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Deep-seated mass rock creep along the Karakoram Highway and its geomorphological consequences in the Middle Indus Valley near Chilas, Northern Pakistan

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ABSTRACT: *Unexpected sudden landslides along the Karakoram Highway (KKH) are a common and feared phenomenon, but the causes have scarcely been related to processes of persistent rock creep, which are to be presented here. Mass rock creep in motion cannot be experienced by direct observation because of being an extremely slow type of mass movement; the rate of velocity measures only ~ 1-10 mm/a. However the results of these extremely slow rock movements are morphologically conspicuous and important from the point of view of engineering geology, especially along glacially eroded valley flanks as in the case of the Indus valley course in question.*

Mass rock creep in the sense of deep-seated gravitational slope movement produces irregular slope profiles with trenches accompanied by opening of joints, fracturing and dilation.

As a consequence the rock walls are progressively failing and exhibiting various phenomena of collapse structures sometimes even reaching the mountain tops and ridges, adjacent to the valley. In the course of our study on mass rock creep in the region of Chilas, ~ 8 km up- and downstream of this village, we can distinguish mainly two modes of slope deformation.

1. *Toppling movements, consisting of numerous book-like rock segments on the upper slope, rotating out of the slope, representing a primary system, resulting in convex slopes, sections through bulging.*
2. *Sliding movements, consisting of several massive rock (slabs) slowly gliding downwards upon each other, showing secondary listric bending of shear planes in the distal part near the slope foot, representing a secondary system, resulting in concave slopes.*

Geologically speaking the mountainous region of Chilas is made up of mafic-ultramafic plutonites of a former oceanic island arc, which have entered the geological literature as Chilas Complex of the Kohistan Arc in the Karakoram.

INTRODUCTION

From literature (among others: Briggs et al., 1997) we learn that gravitational slope movements range from rockfall to rockflow or deep-seated creep. Thus, it implies everything that is collectively called "landslide". Deep-seated creep, on which I would like to focus in this paper, shows the slowest rate of velocity, approximately 10-0.1 mm/a or even zero, i.e. the process is dormant. In our terminological usage creep is not confined to describing the process of pure flow, as was documented by ZISCHINSKY in 1966 and 1969 by the term "Sackung" (English sagging), but also describes other extremely slow movements on slopes such as toppling and very slow rock slides (Chigara 1992; Cruden & Varnes, 1996; Voelk, 2000). It might be added that climate and weathering are not prime factors for mass rock creep, though water can play an important role as soon as open joints or fractures have disrupted the compact mass of the slope. This is due to internal stress factors, which were brought about by gravitational forces usually acting subsequently to classical tectonics, the latter in the sense of mountain building tectonics or orogenesis.

A valley slope deformed by rock creep can be identified on the basis of the following features:

- the slope morphology exhibits certain characteristic forms, e.g. knickpoints, scarps, trenches, bulges;
- the linear features such as trenches run more or less parallel to the ridges and the river course;
- the rock masses involved show conspicuous disintegration and/or fragmentation.

GEOLOGICAL SITUATION

The region of Chilas is situated in the southern part of the Kohistan Magmatic Arc, a former intraoceanic island arc, comprising a sequence of mafic and ultramafic rocks, which is divided into three tectono-metamorphic complexes (Kazmi & Jan, 1997; Searle & Khan, 1998).

