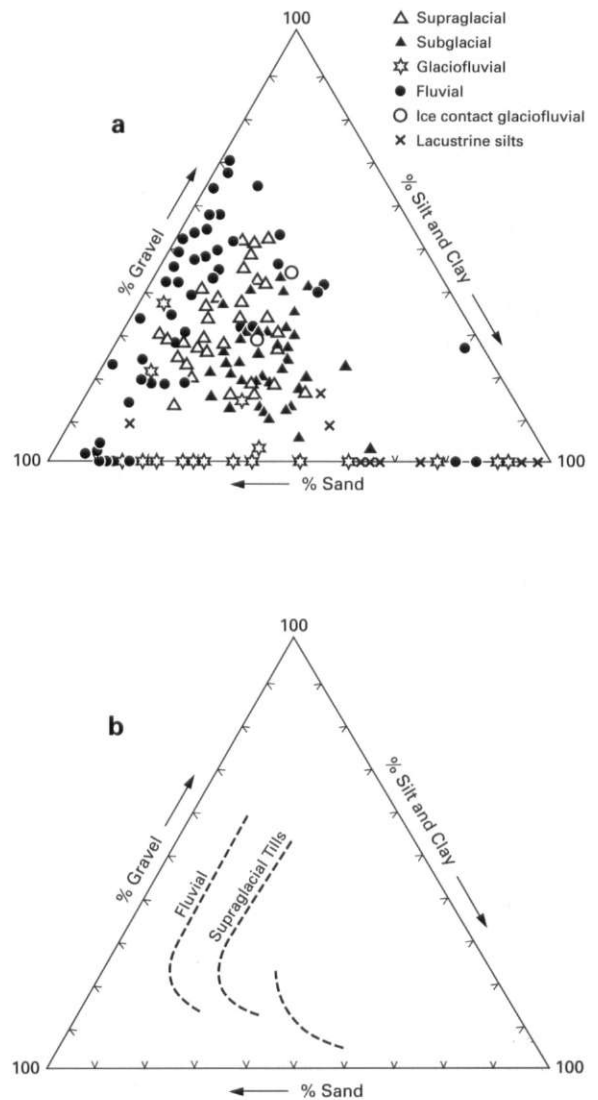


Fig. 7: Ternary diagrams of glacial facies in the Hunza valley
Source: after Li et al. 1984

Dreiecks-Diagramm der glazialen Fazies im Hunza-Tal

Mountain valleys (DERBYSHIRE et al. 1984; DERBYSHIRE 1996). It has been shown by OWEN (1988) and DERBYSHIRE and OWEN (1990) that considerable volumes of these till deposits have been re-sedimented by debris flow processes soon after their initial glacial deposition, resulting in widespread debris flow deposits along the valley floors, forming typical “alluvial fan” geometries (Photo 2).

Glacial Sediments

The sedimentological characteristics of the Hunza valley glacial deposits have been described in some

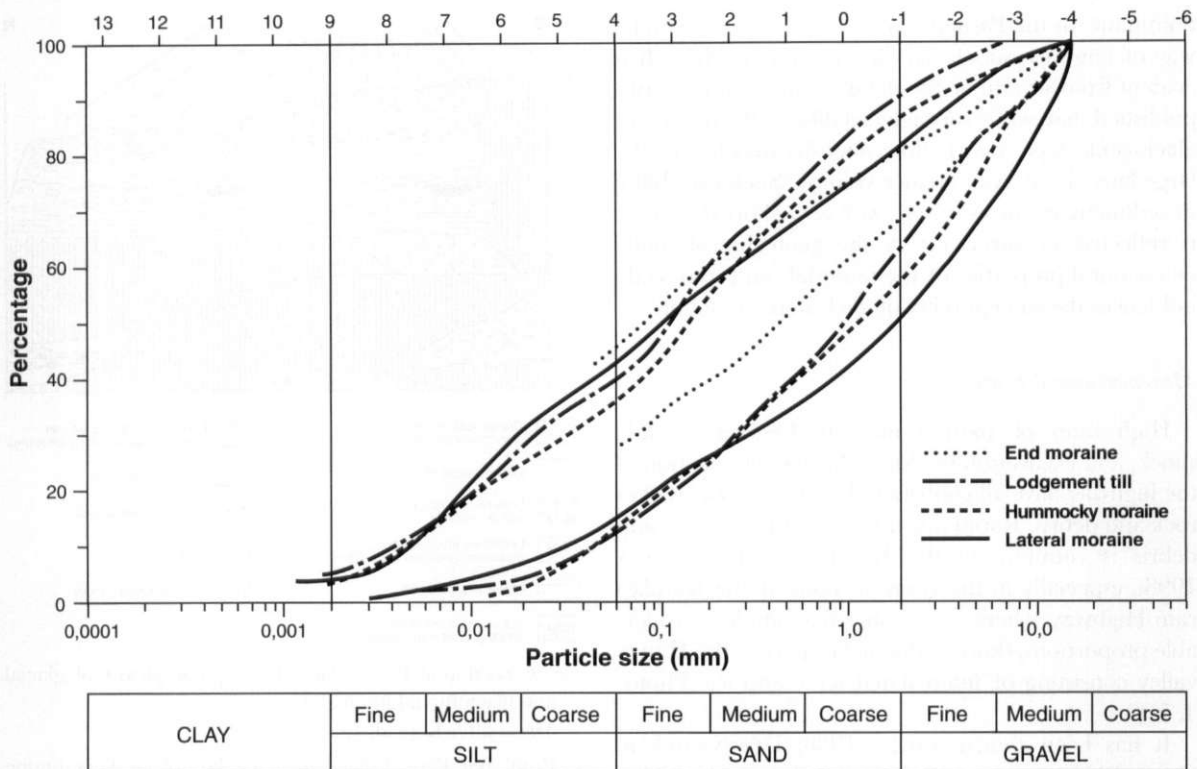


Fig. 8: Particle size envelopes for Hunza valley glaciogenic deposits

Korngrößen-Rahmenwerte von glazigenen Ablagerungen im Hunza-Tal

detail (LI et al. 1984; OWEN a. DERBYSHIRE 1988; 1989; OWEN 1994). These authors emphasised the complex interaction between the glacial, proglacial, paraglacial (non-glacial but conditioned by proximal ice masses: CHURCH a. RYDER 1972), and periglacial environments that result in a gradational series of glaciogenic sediments including subglacial tills of lodgement type, subglacial and supraglacial meltout tills, and tills re-sedimented by debris flow and debris slide processes. They further suggested that such till properties result from a glacial system dominated by supraglacial sediments primarily derived from rock fall and avalanche processes.

The sedimentary characteristics of all these materials are broadly similar (Fig. 7). All are very poorly to poorly sorted, positively skewed, depleted of fines (<10% clay: Fig. 8), and contain sub-angular clasts. The rather wide variation in the bulk density values of the tills is a reflection of the depositional mode: lodgement tills have the highest values, while supraglacial meltout tills have the lowest (Tab. 2 a). The mineralogy of the tills ranges from polymictic to monomictic. The variation in clast lithology is clearly a function of source area and alimentation mode (rock fall, supraglacial and subglacial deposition, avalanching, debris flow, and others), an important factor influencing the geotechni-

cal behaviour. The finer components of the tills are dominated by quartz, orthoclase and plagioclase feldspars, micas, illite, chlorite and kaolinite derived from the erosion and weathering of granitic and metavolcanic rocks (Tab. 2 b). No swelling clay minerals have been identified within the tills (OWEN 1994). However, as Table 2 c shows, the tills have the very low liquid limits to be expected in sediments with low clay contents. The moraines adjacent to the highway above Gilgit are all silt-rich and lack any evidence of induration. Where the highway construction was forced to cut into thick moraines of such material, there is a constant rock fall and debris flow hazard (Photo 3).

