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LANDSLIDE DAMS IN THE HIGH MOUNTAINS OF INDIA, NEPAL AND CHINA - STABILITY AND LIFE SPAN OF THEIR DAMMED LAKES

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ABSTRACT

This paper attempts to work out the stability conditions of 20 landslide dams in the Indi-an and Nepal Himalayas as well as two in China. All of them formed lakes upstream by damming the main river. The categories of study areas that they created differ in their shape, their volume and composition of the deposited landslide material, as well as in the size and life span of their former dammed lakes. This representative group of case studies affords the opportunity to obtain new results on this rare phenomenon.

INTRODUCTION

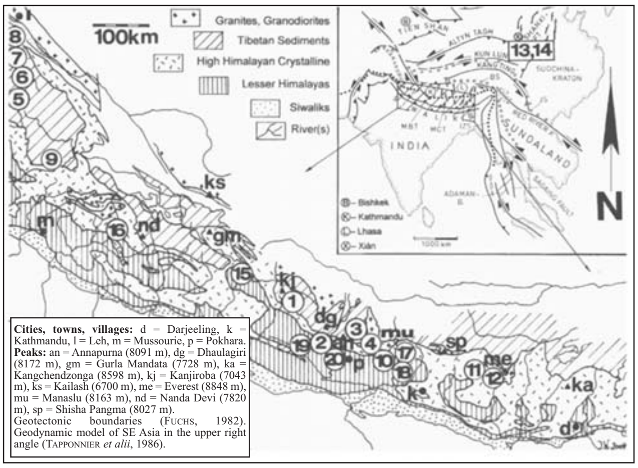
Due to their geo-tectonic evolution, high uplift rates as well as extreme climatic conditi-ons the Himalayas of India and Nepal as well as the Qin Ling Mountains of China have been predestinated for all different kinds and all scales of erosion and mass wasting processes in the past, at present and in future. That is why these alpinotype mountain ranges from the continent-continent collision type hold the deposits of most spectacular landslides.

To elaborate on the results known so far from lake-damming natural rock blockages, a number of rockslide-, rock avalanche- and landslide dams were investigated there so far. Dating of the events occurred mostly by means of morpho-stratigraphic analysis of the Quaternary sequences or by historic investigations (Figure 1, Tables 2-5a,b). These case studies are presented in this paper and the results on the stability conditions of the dams and life span of their lakes are depicted and assimilated in the conclusions.

Creating a helpful tool for estimating potential hazard after the occurrence of a lake-damming landslide was the favorite aim. This resulting "block size stability diagram" is one of the first attempts for a regional comparison of such kind of phenomena.

THE HIMALAYAS OF INDIA AND NEPAL

The Himalayas, the highest mountain range in the world, has been the product of a colli-sion between the Indian Subcontinent and the Eurasian Plate, which started 65 Mill. years ago (Figure 1). Today this zone is marked by the Indus-Zangbo-Sutur with volca-nic rocks and ophiolitic melange zones. Towards south the sedimentary sequence of the Tibetan or Tethyan zone (Proterocoic-Eocene) is exposed, partly forming the summits of the highest peaks on earth with its basal strata (f. i. Mt. Everest: 8848 m). Further south crustal thrust planes formed within the Indian Plate 25-20 Mill. years ago. To-day the most important of these is the Main Central Thrust (MCT), a 10 km thick zone of mylonites south of the High Himalayan Crystalline, the root zone of the classical Precambrian metasediments and crystalline nappes of the Lesser Himalayas. The ongo-ing convergence between the two plates led to another thrust plane, the Main Boundary Thrust (MBT), which departs the Lesser Himalayas from the Sub-Himalayas (Miocene-Pleistocene), the molasse-basin of the mountain range, mainly composed of the Siwa-lik Formation. The actual convergence between the continents is documented by the high uplift rates of the Tibetan Plateau, which have started 5 Mill. years ago.



Cities, towns, villages: d = Darjeeling, k = Kathmandu, l = Leh, m = Mussourie, p = Pokhara. **Peaks:** an = Annapurna (8091 m), dg = Dhaulagiri (8172 m), gm = Gurla Mandata (7728 m), ka = Kangchendzonga (8598 m), kj = Kanjiroba (7043 m), ks = Kailash (6700 m), me = Everest (8848 m), mu = Manaslu (8163 m), nd = Nanda Devi (7820 m), sp = Shisha Pangma (8027 m). Geotectonic boundaries (FUCHS, 1982). Geodynamic model of SE Asia in the upper right angle (TAPPONNIER *et alii*, 1986).

Figure 1 - Locations of rockslide-, rock avalanche- and landslide areas investigated (for names of locations 1-20, see Tables 1-5b); Geotectonics by FUCHS (1982) and TAPPONNIER et alii (1986)

LAKE DAMMING GIANT ROCKSLIDES IN THE NEPAL HIMALAYAS (FIGURE 1)

The rare phenomenon of giant rockslides has been found in the Nepal Himalayas at Ringmo (Suli Gad Valley, Dolpa), Kalopani (Kali Gandhaki Valley, Dhaulagiri Himal), Dukur Pokhari and Latamrang (Marsyandi Valley, Annapurna Himal). These examples are of Pleistocene to Holocene (postglacial) age.

GENERAL DESCRIPTION OF THE GIANT ROCKSLIDE AREAS

In the upper course of Suli Gad River, 30 km north of Dunai town (Dolpo, Western Nepal), one of the largest rockslide deposits in the Himalayas (Weidinger, Ibetsberger 2000) formed a massive barrier, which has dammed Phoksundo Lake (alt. 3,700 m), the second largest lake in Nepal (Figure 2a, 2b; Table 1). This rockslide deposit around Ringmo village affected Dhaulagiri limestones of the Tibetan sediments (FUCHS, 1977). Its detritus is covered by loess, in which intercalations of reddish soil layers were dated with 30-40ka - the landslide's age and the origin of Phoksundo Lake (YAGI, 1997).

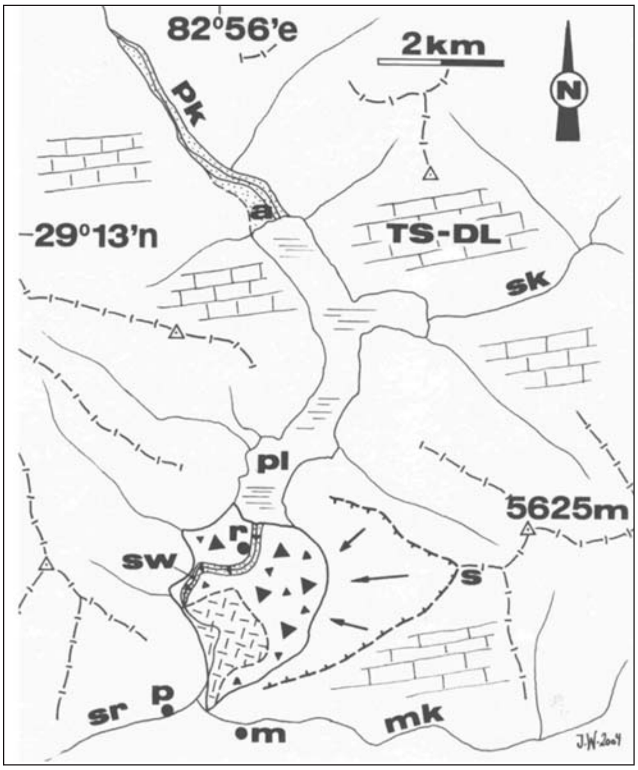


Figure 2a - Geologic sketchmap of Ringmo rockslide; TS-DL = Tibetan Sediments-Dhaulagiri Limestones, a = alluvions, m/mk = Manduwa village and river, p = Palam village, pk/pl = Phoksundo Khola (river) and lake, r = Ringmo, s = scarp, sk = Sagar Khola River, sr = Suli Gad River, sw = spillway (outbreak channel)

In the central part of Kali Gandhaki Valley (Figure 1, Table 1), which crosses three tectonic units of the Himalayas, COCHEN *et alii* (1986), FORT (2000), HANISCH (1995), HORMANN (1974) and WEIDINGER (2004) have investigated a giant rockslide (Figure 3a) that covers an area of 10 km^2. The rockslide masses originated SW of the deposition area near Kalopani village and formed a barrier that dammed the Kali Gandhaki River. From Kalopani towards the north the Kali Gandhaki Valley widens as far as the village of Kagbeni to a more than 30 km long former dammed reservoir of the river. Today this is filled with alluvions, mass wasting and lake sediments (Figure 3b).