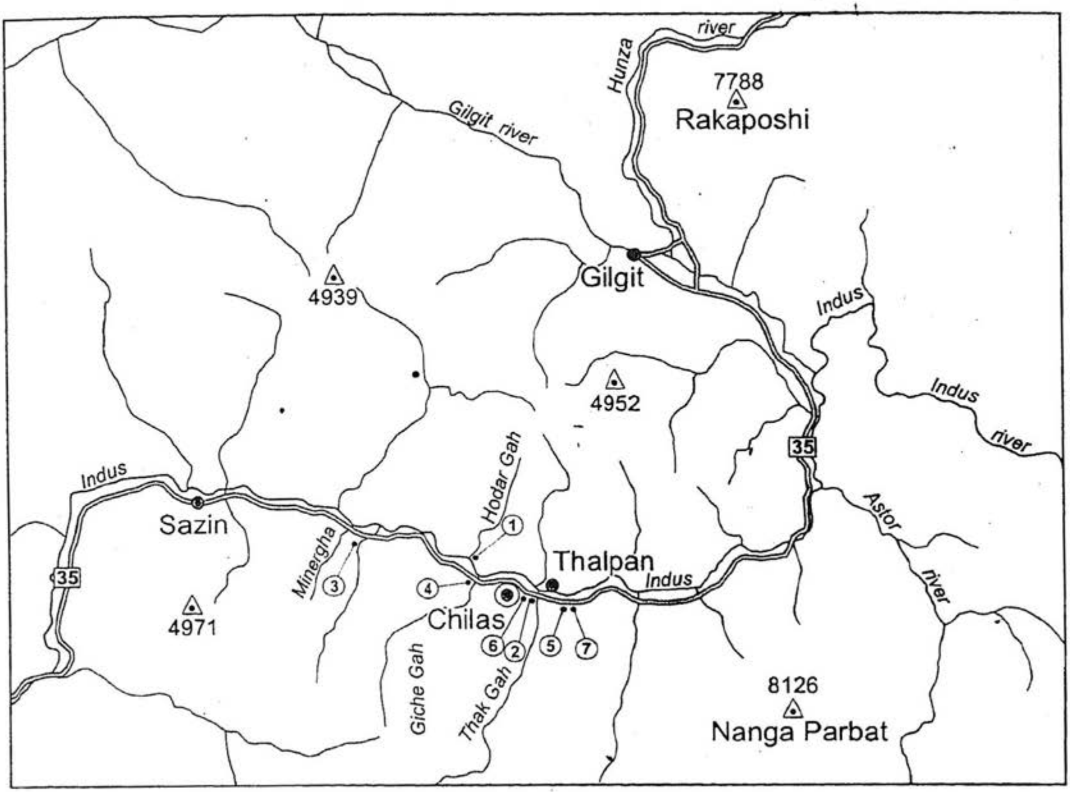
The famous Chilas Complex represents a body of layered norites and gabbros, metamorphosed to granulite and slightly foliated metagabbros and metadiorites. On account of a series of south-verging folds the rock sequence demonstrates a dominant trend of penetrative discontinuities striking NW-SE and dipping 45° to the NE. It also shows well developed, steep jointing in other directions.

GEOMORPHOLOGICAL OUTLINE AND CLIMATE

The Indus valley around Chilas (Fig. 1) was glaciated and deglaciated a few times in the Pleistocene, filled up with glacial, fluvioglacial, fluviodeltaic, fluvial and lacustrine sediments and, of course, more or less excavated again several times (Shroder et al., 1993). By combined action of glacial and fluvial erosion the Indus valley has been shaped into a deep and locally broad trunk valley, but the side valleys are frequently much narrower (Kuhle, 1997).

Nanga Parbat, Haramosh and Karakoram-Himalaya represent formidable high mountain regions in the immediate neighbourhood of the Indus river section in question. They reach an elevation of more than 8000m above sea level (ASI), accomplished by an amazingly rapid uplift of ~ 1.8 mm/a. No wonder that the rate of fluvial erosion is also tremendous in order to compensate for the mountain's uplift. Therefore we have to expect a dramatic impact upon the stability of the valley flanks.

The regional climate of the middle Indus can be characterized as a semi-desert climate, which is strongly semiarid with regard to rates of precipitation. The rainfall exhibits an Sub-Mediterranean touch by having a winter season with singular rain storms and a long marked drought during the summer season. Limited fields of wind blown sands on valley flanks are ascribed to episodic dust storms in the winter season. One observes quite an active process of developing desert varnish upon all exposed rock surfaces in glossy brown to blackish colours.



Slope movement sites	
site 1	E of Hodar Gah creek
site 2	W of Thak Gah creek
site 3	E of Minergha village
site 4	W of Giche Gah creek
site 5	E of Thak Gah creek
site 6	E of Thalpan bridge
site 7	Further E of Thak Gah creek

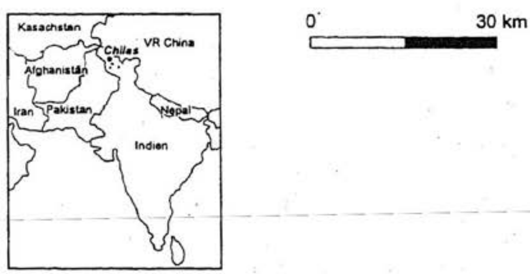


Fig. 1. Sketch of slope movement sites along the Indus valley in the neighbourhood of Chilas, Northern Pakistan.

DESCRIPTION AND INTERPRETATION OF SELECTED OCCURRENCES OF MASS ROCK CREEP

E of Hodar Gah creek (Site 1)

This site may illustrate the nature of a pure toppling feature. The most interesting outcrop is given there by a strangly prominent outstanding slab of rock. It represents a surprising feature of local relief at the outermost end or spur of a glacially abraded smooth ridge. As one can see on the picture (Plate 1) it abruptly rises to more than

5m at the downslope side and still seems to move by rotating out of the slope and turning down to the valley. The lack of varnish at the rim suggests an ongoing movement. At any rate this curious rock represents a classical toppling from postglacial time. The kinematics can be understood by studying Plate 2, which shows how the antithetic faulting took place, namely with the rock left of the steep shear zone moving upward relative to the right side, eventually forming an antislope on the mountain side.