The glacial sediments make up a series of landforms including complex "ablation valleys" (HEWITT 1989), lateral moraines, hummocky moraines, ice-contact fans and a variety of fluted and irregular landforms of subglacial origin. OWEN and DERBYSHIRE (1989) recognized two main types of glaciogenic sediment-landform associations characteristic of the tributary (side) valleys in the Karakoram, namely a Ghulkin type dominated by ice-contact fan landforms, and a Pasu type dominated by hummocky moraine and glaciofluvial outwash plains. In the former case, supraglacial till and till re-sedimented by debris flow and slide processes are

dominant. In the Pasu glacial sediment association, by way of contrast, subglacial tills are more evident. It is evident from several of the detailed maps and sections published that, while supraglacial tills are the dominant glaciogenic type, debris flow deposits making up the large fans are of even greater volume. Such variability in sedimentary facies, often over very short distances, is reflected in variations in the geotechnical (bulk) behavioural properties of the materials and so directly influences the susceptibility of such slopes to failure.

Mass movement deposits

High rates of natural incision, frequent seismic shock, and excavation of slopes during construction of the highway have all contributed to mass movement of rock and debris. Rapid downslope transfer of rock and debris is common in the Karakoram (ITURRIZAGA 1998), especially in the gorge sections of the Karakoram Highway, where scree cones may attain considerable proportions, those in the higher part of the Hunza valley consisting of intercalated scree and ice (Photos 4, 5, 6).

It has been shown (OWEN 1988; DERBYSHIRE a. OWEN 1990) that most of the debris flow units making up what DREW (1873) called "alluvial fans" (and which so dominate considerable stretches of the valley floors in this region) are, in fact, re-sedimented supraglacial tills laid down by mass flowage soon after deglaciation. Many of the debris flow units possess extensive sheet geometries and cover large areas (Photo 7). Frequently, they exceed several hundreds of metres in diameter and may be as much as 10–20m thick. In the geologically recent past, large debris flows and landslides blocked many of the narrower valleys, in some cases causing lakes to build up behind them (OWEN 1988, 1989; Photo 8).

The sedimentological characteristics of the debris flows are very similar to those of the tills from which they are derived (Tab. 2). However, they tend to be slightly finer-grained, to have lower bulk densities (higher voids ratios) and to have flow fabrics consistent with deposition by flow under gravity rather than those typical of subglacial deformation (OWEN a. DERBYSHIRE 1989). The discrimination between undisturbed and re-worked subglacial till is thus important because slopes in re-worked tills constitute a greater hazard.

Glaciofluvial and fluvial sediments

These units consist of poorly sorted to very poorly sorted sands, gravels, and cobbles, their morphological expression including floodplains and low terraces

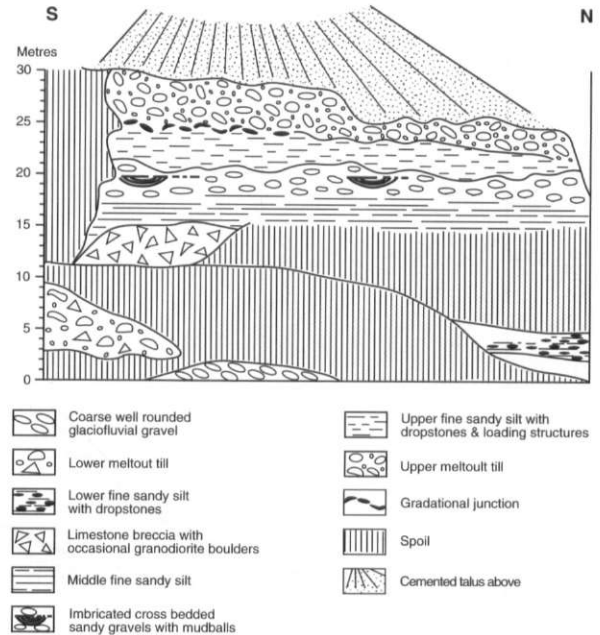


Fig. 9: Section at Pasu village showing complexity of glacial and glaciofluvial intercalation

Source: after LI et al. 1984

Profil bei Pasu Village, das die komplexe Verzahnung glazialer und glazifluvialer Sedimente zeigt

(Fig. 9). They also quite frequently occur as a minor component capping till bodies or as intercalated lenses within the tills or debris flow units (Fig. 10). The floodplains often include sheets of sands, gravels, and imbricated cobbles. The river channel habit varies from complexly braided, high gradient reaches to incised meanders with broad point bars and chute cut-offs. The detailed pattern of deposition is dictated by the large fluvial discharge fluctuations arising from diurnal and season variations in ice melting.

Lacustrine sediments

The deposition of lacustrine sediments in the Karakoram Mountains takes place in several types of lake-basin (OWEN 1988; 1989). These include lakes dammed by tributary valley glaciers, formed behind end moraines or within moraine fields, water-bodies filling glacially eroded bedrock depressions, and lakes created by the damming action of debris flows, rock-falls and landslides. Most of these lakes are short-lived, but the depositional rates within them are very high. For example, historical records show that as much as 10 m of sediment may be deposited within a period of only six months (OWEN 1989). Breaching of the lakes may be

