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ROCK AVALANCHE DAMS ON THE TRANSHIMALAYAN UPPER INDUS STREAMS: A SURVEY AND ASSESSMENT OF HAZARD-RELATED CHARACTERISTICS

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INTRODUCTION: NATURAL DAMMING ON THE UPPER INDUS STREAMS

Rivers of the transHimalayan Indus basin are subject to damming by glaciers and a variety of mass movements. Among the many catastrophic outburst floods, ice dam bursts dominate the historical record, but the two largest were from failure of landslide dams in 1841 and 1858 (HEWITT, 1982, 1998a). Far more numerous are impoundments by debris flows and snow avalanches, and along glacier margins (HUGHES & NASH, 1985; KREUTZMANN, 1994). However, they tend to be small, the inundations or outburst floods of fairly local significance. The largest, most long-lived natural dams in the late Quaternary have been due to deep-seated rock slides and rock avalanches. The paper focuses on the latter.

ROCK AVALANCHE DAMS

In surveys between 1993 and 2001 a total of 186 rock avalanches were identified in the region (HEWITT, 2002b). Most are prehistoric events reconstructed from deposits. Of these, 161 formed cross-valley barriers impounding stream valleys (Table 1). The table identifies main impoundments on the rivers named, barriers not fully breached, and those associated with up-valley lacustrine sediments and with superimposed rock gorges. On average, one rock avalanche was found for every 14 kilometers of stream thalweg surveyed, although actual spacing is highly variable (Figure 1). They occur throughout the basin, with massive rock wall failures occurring in all elevation zones and geological terrains (HEWITT, 1998b; SEARLE, 1991). There are impoundments in every conceivable stage of infilling and degradation. Landforms and sedimentary features associated with the rock avalanche barriers dominate much of today's fluvial zone. Perhaps their greatest role is evident in vast quantities of intermontane sedimentation accumulated behind the barriers. Much of this is being trenched and removed today. Yet, long after being breached and drained the barriers continue to constrain stream flow and sediment movement. Stream thalwegs and patterns of incision are affected by the sequence of rock avalanche barriers even more than by widely discussed tectonic activity (SEEBER & GORNITZ, 1983; BURBANK *et alii*, 1995). Unfortunately, there is a firm date for only one prehistoric event, a

RIVER	Cross-valley RA deposit	Existing lakes	Existing sediment barrier	Lake deposits	Epigenetic Gorge
CHITRAL BASIN					
Upper Yarkhun[1]	7		7	7	7
Laspur	3		3	3	1
GILGIT BASIN					
Ghizar	4		3	4	2
Gilgit	17		13	14	3
Yasin	5		5	4	1
Ishkoman-Karambar	10	1	7	7	2
Hirali	1		1	1	-
Bagrot	6		5	6	1
Batkor	1[2]		1	1	-
Kargah	3		2	3	1
Upper Hunza[3]	12		7	9	3
Chapursan	6		6	6	3
Hispar	1		1	1	1
Lower Hunza	6		4	6	4
Chalt	2		1	2	2
Naltar	5[4]	1	4	4	2
INDUS BASIN					
Middle Indus[5]	21		8	11	8
Right bank tributaries:					
Stak	2		1		
Tormik	2		2	2	1
Shigar	6		1	6	-
Baumaharel	2		2	2	1
Basha	2		1	2	-
Braldu	7		5	7	2
Dumordo	2		2	2	-
Shyok	4		4	4	1
Thalle	7		6	5	-
Hushe	9		7	8	2
Saltoro (lower)	2		2	2	1
Kondus	1		1	1	1
Left bank tributaries:					
Shigarthang	3		3	3	1
Satpara	3	1	2	2	-
TOTALS	161	3	117	115	45

Table 1 - Cross-valley rock avalanche barriers in the Upper Indus Basin. 1 - Parwak to Karambar Pass; 2 - Also dammed Gilgit River; 3 - Baltit to Sost; 4 - Includes Nomal barrier, which dammed mouth at Hunza River; 5 - From the junction with Gilgit River to junction with Shyok River

^{14}C age of 7150 years BP (uncalibrated) for Ghoro Choh I (HEWITT, 1999a). However, all indications are that the majority are late Pleistocene or Holocene events, emplaced on ice-free valley floors since the last major glaciation.