W of Thak Gah Creek (Site 2)

Just W of the Thak Gah tributary, where the Indus river has a stoss side on its precipitous concave bank, a well developed example of a rock slide can be observed (Plate 3, 4). The shear surface shows a listric bending (level of the Karakoram Highway), which is situated more than 30m above the Indus waterline. The slide must have moved slowly by laterally rotating in the manner of opening scissors. This can be inferred by the preservation and final position of the slide mass at the river side (Plate 3). Moreover, as the slide appears to be derived from the margin of a large glacially moulded rock, a roche-moutonnée (left part of Plate 4) it seems probable that the slide occurred after the last valley glaciation (VOELK & SCHMELZER in prep.). From Plate 3 it can be deduced that the presumed roche-moutonnée is covered on the mountain side by younger Pleistocene deposits.

E of Minergha village (Site 3)

This site represents the first example of a series of more complex slope deformations (Site 3 - 7). Viewing the Indus valley slope to the E of Miner Gah from a distance we recognize a valley flank which is interrupted by a set of trenches in a mesoscalic dimension (Plate 6, upper left). Taking a closer look at the slope surface we discover an extraordinary roughness of the superficial aspect; which is caused by an intense joint system crossing a well developed foliation or "layering" parallel to the slope (Plate 7, upper left).

Our interpretation conceives several stages of gravitational movements: (a) toppling movements, brought about by antithetic faults (thick arrows) together with an intensification of joints including innumerable discontinuities steeply dipping uphill; (b) a toppling-induced sliding along various foliation planes which resulted in an anastomosing system of shear planes and wedging features in the compressional zone at the footslope; (c) a possible repetition of the cycle of movements (a + b), which could have led to overthrusting (thin arrow) of the first cycle near the footslope (Plate 7).

Bovis & Evans (1996) were the first geoscientists, to my knowledge, to present the concept of toppling-induced sliding for an interpretation of slope deformations in the Coast Mountains of British Columbia.

The author is of the opinion that this concept represents a real step forward with regard to understanding of slope deformations of foliated plutonic rocks. It is the idea of a sucessive sequence of different rock mechanics, which supplements the principle of a progressive failure. For the slope deformation along the KKH it appeared as the key to interpretations at many cases (Sites 3 - 7).

W of Giche Gah Creek (Site 4)

The geomorphical situation and the slope kinematics W of Giche Gah Creek are to some extent similar to Site 3 (Minergha), but in this case, Site 4, the foliation is only of minor importance, more widely spaced or almost absent. However, in Plate 10 (left middle part) some traces of relictic foliation can be detected; they run parallel to the slide planes (Plate 10, lower left angle). An overall-look (Plate 8) at the upper slope of the site discloses the primary toppling movement through an impressive trench with its uphill-facing scarp (thick arrow). It is, however, the additional occurrence of a set of downhill-facing scarps at site 9 (Plate 8, upper left) that has made the site so interesting to study, because these scarps point to the existence of (secondary) slide movements and supports the observation of a toppling-induced slide movement subsequent to the first antithetic faulting along toppling rocks slabs. One of these slides is nicely documented by a distinct basal (shear) plane; it is inclined towards the river side and situated on the lower slope (Plate 10, lower left angle).

Plate 9 proves the secondary origin of the sliding motion in two ways: (a) by clear cross-cutting the steep antithetic shear planes and their uphill-facing scarps, (b) by the occurence of toppling features in a low angle footslope zone ($< 25°$) where topples cannot originate. This logic implies that the topples are not in situ, but have moved downwards via slide motion from their original place, i.e., from a steeper section higher up the slope.

A similar reasoning as for point (b) could explain the toppling features in the very footslope, which is given by Plate 9. There are two conjugating steep joints to be seen, one set inclined to the hillside (to the left), thus in an inherited antithetic toppling position; the other set is inclined downhill (to the right) and is supposed to represent a "complimentary disruption" as indicated in the model of Savage & Varnes, (1987; Fig. 2c).

Inside the tributary valley of Giche Gah creek the author encountered an instructive example of slope deformation in a transitional stage between toppling and initial sliding (Plate 5). Below a sharp break of valley slope - accomplished by an antithetic shearing of rock up- and outwards (toppling) on a rather steep rock face (~ 60° - 70°) forming conspicuous antislope - one finds a downhill-facing slope exhibiting rocks with an overturned foliation structure due to the antithetic outward rotation. Just downwards of the scarp the slope bulges and shows a rock mass disintegration by visible coarse fragmentation. Traces of listric fault planes in the lower part of the slope indicate an initial sliding movement.

E of Thak Gah Creek (Site 5)

The site offers the opportunity to study the compressional section of slow gravitational downslope movements, which have started as toppling-induced slides (compare Sites 3 and 4).