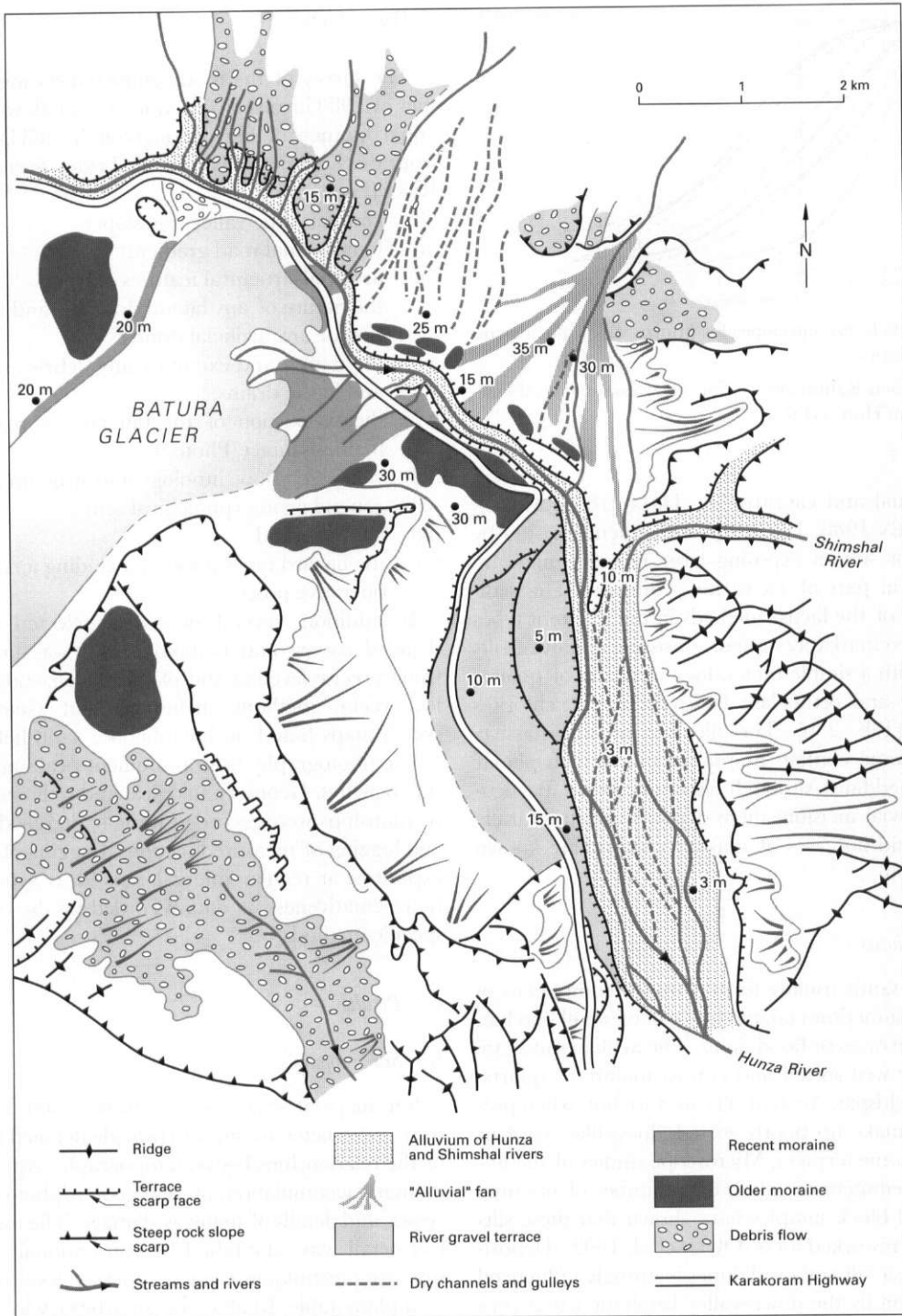


Fig. 10: Map of sedimentary facies near the Batura Glacier terminus, with estimated sediment thicknesses shown for selected sites (in metres)

Karte der Sedimentausbildung im Bereich des Batura-Gletscherendes, mit Schätzwerten der Sedimentmächtigkeit an ausgewählten Stellen (in Metern)

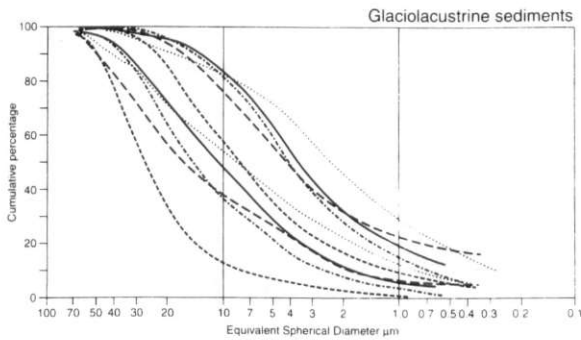


Fig. 11: Particle size envelopes for Hunza valley glaciolacustrine deposits

Korngrößen-Rahmenwerte für glaziolakustrine Ablagerungen im Hunza-Tal

both gradual and catastrophic (DREW 1873; MASON 1929; OWEN 1988; 1989), the subsequent incision by the river or stream exposing large terraces made up wholly or in part of lacustrine sediments. The sedimentology of the lacustrine beds in the different types of lake are remarkably similar, consisting mainly of silts (Fig. 11) with a simple mineralogy made up of quartz, plagioclase and orthoclase feldspars, micas, chlorites and illite (Tab. 2 b). The silts are usually massive, although some contain fine laminations, with planar dm-thick bedding. Although liable to erosion, particularly by fluvial incision, these deposits are structurally compact and no cases of massive collapse are known (OWEN 1996).

Aeolian sediments

Aeolian sands usually form a minor component of valley fills, sometimes taking the form of small barchan dunes on terraces or floodplains. The aeolian sands are moderately well sorted and consist mainly of quartz, mica and feldspar. Aeolian silts are rare but, when present, they make up poorly sorted "loess-like" caps or drapes on some terraces. Microscope studies of the undisturbed sedimentary fabric of a number of oriented and leveled block samples have shown that these silts are akin to reworked loess (OWEN et al. 1992). Deposition of loessic silt and sand dunes is strongly influenced in this region by the down-valley katabatic winds produced by the difference in temperature between the warm valley floors and the cold surfaces of the glaciers. Mobile dunes constitute a local hazard where they inundate roadways and irrigation canals. Dust storms are almost a weekly event in the summer, winnowing away the surfaces of floodplains, fans and moraines, and locally depositing silt and sand drapes.

5 Data collection

The survey of the road completed during the summer of 1988 involved collection of the following data at equal distances of 1 km throughout the 263 km traverse from the Khunjerab Pass to the bridge over the Gilgit River (Fig. 1):

- (i) characteristic valley side slopes;
- (ii) longitudinal road gradient;
- (iii) artificial structural features present;
- (iv) the nature of any lateral drainage and the condition of any artificial drains;
- (v) the nature and extent of any debris on the road and in the drains;
- (vi) the proportion of the 6m tarmac roadbed remaining intact (Photo 9);
- (vii) valley side slope lithology and structure;
- (viii) general geomorphological setting;
- (ix) land use; and
- (x) the hazard types present, including a note on the operative processes.

In addition, several sites were selected for more detailed survey and mapping. This was undertaken using precise leveling and plane-tabling, supported by less-precise methods including field sketches and sketch-maps based on low-oblique, hand-held stereoscopic photography from prominent peaks and valley-side benches. Geomorphological and sedimentological relationships were recorded using scaled field sketches and logging of measured sections. Logging of roadside exposures at regular intervals served as a test of the representativeness of data recorded by the other site-specific methods.

6 Results

6.1 Site mapping

Site maps at scales ranging from 1:500 to 1:2,000 were constructed in order to provide detailed examples of the relationships between topography, types of sedimentary accumulation, present geomorphological processes, and details of highway damage. The topographical detail was established by conventional terrestrial surveying techniques using a 'quickset' level supported by a plane-table. In all cases, an arbitrary local datum was adopted and the sites contoured, the contour interval varying from 3 m to 0.25 m depending upon the area of the site. Geographical Positioning System technology was not available at that time, but ground survey closing error was nowhere greater than ± 2 m horizontally and ± 1 m in the vertical plane. Absolute altitudes posed a problem in this poorly mapped region,