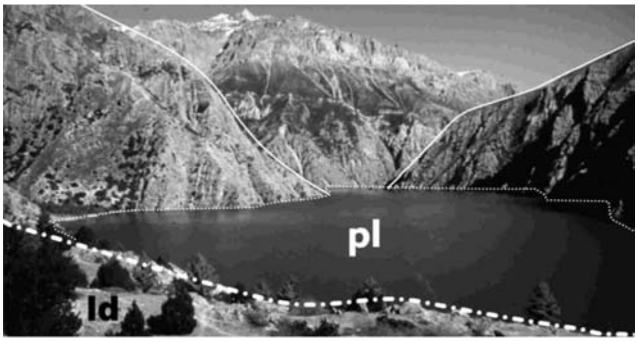


Figure 2b - View of Ringmo rockslide deposit (ld, dashed-dotted line) towards NE; Phoksundo Lake (pl, dashed line); photograph: J. T. Weidinger 1995

Landslide/ Parameters	1. Ringmo	2. Kalopani	3. Dukur Pokhari	4. Latamrang
Preparatory Causal Factors	Tectonics, fabric, glacial erosion and stress release	Tectonics, fabric, glacial erosion and stress release	Fabric, glacial erosion, stress release	Tectonics, fabric, glacial erosion and stress release
Age	30 000-40 000 yr (Yagi 1997)	Post-glacial	Post-glacial	Post-glacial
Movement Type	In-situ collapse	Sledge-like sliding	In-situ collapse, rolling, bouncing	Sledge-like sliding
Geographic Position	Suli Gad Valley/ Dolpa, Nepal	Kali Gandhaki Valley/ Mustang, Nepal	Marsyandi Valley/Manang, Nepal	Marsyandi Valley/ Manang, Nepal
Geotectonic Position	Tibetan Zone of Himalayas	High Himalayan Crystalline	Tibetan Zone of Himalayas	High Himalayan Crystalline, Tibetan Zone of Himalayas
Lithology	Limestone	Augen-, biotite-gneiss	Limestone, shists	Gneiss, quartzite
Material	Disintegrated, re-cemented fragments and blocks	Brecciated, cataclastic and re-cemented blocks	Brecciated, cataclastic and re-cemented blocks and boulders boulder size: ≤2m	Brecciated, cataclastic and re-cemented blocks
Length, width, thickness of dam	2.5/1.5/0.5-0.7km	<4/<6/<1km	<2/<3/<0.5km	<2.5/<3.5/<0.7 km
Volume of deposit	1.5 bill. m³	3 bill. m³	1 bill. m³	Rem. 4.5 bill. m³ from ≥ 5.5 bill. m³
Length/width/ Depth of lake(s)	5/0.8/≤0.2km	≤30/1/<0.1km	≤3/≤1/≤0.05km	estimated: 3/0.5/0.1km
Fahrböschung	Ca. 35°	Ca. 17°	Ca. 20°	Ca. 22° resp. 12°
Volume of lake	350-400 mill. m³	1.5-3 bill. m³	75 mill. m³	≤8.5 mill. m³
Stability of dam	Stable due to re-cementation	Stable due to recementation	Stable due to cementation with sediments	Long time stability due to recementation
Life span of lake	Still existing after 30 000-40 000 yr	Disappeared within late to postglacial times	Filled up with alluvions within short period	Overtopping and piping after <5 000yr

Table 1 - Characteristics and stability conditions of giant rockslide dams and life span of dammed lakes in the Nepal Himalayas

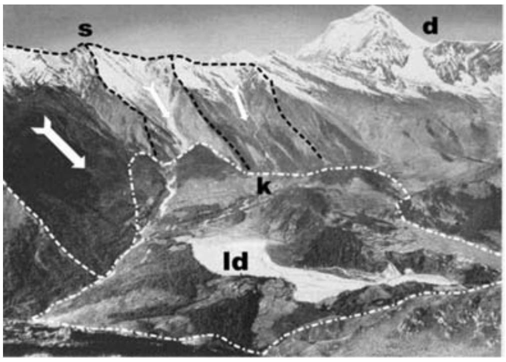


Figure 3a - SE-NW view from Nimek Peak (3900 m) over the Kali Gandhaki Valley towards Kalopani rockslide area (ld, dashed-dotted line); d = Dhaulagiri (8,172 m), s = Sarpang Dhuri (scarp, dashed line), ¡arrow = direction of movement, k = Kalopani; photograph: Hormann, 1974

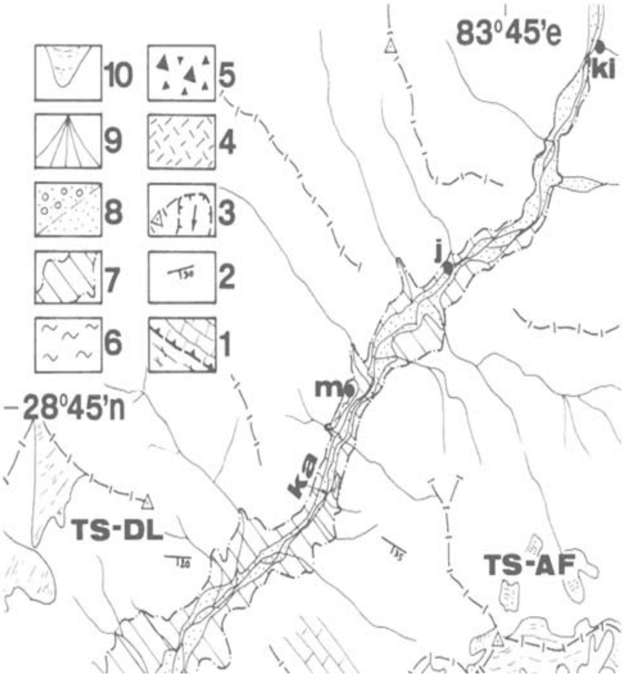


Figure 3b - Geologic-geomorphologic sketchmap of the Upper Kali Gadhaki Valley featuring Kalopani rockslide area and its former dammed lake (Geotectonic boundaries according to Colchen et al. 1986); Legend: HHC = High Himalayan Crystalline, TS = Tibetan Sediments (AF = Annapurna Formation, DL = Dhaulagiri Limestones), 1= hard rock and thrust plane, 2 = dip, 3 = peak, crest, scarp and movement direction, 4 = rockslide deposit (shattered), 5 = rock avalanche deposit, 6 = lake sediments, 7 = extension of former dammed lake at 2800 m, 8 = glacio-fluvial and alluvial gravel, 9 = debris cone, 10 = recent glaciers; j = Jomosom, k = Kalopani, ki = Kagbeni, kg = Kali Gandhaki, m = Marpha, n = Nimek (3904 m), ni = Nilgiris (7061 m), s = Sarpang Dhuri

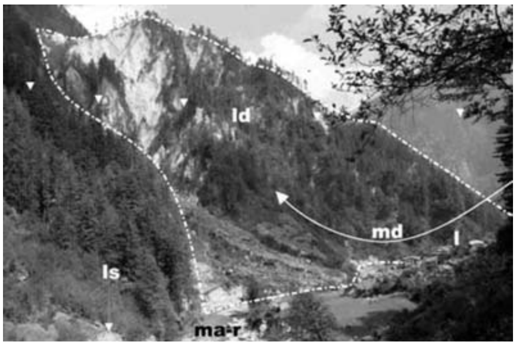


Figure 4a - W-E view towards the eroded dam of Latamrang rockslide (ld, - dotted-dashed line) on the left side of Marsyandi River (ma-r); md = movement direction, ls = lacustrine sediments, arrow = level of former dammed lake (alt. 2650 m); observation point: 400 m west of Latamrang village (l), alt. 2490 m

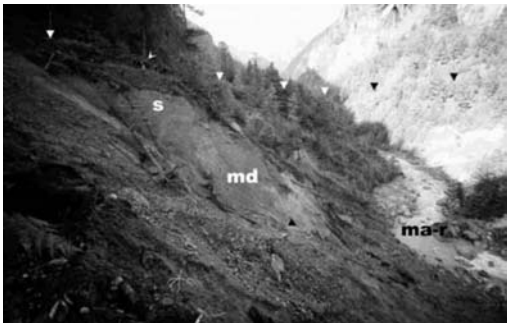


Figure 4b - Outcrop of rhythmically sedimented lake sediments (-s-) that were formed in the reservoir (black triangles = level of former dammed lake) of Latamrang rockslide; in the summer monsoon of 2003 huge areas of the trekking route (white triangles = Trekkers) along the Marsyandi River (ma-r) were endangered by sliding and mudflow (md = direction) processes; position: oro. right side of Marsyandi River, 1 km W of Thanchouk, alt. 2500 m; photo: Weidinger 1993, 2003

Another giant rockslide in the Himalayas was investigated by WEIDINGER (2004) at Dukur Pokhari (Figure 1, Table 1) near the eastern end of the Upper Marsyandi Valley (Annapurna Himal, Nepal). Its source lies on the southeastern ridge of Naur Himal at elevations of 4,700-4,900 m. The folded and steeply SW to W dipping, well bedded formations of the Tibetan Sediments served as preparatory causal factors for the failure of this mountain crest in a direction from NE to SW. The dislocated masses dammed the main river (see Figure 5).

Further down the valley, in the middle course of the Marsyandi Valley, one of the biggest rockslide areas in the Himalayas (Figure 5, Table 1), which once dammed the main river to form a large lake, was identified (WEIDINGER & IBETSBERGER, 2000; WEIDINGER, 2004). Its deposit stretches over 4 km along the Marsyandi River, from the village of Thanchauk (2,480 m) passing Latamrang (2,400 m), with the most accessible and extensive outcrops of the rockslide, as far as Danaque (2,180 m). This area is part of translationally transported and shattered blocks. The possible scarp is known as the eastern part of the Lamjung Himal (6,988 m). Main directions of movement of the rockslide from SW to NE as well as from SE to NW (or SSE to NNW) can be reconstructed. The preservation of lake sediments (Figure 4a, b) on the steep flanks of the former reservoir indicates the postglacial age of this rockslide.

