Journal of Nepal Geological Society, 2000, Vol. 22, pp. 405–412

The 1998 Tatopani Landslide in the Kali Gandaki Valley of Western Nepal: cause and relation to mass rock creep

Hellmut R. Völk
Institute of Geography, University of Heidelberg, INF 348
69120 Heidelberg, Germany

ABSTRACT

The village of Tatopani lies on a small gravel terrace in the middle reach of the Kali Gandaki River, along a narrow course of about 2 km in length. One kilometre south of the village, a major rockfall occurred recently in the region of the Lesser Himalaya, which is built up of low-grade metamorphic rocks of the Kuncha Group, consisting of a thick sequence of foliated phyllites and bedded quartzites as well as interlayering of both lithologies. The monoclinal structure of these metasedimentary rocks is clearly related to the general trend of the Nepal Himalaya near the Main Central Thrust (MCT): strike NW-SE 140–150°, dip 25–45° NE. Besides a clear foliation in the phyllites (s1) parallel to the quartzite bedding (s0), four other discontinuities are also developed as steep joints (j1–j4).

Two joint sets j1 and j2, both crossing each other and both acting in conjunction with the foliation (s1) as a shear plane, were responsible for the wedge failure of the Tatopani Landslide, which led to a rockfall and avalanche of about 400,000 cubic metres and dammed the river for about 72 hours. It is noteworthy that several other – strikingly similar but older – weathered wedge failure surfaces are exposed at various spots all over the same ridge, which is the spur-ridge dividing the Kali Gandaki River from the Gar Khola tributary. This visible slope instability evidenced by relatively small wedge failures is causally connected with a much larger mechanism, namely mass rock creep or "sagging"- a purely gravitational slope deformation. The repeatedly occurring wedge failures producing landslides (rockfalls and rock avalanches) are caused by extreme shear stress and deep-reaching joints and fissures during mass rock creep. Only the final trigger for landslides or rockfalls is provided by extreme and lengthy monsoon rainstorms, which reinforce the cleft-water pressure inside rock discontinuities and openings, especially along the impermeable interface of quartzites and phyllites (s0 = s1) at the base of the wedge failure.

The right (western) bank above the village is morpho-dynamically active also through mass rock creep and "pushes" laterally against the river course. However, the kinematics of the rock slope is rather different because the foliation geometry is more important. The foliation dips obliquely towards the riverside and consequently has facilitated extremely slow large-scale dip slope movements along quartzite-phyllite interfaces (s0) without any catastrophic danger. However, the creeping slope movements of thick quartzite members caused a set of conjugate extension faults producing toppling at the distal slope margins.

Rock avalanches from the spur-ridge on the eastern (left) bank of the Kali Gandaki River S of Tatopani will always remain a threat, especially when excessive seasonal rains increase the cleftwater pressure inside the invisibly slow creeping system of the steep bank in an extraordinary manner.

INTRODUCTION

The well-known village of Tatopani situated at only 1,190 m above sea level in the Lesser Himalaya of Western Nepal lies on the right (western) bank of the Kali Gandaki River (Fig. 1). A landslide (rockfall) occurred there on 26 September 1998 from the eastern bank at an elevation of about 250 m above the river. The landslide came down as a rock avalanche onto the floodplain of the river approximately 1 km downstream of the village. The debris cone blocked the river and created a temporary landslide dam. The river was dammed for 72 hours and the water level reached nearly the centre of the village. After breaching the dam by fluvial overflow, the lake lowered to a level of only 5 m above the former waterline.

GEOLOGICAL OUTLINE

The Lesser Himalayan rocks comprise mainly flyschoid metasedimentary rocks, such as foliated phyllites and bedded quartzites, known as the Kuncha Group (Fig. 2), with a few minor basic sills and dykes (Shrestha et al. 1993; Amatya and Jnawali 1994). The bedded metasedimentary rocks show quite clearly the three lithological members:

- pure quartzites: well-bedded (s0-planes), only minor intercalations of phyllitic material as single laminae;
- pure phyllites: strongly foliated (s1-planes), only minor intercalations of quartzites; and
- alternating quartzites and phyllites.