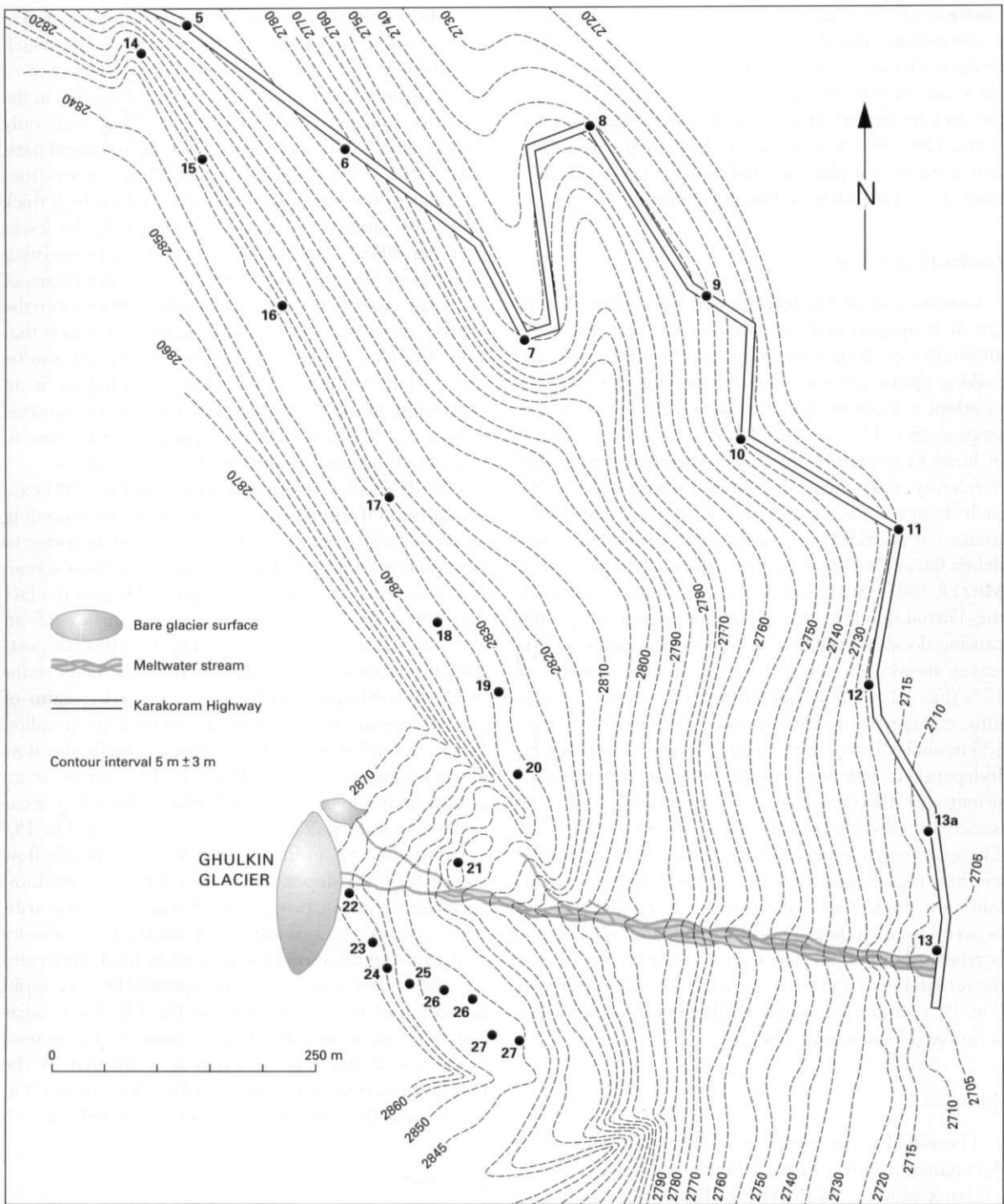


Fig. 12: Site map, with 5 m contour interval, of the central and northern margins of the Ghulkin Glacier
 Lageskizze vom Mittel- und Nordrand des Ghulikin-Gletschers (mit 5-m-Konturlinien)

but best approximations were derived from the existing map series. The individual topographical maps were also used as base data for gravity meter measurements

(Texas Instruments Worden gravimeter) designed to establish the thickness and geometry of some of the young sedimentary units along the Highway. The com-

bination of these two mapping procedures provided a three-dimensional representation of the sediment wedges that are recurrent sites of highway hazard: these are shown here in maps and sections. Three of the sites are described briefly below (see Fig. 3 for locations). Only the Ayeenabad site lacks a gravity profile and a contoured plan, instead being represented by a map of its constituent sedimentary units.

Ghulkin Glacier snout

Construction of the KKH posed substantial difficulties at it approached the Ghulkin Glacier. The only alternative to blasting the road out of a sheer rock face making up the left (east) bank of the Hunza River, was to adopt a highway line that skirted the snout of this large glacier. This 1.5 km of highway rests on a series of large ice-proximal fans cut by meltwater rivers that frequently shift their alignment unpredictably. One such change in the alignment of a subglacial meltwater source cut the KKH in August 1980, depositing a new debris fan across 400 m of the highway (DERBYSHIRE a. MILLER 1981). Such events continue to affect the road, the diurnal floods of the glacier melt season frequently causing floods that temporarily close the highway. The survey showed the fan to have an average gradient of 17% (Fig. 12). The dominant meltwater stream at that time emerged from an exposure of glacial ice some 155 m above the culverts carrying it beneath the KKH. Independent evidence from a gravimetric survey is consistent with the view that a ca. 50 m thick tongue of buried ice extends beneath survey point 21 (Fig. 12). The gravimetric survey also suggested that the buried ice thins rapidly northwards, with the fan debris maintaining a thickness of about 65 m along the traverse between survey points 21 and 14. The highway on this northern flank of the fan is thus relatively stable, but the remainder of the fan to the south of survey point 12 (Fig. 12) remains vulnerable to disruption by meltwater action and local ice collapse.

Ayeenabad

The KKH is cut from one to three times a year at Ayeenabad, where it crosses the alluvial fan of a small, left bank tributary of the Hunza River (Fig. 13). In July 1988, the road was cut for three days by an extensive debris flow, composed of granodioritic boulders in a dense, coarse sandy matrix, thickness varying from >1 m upstream to less than 10 cm at the downstream end. In fact the accumulation (facies 5 in Fig. 13) was complex, composed of various layers of diamictic material overlapping each other, each separated from

the other by an arcuate step. This was also expressed in the form of a multi-lobate front to the debris-flow. Such a pattern suggests emplacement by several waves of material, with the deposition of coarser boulders in the proximal, steeper (10°) part of the flow, with only coarse sands in the more gently sloping (4°) distal part. The surface morphology of the flow varies from irregular in the upper part (cobbles covered by a thick veneer of sand) to a more even surface in the lower part. Sand-flows, partly constrained by the pre-existing topography (i.e. channels scoured by former events of the same type), tend to spread as thin sheets over the former, distal parts of the fan. Shallow channels that have drained the water out of the system can also be observed in the distal areas. This morphology is an expression of the changing rheology of the process during its development, in response to variation in water content (rainfall and/or dewatering effects).

The debris-flow triggering factor in the 1988 case was heavy and continuous rainfall during the preceding 3–4 days, a situation that can occur from late spring to autumn and which is liable to occur at least once a year. The source of the material is cryptic. Despite the fact that debris flows develop here on the surface of an alluvial cone-terrace (facies 6 in Fig. 13), the transported debris does not derive directly from the main channel of this tributary but from the perched remains of glacial deposits overhanging the main Hunza valley. When rainfall is abundant, it greatly swells the flow down a nearby waterfall (Fig. 13). This serves as an avalanche track for the glacial debris which first accumulates as a steep (22°) debris cone ('talus' in Fig. 13), but may then be suddenly reworked as a debris flow on much gentler slopes. When the debris flow develops, it can sometimes cause partial damming of this tributary stream. This results in a decrease in velocity leading to aggradation of sediments behind (upstream) the debris flow, a process that explains the very rapid formation of terraces (facies 1 in Fig. 13) closely adjacent to the channel of this Hunza tributary. The annual frequency of this type of event is confirmed by the faithful preservation of former debris flows (facies 3 in Fig. 13) and their incipient, sparsely vegetated soil.