STABILITY CONDITIONS OF GIANT ROCKSLIDE DAMS AND LIFE SPAN OF THEIR DAMMED LAKES (TABLE 1)

At Ringmo the failure mechanism has played the major role for the stabilization of the rockslide dam and the life span of Phoksundo Lake. The scarp of the rockslide, an almost vertical wall (Figure 6), indicates an in-situ collapse of the former mountain crest with high angle and a relatively short distance of dislocation. That is why huge, not disintegrated but interlocking blocks of several dozens of meters in diameter domi-nate the deposit. Together with intercalated, finely grained material that was secondarily compacted by mineralization of mountain waters, they have proven a positive influence on the dam's stability.

The spillway through the deposit is just slightly eroded - only an extraordinary event such as a mountain flank collapse into the lake could cause severe damage (SCHNEIDER, 2004). Although the catch-

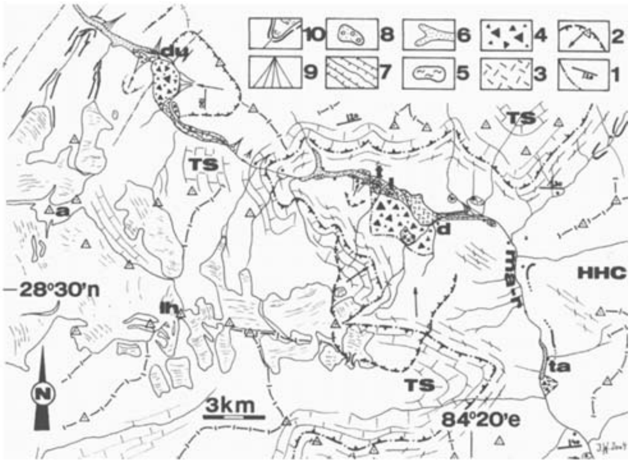


Figure 5 - Geologic-geomorphologic sketchmap of the Lower Marsyandi River (ma-r) valley; rockslides of Dukur Pokhari (du) and Latamrang (l) and the rock avalanche of Tal (ta, see section 3); (Geotectonic boundaries according to Colchen et al. 1986). Legend: HHC = High Himalayan Crystalline, TS = Tibetan Sediments; 1 = hard rock, fault, dip, 2 = peak, scarp and movement direction, 3 = rockslide deposit (shattered), 4 = rock avalanche deposit, 5 = lake sediments, 6 = extension of former lakes, 7 = terraced lake outflows, 8 = alluvial gravel of former spillway, 9 = debris cones, 10 = recent glaciers and moraines; a = Annapurna II (7,937 m), lh = Lamjung Himal (6,938 m), d = Danaque, t = Thanchouk

ment area extends some 150 km^2, Phoksundo Lake is still not filled up with alluvial and/or lake sediments. This is a matter of the local climatic conditions within the rain shadow behind the Higher Himalayas.

It is assumed that the bulk of Kalopani rockslide material was dislocated en masse, having been shattered and brecciated with decreasing intensity from the bottom to the top and overridden by typical angular boulders. Similar observations have been made by Hewitt (1998, 2002), Schramm *et alii* (1998), Strom (1999), Weidinger & Schramm (1995a, b), Weidinger *et alii* (1996) and Weidinger *et alii* (2002a). This kind of natural dam remained stable for a long time. That is why the former reservoir of the dam in the northern part of Kali Gandhaki Valley bears a complex sequence of moraines (Iwata *et alii*, 1982; 1984; Fort 1980; 1985), glacio-fluvial and alluvial sediments, mass wasting deposits from the Nilgiris, periglacial phenomena and the 200 m thick infillings of a huge lake, the Marpha Formation, aged 79 +- 11 kyr^{-1} (Baade, Mausbacher 1998; Bade *et alii*, 1998). Hanisch (1995) connects the origin of these lake sediments only with Kalopani rockslide, suggesting a former crown of the dam at 3200 m altitude, which is much higher than the recent one, while Weidinger (2004) assumes different aged lake sediments generated by Kalopani rockslide dam and ice-debris avalanches from the Nilgiris (Weidinger, 2004); at least a former dammed lake at 2800 m altitude is also evident for him (Figure 3b).

The angular character of the blocks at Dukur Pokhari rockslide is a consequence of the bedded rocks of the source. The basal zone of this rockslide shows a much higher disintegration (Figure 7), indicating high and destructive mechanical energy during the event. Thus the mechanism of sliding of this composite rockslide occurred in a translational manner at the bottom and in the form of rolling on the top. Despite the formation of a spillway at the distal part of the masses at the border to the hard rock, the dam kept stable. Due to sufficient availability of glacio-fluvial sediments, the basin behind was silted and filled up within a short period.

Figure 6 - S-N view towards the Ringmo rockslide area (ld, dashed-dotted line); s = scarp (dashed line), arrows = direction of movement, pl = position of Phoksundo Lake; photograph: H. J. Ibetsberger 1995

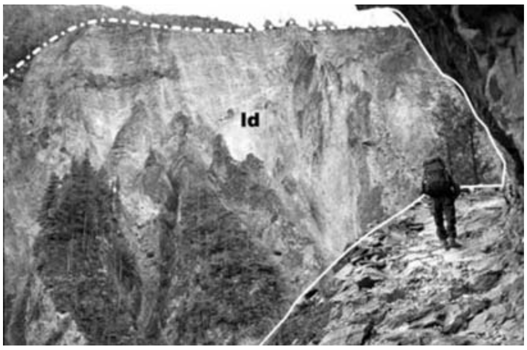
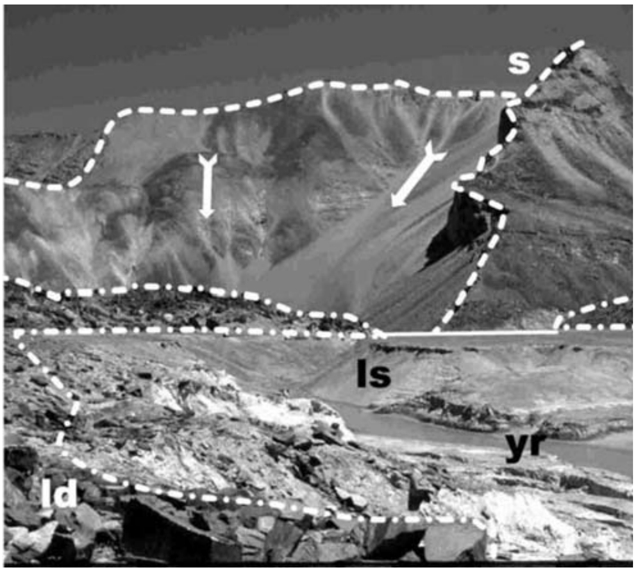


Figure 7 - SE-NW view towards Dukur Pokhari rockslide (ld, dashed-dotted line); position: 1.5 km west of Bhratang, alt. 2900 m; photograph: J. T. Weidinger 1993

Due to the extraordinarily high volume of Latamrang rockslide, the natural dam existed for relatively long time, although waters of the dammed lake could seep through the landslide deposit and tunnels were formed by piping, finally leading to the collapse of the dam. In this way a volume of ca. 260 x 10^6 m^3 has been eroded from the bottom of the valley to the height of the former water level of the lake (Figure 8). Terraces of alluvial sedimentation on top of the rockslide deposit at an altitude of 2600 m serve as good indicators of the former elevation of the water in the reservoir and for the level of the spillway of the lake.

RESULTS, CONCLUSIONS AND GENERAL DISCUSSION ON GIANT ROCKSLIDE DAMS

Besides the huge volume of deposited material, the mechanism of sliding has played a major role in the stability of giant rockslide dams. In-situ collapses of the rock masses dominate, with relatively short distances of dislocation and/or rapid translational movements



Figures 8 - View of Sarai Kenlung rock avalanche; s = scarp (dashed line), arrows = direction of movement, ld = landslide deposit (dashed-dotted line), ls = lake sediments, yr = Yunan Chu River; photograph: J. T. Weidinger 2000

Figures 9 - View of Tso Tok Phu rock avalanche; ld = landslide deposit (dashed-dotted line), l = Tso Tok Phu Lake, ki = Kioto Limestones; photograph: G. Fuchs 1985

causing huge blocks of material shattered by mechanical stress during sliding. Theses shattered but not disintegrated masses have been the base for secondary stabilization of the landslide dams and the life span of the lakes dammed. They underwent recompactation and secondary cementation by mineralized springs and/or mountain waters. Nevertheless, very few areas still have a dammed lake in their impoundments. Other geological processes, such as sedimentation into the reservoirs and/or erosion over thousands of years cause the lakes to disappear.