It is assumed, that the site shows two slides upon each other, but separated by a compressional anastomosing shear zone in between (Plate 11). The latter one consists of a series of elongated shear bodies or lenticular shear pods in slight inclination towards the river. The shear pods seem somewhat similar to the bottom features of Site 3 (Plate 7), but the rock material of site 5 appears to be more strongly tectonized regarding the internal fabric (Plate 12). Both slide bodies, underneath and above the shear zone, exhibit steeply dipping joints, which

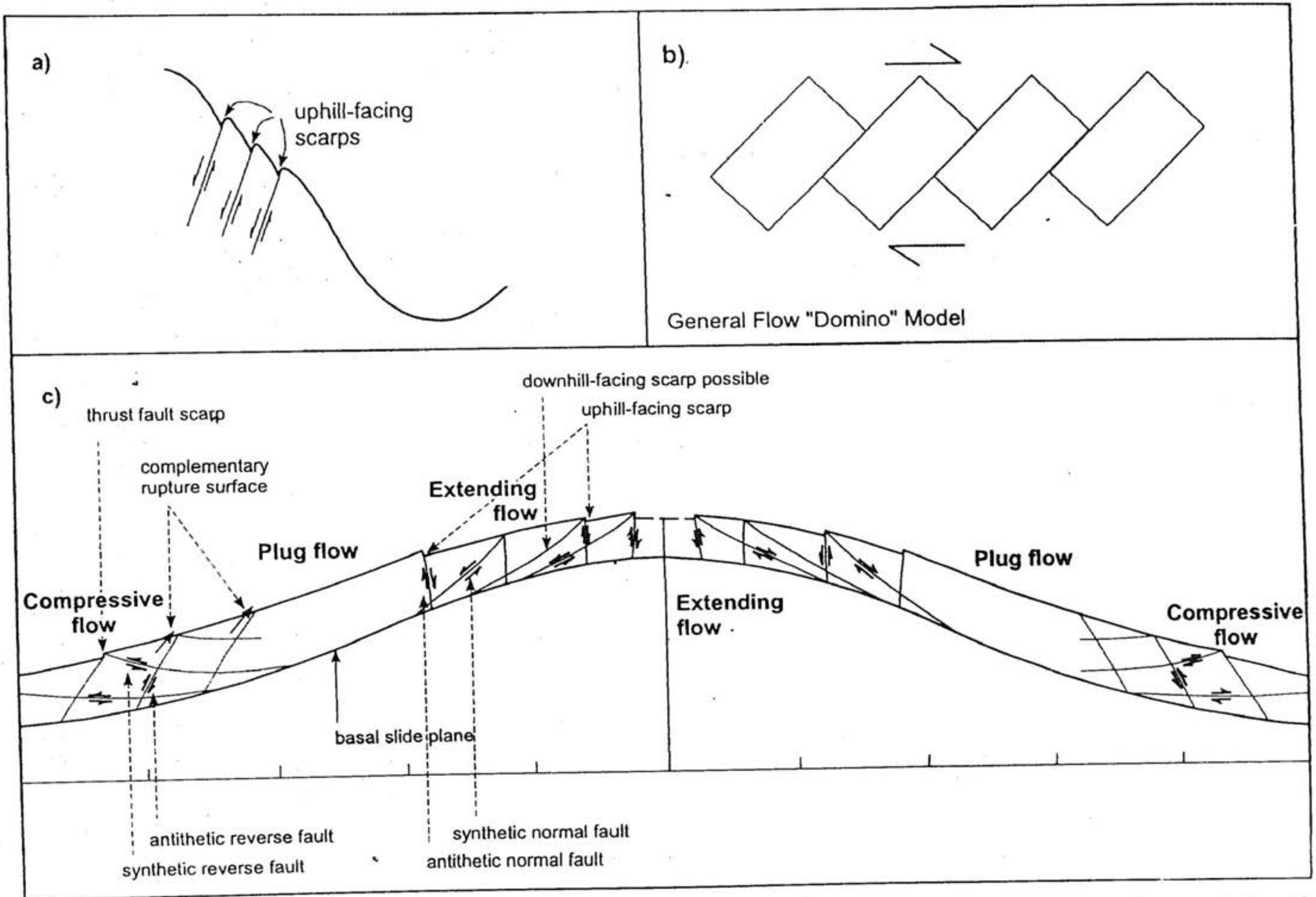


Fig. 2. a) Toppling mechanics with uphill-facing scarps (Bovis, 1982). (b) General flow domino or book shelf model (Hanmer & Passchier, 1991). (c) Model of flow regions and predicted senses of shear on rupture surfaces for a symmetric gravitating ridge (after Savage & Varnes, 1987; terminologically supplemented).

Plate 1. This peculiar outstanding rock at the mouth of Hodar creek (Site 1) demonstrates the typical toppling phenomenon with an uphill facing scarp. As indicated by arrows this giant block has rotated out of the slope towards the Indus valley (left) by app. 45°, from right to left side in the picture. Lack of desert varnish at the base of the antithetic fault plane (light coloured zone at legs of person) points to a still ongoing process of tilting.