Jaglot Gah

At Jaglot Gah, the KKH follows the left (east) bank of the Hunza River which here cuts transversely across a large compound set of moraine ridges running approximately east-west (Fig. 14). The relative relief on the upper surface of this moraine complex is of the order of 8 m, but incision by the Hunza River has created a steep cliff over 200 m high. The gravimetric

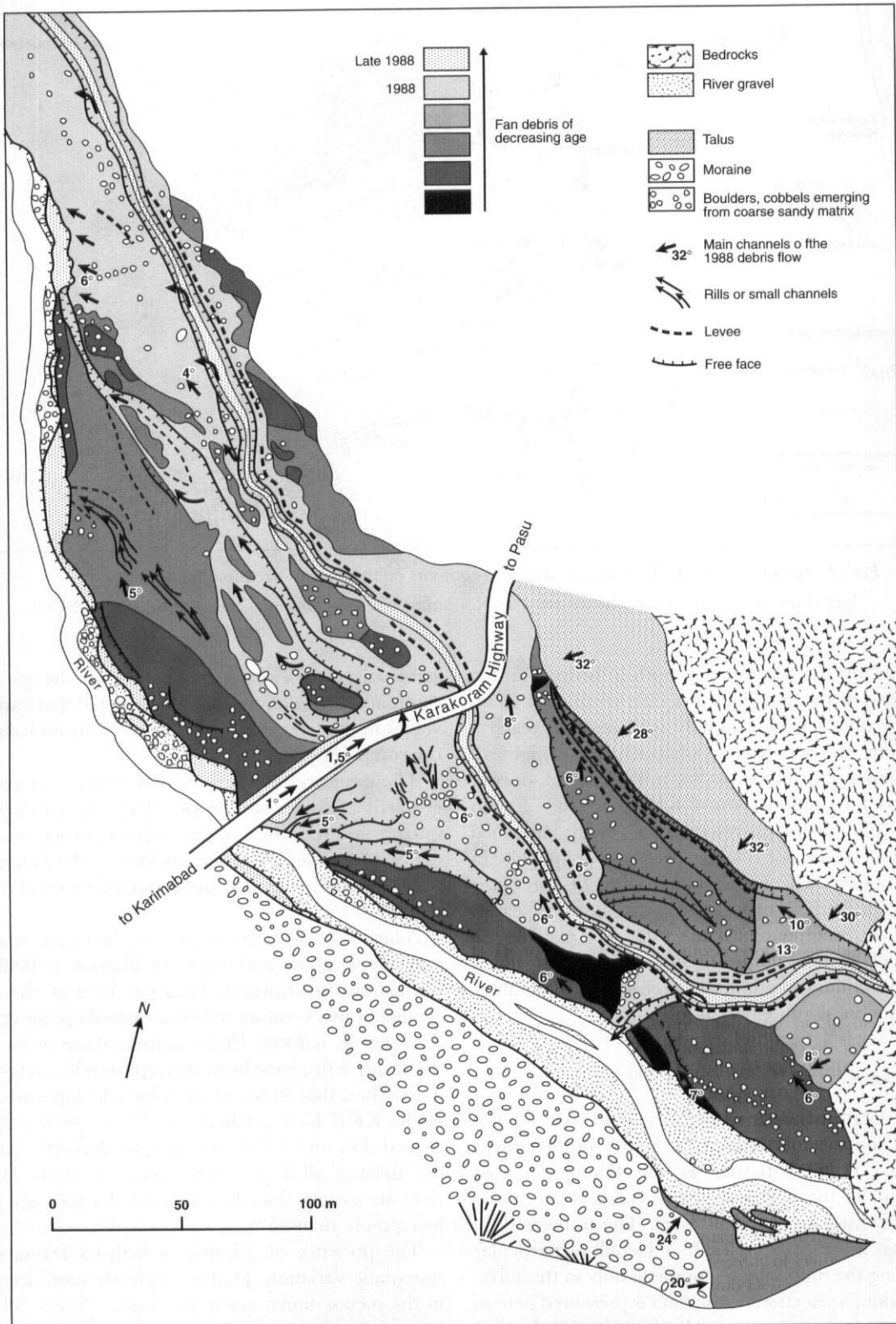


Fig 13: Sedimentary facies map of the Ayeenabad site
 Karte der Sedimentausbildung im Ayeenabad-Gebiet

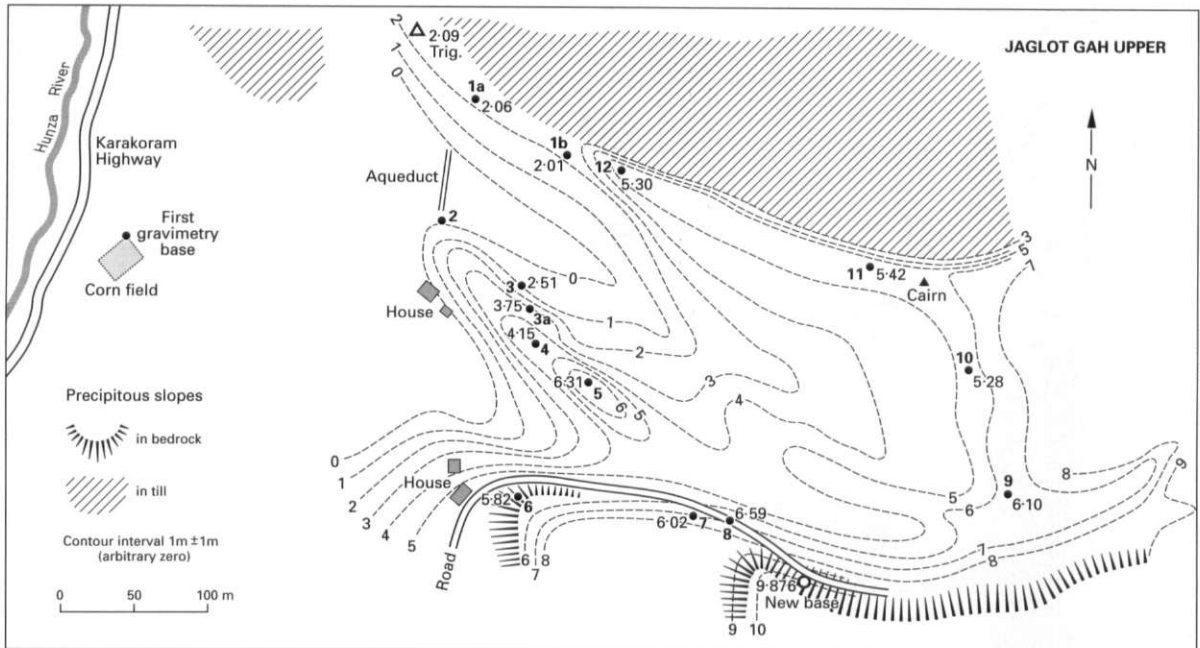


Fig. 14: Site map of the Jaglot Gah site, with 1 m contours on the plateau-like moraine surface

Lageskizze des Jaglot-Gah-Gebietes (mit 1-m-Konturlinien auf der plateauartigen Moränenoberfläche)

survey at this site suggested a depth to bedrock in the ridges east of the aqueduct of a little more than 40 m, with the till thickening rapidly westwards to reach a maximum of over 180 m adjacent to the highway. The inference is that some six million m^3 of unconsolidated till overlooks the KKH along this 400 m stretch, an enormous reservoir of easily disturbed material consisting of boulders, cobbles and pebbles in a silty matrix. The recurrent blocking of this short length of the KKH, by wet flowage in the rainy season and by the winnowing away of the silty matrix with release of destructive boulders in the dry season, is likely to continue indefinitely. There is no obvious alternative line for the highway at Jaglot Gah.

6.2 Highway logging: a review of the data-base

The detailed field logs form the data-base for this study of the 263 km length of the Karakoram Highway from the Chinese border at the Khunjerab Pass (4,600 m) to the bridge over the Gilgit River, about 5 km downstream of Gilgit town. The framework of these logs is presented as Table 3. Details of particular sites along the highway are complete only in this table. In addition, a selection of the data is presented here in a set of computer-drawn graphs (Figs. 15–18) showing the incidence of particular conditions or environments against distance in km below the Khunjerab Pass. This

summarized data set forms the basis of the statistical summary that follows. It should be noted that variance values in the field logs are replaced by mean values in the computer-generated graphs.