LAKE DAMMING ROCK AVALANCHES IN THE INDIAN AND NEPAL HIMALAYAS AND IN THE QIN LING MOUNTAINS OF CHINA (FIGURE 1)

Generally, rock avalanches are much more common than giant rockslides, especially in areas with tectonic history, different lithologies, stress release due to deglaciation, and high morphologic overprint causing steep valley flanks and deep gorges. This study presents examples from the Tibetan Zone of the Himalayas and the High Himalayan Crystalline. Data on two features from the Qin Ling Mountains of China within a similar litho-tectonic position have been added.

GENERAL DESCRIPTION OF LAKE-DAMMING ROCK AVALANCHES IN THE TIBETAN HIMALAYAS OF INDIA (TABLE 2)

Frequently occurring earthquakes often serve as triggers for rock avalanches in the Tibetan Zone of the Himalayas, e.g., in Southern Zanskar, India. One of the reasons might be the changing lithological conditions of the sedimentary sequence of the Zans-kar Synklinorium (Figure 10; partly according to FUCHS & LINNER, 1995).

North of Kyelong town (district Lahul) the road from Manali (Himachal Pradesh) to Leh (Ladakh) crosses two deposits of rock avalanches (MITCHELL *et alii*, 2001; 2002; WEIDINGER *et alii*, 2002a; Figure 10). At Pateo, where the N-S striking Bhaga River Valley has its confluence with an eastern tributary, a rock avalanche deposit is located at altitudes of 3850-3925 m. It covers an area of 2 km^2 and once dammed 2 lakes. 5.5 km NNE of the Bara Lacha pass (4810 m) another barrier once dammed the main N-S striking valley of Yunan Chu, forming a lake at its confluence with an eastern tributary near today's Sarai Kenlung (Figure 8).

Near Chumik Marpo (4650 m), 6 km ESE of Sirichun Pass and 5 km SE of Phirtse Pass (5400 m), an area of 0.5 km^2 is covered by a blocky stream of boulders in the upper course of the Lingti Chu River. It once dammed a lake valley due W. 42 km further NNW another rock blockage dammed the still existing lake Tso Tok Phu (5 km SE of Tanak monastery, Figure 9) in a northern tributary valley of Tsarap Chu River, affecting an area of about 0.4 km^2 (Figure 10).

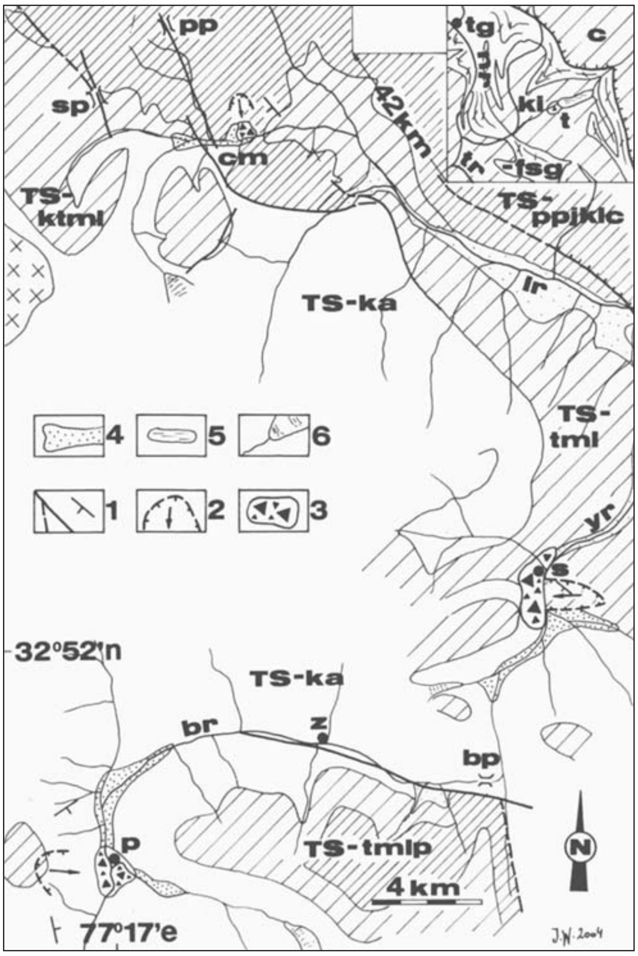


Figure 10 - Geologic sketch map of SE Zanskar with the positions of the lake-damming rock avalanches of Pateo (p, 3740 m), Sarai Kenlung (s, 4540 m), Chimik Marpo (cm, 4,650 m) and Tso Tok Phu (t); Legend: TS = Tibetan Sediments (ka = Karsha, k = Kurgiagh, t = Thaple, m = Muth, l = Lipak, p = Po, pj = Panjal, kl = Kuling, c = Triassic-Jurassic Carbonate, f = Ferruginous, s = Spiti, g = Giumal Formations; 1 - hardrock, faults, dip, 2 - scarp, direction of movement, 3 - rock avalanche deposit, 4 - former dammed lake, 5 - recent dammed lake, 6 - recent glaciers and rivers; bp = Bara Lacha Pass (4810 m), br = Bhaga River, lr = Ligti Chu River, nr = Niri Chu River, pp = Phirtse Pass (5400 m), sp = Sirichun Pass, tg = Tanak Monastery, tr = Tsarap Chu River, yr = Yunan Chu River, z = Zingzingbar (3900 m)

Landslide/ Parameters	5. Pateo	6. Sarai Kenlung	7. Chumik Marpo	8. Tso Tok Phu
Preparatory Causal Factors	Fabric, glacial erosion, stress release	Tectonics, fabric, faulting, glacial erosion	Tectonics, fabric, faulting	Tectonics, fabric, faulting, glacial erosion
Age	Post-glacial	7 510 +/- 110 yr BP (Mitchell et al. 2002)	Post-glacial	Post-glacial to sub-recent
Type of movement	Rolling, bouncing	Rolling, bouncing	Rolling, bouncing	Rolling, bouncing
Geographic Position	Bhaga Valley/Himachal Pradesh, India	Yünan Chu Valley/ Zanskar, India	Lingti Chu Valley/ Zanskar, India	Tributary of Tsarap Chu, 13 km NNE of Phuktal, Zanskar
Geotectonic Position	Tibetan Zone of Himalayas	Tibetan Zone of Himalayas	Tibetan Zone of Himalayas	Tibetan Zone of Himalayas
Lithology	Limestone, dolomite	Conglomerate, quartzite, shists, dolomites	Quartzite, basalts, sandstone, limestone, dolomite, shales	Limestone, dolomite, marls
Composition of Material	Boulders/rock fragments, size: ≤0.5m	Boulders/rock fragments, size: ≤10m	Boulders	Boulders
Length. wide. thickness of dam	2/1.5/0.05-0.1km	3/1/0.2km	0.8/0.8/0.05km	0.7/0.7/0.05km
Fahrböschung	Ca. 18°	Ca. 24°	No data	No data
Volume of deposit	Ca. 150 mill. m^3	Ca. 350 mill. m^3	Est. 60 mill. m^3 (before erosion)	Est. 60 mill. m^3
Length/width/depth of lake(s)	1^{st}: 6/≤1/≤0.1; 2^{nd}: 2.5/≤0.5/≤0.1km	2.5/≤1/≤0.1km	2.5/0.2-0.9/?km	1.5/0.4/?km
Water volume of lake (s)	1^{st}: 300 mill. m^3 2^{nd}: 62.5 mill. m^3	125 mill. m^3	est. 110 mill. m^3	est. 30 mill. m^3
Stability of dam	Deep gully erosion through the deposit	Stable due to cementation with sediments	Unstable due to erosion along spillway	Stable due to cementation with sediments
Life span of lake	Both disappeared within short periods	≤3 000-5 000 yr	Disappeared due to erosion	Still exists

Table 2 - Characteristics and stability conditions of rock avalanche dams and life spans of lakes in the Tibetan Zone of the Himalayas in India

STABILITY CONDITIONS OF ROCK AVALANCHE DAMS IN THE TIBETAN HIMALAYAS AND LIFE SPAN OF THEIR DAMMED LAKES (TABLE 2)

The material of Pateo rock avalanche disintegrates to coarse-grained and irregular boulders due to weathering along the bedding. That is why the dam is composed of a material with high content of fine as well as large angular blocks and boulders. No la-custrine sediments were recognized in the impoundment(s), but several alluvial terraces give evidence of former landslide dammed lakes behind the barrier of the rock avalanche - one to the north and one to the east. Their spillways have formed deep gullies into the deposit (Figure 11), so that the dam still acts as a hazard in a case when landslide material generated by undercutting of the steep flanks blocks the river again. Then new lakes could form, endangering villages down the valley by overtopping the new dam.

As seen on the southern rim of the scarp of Sarai Kenlung rock avalanche (Figure 8), the displacement of its material of conglomerates, quartzites, (carbonate) sandstones, slates and thin lenses of dolomite seems to have started along a fault structure that has cut off the material vertically and striking E-W from the bedrock; the sliding surface was created along the bedding of the bedrock - one more reason for creating a deposit like a huge blocky stream. Today the former dammed lake towards the south behind the rock avalanche is filled with lacustrine and alluvial sediments of recent rivers and glaciers. The most interesting part of the former lake close to the barrier is composed of eroded terraces of lake sediments with different levels. Additionally the spillway and the proximal part of the landslide give evidence of several outbreaks of the lake.