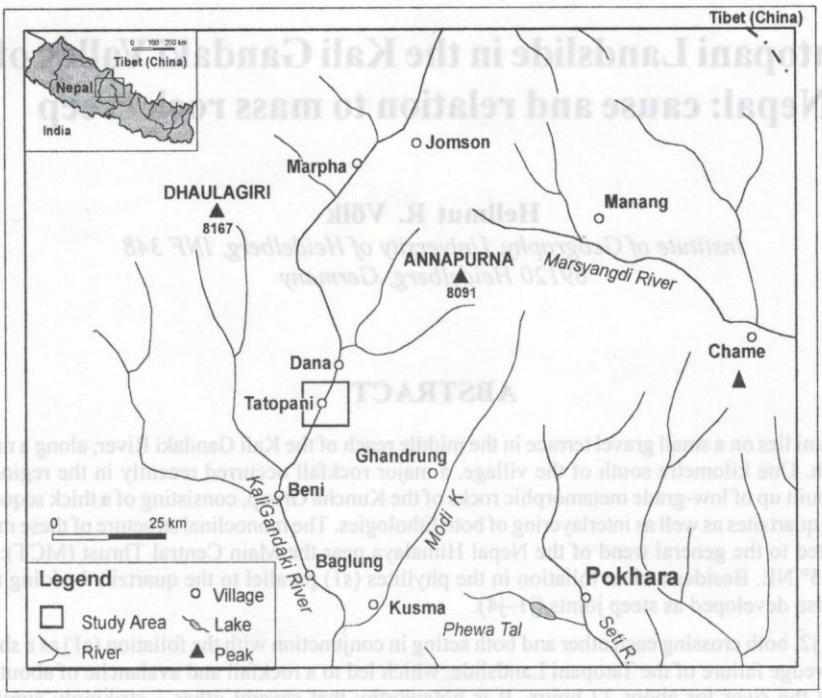

Fig. 1: Sketch map of the Kali Gandaki River showing the location of the Tatopani Village in the Lesser Himalaya south of Mt. Dhaulagiri and Annapurna

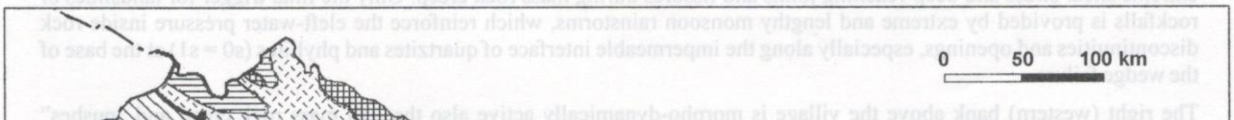

Fig. 2: Map of major geotectonic and morpho-tectonic units of Nepal

From the structural point of view, the situation can generally be described as quite uniform (strike WNW-ESE 120°, dip 35° NNE).

ROCK STRUCTURE AND MASS MOVEMENTS

The eastern and western banks of the Kali Gandaki River at Tatopani exhibit quite different slope stability conditions. The geomorphological conditions, rock structure, and mass movements on the two banks are summarised below.

Western bank

The monoclinal structure of the rocks in the surrounding of Tatopani is determined by a pronounced foliation (s1) or bedding (s0) with a dip of 25° NE, i.e. the dip is inclined upstream and oblique to the course of the Kali Gandaki Valley, which runs NNE. In such a situation, one would suppose that this bank would be endangered by failures along the foliation planes which might act as slip interfaces oblique to the thalweg, especially along the incompetent weak phyllitic members. However, there is in fact no dangerous slope movement, and therefore the village of Tatopani does not experience a special threat for the time being. Still, there exist very slow and continuous mass movements of gigantic dimensions, persisting over thousands of years, owing to a process which belongs to the category of mass rock creep, and is also responsible for the narrow course of the Kali Gandaki River there in correspondence to a counteracting slope movement from the opposite bank. It should be mentioned that a set of steep joints dissects the thick quartzite member (Plates 1 and 2) and eventually will cause toppling here and there near the river.

This mass rock creep is acting parallel to the foliation, quite unlike to the kinematics of the left (eastern) bank. Two kinds of geotechnical reaction are visible: shear pods (German: phacoids) in the ductile phyllites, and along small quartzite intercalations inside thick phyllitic members (Plates 3 and 4).

