6. Himalayan Landforms and Processes

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Nepal includes some of Earth's most dramatic geomorphology, with nine of the world's fourteen mountains which exceed 8,000 m, the world's deepest valley (Kali Gandaki between Dhaulagiri and Annapurna, 5,670 m; Kuhle, 1982, see page viii) and the precipitous west face of Dhaulagiri I which is over 4,600 m high (Fig. 15.2a). Himalayan landforms and the processes that create them depend firstly on the specific uplift and incision dynamics of the different tectonic units (Godard *et al.*, 2014; Fig. 6.1), secondly on the bedrock and its chemical and physical properties (Fig. 3.2) and finally on the seasonal distribution of precipitation, particularly the monsoon (Fig. 4.21).

6.1 Uplift and slope stability

The stability or otherwise of land surfaces has a major impact on speciation and biodiversity. Just as the age and dynamics of the Himalayan uplift continue to be a source of debate (Chapter 8.4), so is the contribution of local effects of slope

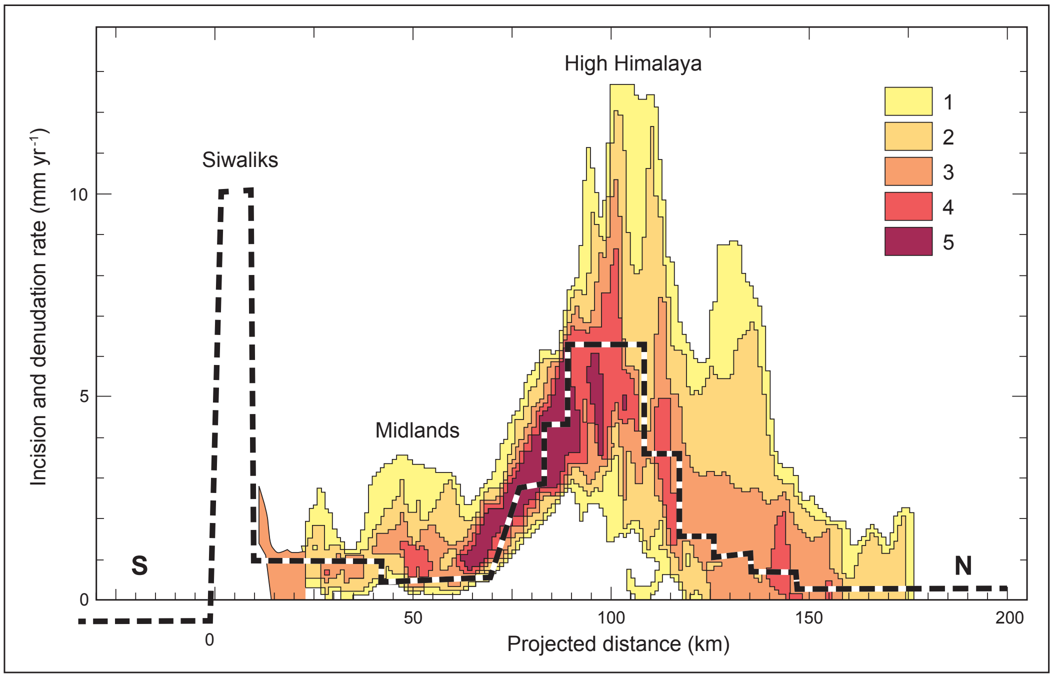


Fig. 6.1: Stacked incision rates with their confidence domains projected onto a N18°E profile for the Kali Gandaki, Marsyangdi, Buri Gandaki, Trisuli and Sun Kosi. The shading indicates overlapping confidence domains and the dashed line is a simplified 2D model. Incision rates at the Siwaliks are interpolated from dated terrace studies and structural studies, and the large peak in rates there relates to the region's high runoff and weak molasse rock. Modified from Lavé and Avouac (2001).