Exposures in the scarp area of Chumik Marpo rock avalanche, NNW of the deposit, show a mixture of very hard and thick-bedded rocks with ductile ones - a composite material with big boulders and fine ones in between. This feature is similar to that in Pateo and might be the reason for the erosion of the dam after a short life span of the full lake - the rest of the basin was silted up and filled up with alluvial sediments.

The blocky materials of the Kioto Limestone (Figure 9), which primary composed the deposit of the Tso Tok Phu rock avalanche, obtained its stabilizing input from fine sediments of the seeping waters. Due to dry weather conditions, low rate of sedimen-tation into the reservoir, and low rates of erosion, the lake still exists.

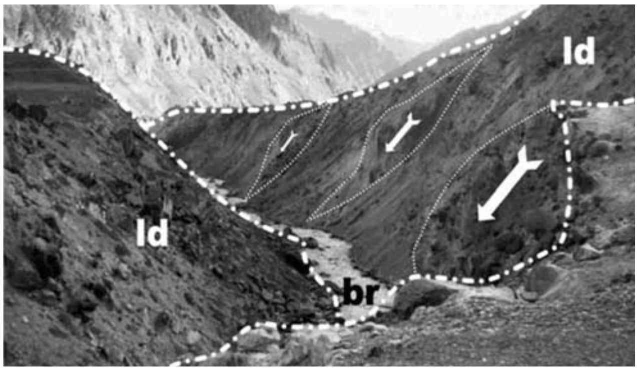


Figure 11 - Deeply eroded gully of Bhaga River (br) through the Pateo rock avalanche deposit (ld, dashed-dotted line), seen from Pateo (alt. 3950 m); (arrow and dotted line) = potential masses for collapsing into and damming the river temporarily; photograph: J. T. Weidinger 2000

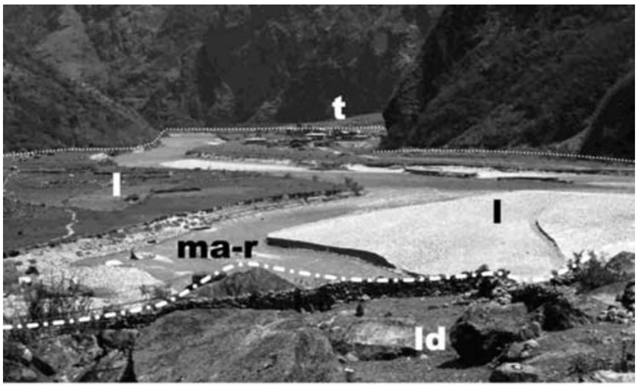


Figure 12 - View towards N to the former lake (l, dotted line) dammed by the rock avalanche (ld, dashed-dotted line) of Tal (t); ma-r = Marsyandi River; observation point: 1 km S of Tal, alt. 1650 m; photograph: J. T. Weidinger 1993

Landslide/ Parameters	9. Bawa Pass	10. Tal	11. Lamabagar (*)	12. Gath-Chaunrikharka (*)
Preparatory causal factors	Fabric, glacial erosion, stress release	Glacial erosion, stress release	Fabric, glacial erosion, stress release	Fabric, glacial erosion, stress release
Age	Post-glacial	≤1 000 yr	3 generations	Post-glacial
Type of movement	Rolling, bouncing	Rolling, bouncing	Rolling, bouncing	Rolling, bouncing
Geographic position	Garak Chu Valley/ Himachal, India	Marsyandi Valley/ Nepal	Tama Koshi Valley/ Dolakha, Nepal	Dudh Koshi Valley/ Solukhumbu, Nepal
Geotectonic position	High Himalayan Crystalline	High Himalayan Crystalline	High Himalayan Crystalline	High Himalayan Crystalline
Lithology	Gneiss, granite	Sillimanite gneiss	Gneiss, migmatite	Gneiss
Composition of Material	Boulders; size: 2-5m	Boulders; size 0.2-10m	Boulders/rock fragments	Shattered, mainly cohesive rock
Length, wide, thickness of dam	1/0.5/0.2 km	1/0.5/0.1 km	2/1/0.3 km	3.4/1/0.1 km
Volume of deposit	16 mill. m^3	4.5 mill. m^3	ca. 30 mill. m^3	100 mill. m^3
Fahrböschung	No data	No data	No data	No data
Length/width/depth Of lake	<1/ca.0.3/<0.2km	1/0.3/<0.1km	3/max.0.1/max. 0.3km	5/0.8/0.09-0.1km
Water volume of lake(s)	Ca. 30 mill. m^3	10-15 mill. m^3	18 mill. m^3	90 mill. m^3
Stability of dam	Stable due to cementation with sediments	Stable due to cementation with sediments	Still stable	Failed by overtopping and erosion
Life span of lake	Filled up with alluvions within short periods	Filled up with alluvions within ≤200 yr	Silted up within short period	Silted up following a first outbreak after 120 yr

Table 3 - Characteristics and stability conditions of rock avalanche dams and life span of their lakes in the High Himalayan Crystalline; (*) data by Uhlir, 1998

GENERAL DESCRIPTION OF ROCK AVALANCHES IN THE HIGH HIMALAYAN CRYSTALLINE OF INDIA AND NEPAL (FIGURE 1, TABLE 3)

South of Bawa Pass (4800 m, Himachal Pradesh, India) a rock avalanche dam (alt. 3380-3600 m) originated from the left (SE) side of the valley, where it changes its strike from E-W to N-S. The blocky material has dammed Garak Chu River close to its confluence with Lanak Chu River. The impact of this main event triggered another, smaller rock avalanche on the opposing valley wall, which had just a little influence on the hydrologic conditions there.

One of the most important sites of rock avalanches of the lower Marsyandi Valley is the deposit near the village of Tal (alt. 1600 m, Figure 5). 7 km south of the confluence of the Dudh Khola River with the main river, this rock avalanche, which occurred perpenticularly to the N-S striking valley, dammed the river to form a lake. Today this former basin is silted up with lake and alluvial sediments of the river (Figure 12).

Similar sites of rock avalanches can be found in eastern Nepal, about 10 km north of the Main Central Thrust, at Lamabagar (86°13'E, 27°55'N; crown elevation of the dam 1970 m) and Chaunrikharka (86°43'E, 27°42'N; crown elevation of the dam 2550 m) villages, the latter located close to the eroded Gath-Phakting sediments, the formerly dammed lake (Heuberger & Weingartner, 1986; Uhlir, 1998).

STABILITY CONDITIONS OF ROCK AVALANCHE DAMS IN THE HIGH HIMALAYAN CRYSTALLINE AND LIFE SPAN OF THEIR DAMMED LAKES (TABLE 3)

The area of the impoundment behind the rock avalanche of Bawa La documents the damming of a lake at an altitude of 3560 m the Garak Chu Valley upwards as far as the confluence with the tributary of Puiti Chu River. Due to the small distance of dislocation, the material of the rock avalanche dam is course and blocky. So flowing and seeping waters did not damage the dam, but stabilized it by deposing sediment freights between the boulders. Therefore the dam increased its stability for a long time. Later on a spillway of the dammed waters was formed at the distal side of the deposit, between the rock avalanche and the hard rock of the opposing valley wall. The river has cut through this barrier; at least two alluvial terraces along the impoundment document two longer stages and lake levels, before it disappeared completely.

One of the reasons why the impoundment of Tal (Figure 12) was silted up before a dam breaching was the mechanism of the rock avalanche. The dislocated mass contains mostly boulders lacking in finely grained material. Additionally, secondary cementation and compactation of the boulders with fine sediments left by flowing and seeping mountain and lake waters provided the most important influence on the stability of the dam after the event (Shaller, 1991). The dam remained stable and the lake disappeared due to sedimentation into it. The spillway at the distal part of the deposit was successively cut down by erosion. This occurred as the village of Tal (which means lake) was founded on the shore of a still existing lake at most 500 years ago.

According to Uhlir (1998), both rock avalanches at Lamabagar and Gath-Chaunri-kharka display long stability, which confirms that the large volume, the cohesiveness of the deposited material and rapid siltation in the impoundment are the most important factors for the stability and life span of these natural rock blockages. Lamabagar with its boulder-armed spillway has been stable for more than 3 generations and is completely silted up, although the frontal part still bears some shallow waters during the rainy mon-soon season. The remnants of the postglacial Chaunrikharka dam and the sediments of the formerly dammed Gath-Phakting Lake behind it indicate a dam stability of at least 120 years. After a first outbreak an entirely silting up with periodical downcutting of the dam followed, which is documented by alluvial terraces within the outflow channel.

GENERAL DESCRIPTION OF LAKE-DAMMING ROCK AVALANCHES IN THE QIN LING MOUNTAINS OF P. R. CHINA (FIGURE 1, TABLE 4)

Rock avalanches are common in the P. R. of China and seismic activity is their main trigger. As some of them have occurred within Mesozoic granites of the Qin Ling Mountains (Figure 1), an orogenic belt of the collision type (Hsu *et alii*, 1987) with comparable litho-tectonic conditions to the Himalayas, results from that area are included in this study.