Plate 2. Detailed picture of an antithetic fault movement toppling indicating typical gravitational toppling mechanics in connection with Plate 1, Site 1, Hodar. The slope is descending to the left (riverside). Note the crashing and partly grinding of hard rock into rock powder or fault gouge along the shear surfaces. The left part of outcropping rock, weakly foliated, has moved upward relative to the right part along a vertical shear zone (cf. Fig. 2 a, b).

Plate 3. This aerial picture facing a planar slide (Site 2) E of Thak Gah creek was taken from the opposite Indus valley side, near Thalpan village. The Indus river is visible in the lower part of the picture running from left to right (E - W) adjacent to the slide mass. The latter one has slid on a listric shear plane and thereby has rotated laterally, forming an angle of ~ 30° as indicated by arrows; on this assumption the structure of the slide mass would fit onto the head scarp.

Plate 4. This picture shows the same site as Fig. 4, but viewing the Indus river downvalley. It demonstrates the isolated slide mass, which is separated from the upslope area by a trench (highway). Note further the rocky hills surrounded by alluvial sand and gravel at the opposite river bank. They are assumed also to have moved gravitationally from an upslope area down to the floodplain, because they show the typical fracturing pattern of the rock mass.

are supposed to represent relict features of toppling movements prior to the mise-en-place of these slide units, i.e. during primary toppling motions higher up the slope. In the upper slide unit we recognize renewed extensional features of the toppling type, because of the strong, persistent Indus river incision adjacent to the outcrop (Plate 11, left margin). The detailed picture of shear pods in Plate 13, taken near to the above described outcrop (Plates 11, 12), intends to demonstrate that these rocks are gravely strained and certainly not in situ.

E of Thalpan Bridge (Site 6)

This site at the lowermost footslope near the recent Indus river incision can demonstrate the present collapse of highly strained slide remnants forming stacks (Plate 14), which obviously overlie a distinct low angle (<25°) shear plane (Plate 17). Regarding these stacks of brittle, highly fractured rocks we easily recognize the disintegration of these rocks (Plate 15 and 16) along their fissures. This strain occured mainly on account of toppling movements, although we must realize that the deformation pattern did not happen at the site, but two stages earlier, namely during primary slope movements (toppling) in a much steeper uphill slope. Then, in our opinion, followed a toppling-induced slide towards the thalweg, the observed stacks were part of the rockslide. This can be inferred by two distinct shear plains, one underneath and one above the stacks. At present these slide remnants or stacks have come to rest upon a well developed shear plain showing a polished stair-stepped thrust surface (slickensides) with striations, slickenlines and even crescentic grooves (Plate 17). It is remarkable, as already mentioned, that the stacks even exhibit small relicts pieces of a slide plane as capping surface (Plate 14, 16). This means that the rocks in question were part of a slide with an inherited joint pattern now falling apart.

Further E of Thak Gah creek (Site 7)

About 4 km E of Thak Gah creek one encounters Site 7, which is suited to describing a typical distal position of a toppling-induced slide along the KKH. We meet a low level area with a very rugged micro-relief stepwise ascending from the Indus river bank to the mountainous background at some distance (Plate 18, foreground). At first sight, the most variably deformed rocks seem to confuse the spectator, who also observes - besides many steep joint structures with varying dip direction - some subhorizontal structural features (Plate 19). The exposed rocks obviously represent a coexistence of toppling and sliding features, similar to the considerations for Sites 3 - 6. The author recognizes an overlap of slides separated by thrust planes (Plate 18). Nearest to the river side the compressional situation is currently converting into a renewed extensional one, due to ongoing river incision.

CAUSES AND GEOMORPHOLOGICAL CONSEQUENCES OF SLOPE DEFORMATION

Since we know, that the Indus valley around Chilas was probably glaciated several times (Shroder et al., 1993; Kuhle, 1997; Voelk & Schmelzer, in prep.) we must imagine that a well developed U-shaped Indus valley had existed in early postglacial time, i.e. after the last valley glacierization.

From that time onwards the erosionally oversteepened valley flanks experienced a phase of glacial rebound and release of locked-in stress. This meant, that the rock slopes have not remained in a stable position as formed by glacial and fluvioglacial action, because a vigorous fluvial undercutting of river banks has started, too. So the slopes have been subjected to strong gravitational tensions, which led to deep-seated rock creep or "rock flow" (Savage & Varnes, 1987)

Plate 5. A view upon the left side of Giche Gah creek (Site 4), inside the tributary downvalley to the main river Indus in the background. It shows a typical example of gravitational slope deformation: firstly in the upper slope two trenches with uphill-facing scarps produced by toppling movements (thick arrows), which have resulted in an oversteepening of the foliation (stippled lines); then a secondary toppling-induced initial sliding (thick arrow) below a downhill-facing scarp and finally bulging of the lower middle slope. The bulging has been produced by dilation due to extensive fragmentation of rocks into coarse blocks.