Fig. 6.2: Langtang village (28°12'N/85°30'E) (a) in April 2013 before its destruction and (b) after destruction on 25 April 2015. (SG, JL)

instability to the generation and maintenance of biodiversity in Nepal. It is certainly the most important cause of primary progressive plant succession in landslide areas. At least two Himalayan plant groups especially rich in species in altitudes above 1,000 m, *Impatiens* and Urticaceae, are well known disturbance indicators and suggest that this lack of equilibrium is a major impulse for speciation. The primary driver of instability and disturbance is the uplift of the Himalayas. Uplift precedes denudation, but precise rates of uplift and incision and the rate of denudation cannot be easily related to the environmental history of the landscapes (Fig. 6.1). In any case, denudation processes are rapid, and landscapes are not in equilibrium.

Rates of uplift and incision vary considerably across the different tectonic units of the Himalayan Arc and with the techniques used. Incision rates based on river profile measurements revealed values of up to 15 mm yr^{-1} in parts of the Siwaliks, only around 1 mm yr^{-1} in the Midlands and up to 6 mm yr^{-1} in the High Himalayas of Central Nepal (Fig. 6.1). Denudation rates deduced from ^{10}Be concentrations in detrital sediments in a ~200 km wide region in Central Nepal show the same trends, but are significantly lower: average denudation rates sharply increase from < 0.5 mm yr^{-1} in the Lesser Himalayas to ~1 mm yr^{-1} northwards, and then accelerate to 2–3 mm yr^{-1} on the southern flank of the Great Himalayas (Godard *et al.*, 2014). Incision rates obtained by dating rock surfaces (^{10}Be) revealed rates exceeding 1 mm yr^{-1} in parts of the NW Himalaya (Dubey *et al.*, 2010), while rates of fluvial incision in the upper Yarlung Zhangbo Gorge range from 7 to 21 mm yr^{-1} (Stewart *et al.*, 2008).