Our two rock avalanche dams in the Cui Hua Mountains 30 km south of Xi'an (Dong Cha Valley, Shaanxi) were triggered by an earthquake in 780 BC (Weidinger *et alii*, 2002c). The lower of them - the composite dam of the three Cui Hua rock avalanches (Figure 13, both sides) - dammed one of the only three thus dammed lakes in China, the Tianchi Lake. On the shore of this "Lake of Heaven" (alt. 1210 m) local people have founded a village called Chui Tsho Tshe close to an ancient spillway of the lake to enjoy the benefits of this natural water storage. The upper Liu Dshe Tse rock avalanche dam, situated about 5 km from the Tianchi Lake towards the south, did not dam a lake because of permeability on the bottom of the impoundment created by tectonic structures.

STABILITY CONDITIONS OF ROCK AVALANCHE DAMS AND LIFE SPAN OF A DAMMED LAKE IN THE QIN LING MOUNTAINS OF P. R. CHINA (TABLE 4)

The upper surface of Cui Hua rock avalanche - a giant fan-like cone up to the main scarp in the west - exhibits extremely huge blocks and boulders. Instead of piping inside the rock avalanche, seeping waters have given a stabilizing input by filling voids between the blocks with fine-grained sediments. Nevertheless, in the upper part of the deposit water can still easily flow through the big boulders and the coarse-grained material. That is why the northern shore of Tianchi Lake has been sealed by the locals with artificial cementation, preventing the water from seeping through the material of the rock avalanche. Due to this stabilizing input, the natural dammed waters of Tianchi Lake are kept at a higher level, thus functioning as a water reservoir. And with an isometric shape of the deposit and a volume of more than 100 times that of the dammed waters behind it, the barrier of the Cui Hua rock avalanche must be safe from a breaching of the dam.

Landslide/Parameters	13. Liu Dshe Tse	14. Cui Hua
Preparatory causal factors	Tectonics, erosion, seismic activity	Tectonics, erosion, seismic activity
Age	Sub-recent (2 784 yr)	Sub-recent (2 784 yr)
Type of movement	Rolling, bouncing	Rolling, bouncing
Geographic Position	Dong Cha Valley/ Shaanxi, P. R. China	Dong Cha Valley/ Shaanxi, P. R. China
Geotectonic Position	Crystalline of the Qin Ling Mountains	Crystalline of the Qin Ling Mountains
Lithology	Gneiss, granite	Gneiss, granite
Composition of Material	Boulders diameters: ≤20 m	Boulders Diameters: ≤70 m
Length, width, thickness of dam	1/1/0.5 km	1/1/0.3 km
Volume of deposit	1 bill. m³	350 mill. m³
Fahrböschung	No data	No data
Length/width/ Depth of lake(s)	No lake dammed	1/≤0.3/≤0.02 km
Water volume of lake	No stored water	≤3 mill. m³
Stability of dam	Stable	Still stable (cementation, human impact)
Life span of lake	Due to permeability (tectonic structure) of bottom, no water	Still existing after 2 784 yr

Table 4 - Characteristics and stability conditions of rock avalanche dams and a lake in the Qin Ling Mountains (P. R. China)

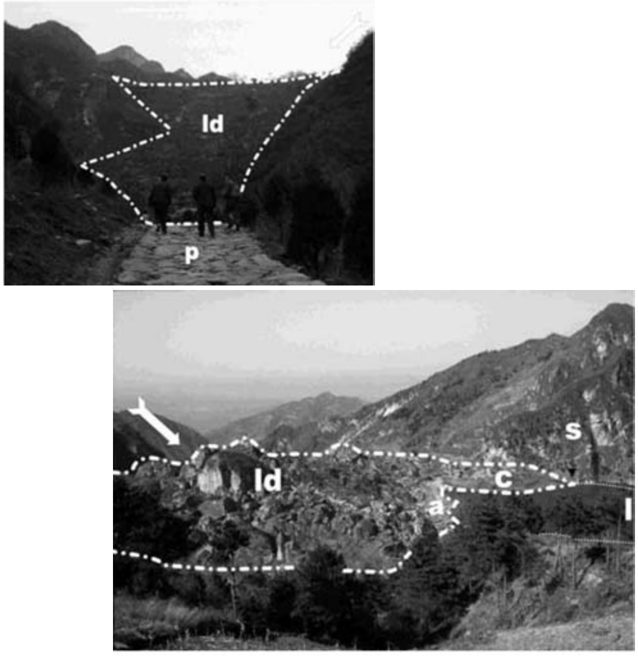


Figure 13 - Left side: view from the pathway (p) towards SSE, to the barrier of Cui Hua rock avalanche (ld, dotted-dashed line); arrow = direction of movement. Right side: The village of Chui Tsho Tshe (c) on top of Cui Hua rock avalanche (ld, dotted-dashed line); s = spillway of the dammed Tianchi Lake (l, dashed line) regulated for agriculture; s = artificial sealing of the lake

RESULTS, CONCLUSIONS AND GENERAL DISCUSSION ON ROCK AVALANCHE DAMS

Failure occurred as rolling and bouncing boulders, and is the main reason for the stability of these natural dams. The primary deposited materials of the landslides were mainly composed of poorly sorted blocks and boulders, while secondary fine-grained sediments that were introduced by seeping river and lake waters have been inter-spacing, compacting and cementing them. Additionally, these dammed lakes were filled with alluvial and lacustrine sediments before the dams could breach.

Therefore the stability of these natural dams, the life spans of the dammed lakes, and the potential of hazard for the main valleys downwards were controlled by the rates of sedimentation into the lakes, the sufficient availability of alluvial sediments, the freights of sediments of the river under extreme humid conditions, as well as the rates of seeping waters through the landslide materials. Although erosion and sedimentation has left only Tianchi Lake, each of these examples had a long life span.

LAKE-DAMMING LANDSLIDES IN THE LESSER HIMALAYAS OF INDIA AND NEPAL (FIGURE 1)

Landslide dams made of shattered fine debris pose a frequent and serious problems to life and infrastructure; their dammed lakes are always of very short life span as these dams tend to breach by overtopping within short time. This special kind of an in-situ collapsed debris stream as the mechanism of a landslide is typical of the Lesser Himalayas.

GENERAL DESCRIPTION OF LANDSLIDES IN THE LESSER HIMALAYAS (TABLES 5A, B)

The rock avalanche of Ghatta Khola Valley (WEIDINGER 1997; WEIDINGER & IBETSBERGER, 2000) is located in Western Nepal's Lower Himalayas (FUCHS, 1977; Figure 1). It has dammed the main river, which descends from NNW to SSE, up to an altitude of 3010 m. The geometric shape of the landslide deposit is exposed as a cone of debris towards the scarp in the SW and an isometric hill towards the zone of impact in the NE.

In the Lower Himalayas of Kumaon (Uttarakhand, India; FUCHS & SINHA, 1978), one of the rare lakes on the southern slopes of the Himalayas, the Gohna Tal, has existed throughout the 20th century. Five km north of Chamoli village its water surface was situated at an elevation of 1680 m, on the northern banks of the river Birahi Ganga, a tributary of the Alakananda (easternmost origin of Ganga River). A landslide that occurred in September 1893 during heavy rainfalls dammed the main river, forming a lake with increasing size within a year until its first outbreak (Figure 14).

From the Buri Gandhaki Valley (Manauslu Himal, Central Nepal) Jacobsen (1990) reported two rock avalanche deposits that have dammed the main river during recent times. One of them is located 1.5-3.0 km south of the village of Jagat, 40 km SE of Manaslu Peak (8162 m); the other one is near the village of Labubesi, just 30 km NE of Gorkha.

The landslide of Dharbang in the Myaghdi Khola valley (western tributary of the Kali Gandaki River) is located within the Lesser Himalayas of Western Nepal (FUCHS, FRANK 1970; Figure 1). The special geotectonic location (YAGI, 1992; YAGI *et alii*, 1990) and the climatic circumstances during monsoon where the preparatory causal factors and the triggers of two landslides that occurred in 1926 and rejuvenated in 1988 (IBETSBERGER & WEIDINGER, 2000; WEIDINGER & IBETSBERGER, 2000). The S-N falling masses destroyed the former villages on the right bank of the river twice and dammed the river temporary at an altitude of 1100 m (Figure 15).

The 1998 landslide of Tatopani in the lower Kali Gandhaki Valley (Nepal) repre-sents another example of the collapse of a mountain flank triggered by enlarged pore water pressure during long

Figure 14 - Geologic sketch-map of Gohna Tal landslide; LH = Lesser Himalayas, s = scarp (2900 m), arrows = direction of movement, ld = landslide deposit, gt (dotted-dashed line) = max. extension of the lake, a = last extension and alluvial fillings of the lake, c = terraced outbreak channel along the Birahi Ganga River (b), g = Gohna village (1600 m), p = Pagna village, pg = Pul Gadera River, pn = Begar Nala River.