Plate 6. The southern valley flank of the Indus river near the village of Minergha (Site 3) is characterized by several trenches, which interrupt the flank and show uphill-facing slopes on the downward side of the trenches, indicated here by arrows. These features are assumed to have originated by toppling movements. Note the coarse, locally even blocky slope (cf. Plate 7)!

Plate 7. This view shows a slope profile of site 3 (Plate 6) in more detail looking upvalley along the Indus valley flank. The primary toppling movement (thick arrows) at the upper right of the picture has produced a break in the slope. Innumerable joints (from upper left to lower right) parallel to the toppling shear plane cross cut the foliation which runs more / less parallel to the slope (from upper right to low left). This kinematic might explain the rectangular fragmentation of the exposed rocks. Note the combined secondary movements of slippage oblique to the foliation (lower part of picture) leading to wedges and incipient shear pods (German phacoids) along a zone of moderate inclination (app. 45°) towards the thalweg on the left, outside of picture.

Plate 8. View upon the southern valley flank of Indus river looking up-valley W of Giche Gah creek, site 4. High up in the slope one observes a trench with a large uphill-facing scarp (shadow), which is interpreted as a toppling feature (thick arrow) related to a primary gravitational slope movement. This in turn is followed by toppling-induced sliding and finds its expression by a set of normal fault scarps (thin arrows) at the slope profile near the descending horizon (middle part). These scarps are downhill-facing towards the river bank (out of picture) to the left, a morphology which indicates sliding kinematics. Note also the curious scarplets characterizing the rock slope in the lower part, middle to right in the picture.

Plate 9. The rock deformation at the footslope of site 4 approaching the Indus thalweg (on right) W of Giche Gah, similarly demonstrates two types of mechanism: firstly, primary toppling of large rock slabs showing sheared joints (thick arrows), steeply dipping to the mountain-side (left), secondly, traces of steep normal faults dipping to the valley side (on right) and being secondary because cross-cutting the former ones. The normal faults are to be connected with a basal slide plane (concave arrow) which is assumed to exist underneath the outcropping rocks.

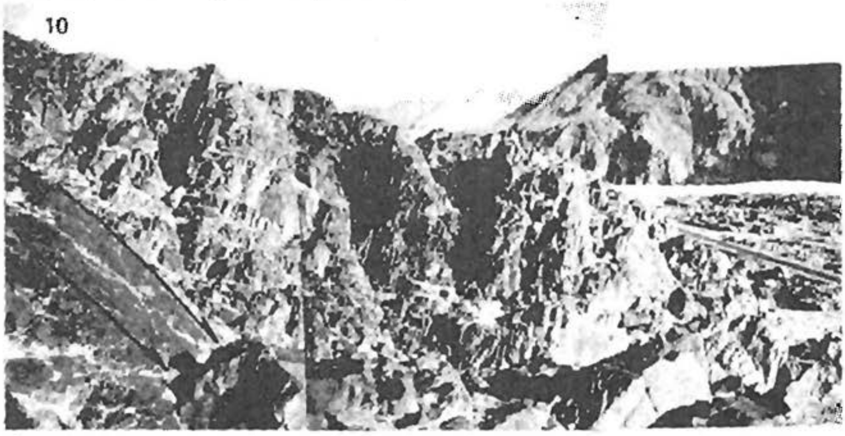


Plate 10. This view down-valley along the Indus river at site 4, W of Giche Gah, exhibits the inferred combination of gravitational slope movements: in massive, only faintly foliated magmatic rocks, somewhat upslope of the situation of Plate 9. Impressive upward-facing scarps of toppling movements (thick arrows) dominate the picture (mainly in the upper section), whereas the slide plane is visible (thin arrows in the lower left) dipping more or less parallel to the relictic foliation at left middle section towards the Indus river bank (at right).

Plate 11. This view shows an outcrop along the Indus river E of Thak Gah creek (Site 6) looking upstream. In the middle part of the outcrop one mainly observes a typical example of a compressional zone with an anastomozing pattern of slide planes showing lenticular shear pods (stippled lines), which stretches with appr. 30° from the upper right to the lower left towards the thalweg of Indus river. Yet below this zone (lower right corner of picture), we recognize short relictic joints steeply inclined towards upslope (short thick arrows), capped by a polished shear plane which functions as a basal plane delimiting the shear pod zone above. Similarly the pattern of discontinuities in the upper part of the outcrop above the slide zone appears to be dominated by steep joints and scarps partly uphill-facing relictic scarps of recently toppling (upper short arrows), partly traces of normal faults. We interpret the rock mass of the outcrop as being not in situ, but emplaced by several slides.