The *environment* is characterised by data on average gradient of valley-side slopes (Fig. 15), jointing frequency and condition in the bedrock, structures, incidence of exposed bedrock, incidence of Quaternary sediment cover (Fig. 16), and geomorphological setting (Fig. 17).

A fact of major importance is the high proportion of steep slopes above and below the highway to be found throughout this transect. Data for three of the slope gradient ranges considered geomorphologically critical (CARSON a. KIRKBY 1972), namely those at ca. 27° , $>33^\circ$ and $>40^\circ$, have been derived from the data-base. These show that 28.6% of all valley side slopes adjacent to the KKH have gradients of 27° or greater, 22.8% exceed 33° , and 13.2% are steeper than 40° . Almost one third of all slopes on the left bank of the Hunza river are steeper than 27° , the value for the right bank being more than 25%.

The presence of jointing in bedrock shows some systematic variation. Jointing is clearly more frequent in the metasedimentary series, about 13% of all sites being jointed compared to less than 2% in the "undifferentiated" bedrock types, and only 6% in the metamorphic/metavolcanic series. Grade 3 jointing (i.e.

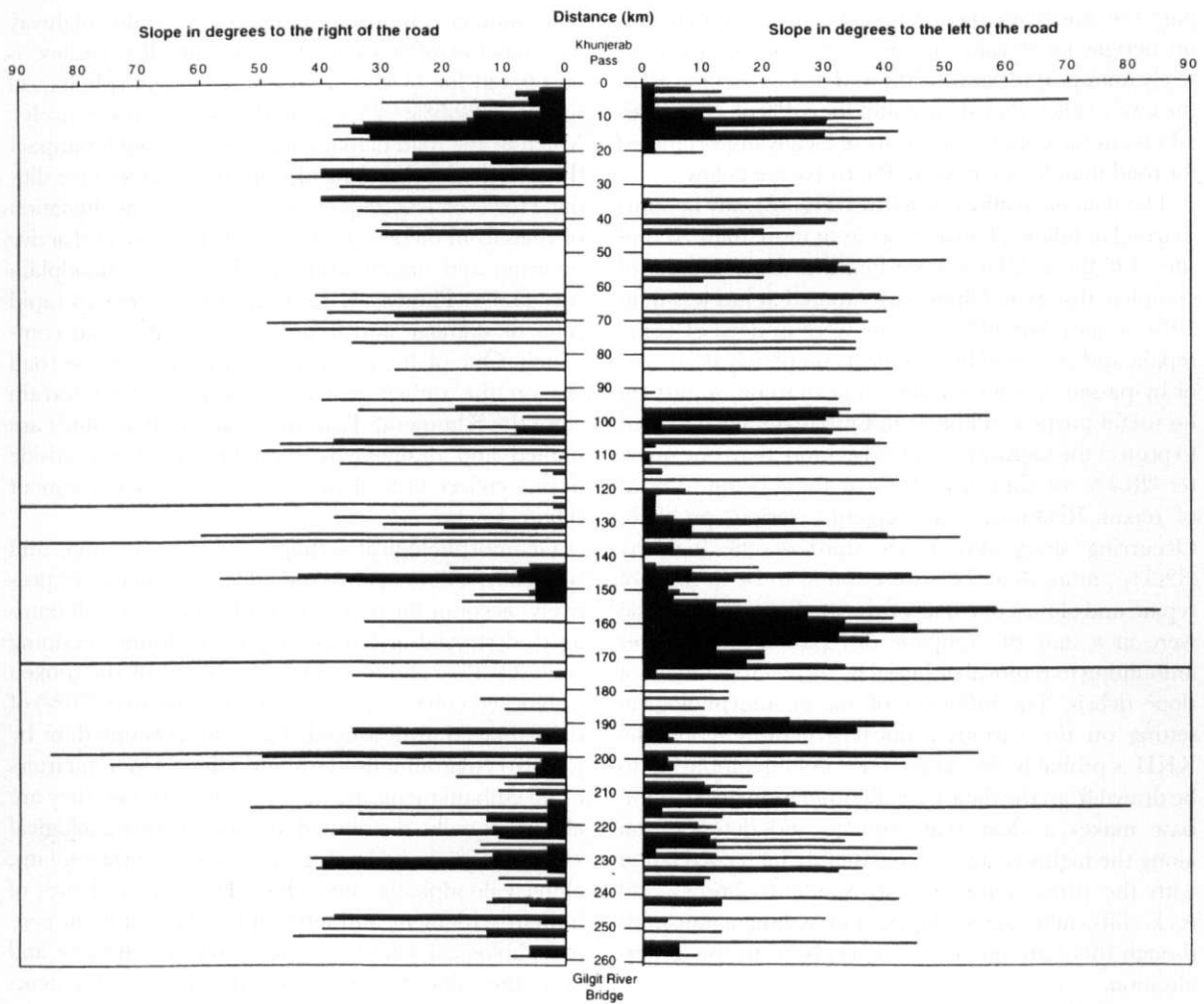


Fig. 15: Slope in degrees to left and right of the KKH from Khunjerab Pass (0 km) to the Gilgit River Bridge (260 km)

Hangneigung (in Grad) entlang der linken und rechten Seite des KKH von Khunjerab Paß (0 km) bis zur Gilgit River-Brücke (260 km)

open joints) shows the same trend, the values being 10.0%, 1.1% and 4.6%, respectively. Taking the transect as a whole, grade 3 jointing was recorded at over 15% of the 273 observation sites along the highway, a relatively high value and one of some importance given the frequent incidence of very steep slopes.

Of the nine geomorphological settings logged at each km post, three are clearly predominant. Gorges and rock cliffs were recorded at almost 25% of all sites, talus/scree slopes occur at more than 24% of sites, while sediment fans (for definition, see DERBYSHIRE *et al.* OWEN 1990) occur at 36% of all sites. Sediment fans are thus the most common geomorphological environment. As is shown later, the high incidence of fan and talus slopes is of great importance in influencing the deterioration of the highway.

All other geomorphological settings show a much lower frequency of occurrence, although some clear contrasts remain between the upper and lower reaches of the Hunza River. Terrace surfaces make up almost 14% of all sites but, as expected, they are much more frequent in the lower reaches (17.5%) than upstream (4.1%), reflecting the importance of braided channels in basin reaches of the valley and at sites influenced by actively-encroaching lateral sediment fans.

Till and hummocky moraine sites (6.9%) are fairly evenly distributed down the valley (upper 7.8, lower 5.8%), but river cliffs in terraces (with a similar over-all incidence of 6.8%) show a marked asymmetry (upstream 2.1%, downstream 12.5%). Sites located in re-entrants and tributary gullies (6.1%) also show an expected higher incidence downstream (10.8%) com-

pared to upstream sites (2.1%). Finally, although sites on periglacial terrain and avalanche tracks are relatively unimportant statistically and do not occur at all in the lower valley, they do account for 6.4% of all recorded sites in the upper valley and are locally important *loci* for road maintenance work (Photo 10; see below).

The data on artificial structures (Fig. 18) may be summarised as follows. Culverts occur at more than 20% of sites. Of these, 39.6% were found to be in a state of complete disrepair. Chutes are situated at just less than 10% of sites, but 44% of these were in need of some repair, and 16% had been almost completely destroyed or by-passed by gully erosion and extension, so serving no useful purpose (Photo 10). Embankments designed to protect the highway occurred at more than one quarter (28.4%) of sites, over 16% of these being in need of repair. Retaining walls present a serious problem. Occurring along almost one third of the highway (32.3%), more than 72% were found to be in need of repair, and almost one half of the total number (46.4%) were in a state of complete disrepair in many cases amounting to removal or burial by the encroachment of slope debris. The influence of the geomorphological setting on the various artificial structures along the KKH is probably the single most useful relationship to be drawn from the data-base. Examination of the data-base makes it clear that damage and deterioration along the highway show a consistently high correlation with the three dominant environments (gorges and rock cliffs, talus/scree slopes, and sediment fans), although there are one or two exceptions to this generalisation.