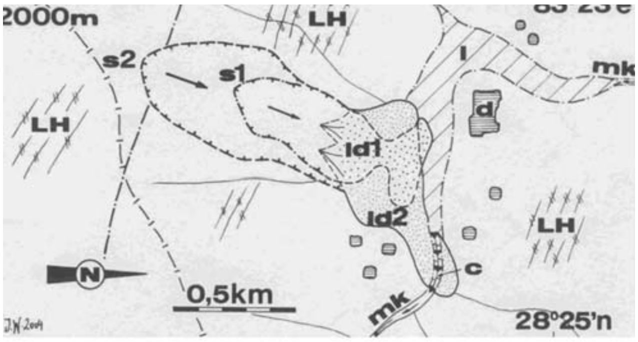


Figure 15 - Geologic sketch map of Dharbang landslide; LH = Lesser Himalayas, s1/2, ld1/2 = scarp and landslide deposit from 1923 (1400 m) respectively from 1988 (1750 m), arrows = direction(s) of movement, l = temporary dammed lake 1988, c = outbreak channel along the Myagdi Khola River (mk), d = Dharbang village, houses (1150 m)

periods of heavy monsoon precipitation. It occurred in the Lesser Himalayas in an area of a gigantic mass creeping process towards the valley (VOLK 2000). After initial movements on September 7 and the opening of the main plane of failure on September 10, 400,000 m^3 of rock originated from about 250 m above the Kali Gandhaki River, fell down from the eastern side of the valley on September 26, and accumulated in the form of a huge debris fan that functioned as a barrier, damming the river temporary.

STABILITY CONDITIONS OF LANDSLIDE DAMS IN THE LESSER HIMALAYAS AND LIFE SPAN OF TEMPORARY DAMMED LAKES (TABLE 5A, B)

The boulders of Ghatta Khola landslide are flattened and cracked along pre-existing joints. Huge ones reach diameters of 4-5m, although the bulk of the material is much smaller. Due to an avalanching mechanism of the landslide, the material was not that heavily shattered. That is why seeping waters through the deposit have caused stabili-zation due to sedimentation between the boulders. The sediment-filled youngest basin of the lake behind the deposit and terraced lake sediments on the flanks give evidence that an older lake with higher level must have had an active spillway and/or unspectacular outbreaks. Simultaneously Ghatta Khola River, originating from Ghurchi Lagna pass (alt. 2500 m) and draining an area of 25-30 km^2, has silted up the entire impoundment.

Much more spectacular was the catastrophic outbreak of the lake Gohna Tal, which devastated the valley of Alakananda River over a long distance downwards, when the dam failed on the August 26 1894, most probably because of overtopping. Subsequent catastrophic outbreaks of the lake are documented by at least four river terraces of different ages within the eroded flanks of the landslide deposits and downstream in the valley, which were created during and after flood events (Figure 16). Further on, local eye witnesses observed that the water level of Gohna Tal was lowered to a depth of 120 m. This water volume (80 mill. m^3) was silted up with lake and alluvial sediments within a period of 78 years. This high rate of sedimentation was a function of the monsoon climate and the huge catchment area (200 km^2) in the vicinity of the Nanda Ghunti massif (6,500 m). In the 1972 monsoon Gohna Tal disappeared completely after a massive slide within the landslide deposits near its spillway.

Jagat and Labubesi display a similar situation as in Gohna Tal. Both lakes were dammed in recent times; both had a very short life span. One of the main reasons is the high average rate of sedimenta-

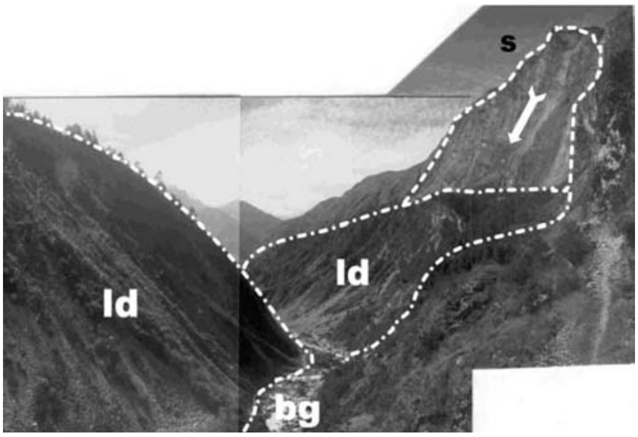


Figure 16 - View from the western end of the former dammed Gohna Lake (alt. 1,660 m) towards the W; s = scarp of the landslide (dashed line), arrow = direction of movement, ld = deeply eroded deposit of the landslide on both sides of the Birahi Gang River (bg)

Landslide/ Parameters	15. Ghatta Khola	16. Gohna Tal	17. Jagat (*)
Preparatory causal factors	Stress release	Climatic conditions, stress release	Fabric, erosion, stress release, climate
Age	Post-glacial	1893	Between 1962 and 1979
Type of movement	Rolling, bouncing	Debris stream	Debris stream
Geographic position	Ghatta Khola Valley/ Western Nepal	Birahi Ganga Valley/ Garhwal, India	Buri Gandhaki Valley/ Nepal
Geotectonic position	Lesser Himalayas	Lesser Himalayas	Lesser Himalayas
Lithology	Dolomite, shists	Dolomites,limestone, marls, shists	No data
Composition of material	Boulders boulder size: ≤5m	Shattered, pulverized, cataclastic rock	Pulverized and cataclastic rock
Length, wide, thickness of dam	0.3/0.3/0.2 km	1.1/1/ 0.3 km	No data
Volume of deposit	4.8 mill. m^3	150-200 mill. m^3	No data
Side effects		Dammed one lake, its outbreak in 1894 claimed one victim	Dammed one lake
Fahrböschung	Ca. 21°	Ca. 35°	No data
Length/width/ depth of lake(s)	0.3/0.1/0.1km	4/0.35-max.1/≤0.3km	Est. 5/0.4/0.1/km
Water volume of lake	≤1 mill. m^3	250 mill. m^3 (both before 1st break)	No data
Stability of dam	Stable due to cementation with sediments	Outbreaks and erosion through deposit	Outbreaks and erosion through deposit
Life span of lake	Filled up with alluvions within ≤100 yr	Outbreaks/filled with alluvions within 78 yr	Outbreaks, filled with alluvions <17 yr

Table 5a - Characteristics and stability conditions of a post-glacial and recent landslide dams and temporary dammed lakes in the Lesser Himalayas, (*) data by JACOBSEN 1990

Landslide/Param.	18. Labubesi (*)	19. Dharbang	20. Tatopani (**)
Preparatory causal factors	Fabric, erosion, stress release, climate	Stress release, human impact, climate	Fabric, erosion, stress release, climate
Age	1968	1926, 1988	1998
Type of movement	Debris stream	Debris stream	Debris stream
Geographic position	Buri Gandhaki Valley/Nepal	Myagdi Valley/Nepal	Kali Gandhaki Valley/ Nepal
Geotectonic position	Lesser Himalayas	Lesser Himalayas	Lesser Himalayas
Lithology	No data	Shists, slates, phyllite, quartzite	Phyllite, quartzite
Composition of material	Pulverized and cataclastic rock	Pulverized and cataclastic rock	Pulverized and cataclastic rock
Length, wide, thickness of dam	No data	1.5/0.3/0.1 km (1988)	No data
Volume of deposit	No data	5 mill. m^3 (1988)	400 000 m^3
Fahrböschung (Heim 1932)	No data	Ca. 23°	No data
Side effects	Dammed one lake	Dammed one lake (claimed 600 victims in both events)	Dammed a lake, which endangered the health resort Tatopani
Length/width/depth of lake(s)	Est. 5/0.4/0.2/ km	0.7/0.1/0.05 km	≤1/≤0.1/0.02 km
Water volume of lake	0.05 km^3 (Jacobsen, 1990)	≤1.75 mill. m^3	≤1 mill. m^3
Stability of dam	Outbreaks and erosion through deposit	Failed due to over-topping and erosion	Failed due to over-topping and erosion
Life span of lake	Outbreaks, filled with alluvions <17 yr	<6 hours	<72 hours

Table 5b - Characteristics and stability conditions of landslide dams and temporary dammed lakes in the Lesser Himalayas; (*) by JACOBSEN 1990, (**) by VOLK 2000 tion by the river. Jacobsen (1990) calculated the freight of sediments into the former dammed lake at Labubesi at more than 16000 t/day, as the entire impoundment were filled up with lake and alluvial sediments within less than 17 years (until before 1985). Similar amounts must be taken under consideration for the Jagat landslide, as in 1979 the sediments of the impoundment had already reached and partly buried an older landslide deposit upstream. Simultaneously the spillways of the lakes easily eroded and cut through the barriers of a totally crashed and fine-grained landslide material until the lakes were geological history (Figure 17).

Because of the rapid breaching of a natural rock blockage, the Dharbang landslide of 1988 maintains an extraordinary position among all those investigated in the Himalayas so far. The source of the landslide material must have been soaked with precipitation waters during the monsoon season before the event. Heavy rainfalls during late September caused the rock failure and the rapid damming of a lake. Morphology and internal structure of the remaining deposition area after the lake's outbreak (Figure 18) show that the movement of the slide was an in-situ collapse due to increasing pore water pressure and weight.

