Very large landslides in the Himalayas

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Landslides are a major component of geomorphological processes on the steep slopes of the Himalayan mountains. Three slides in the Annapurna region demonstrate a sequence from large to very large failures.

The Himalayan mountains of Nepal offer some splendid geological sights in a terrain only reached by some of the most spectacular and enjoyable walking anywhere in the world. Justifiably, the most popular trekking region is around Annapurna, in western Nepal, and some of its rock structures featured in a recent issue of *Geology Today* (v.11, p.186, 1995). The Annapurna and Dhaulagiri Himals (ranges) are essentially a huge south-facing escarpment of massive, strong, Palaeozoic limestone (Fig. 1), thickened by nearly isoclinal overfolding and thrust over gneisses and schists which crop out to the south. Scarp faces therefore create the steepest slopes on the southern aspects – the South Faces, which are renowned and reveered among mountaineers.

Perhaps even more dramatic than the geology of these mountain lands is their geomorphology. Steep slopes are the key feature of Himalayan geomorphology. Rapid Pleistocene uplift, which continues today, has created local relief measurable in kilometres; in the Annapurna range the mountain summits stand at around 8000 m, while the foothills and valleys just 25 km to the south lie at about 1000 m. Rivers draining south, fed by snowmelt and monsoon rains, have cut deeply entrenched valleys whose slopes are incredibly steep and very unstable. The scale of these slopes is difficult to appreciate by anyone grounded in the gentle and relatively stable environments of Britain, and the processes on them are very different from those on British hillsides.

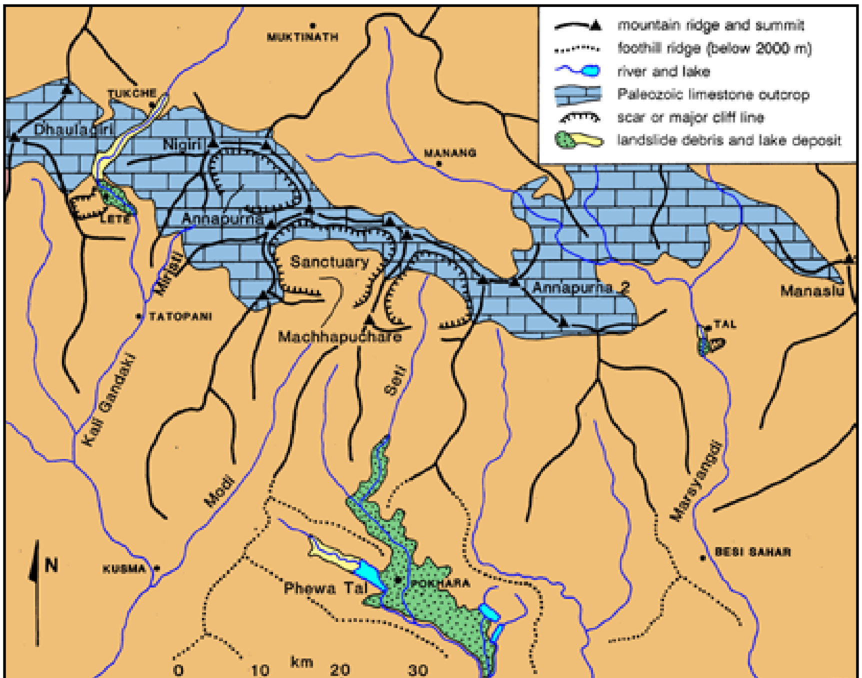

Fig. 1. Outline map of the Annapurna region, showing the three landslide sites and other locations mentioned in the text.

Mass movement is the dominant erosional process on the steep and youthful Himalayan slopes. Landslides, rockfalls and debris flows account for most of the denudation on the slopes, and only on the valley floors does water take over as the dominant mechanism of sediment transport. Landslides may be regarded as one end of the spectrum of slope erosion processes, in opposition to the grain-by-grain movement of rainwash. In Britain's environment, rainwash is the main process, but in Nepal the landslides dominate.

Dramatic slope failures are annual events in the Himalayas. Every monsoon season, houses are destroyed and paths are carried away by landslides. Many of the trails which follow the inhabitable valleys are merely notches cut into eroding slopes of landslide debris; their stabilities range from marginal to disastrous, and they are best avoided during heavy rain. The highest mountain slopes are largely above the reach of the monsoonal rains; they produce snow avalanches daily, and rock failures more widely spaced in time.