Road-edge drains were present along 38.4% of the highway in the surveyed region. They were in a sorry condition, however: 91% were in need of some repair, and nearly two-thirds (59.85%) were completely blocked or broken. These serve no useful purpose and, in many cases, they cause undermining of the metalled road surface.

Land use in four categories (pastoral, cultivated, tree cover, and settlements) was noted at 78 of the 273 km posts, i.e. 30% of all survey points. More than 74% of these occur below km 140.

The KKH is a very steep road between the Khunjerab Pass and the Gilgit River. Only 5.3% is more or less horizontal ($\pm 0.5^\circ$), over one quarter (27.6%) is inclined at 3° or more, and over 10% of its length is steeper than 4° . That part of the highway steeper than 3° lies in the three dominant geomorphological environments (gorges and rock cliffs 17.8%; sediment fans 22.7%; and talus/scree slopes 20.7%). This pattern is almost perfectly reproduced in the sections steeper than 4° , and is closely reflected in the statistics for road sur-

face damage. Almost three-quarters of the highway that has lost 50% or more of its metalled surface is accounted for by these same three geomorphological settings (22.5%, 25.3% and 23.9%, respectively). Much of the road damage is a result of boulder impact (Photo 4), mass slumping of slope debris, and scree sliding. However, less frequent processes such as eluviation of fines from till beneath the highway (10%) and active scouring and undercutting in alluvial and floodplain sites (5.6%; Photos 11, 12) may also give rise to rapid rates of damage and frequently sever the road completely. One of the best preserved sections of the road lies on the rather gently-sloping permafrost terrain close the Khunjerab Pass, where snowfall amounts are limited and drainage is good because the roadside drains collect little debris in this slope environment (Photo 13).

Geomorphological settings 1, 5 and 8 (gorge and rock cliffs, sediment fans, and talus/scree slopes, respectively) account for over two-thirds (68.6%) of all damaged, destroyed or blocked road-side drains, retaining walls (69.4%), and for over half (58.5%) of the broken or blocked culverts. More than three-quarters (76%) of the damaged or destroyed chutes are accounted for by just two environments (fans and talus). Three-quarters of all embankments are in a state of disrepair: they are almost equally distributed in five geomorphological settings (15% in bedrock gorges, terrace surfaces, fans, alluvial floodplains, and talus). The scattered sites of human settlement and agriculture are mainly in geomorphological settings 4 and 5 (terrace surfaces and fans), the values being 100% in the case of settlements and 56.4% in the case of cultivated ground.

The principal hazards (Fig. 19) include rock and debris slide and fall; flash flooding and fan progradation (including glacial meltwater fans); undermining by fluvial abstraction (especially in the case of the Hunza River, but also on parts of the Khunjerab River); and failure of cliffs of glacial till by saturation of silt matrix giving rise to mass flowage (in the wet season) and aeolian removal of silt matrix and consequent release of boulders (in the dry season). The latter process has received little mention in the literature. The rockfall/debris fall hazard is widespread in the lower valley, but of significance only in the central (gorge sections) of the upper valley. A broadly similar pattern is shown by the mud flow/debris flow hazard, but road failure by subsidence is a much more common hazard in the steeper, upper part of the Hunza valley. The flood hazard is fairly evenly spread down the whole valley. Locations where debris covered glacier ice directly threatens the KKH are relatively few in number. However, the effects at such sites are usually severe (Photo 14).

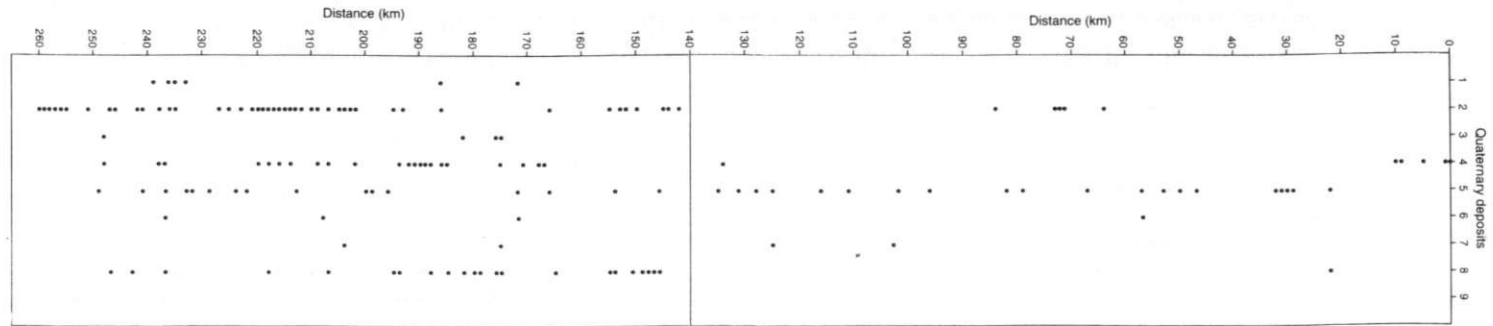


Fig. 16: Incidence of Quaternary deposits along the KKH between Khunjerab Pass (0 km) and the Gilgit River Bridge (260 km)
 Vorkommen von Quartärablagerungen entlang des KKH vom Khunjerab Paß (0 km) bis zur Gilgit River-Brücke

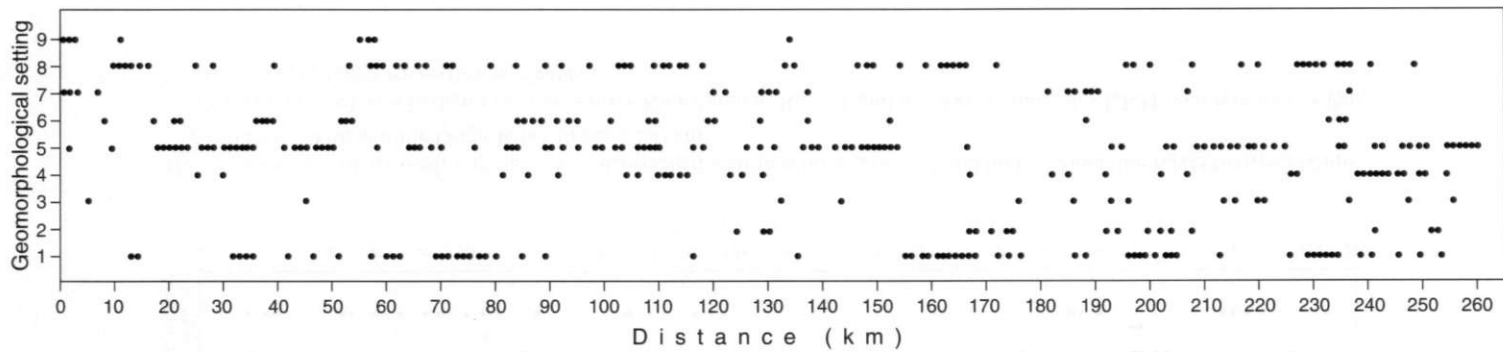


Fig. 17: Geomorphological settings along the KKH between Khunjerab Pass (0 km) to the Gilgit River Bridge (260 km)
 Geomorphologische Umrahmung entlang des KKH vom Khunjerab Paß (0 km) bis zur Gilgit River-Brücke (260 km)