Plate 12. This detailed view of Plate 11 (middle part) is focused on the lenticular shear pods forming a zone of compression at the foot of a larger sliding complex. In addition we are able to recognize intercalated small zones of intensified shear strain showing small scale rock "lentils", at lower left and lower right of picture. In the foreground a few relictic steep joints can be observed inside a shear pod, which points to a toppling motion previous to the sliding emplacement, when the rock mass was in a steep slope position high up at the valley flank, where alone they can have originated.

Plate 13. This photograph, taken at the same Site 6, E of Thak Gah creek as Plates 11 and 12, again demonstrates the compressional slide-origin of these rocks. One observes a general shearing movement from upper right to lower left, especially the development of lenticular shear pods (German: phacoids) and of crashing rocks in connection with wedging at various spots in the outcrop. It proves that these rocks are not in situ.

Plate 14. This picture, which is taken E of Thalpan bridge (Site 6) looking upstream along the Indus river (left), shows in the foreground a rugged terrain of rock stacks characterized by steep scarps and joints, running obliquely to the viewer. Note a small relic of a former shear plane obliquely situated at the top of a stack adjacent to the right side of the highway (cf. Plates 15, 16).

Plate 15. Evident toppling features bound the Karakoram Highway E of Thalpan bridge on the same site as Plate 14, but viewed downstream. The steep open joints are inclined towards the left (mountain side). Some faint features of foliation can be observed in the middle of the outcrop dipping (30°) to the right, i.e. to the river side with standing person. The blocky appearance can be explained by the intersection of foliation (= shear) planes, with the steep joint (= shear) plane. These rocks with its wide open fissures represent an extremely released stage at the edge of the river bank being apt to fall apart in the near future (cf. Plate 16). Note, that these rocks are assumed to be not in situ, because they represent a relictic part of a rock slide from the upper slope which rests on a distinct and well documented shear plane (cf. Plate 17).

Plate 16. This picture from Site 6, adjacent to Plates 14, 15 and 17 shows toppling features analogous to Plate 15, but the fragmentation has led to smaller components of rocks, due to an intensified shearing motion, more or less parallel to the foliation inclined to the left (dotted lines) as well as old and now renewed antithetic motion along steep joints. Small relics of a former shear plane (dark coloured by desert varnish) are visible both at the top of the outcrop and at the base (left behind the outcrop). Note that these outcropping dismembered rocks as a whole are not in situ, because they are relictic parts of a series of rock slide masses, which originated from the upper slope and came to rest on the footslope.

Plate 17. Viewing upvalley along the Indus river, E of Thalpan bridge, Site 6, one recognizes well exposed varnished shear planes with steps and streaks in the foreground, dipping towards the thalweg, left side. Relicts of the slide masses, which have overlain and created these planes in the past occur in the immediate vicinity in the form of those isolated stacks of rock as depicted in Plates 14, 15, 16.

Plate 18. Profile of a protruding slide complex (cf. Plate 20) further E of Thak Gah creek, Site 7, looking upstream along Indus river (left, out of picture). We find three kinds of gravitational movements: in the first place a set of slides thrusting upon each other (arrows); secondly, a set of steep (vertical) joints as relictic features of toppling motion from the original previous upslope position. Thirdly traces of downhill facing scarps (rupture surfaces) and steeply inclined joints (shear planes) at the very left of the complex near the river side. The slide complex appears to have advanced unusually far across the river course (cf. Plate 20).

Plate 19. Detailed part of Plate 18, Site 7. It demonstrates again that these rocks are not in situ, but originated from gravitational sliding movements. In the lower and upper section one observes diverse directions of foliations and joints (thick arrows), mainly dipping uphill (to the right). The upper section separated from the lower one by a shear plane (thin arrow), shows similar features, but is different in detail. It is assumed, that the outcropping rocks represent a set of slides with relictic toppling features derived from a much higher and steeper upslope area. The mass has come to rest on the flat footslope approximating the Indus river (cf. Plate 20).

almost everywhere along the Indus valley with the exception of those sections where Pleistocene deposits, e.g. glacial till or paraglacial conglomerates and sands, were supporting the rock slopes.

The geomorphological consequences can be recognized in two dimensions:

Plate 20. This aerial photograph viewing downvalley shows the course of the Indus river bending around the protruding slide complex (arrow), further E of Thak Gah creek (Site 7); note a significant swing of the river to the right (middle ground of picture). The village of Chilas (dark streak) appears situated on a large pediment-terrace in the background.

a) General tendency of lowering of the slope inclination on a large scale. For example, the observed rock creep or "rock flow" locally has produced slowly advancing foot slopes pushing the Indus thalweg towards the opposite flank and forcing the river course to bend around the slowly approaching (creeping) rock mass (Plate 20, 21).
b) A general geomorphological change of outer appearance on a meso- and micro-scale. Innumerable surface exposures of rocks for example show an unexpected roughness or curious irregularities such as blocky, spiky or pointed surfaces, which definitely do not fit a glacially polished landscape, but must be ascribed to subsequent gravitational rock deformation by slope "tectonics" (e.g. the "pinnacles" on Plate 8, right side).