Every valley and every trail in the Annapurna region provides examples of the smaller landslides, and any return visitor can recognize the scale of processes by the changes to trail profiles and routes. Among the larger landslides, there are three which are encountered in order of increasing size by anyone making the classic trek known as the Annapurna Circuit. These are at Tal in the Marsyangdi Valley, at Lete in the Kali Gandaki Valley, and at Pokhara on the southern flanks (Fig. 1).

The Tal landslide

Between Annapurna and Manaslu, the Marsyangdi Valley has a deep V-shaped profile where it lies at an elevation too low to have carried a Pleistocene glacier. The trail to Manang follows the river, but has to rise more than 150 m over a bank of landslide debris, just south of the village of Tal. This fell from the precipitous east bank, leaving a scar hundreds of metres high. It was a single massive failure defined by very steep fractures, and the volume of the slide mass was around two million cubic metres.

The landsilde debris consists of blocks of gneiss and schist, each up to 20 m across. The river appears to find its way between these blocks; it is out of sight until it emerges in a narrow canyon at the downstream end of the slide mass. Even though the water has now washed out some of the fines to make its route through the debris, the landslide did temporarily block the valley. A lake was formed but has since filled with fluvial debris which probably reaches a depth of 50 m. Because the Marsyangdi gadient is so steep, the lake site and its sediments extend only a kilometre upstream of the landslide dam. The village name of Tal means Lake, and the now slightly entrenched lacustrine flats provide the flat ground for the village fields (Fig. 2). Memories of the lake remain in the village name and also in local folklore. The date of the landslide is not known, but appears to be within the last few hundred years.

Fig. 2. The view upstream from the debris pile of the Tal landslide. Fractures recognizable in the steep right-hand slopes are parallel to those which defined the slide. Tal village stands on an alluvial fan near the head of the old lake flats.

The Lete landslides

Like the Marsyangdi, the Kali Gandaki River has a catchment on the edge of the Tibetan Plateau and drains through the Himalayas. Its antecedent valley was entrenched between the Annapurna and Dhaulagiri massifs while the Himalayan axis was uplifted to its present height, and it is therefore one of the deepest valleys in the world. The valley follows a major fault south-west between the limestone mountains, but then has two south-easterly segments where it sidesteps onto two more, parallel faults (recognizable in Fig. 1, where it joins the Miristi Khola and Modi Khola). The Kali Gandaki's first deflection is past Lete, where it is confronted by the south-east ridge of Dhaulagiri – an escarpment of thick, strong, bedded gneisses which dip north-east at about 40°.

With its gradient steepened by the Himalayan uplift, the Kali Gandaki has entrenched its course and cut into the toe of the gneiss dipslope, where it flows along the strike. There must have been repeated failures all along this segment of the valley, where undercut slabs of gneiss slipped on their steep bedding planes, and the more recent features form the Lete slide complex (Fig. 3). The villages of Lete and Kalopani stand on a boulder-strewn terrace whose almost flat top provides very stony land for cultivation. The whole terrace is just landslide debris, conveniently exposed in sections where the Kali Gandaki has entrenched into it. Angular blocks up to 15 m across form a dramatic lag deposit along the river bed, where the finer debris has been washed away (Fig. 4). Off the downstream end of the Lete terrace, the trail descends nearly 500 m before reaching a rock floor for the river bed. Vast banks of poorly stratified debris appear to represent the distal segments of debris