Shear pods–lenticular shaped bodies–are considered typical phenomena of extensional gliding zones in heterogeneous lithology, e.g. brittle quartzite in ductile phyllites (Fry 1984; Eisbacher 1991). The brittle quartzite members, on the other hand, respond quite differently, namely by showing numerous fractures and openings across the bedding plane (Plate 5).

From both of these clear signs of tensile strain, we can conclude for the western bank that the whole series of metasedimentary rocks is internally sheared, stretched, and dismembered into various slices. These slices are gravitationally drifting towards the thalweg, with thick quartzitic sequences gliding down on phyllitic ones (Plate 6). But, there is no immediate danger of large rockfall at the moment.

Eastern bank

This valley side is in fact the threatening one and produced the landslide discussed in this paper. This has happened despite the dip of foliation oblique to the mountain slope, and therefore supposedly the foliation plays a minor role in potential rock failures (Plate 7).

By observing the eastern valley slope, one is able to detect various relict scars of earlier landslides. These failures

Plate 1: View of the village of Tatopani in the Kali Gandaki Valley upstream of the recent landslide, which has dammed the river to form a small lake along the village in the middle part of the picture. Note the steep joints in the quartzite member exposed in the left (western) foreground, and the relict failure scar on the right (eastern) front.

Plate 2: Upstream view of the Kali Gandaki River and its steep banks; on the left-hand (western) side can be seen mainly coarse, bedded quartzites in light grey colours showing steep joints crosscutting the bedding planes, which dip towards the thalweg, and are overlain by darker phyllites in the lower background. Note the white streak, a tiny debris flow (typically) marking a shear plane of the quartzite-phyllite interlayering in the right foreground.

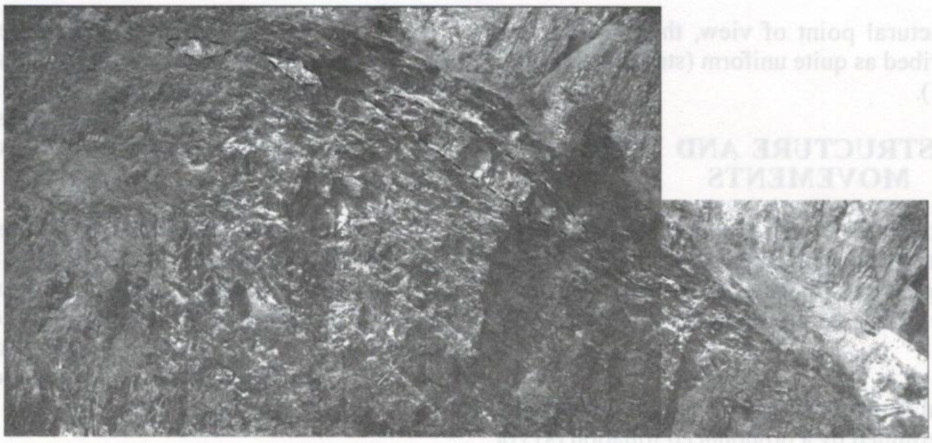

Plate 3: Phyllite members with quartzite intercalations (detail of Plate 6), which are deformed into lenticular shear pods (marked by dotted lines) on the right or western bank, indicating tensile shearing movements along the foliation of these metasedimentary rocks. There are also some steep joints, which are crossing the foliation planes, and thus increasing the appearance of strained disordered rock.

Plate 4: Phyllite, containing lenticular shear pods, indicates extensional movements along the foliation. Outcrop on the western bank near Tatopani

Plate 5: Bedded quartzite on the western bank near Tatopani, exhibiting extensional features marked by shearing along the bedding as well as cracks and openings across it