IMPOUNDMENT DIMENSIONS AND MORPHOLOGICAL CLASSES OF ROCK AVALANCHE DAMS

With few exceptions, the dams had an initial effective height, *i.e.* the lowest part of the cross-valley barrier – greater than 10 m. More than half exceeded 25 m, about 20% exceeded 100 m, and two were over 1000 m (Table 2). Dam height is positively correlated with rock avalanche size and width (parallel to stream valley), but there is considerable variability related mainly to terrain. The highest barriers involve relatively large volumes of rock avalanche debris that formed cross-valley ramps thickened by stalling against the impact slope.

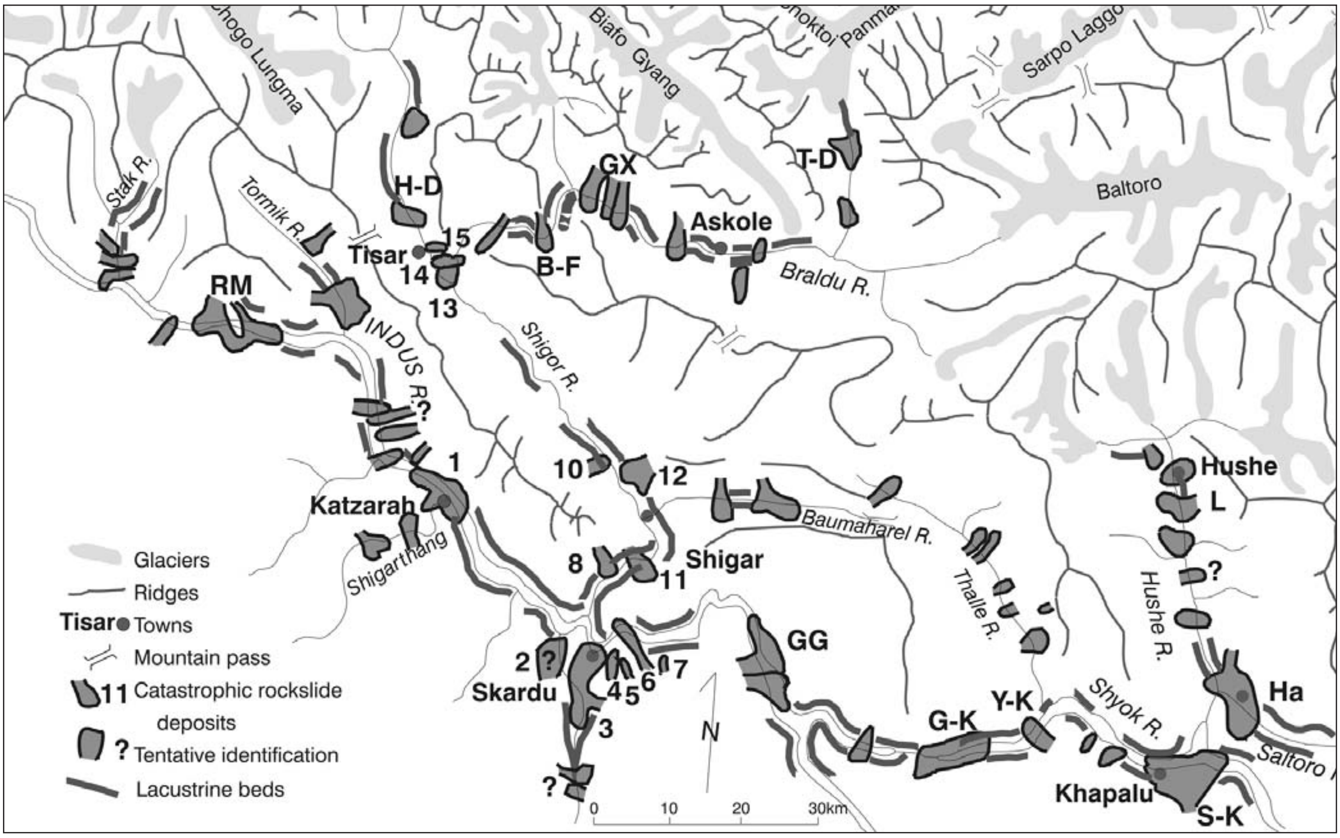

Figure 1 - The incidence of rockslide - rock avalanche dams along the Indus streams in Baltistan. These illustrate something of the scale and scope of post-glacial blockages discovered so far in the Central Karakoram. Where extensive lacustrine deposits are associated with the landslide dams they are shown schematically

Height class	Main dam	Secondary[1]	Sum	% of all
Partial Dam (Type I)[2]	13	7	20	9
Cross -valley dams				
< 10 m	5	6	11	5
10-50 m	82	46	128	56
50-100 m	28	6	34	15
100-250 m	27	-	27	12
250-500 m	2	1	3	1
500- 1000 m	2	1	3	1
> 1000 m	2	-	2	1
SUM	161	67	228	

Table 2 - Estimated initial, effective (i.e. the lowest part of the cross-valley barrier) heights of landslide dams on the transHimalayan streams from the survey sample of 161 rock avalanche events (cf Table 1). 1 - Partial inventory only (see text); 2 - See Table 3

Types and Subtypes	The examples from the region.
A. Single RA lobe/ single impoundment	
TYPE I - partial or groyne-like	
a) main valley source (i.e. wall of valley dammed)	Gomba Thurgon, Skardu Basin, Baltistan
b) tributary valley source	Hassainabad II, Skardu Basin, Baltistan
TYPE II - full cross-valley barrier	
a) main valley source	Dhak Chauki, Gilgit Basin
b) tributary valley source	Litak. Hushe Valley, Baltistan