Plate 21. The picture shows the profile of the southern Indus valley flank near the mouth of Giche Gah creek (Site 4) looking downvalley. It demonstrates how the river is forced to bend around advancing tongues of rock creep accomplished by sliding mechanism (arrows). Rock tongue in the foreground is situated just at the mouth of the Giche tributary; note further the dark coloured rock slide tongue in the right / middle background, a few kilometers downvalley, representing again a rock creep-forced river-bend.

DISCUSSION

Two types of slope deformation play a special role in the area of investigation: rock toppling and rock sliding. After Selby (1982, p.166 and 171) toppling means an "overturning of rock columns" and sliding is defined by a well-developed shear plane underneath, which mainly runs straight. Both mechanics, however, are often not fully realized with deap-seated creep. As depicted in Figures 2a and b of this paper toppling units do not rotate completely and, on the other hand, slides do not always show simple shear planes at their base, but frequently exhibit a listric shear zone, divided into a set of shear planes intersecting each other in an anastomosing pattern what was nicely documented by Chigira (1992).

It is interesting to note that Bovis and Evans (1996) concept of a transition between initial toppling to toppling-induced slide, which was adopted by the present author, has provided a key of insight for most cases along the Indus river. However, we had to complement that concept by the assumption of inherited toppling features for those slides which now have arrived on the footslope, i.e. on a low gradient area, where toppling cannot be formed (Goodman & Bray, 1976). Therefore we believe that those toppling features were derived from the steeper upslope area, i.e. inherited from primary mechanics.

What can we call the slope deformations as far as depicted in this paper? The present author is inclined to employ the term "deep-seated rock creep" as already applied so far, quite in accordance with Chigira (1992). But it should be mentioned that there are also other partly more genetically orientated terminologies: Radbruch et al., (1976) and Varnes et al. (1989) prefer to speak of "gravitational spreading", Hutchinson (1988) of "slope sagging". After all Savage and Varnes (1987) presented a theoretical model for toppling-processes in upslope areas, a model in which they claim that "plastic flow" occurs in the failed region in response to gravity loading. The predicted senses of shear, given in Figure 2c, were classified into four directions. Table 1 has been complemented by the present author with regard to "type of movement" and "morphological features".

TABLE 1. SHOWING THE RELATIONSHIP AMONG SHEAR SENSE, TYPE OF MOVEMENT AND MORPHOLOGICAL FEATURES

Shear Sense	Type of Movement	Morphological Feature
Antithetic normal faults	toppling	uphill-facing scarps
Synthetic reverse faults	thrusting	stair stepped slopefoot (ramps)
Synthetic normal faults	sliding	downhill-facing scarps and slickensides on basal slide
Antithetic reverse faults	reverse rupturing	uphill-facing scarps

In the literature for microtectonics (e.g. Hanmer & Passchier, 1991) toppling-movement is considered part of a rheologically controlled flow and described as "domino or book-shelf model" displaying antithetic slips between the "books" (Fig. 2a, b).

Although the present author is not yet fully convinced of the appropriateness of those flow models for gravitative slope deformations as presented in this paper, they appear to be attractive and worth considering.

CONCLUSIONS

Scientific aspects

Summarizing the rock slope deformation around Chilas we have to distinguish two different modes of deformation:

- A primary system of toppling, as a rule in the upslope area. The movement occurs in the form of a collapsing "book-shelf" with upward-facing scarps and discloses extensional characteristics. The transitory nature of these movements is to be noted.

- A secondary system of toppling-induced sliding in the lower mid-slope and thrusting in the down-slope area, leaving downward-facing scarps. Lenticular shear pods (German phacoids) of variable size prove the compressional character of most foot slope zones.
- A tertiary tendency of renewed toppling at the steep edge of the recent and present Indus river (channel) incision, which seem to initiate the next cycle of slope movements.

The geomorphological effect of deep-seated creep on the Indus river course appears to be remarkable in view of a mesoscalic dimension, i.e. 500 - 1500m, whereby the river is forced to bend around places of a strongly prograding (creeping) slopefoot along its course.

Generally it can be stated that a large number of outcropping hard rocks in the investigated area along the Karakoram Highway cannot be considered as to be in situ, as they have been moved gravitationally.

Geotechnical aspects

Slope stability of the rock walls adjoining the mountain side of the Karakoram Highway is highly diminished at places with occurrences of active mass rock creep due to extreme rock fragmentation and bulging of slopes pendant above the highway. Practically all hard rock-derived pieces of debris falling or gliding onto the highway are produced by small rock failures, which accompany the continuous mass rock creep above the highway.

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