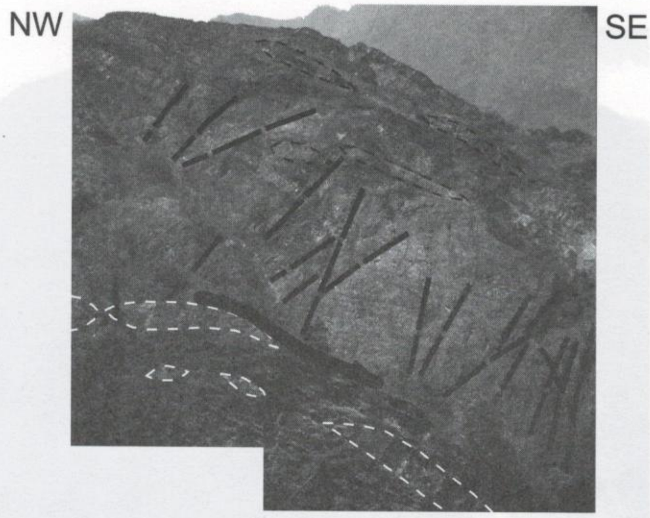

Plate 6: View of the western bank near Tatopani showing the metasedimentary rocks of the Lesser Himalaya in some disorder and gravitational deformation due to deep-seated creep (drift) along the foliation, especially inside the phyllites and along the interface between quartzite and phyllite members, directed towards the thalweg of the Kali Gandaki River to the right, outside the photograph. Ductile phyllites (dark rocks) serve as gliding zones between thick quartzite members consisting of light grey, bedded rocks. Thick quartzite sequences are slowly gliding down on phyllitic ones (indicated here by a half-arrow symbol). Quartzite shear pods (phacoids) in the phyllites (thinly dotted lentils at lower left; cf. Plate 3), wedging of quartzite members (thinly dotted lentils at upper right), and disruption of thick quartzite members by steep joints (thickly dotted lines in middle part) testify to the extensional movements towards the thalweg.

were made possible by four different sets of steep joint (Plate 8): j1 (NNW-SSE), j2 (NE-SW), j3 (ENE-WSW), and j4 (WNW-ESE).

THE TATOPANI LANDSLIDE

The Tatopani Landslide occurred in 1998 at a mountain ridge of the eastern bank, which makes up a divide between the Kali Gandaki River and the large Gar Khola tributary ending downwards to the Kali Gandaki thalweg as a dividing spur (Plates 8 and 9). Generally, these spur-ridges are frequently susceptible to all kinds of mass movement in high mountains entrenched by deep valleys.

The landslide can be described as a wedge failure producing a major rock fall of 400,000 m^3. Its failure planes make a triangle confined by the two main joints, j1 and j2, in combination with the general foliation s1. Clearly dominant is the long j1-joint on the vertical backside of the detachment-niche, a rock wall, which is crossed on the narrow side by a j2-joint. The bottom of the triangle, finally, is formed by the foliation s1, which represents the top of a phyllite member.

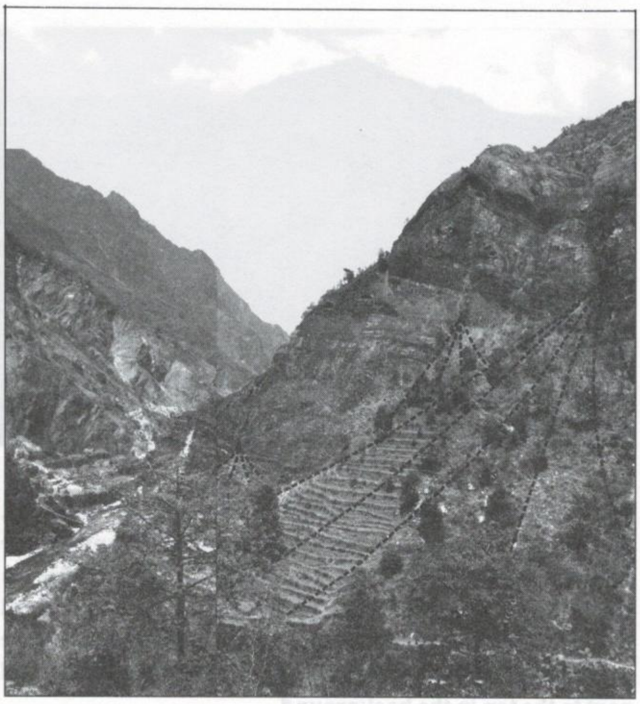

Plate 7: To the right we recognise the steep eastern bank along the dismembered spur-ridge between the Gar Khola tributary and Kali Gandaki Valley looking upstream i.e. northwards. The steeply inclined shear ("fault") planes are visible either by a whitish streak of a tiny debris flow seeping out of the slope, by an open fissure (left of middle part in the picture) connected with a tiny cone of scree, or with larger cones of scree adjoining the more important bigger shear planes, e.g. a terraced scree cone below a steep scar or scarp, i.e. a relict shear feature on the upper right of the picture.