B. Double lobe or 'deformed T-type/ single impoundment	
Type III - full barrier spreading up and down valley floor	
a) main valley source	Upper Henzul, Gilgit Basin; Haldi, Saltoro valley, Baltstan
b) tributary valley source	Dulung Bar, Darkot valley, Gilgit Basin
Type VI - combines deep-seated rockslide and rock avalanche(s)	Nomal Complex, Hunza valley, Gilgit basin

Table 3 - Rock Avalanche Dams: a morphological classification taking account of conditions in the Upper Indus Basin (after Costa & Schuster, 1987; Hewitt, 2002). Types Ia, IIa, IIIa, IIIa, and VIa, are essentially as Types I, II, III and VI respectively in Costa & Schuster's (1987) classification for landslide dams generally

Various classifications have been developed to characterise landslide dams. Those of Heim (1932), Swanson *et alii* (1986) and Costa & Schuster (1987) emphasise barrier morphology in relation to valley topography. Costa and Schuster's classification was adopted with several modifications to reflect specific rock avalanche and regional conditions (Tables 3 and 4). Some 30% of the dams conform to their Type II, and 31% in Type III, but Types IV and V are rare or absent. These categories are reassigned as new classes associated with complex emplacement and multiple impoundments. These comprise 34% of the inventory, and account for most of the largest impoundments, including 82% of dams that exceeded 100 m in height and all those over 250 m.

The Stability of Rock Avalanche Barriers and Breaching Histories

Extensive, multi-year lacustrine and other deposits, upstream and against the flanks of the larger dams, record relatively long-term survival. In most cases, the evidence suggests relatively gradual or phased breaching, despite the extreme geomorphic environment (Figure 2). Rock avalanche processes in rugged terrain, their composition, emplacement and morphology appear to promote stable barriers and resistance to erosion.