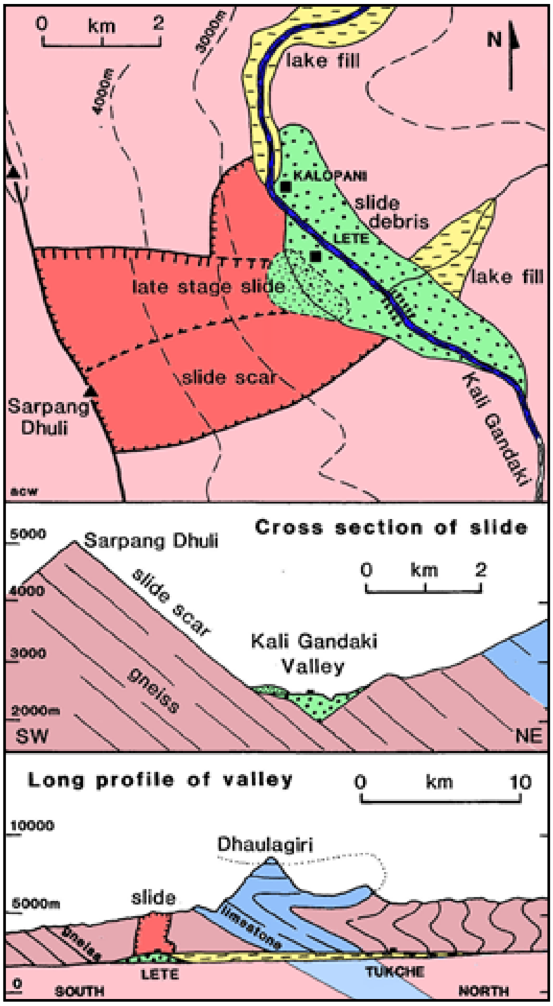

Fig. 3. Map and profiles of the Lete landslides. The long profile of the Kali Gandaki valley shows the structure visible on the western valley side, with the recumbent fold of Dhaulagiri high above; at floor level, the steep dips to the north are not apparent at the slide site, where the valley locally turns along the strike and its updip slope has therefore failed.

Fig. 4. The downstream end of the landslide debris forming the Lete terrace. On the right, the Kali Gandaki cascades down its freshly excavated gully, leaving a lag deposit of massive boulders in its bed.

(a)

(b)

flows which extended down the valley from their landslide sources. When the slides occurred, debris crashed into the valley and also slopped up the opposite slope; there is a clear tide mark of boulders scattered over the hillside north-east of Kalopani.

Layering in scattered exposures of the slide material suggests that the Lete terrace was derived from an unknown number of sequential events. The source area now appears as huge, steep slabs of gneiss, defined by their bedding and broken into wedges by large oblique fractures, which leave cliffs along the northern edge of each segment of slide scar. A late-stage event was a single wedge failure which dumped a hill of debris on top of the Lete terrace (Fig. 5); the fresh slip scar left by this slide is a spectacular sheet of bare rock reaching to the crest of the escarpment 2500 m above. The total volume of slide debris forming the Lete terrace is more than 500 million cubic metres, some of which has been removed by the river entrenchment. Debris from the late-stage scar amounts to only a small fraction of this.

The Lete landslides blocked the Kali Gandaki Valley and impounded a great lake which has subsequently been filled by river gravels (Fig. 6). The lake flat extends 15 km back up the valley. It has not yet stabilized, and vegetation is not yet established, although it is beginning to encroach at the top end, north of Tukche. The braided channels of the Kali Gandaki on top of this lake fill are a conspicuous feature of this dramatic valley through the Himalayas. The date of the main Lete landslide event is unknown. Local folklore includes reference to a lake in the valley, and the features are fresh enough for an age of less than 1000 years; it may be contemporary with the Pokhara slides (see below). The age of the small late-stage slide is probably closer to 100 years.

The Pokhara landslide debris

Pokhara, the second city of Nepal, sprawls across a flat-floored basin within the foothills south of Annapurna (Fig. 7). The Seti Khola drains through the basin, and is entrenched in

Fig. 5. (a) View along the Lete terrace, looking a little north of west. The fresh scar of the latest slide is at the extreme left, with its debris pile directly below. Dhaulagiri is behind the clouds, and the entrenched Kali Gandaki is off to the right. (b) A closer view of the late-stage slide at Lete. The wedge failure developed on the bedding plane which is still bare (partly covered in snow) and the steep fractures to its right; the debris pile in the foreground has partly exposed boulders and also a sparse tree cover.

Fig. 6. Looking due south to the Lete slides. The bare gravel plain is the post-slide lake infill, with an alluvial fan intruding in the right foreground. Across the end of the gravels, the slide debris forms the rounded bank, with the river now cutting through its right side. The snow-covered slabs on the right are the main slide scars.

its floor to reveal a sediment sequence 60–100 m thick, known as the Pokhara Formation. Terraces line some of the Seti banks. At first sight this appears to be a normal series of glaciofluvial fills, accumulated in a basin created by differential uplift of the Mahabharat foothills immediately to the south. But the Pokhara Formation is a debris flow deposit from a massive landslide event.

Fig. 7. (left) The flat floor of the Pokhara basin east of the city; the Seti Khola is entrenched through the thickness of the Pokhara Formation.