While sliding, crashed rocks and mineral particles together with water formed a suspension with no inner rupture under rheologic conditions. Instead of becoming compacted, the bulk of the landslide mass became more and more saturated with water. That is why the dam failed by overtopping and material was washed away rather than breaching during the lake's outbreak flood.

The fine-grained gravel and debris of Tatopani landslide provides a similar situation of a dammed lake with a very short life span. Its level of water reached the height of Tatopani village, a thermal water health resort and tourist site located 1 km valley upwards on the alluvial terrace of the right side of the river. The natural rock blockage failed due to overtopping, the landslide material was washed away, and the lake sank to a depth of 5 m. Recently even this remaining water disappeared by the accumulation of alluvial sediments and the erosion of the spillway.

RESULTS, CONCLUSIONS AND GENERAL DISCUSSION ON RECENT LANDSLIDE DAMS

Giant mass creeping processes following deglaciation and postglacial erosion with deep pre-existing joints and fissures have preformed the slopes and mountain flanks of the Lesser Himalayas. In addition, sliding planes parallel to foliation and strata of rocks with intensive tectonic history have added to destabilization. In addition the landscape has been influenced by erosion processes, human activity, and extreme climatic conditi-ons. Every year hundreds of such landslides occur, especially in areas with high rural activity of the locals, where deforestation has been the beginning of a dilemma with fatal consequences when annual summer monsoon season with high precipitation triggers extraordinarily large landslides (Ives & Messerli, 1989). In some cases these slides dam lakes, but due to lithology, weathering and high pore water content, the barriers are extremely unstable and usually fail within short periods.

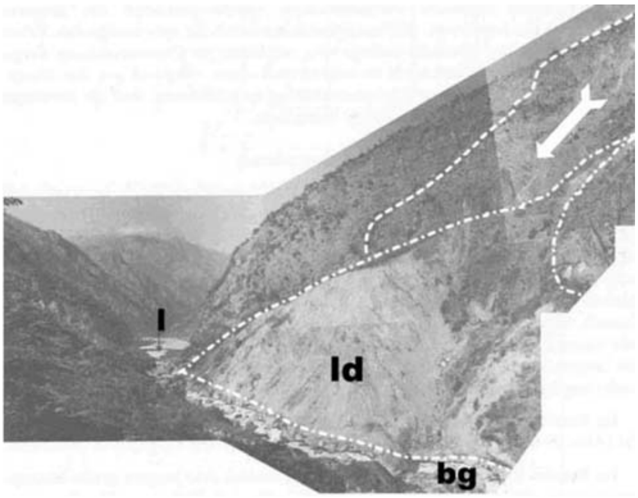


Figure 17 - N-view towards the remnants of Labubesi landslide (ld, dotted-dashed line); bg = Buri Gandhaki River, l = silted up impoundment (dashed line), the former dammed lake, (dotted-dashed line) = scarp, arrow = direction of movement. Observation point: 1150 m; photograph: Jacobsen 1990

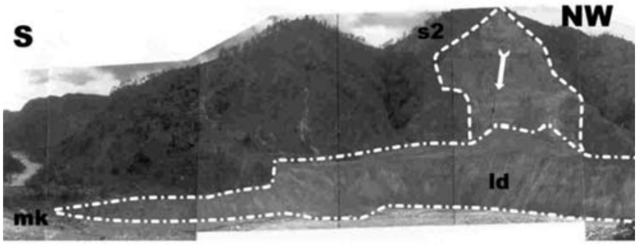


Figure 18 - Panoramic view over the remnants of Dharbang landslide area (ld, dotted-dashed line); note the morphology of the cone of landslide debris); s2(dashed line) = scarp (1988), arrow = direction of movement, mk = Myagdi Khola River; photo: J. T. Weidinger 1994

The almost pulverized rocks are the main reason for the seepage (piping) of the dammed lake's water through the material of the landslide and the initial breaching of the dam after short times. That is why mountain waters originating from theses landslide materials show higher eC (electrical conductivity) than those from compact hardrock (Schramm & Weidinger, 1996; Weidinger *et alii*, 1995).

As these lithologies and geo-tectonics of the Lesser Himalayas are similar to areas in the Alps, the results of this study are comparable with landslides there, e.g., the lake damming rock avalanche of Val Pola 1987 (Huber, 1992). Also mixtures of rock and ice avalanches such as those from Huascaran (6654 m) in the Cordillera Blanca in Peru (Patzelt, 1983), where the Rio Santa River was dammed up to a lake of 2 km in length for 30 minutes, are comparable.

OVERALL DISCUSSION AND CONCLUSIONS

Generally the stability of lake-damming natural rock blockages is attributed to their morphology (e.g. Casagli & Ermini, 1999; Hermanns *et alii*, 2004; Korup 2004), volume of debris, composition of the material including different lithological behaviors (Costa & Schuster, 1988; Schuster, 1986) as well as climatic conditions and the rates of sedimenta-tion and/or freights of alluvial sediments in the lake. The analysis of twenty case studies presented in this paper shows that there are other subsequent important factors affecting the stability of landslide dams by influencing the mechanical behavior of the landslide material:

- *Movement-type* such as i) en masse translational rock sliding, ii) rock avalan-ching with rolling and bouncing components, iii) in-situ collapsed landslides with crushed material partly supersaturated with water.
- *Disintegration grade* of the landslide mass, which depends on i) the volume of the mass, ii) the mechanism of sliding and iii) the distance of displacement.
- Shattering grade and cataclastic reactions depending on i) the involved litho-logies and ii) their intensity of weathering.
- *Grain-boulder block-size distribution* of the landslide debris, e.g., i) not dis-integrated and interlocked blocks, ii) boulders and iii) shattered and crushed material, which is influenced by the type and distance of dislocation (Davis & McSaveney, 2004).
- *Secondary cementation/compaction* (which again influences the grain, boulder and blocksize) not only by seeping waters and/or transported sediments but also by natural mineralized and/or thermal springs in the landslide areas.
- *Mixture of landslide and moraine material*, as morainic material is highly susceptible to overtopping and piping of a dam.
- S*ize of the catchment area, climatic conditions and rates of sedimentation* of the landslide-dammed river, as the availability of lake and alluvial sediments and their rapid transport is most important for silting up the impoundment be-fore the breaching of the dam.

BLOCK SIZE STABILITY DIAGRAM A CLASSIFICATION FOR NATURAL ROCK BLOCKAGES AND THE LIFE SPAN OF THEIR DAMMED LAKES

The above conclusions led to a diagram - a simple but helpful tool for estimating potential hazard - which should help in determining whether a lake-damming landslide is stable. The diagram correlates the grain, boulder and block size of landslide material and the stability of a dam (life span of the dammed lake), with the result that the greater the average diameter of the components, the longer the life of the dam and the lake (Figure 19). This calculation is evident by the field data analyzed in this study, although it was not possible to determine the grain size of the landslide materials, e.g., as done by Casagli *et alii,* (2003). Finding the average grain, boulder and block size was more like an estimation by analyzing different outcrops. En masse translational dislocated blocks, which were shattered by mechanical stress during sliding, are counted as single pieces as they have often been recompacted by secondary cementation.

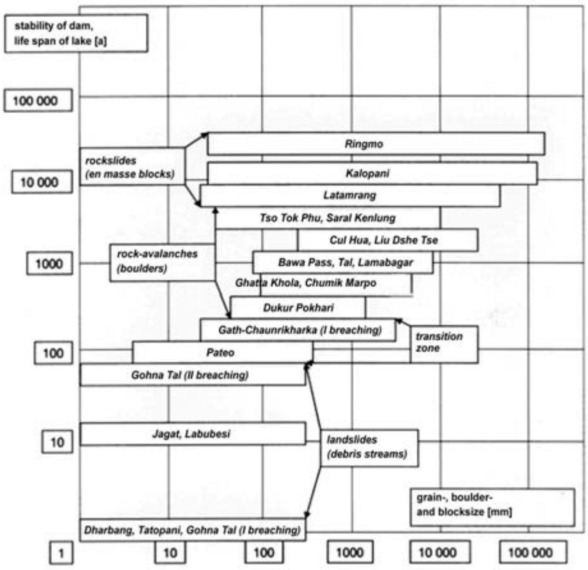


Figure 19 - Grain Boulder Block Size Stability Diagram of lake-damming rockslides, rock avalanches and debris stream landslides from India, Nepal and China

The scientific message of this “brain-boulderblocksize-stability diagram” for determining the life span of landslide dammed lakes is the following: not only very large, en masse dislocated blocks with dozens of meters in diameter are stabilized and recompacted by secondary cementation, but also boulders of meter-size as seeping mountain waters give a stabilizing input by cementing the interspaces with fine-grained sediments (transported by the water) instead of piping inside the deposit. The critical stage of this system is defined by average grain size of the deposit that can easily be transported out by the waters. The weakest stability conditions are represented by debris-stream dams, however they have been shown to fail rapidly by overtopping and/or piping.

Although this is a first attempt at finding a way to solve the problem of prognosis, more examples of lake-damming landslides must be investigated to verify this diagram. Prevention of those kinds of catastrophes is therefore not only a matter of detailed mapping of predestined zones but also an attempt to achieve a visionary forecast.

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