Where the evidence is preserved all except one barrier was overtopped prior to breaching, as in most landslide dams, but this has not necessarily or usually led to catastrophic failure. Dams may be overtopped in proximal, medial or distal part parts of the cross-valley barriers, or diagonally. Most barriers are too heavily eroded or buried in later sediments to allow reconstructions of the breaching sequence. However, 20% (29 cases) preserve evidence of it, and some useful indications of controlling conditions. At first, overflow channels reflect initial dam morphology, but in the half the cases the main breach occurred along other paths (Figure 3). While 80% of the initial overflows were in proximal or medial locations, proximal and distal locations dominate the main breaching process. Moreover, these breaches tend to occur at the interface of the landslide material and bedrock valley wall. This suggests that, while overtopping is the norm, seepage and sapping along the line of the valley wall may be a significant cause of major breaching, reflecting a more vulnerable seal there and, often, intercalations of weaker or more permeable sediments plastered against the valley wall after being picked up at the front of the rock avalanche. Again, however, there are few indications of early or complete catastrophic failure, as opposed to gradual, or sudden but partial, failures.

Bedrock controlled outlets

Another important subset of these dams involves spillways superimposed upon bedrock flanks or spurs of the pre-existing valley. The size and morphology of rock avalanche dams make it unlikely the overflow channel will exactly match the buried river's course. Where the valley has a wandering course, spillways can be let down on one or more bedrock spurs to create superimposed gorges. Some 45 of these have been identified with the rock avalanche dams (Table 1). In some cases, streams are superimposed on bedrock during the trenching of sediment fans and other bodies of sediment built up behind the barriers, for example across the distal rim of the Turi Parwak fan in the Miragam-Parwak event in Chitral. This has been the controlling base level for the trenching of the rock avalanche dam below for some centuries, although originating with the dam. In all of these cases, it is the rate of incision in bedrock that controls lake drainage, the trenching of the landslide barrier and removal of upstream sediments (Hewitt, 2002b).

Hybrid Dams

Of special interest are barriers consisting of rock avalanche and other materials. This complicates stability analyses and dam histories. Some twenty five of these hybrid dams were found and are divided into three classes in which:

Category	a) Valley wall source	b) Tributary valley source	Sum	%
Type I	11	8	19	12
Type II	35	14	49	30
Type III	29	8	37	24
Type IV	19	18	37	24
Type V	8	10	18	10
Type VI	1	-	1	-
SUM	103 (64%)	58 (36%)	161	

Table 4 - Morphological classification of rock avalanches that dammed Upper Indus streams

Figure 2 - The Litak rock avalanche dam on the Hushe River, Shyok Basin, showing multi-year lacustrine deposits some 100m thick behind the now fully breached barrier (photo Hewitt, 2001)

Figure 3 - Well-preserved initial over flow channel (arrows) of the Gakutch rock avalanche dam on the Gilgit River. Thick deposits of lacustrine sediments on the upvalley flank indicate this spillway operated for some decades. It was replaced by a rock gorge superimposed on a bedrock spur against the proximal valley wall to the right of the photograph. This is where the outflow is now, approximately 120m below the abandoned channel

i) rock avalanches over-ran glacier ice and glacial deposits (9),

ii) rock avalanches disturbed and created 'tectonised' and thickened areas of valley fill materials, or incorporated large masses of them (10),

iii) rock avalanches were partly transformed to debris avalanches or debris flows by uptake of moisture and sediment (6).

Each of these introduces further or different complications in the character, stability and life cycle of the dam. Some major impoundments formerly believed to be due to glaciers prove to involve rock avalanches advancing over glacier termini or lateral and terminal moraines to actually seal the dam (Figure 4). The Malangutti, Shimshal; Batura, Hunza and Charakusa, Hushe, dams, their extensive lacustrine deposits and related features are examples.