The Pokhara sediment is crudely stratified, but it is poorly sorted, with many layers of coarse matrix-supported conglomerate (Fig. 8). It is composed largely of limestone fragments in a muddy matrix with some carbonate cementation; gneiss fragments are in the minor-

Fig. 8. (right) Limestone conglomerates which are the debris flow deposits of the Pokhara Formation, exposed in the river trench downstream of Phewa Tal.

ity. Larger blocks are recognizable as the Palaeozoic limestone whose nearest outcrops are in the higher parts of the backwall of the giant cirque between Macchapuchare and Annapurna 2, from which the Seti Khola drains (Fig. 1). Wood and charcoal fragments from the debris have been dated at laboratories in France and Japan, and all ages are less than 1000 years. The ages are close to the limit of the radiocarbon method and have a spread of 600 years, but there is no discernable age difference between material from the top and the base of the Pokhara Formation. The volume of material is 4000 million cubic metres, and it was deposited in a single catastrophic event or in a short sequence of similar events.

The source of the Pokhara material must be the limestone cliffs round the great cirque at the head of the Seti, 30 km upstream and 5 km higher up (the term cirque is used purely descriptively, as it contains a number of glaciers). Rockfalls from these precipitous cliffs still occur, and their debris buries the glaciers at their feet. Limestone rubble lies on the cirque floor to hundreds of metres thick; it is a mixture of landslide debris and glacial till. This material is clearly the source of the Pokhara sediment.

Some trigger event caused the debris to move from its source cirque down to Pokhara. An earthquake is the likely trigger; monsoonal rain, a glacier surge or a jokulhlaup flood are improbable contenders. The structure of the Pokhara Formation means that it can only have moved as huge debris flows. An earthquake triggered unusually large rockfalls from the limestone cliffs; the debris landed on the unstable masses of older debris and glacier ice within the cirque; this headloading caused the whole mass to landslide from the cirque into the Seti valley; frictional heat melted the ice and snow; this increased the water content and helped fluidize the material; it developed into massive debris flows down the steep valley; and these came to rest only in the Pokhara basin, where the gradient is greatly reduced. This can only be a hypothetical scenario, but it is a very real concept; all the processes were matched by the 1970 debris flow in the Peruvian Andes, when 100 million cubic metres of rock and ice reached 15 km from Mt Huascaran to bury the town of Yungay.

When the debris filled the Pokhara basin, it dammed three tributary rivers, forming three marginal lakes (Fig. 1). The largest of these was Phewa Tal; local legend clearly describes the drowning of a village when this lake was formed, and such local folklore is generally based on some real event in recent history. Downstream of Pokhara, overflow streams found the natural lines along the edges of the central debris mass.

A likely date for the Pokhara event is 1464, when a powerful earthquake caused major documented destruction in the Kathmandu Valley. That time was during the Neoglacial Little Ice Age, when ice supply in the Seti Khola cirque was at a maximum, and is also compatible with both the radiocarbon dates and the Phewa Tal legend. Much of the upper Seti valley is bare rock, as if stripped by a recent debris flow, but the lower parts are thickly vegetated where the hot and wet climate encourages rapid regrowth.

It would be excessive to describe the great cirque between Machhapuchare and Annapurna 2 purely as a landslide scar, but landsliding does appear to have contributed to its largely glacial excavation. This begs the question concerning processes within the two comparable giant cirques just to the west – the famous Sanctuary between Annapurna and Machhapuchare, and the Miristi Khola basin between Annapurna and Nilgiri (Fig. 1). There are no obvious signs of landslides at these sites, but there are coarse sediments very similar to the Pokhara Formation, forming a terrace remnant at Kusma, where their catchments converge (Fig. 1). The Kusma conglomerates have fewer limestone fragments than the Pokhara material, but their sedimentary structures are very similar. Both contain large caves; originating as piping failures, these now carry streams and rivers, and have been modified by stream erosion and stalagmite deposition. In contrast to the few stalagmites in the Pokhara caves, the main Kusma cave is liberally decorated with calcite flowstone and dripstone. This suggests that it is much older, in an older host material. Perhaps a remnant of even more massive, prehistoric landslides in the dynamic environment of the rising Himalayas?

Suggestions for further reading

Bristow, C. 1995. A short walk in the Himalayas, *Geology Today*, v.11, pp.186–190.

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