Searching for the triggers of this rockfall, we have to look at the uppermost part of the phyllite member below the failure scar where dark wet patches are observed on light grey phyllitic rocks (Plate 10). The patches are apparently derived from cleft-water, which seeps through the permeable quartzite member over the impermeable grey phyllites below and stains it with dark spots. Therefore, it was probably cleft-water overpressure at the interface of quartzite and phyllite, which brought about the failure. The rockfall occurred in two stages: the first stage was related to the short joint wall (j2) on the right-hand side and happened on 7 September 1998, some hours after a period of tremendous monsoon rainstorms during the weeks of August and September; and the second stage was initiated by the spontaneous opening of a large vertical fissure along the

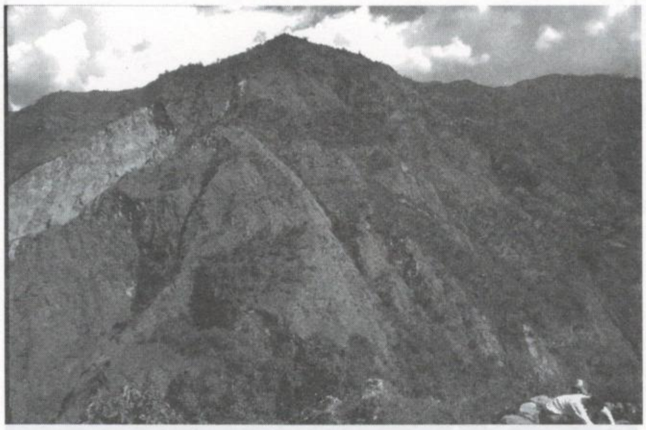

Plate 8: Similar to Plate 9, but taken from a greater distance, it exhibits the morpho-tectonic dissection of the spur-ridge between the Gar Khola (right) and Kali Gandaki Valley (in the front). Note the relict failure scars on the frontal mountain pyramid and also to the right of the recent failure as well as the step-like rise of the ridge crest from the frontal part to the top in the background.

Plate 10: This picture shows some features of Plates 8 and 9 in more detail, especially the potential failure sites adjacent to the recent one. Also note the faulted left part of the frontal mountain pyramid with its precipice, namely a relict failure scar at the Kali Gandaki Valley slope in the foreground.

long joint wall (j1) on 10 September 1998, which was reported by farmers. Only 16 days later, i.e. on 26 September 1998, the larger rock fall occurred and produced the coarse-grained (mainly quartzitic) rock avalanche down to the river.

CAUSE OF THE TATOPANI LANDSLIDE

Plate 9: View across the Kali Gandaki Valley, looking onto the asymmetric wedge failure of the 1998 Tatopani Landslide (rockfall and avalanche), located near the front of the spur-ridge, on the eastern bank of the Kali Gandaki River. The light coloured upper section of the failure scar along joint j1 is made up of quartzite, while the smaller lower section is phyllitic and exhibits dark spots of cleft-water seeping out of the quartzite beds over the underlying impermeable phyllite member.

If we wish to understand the real or deeper cause of the Tatopani Landslide, we have to analyse the geological structures on a somewhat wider scale, including the whole mountain spur-ridge separating the Kali Gandaki River and Gar Khola. The spur-ridge is structurally divided into a regular set of "fault-planes" (j1) all parallel to the Kali Gandaki River (Plates 11 and 12: Fig. 3). It must be stressed that these "faults" are not strictly tectonic ones (Hoppe 1998), but a combination of tectonically induced discontinuities and gravitationally imposed cracking and faulting, by which a series of rock slabs had slid down by shearing along each other very slowly. This structural rock creep has also created quite typical slope morphology by creating a step-like shape with morphological breaks of benches and scarps, especially on the crest of the spur-ridge. Quite a similar process has been studied by the author on slopes in the Indus Valley along the Karakoram Highway, northern Pakistan (Völk *in press*).