LONG-TERM EFFECTS OF ROCK AVALANCHE DAMS ON VALLEY DEVELOPMENT

Formerly, many of the rock avalanche dams and related lacustrine sediments were attributed to late-glacial ice or moraine dams (BURGISSER *et alii*, 1983; HEWITT, 1999). Now it is apparent that the late-, and post-glacial history of these valleys involves great numbers of large landslide dams. These have played a major role in landform development throughout the fluvial zone, helping to create a naturally fragmented river system by controlling sediment movement and routing of floods from other causes (HEWITT, 2002b).

QUESTIONS OF THE CONTINUING RISK FROM ROCK AVALANCHES AND LANDSLIDE DAMS

The new picture of natural dams on the upper Indus poses hitherto unrecognized dangers such that questions of continuing risk assume some urgency. Nearly all the rock avalanche deposits have settlements on or near them. The main areas of habitation and agricultural land lie on river flats, former lake beds, terraces and sediment fans built up behind the landslide barriers (HEWITT, 2001). Most roads, airports, hotels and other tourist destinations are also here (JONES *et alii*, 1983). With more people, wealth and infrastructure at risk than ever before, the prospect of further rock avalanches, of inundations above a dam, or catastrophic outburst floods, appears unusually threatening. However, risk assessment is hampered by enormous difficulties of slope stability analysis, lack of information about what triggered the known landslides, and when they occurred. The full paper discusses how to remedy these problems and, in particular, the need to date and establish the time series properties of the catastrophic landslide dams.

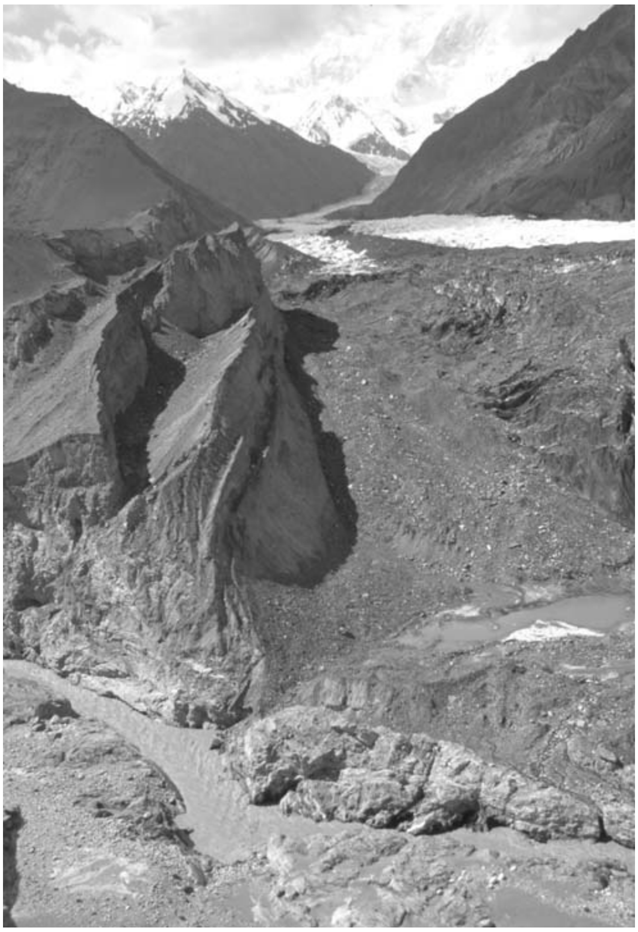

Figure 4 - View over the east flank of the Malagutti Glacier in Shimshal, north central Karakoram, from the surviving surface of the rock avalanche which formerly buried the glacier terminus. The lateral moraines in the middle ground are post-landslide. Almost the entire rock avalanche has been removed but, in addition to the remnant whence the photograph is taken, its debris still covers the highest moraines at the left edge of the photo. Up-valley of these are extensive lacustrine sediments up 150 m thick. In the foreground, the complex pattern of channels superimposed on bedrock follow the line where the dam was breached

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