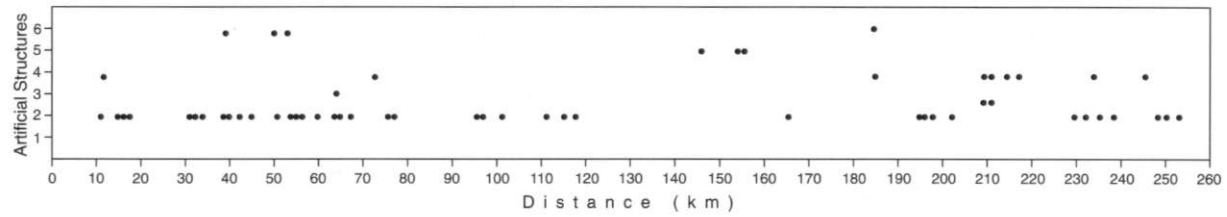


Fig. 18: Incidence of seriously damaged or destroyed artificial structures (grades 4 and higher) along the KKH between Khunjerab Pass (0 km) and the Gilgit River Bridge (260 km)

Vorkommen stark beschädigter oder zerstörter Kunstbauten (Rang 4 und darüber) entlang des KKH vom Khunjerab Paß (0 km) bis zur Gilgit River-Brücke (260 km)

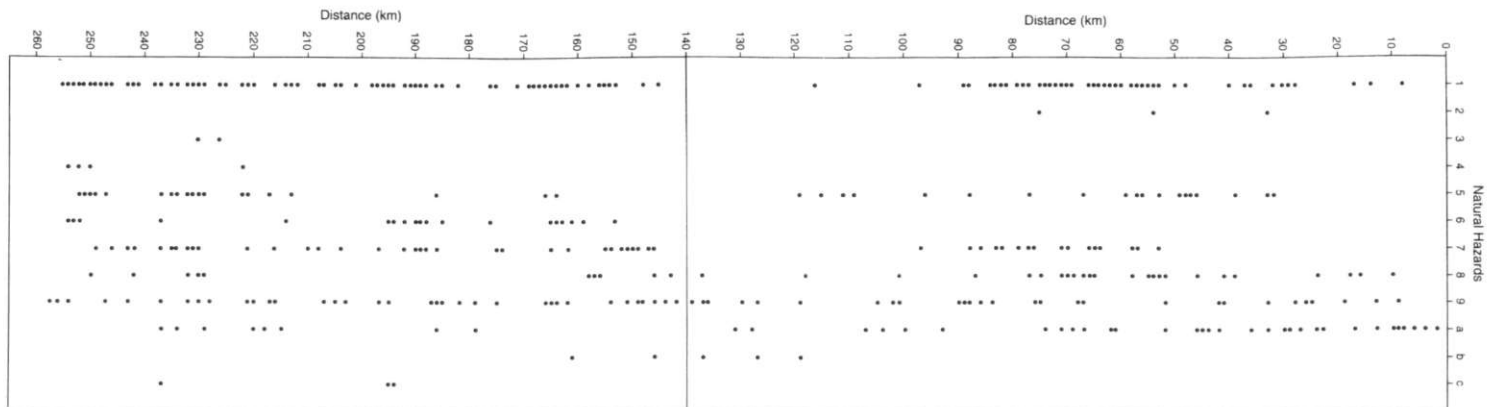


Fig. 19: Types of natural hazard along the KKH between Khunjerab Pass (0 km) and the Gilgit River Bridge (260 km)

Typen naturräumlicher Hazards entlang des KKH vom Khunjerab Paß (0 km) bis zur Gilgit River-Brücke (260 km)

7 Discussion

The data presented here indicate that the Karakoram Highway deteriorated at an accelerating rate in the period 1980–1988.

There is a relatively clear zoning along the KKH of high and low hazard zones. The stretches with lowest hazard are found on the very large, gently sloping, duricrusted late Pleistocene debris fans. The highest hazard zones are associated with active scree slopes (surface gradients 36–41°), active glacial and nival meltwater fans, eroding lateral moraines at tributary valley junctions, and steep reaches of the major streams (e.g. the Khunjerab River). The zones of specified hazard pointed out in a survey of the lower half of the Hunza valley (JONES *et al.* 1983), and equivalent to km 113–260 of our survey, remain active with evident deterioration of conditions having occurred in the period between the two surveys (1980–1988). Direct comparison of the two surveys over the common ground of the lower valley is not practicable because different recording schemes were adopted. The earlier survey obtained data by “stopping at least once within each geomorphological unit recognized” (JONES *et al.* 1983, 339), while our survey is based on stops at every km post. Nevertheless, comparison of selected data from our lower valley data-set with similarly defined information shown in Figure 22 of the paper by JONES *et al.* (1983) suggests significant deterioration of road and site conditions over the eight year period. For example, the 113–260 km stretch of the road showed 11 instances of bridge damage in 1988 compared to 5 in 1980, 7 as against 2 blocked culverts, 10 compared to 5 cases of road subsidence, 33 compared to 18 mudflow sites, 19 compared to 9 scree fall locations and 67 as against 30 sites with debris or rock falls.

Certain structures are consistently under-designed on the KKH. For example, the culverts are invariably too small for either the apparent catchment area, the grain size of the adjacent slope debris, or both. Although not always of too small a diameter to transmit peak water discharges, some are clearly smaller than the mean diameter of the boulders in the debris upslope of them. As a result, they are being plugged and damaged and, in many cases, sediment and water now entirely bypasses them.

8 Conclusion

Progressive improvements in road communications in the Hunza valley since 1947, and particularly the opening of the KKH in 1978, have led to some funda-

mental changes in the social and economic geography of this region. KREUTZMANN (1993; 1994) has shown how, first the jeep roads, and then the KKH enhanced the mobility of the village populations leading to re-settlement within the valley and to out-migration to Gilgit and beyond. There have been some striking collateral changes in village form and function, land use and within-valley commuting.

Such changes are irreversible, and present and future patterns of settlement and economic activity in the Hunza valley will remain intricately dependent upon the quality and maintenance of the KKH. This is a formidable commitment in terms of both financial and human resources, as the rates of deterioration of the highway indicated by this survey suggest. The main geo-hazards are sliding and falling rock and debris, flash floods, fan progradation, collapse induced by fluvial abstraction, and cliff failure in thick deposits of glacial debris. Although examples of these may be found in places along most sections of the highway, the vulnerability of the KKH shows considerable variation along its length. Three of the nine recognized geomorphological settings predominate as sites of rapid degradation and change: gorges and rock cliffs, talus/scree slopes, and sediment fans, the latter being the commonest geomorphological environment along the highway. Moreover, geomorphological setting is the greatest single influence upon the condition of the various artificial structures along the KKH. More than three-quarters of the damaged or destroyed drainage chutes and culverts occur in just two geomorphological environments (fans and talus slopes). The survey found that three-quarters of all embankments are in a state of disrepair.

From its earliest days, the KKH has been kept open by a substantial labour force (with military personnel present on a continuous basis), supported by limited mechanical equipment for earth moving operations. However, operations undertaken to keep the highway open do not appear to include evaluation of the sustainability of the original road alignment in the light of developing hazards. In the absence of a programme of systematic re-appraisal and re-design, more than half of the surface of the KKH was destroyed in the 8-year period 1980–1988. As suggested by certain recent improvements along sections of the roadway, new strategies are required so as to reduce the risk of further deterioration of the highway, with associated escalation of maintenance costs. Periodic monitoring and adaptation of alternative design strategies in the most vulnerable stretches of the road may go some way to alleviating the problem, but will require considerable commitment.

Acknowledgements

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