Looking against the spur-ridge in a section along the northern bank of the Gar Khola tributary, we clearly recognise the above-mentioned set of deep reaching "fault" planes, which are morphologically manifested by steeply inclined "fault" scarps with inclinations of 75–45° dissecting the bank (Plates 11 and 12; Fig. 3).

Plate 11: Cross-section of the spur-ridge (W-E) south of the landslide site of 1998 along the Gar Khola bank. It demonstrates the morpho-tectonic shape of the faulted spur-ridge firstly by furrows, which are inclined from the right to the left towards the trunk valley of the Kali Gandaki River, and secondly by flatter and steeper crest morphology or even uphill-dipping forms at the left margin.

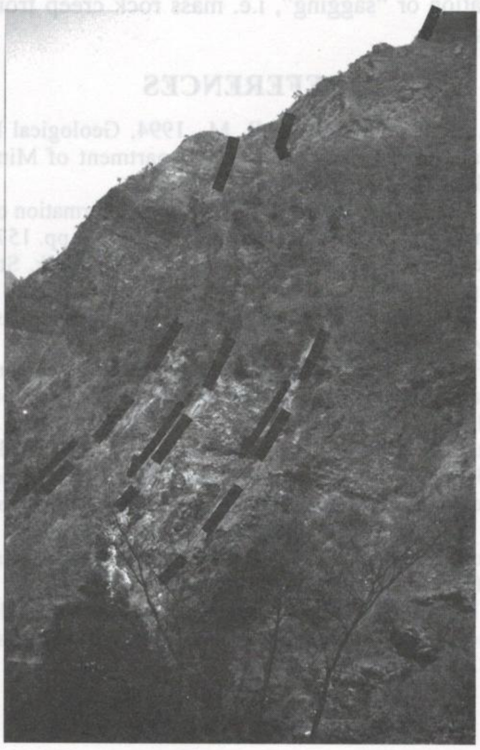

Plate 12: This view is similar to Plate 11, and was photographed after a heavy rainstorm, through which the steep shear ("fault") planes were marked with tiny debris flows of cleft-water rich in fine suspension out of the slope. Steep slope sections on the ridge crest correspond to shear planes.

Moreover, – and this is a strong indication for shearing movements inside the slope almost every outcropping "fault" plane is visibly marked by a streak of light-coloured tiny mudflow and/or debris cone, apparently produced by local suspension-rich water out of the mountain slope during rainstorms. These tiny "mudflows" contain quartzitic and sericitic rock powder, which is the product of shearing of the sliding rock slabs (Plates 2, 7, and 12).

Such stepped mountain slopes are formed by extremely slow mass movements, namely deep-seated rock creep, which appears to be possible along well-defined shear planes (Chigira 1992). These shear planes thus separate large, steeply inclined rock slabs to form rock cliffs (scars) and/or steep slope surfaces on the crest of the spur-ridge. Each shear ("fault"-) plane is almost vertical (75°) at the ridge crest whereas the lower part seems to be bent into a listric shape.

RELATIONSHIP BETWEEN MASS ROCK CREEP AND LANDSLIDE OF TATOPANI

If we search for a causal connection between the mass rock creep on the spur-ridge of the eastern bank near Tatopani and the actual rock failure, there we arrive at the conclusion that the landslide depended on deep-seated rock creep. The logical linking is strongly indicated by the identification of fissures, "faults", and shear planes with the wedge failure. It appears to be a matter of cause and effect not only for the current rock failure but for more than half a dozen older ones, which are manifested by relict failure scars in the vicinity of the fresh failure (Plates 8, 9, and 10). The climate-

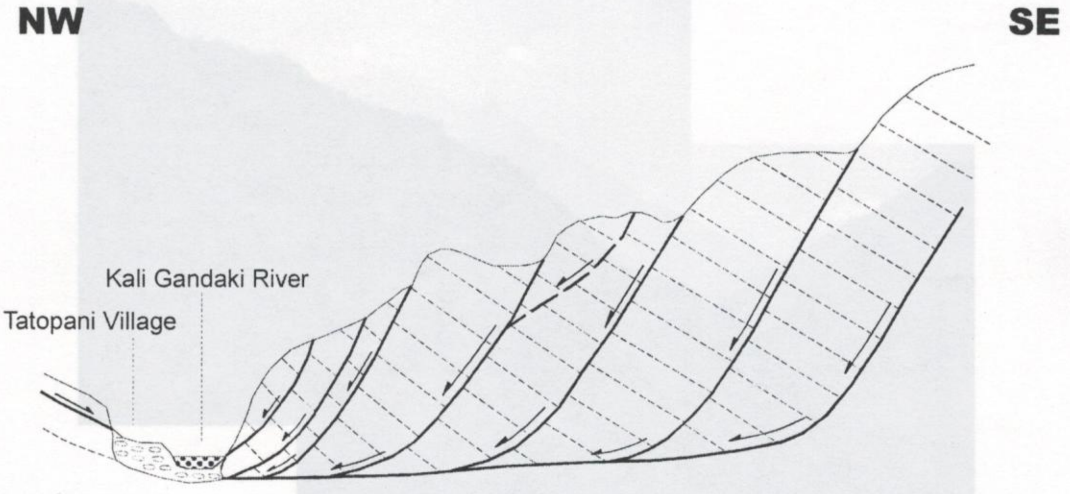

Fig. 3: Diagrammatic section through the spur-ridge south of Tatopani, eastern valley flank, showing inferred "sagging" by gravitational faulting along joint set (j1) which runs parallel to the Kali Gandaki River ca. 1 km south of the village. Sketch not to the scale. Note: main failure plane of landslide (rockfall) just behind the section coincides with joint (j1) system.

triggered spontaneous landslides always occur on already destabilised and weakened rock slabs of the long-term mass movements, which act as deep-seated rock creeps inside the valley slope down to a depth of 100 – 800 m. The process of persistent creeping slope movements is attributed to the continuous river incision, which is kept alive by the persistent uplift of the Himalayas.

CONCLUSIONS

The Tatopani Landslide in 1998 was a climate-triggered event of middle to small size (400,000 cubic metres). It occurred (with some delay) as a consequence of an excess monsoon precipitation.

The event of 1998 must be considered as one in a series, caused fundamentally by persistent mass rock creep in the spur-ridge at the junction of the Kali Gandaki River and Gar Khola during the Post Glacial Quaternary times.

Investigations of landslides, especially rockfalls by engineering geologists, should always take into account the proceeding weakening processes of deep-seated rock creep ("sagging") at the site and in the surroundings of the failure.

The narrow course of the Kali Gandaki River at the village of Tatopani appears to be the result of large-scale slope deformation or "sagging", i.e. mass rock creep from both valley slopes.

REFERENCES

Amatya, K. M. and Jnawali, B. M., 1994, Geological Map of Nepal with Explanatory Note. Department of Mines and Geology (DMG), Kathmandu, Nepal.

Chigira, M., 1992, Long-term gravitational deformation of rocks by mass rock creep. Engineering Geology, 32, pp. 157–184.

Eisbacher, G. H., 1991, Einfuehrung in die Tektonik, Stuttgart, 310 p.

Fry, N., 1984, *The field description of metamorphic rocks*. Open Univ. Press, New York, 110 p.

Hoppe, P., 1998, Transverse faults and block movements in Nepal Himalaya: results from satellite interpretation. Jour. of Nepal Geol. Soc., v. 17, pp. 1–5.

Shrestha, S. B., Maskey, N. D., Sharma, T., and Bashyal, R. P., 1993, Atlas of Mineral Resources of the ESCAP Region Vol. 9. Geology and Mineral Resources of Nepal with Geological Map of Nepal 1:1,000,000 and Explanatory Brochure. United Nations, Economic and Social Commission for Asia and the Pacific, Bangkok, Thailand, 107 p.

Völk, H. R., *in press*, Mass rock creep along the Karakoram Highway in the middle Indus Valley near Chilas, Northern Pakistan. Geol. Bull. Univ. Peshawar.