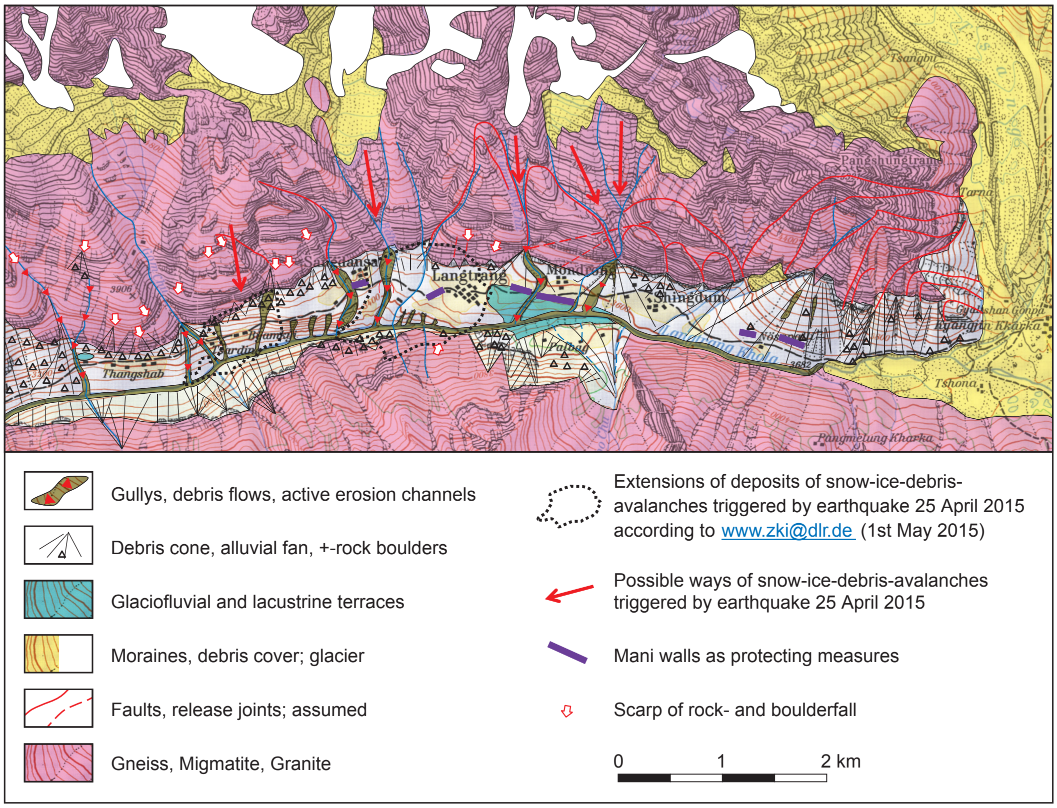


Fig. 6.3: Geomorphological sketch map of the upper Langtang Valley with the direction of movement and the deposition areas of the avalanches of snow, ice and debris which took place in April 2015 following the Gorkha (Base map Alpenvereinskarte Langthang Himal-Ost 1:50.000). It is possible that similar, but much smaller, incidents were observed in the past, as local people have erected mani walls as torrent and avalanche control-measures in exposed areas and around geomorphologically active fans and debris cones (Weidinger, 2002).

6.1.1 Earthquakes

Earthquakes are a prominent feature of Himalayan plate tectonics and a major threat to human life as little housing is designed to be earthquake-resistant. The entire arc is very seismically active, with three major earthquakes exceeding magnitude 8 on the Richter scale occurring within only 50 years (Kangra, 1905; Bihar-Nepal, 1934, Assam, 1950; see Fig. 3.4). Most studies of the impact of earthquakes have considered their effects on densely populated urban areas like the Kathmandu Valley and the Vale of Kashmir. Although the consequences for plant life and vegetation dynamics have rarely been studied (J. Zhang *et al.*, 2011), they are presumed to have a considerable impact on the geomorphology through large landslides and sudden point dislocations, such as at Dehra Dun which was lifted by 13 cm during the Kangra earthquake (Valdiya, 1993). An earthquake in 1255 CE contributed to the frontal uplift of river terraces in eastern Nepal by 20 m, devastated Kathmandu and killed the Malla ruler Abhaya (Sapkota *et al.*, 2013). Clear traces of the rupture were left along 150 km of Nepal's Main Frontal Thrust (MFT) fault, between 85°50′ and 87°20′E, indicating a magnitude of 8.8 (Lavé *et al.*, 2005). Geomorphological mapping of fluvial deposits, palaeoseismological logging of river-cut cliffs and trench walls, and modelling of calibrated ^{14}C ages, show that the Bihar-Nepal earthquake broke the surface with traces of the rupture along the Main Boundary Thrust (MBT) between 85°50′ and 87°20′E. The MFT apparently absorbs most of the 21 mm yr^{-1} crustal shortening associated with the ongoing collision, and the interseismic deformation is released in earthquakes (Lavé and Avouac, 2012).

On 25 April 2015 Nepal and neighbouring countries were hit by an earthquake of magnitude 7.8 (Aydan and Ulusay, 2015), the most significant seismic activity in the country for almost 80 years. A brief tectonic summary (USGS, 2015) describes this disastrous event as the result of thrust faulting on or near the MFT. At the epicentre of this earthquake, in Gorkha district, 77 km northwest of Kathmandu, convergence rates between the Indian and the Eurasian tectonic plates are at a rate of 45 mm yr^{-1} towards the north-northeast. Preliminary information on the location, size and focal mechanism of this earthquake are consistent with it having occurred on the main subduction thrust interface between these two plates. More than 8,000 people were killed, and there was considerable devastation in the historic centres of the ancient cities of Kathmandu, Patan and Baktapur which are world heritage sites and major tourist attractions.

Several days after the earthquake, news emerged from the Langtang Valley about two large avalanches of rock and ice which originated from the flanks of the northern side of the valley. One of these avalanches buried Langtang village and the other Chyamki, with a combined death toll of more

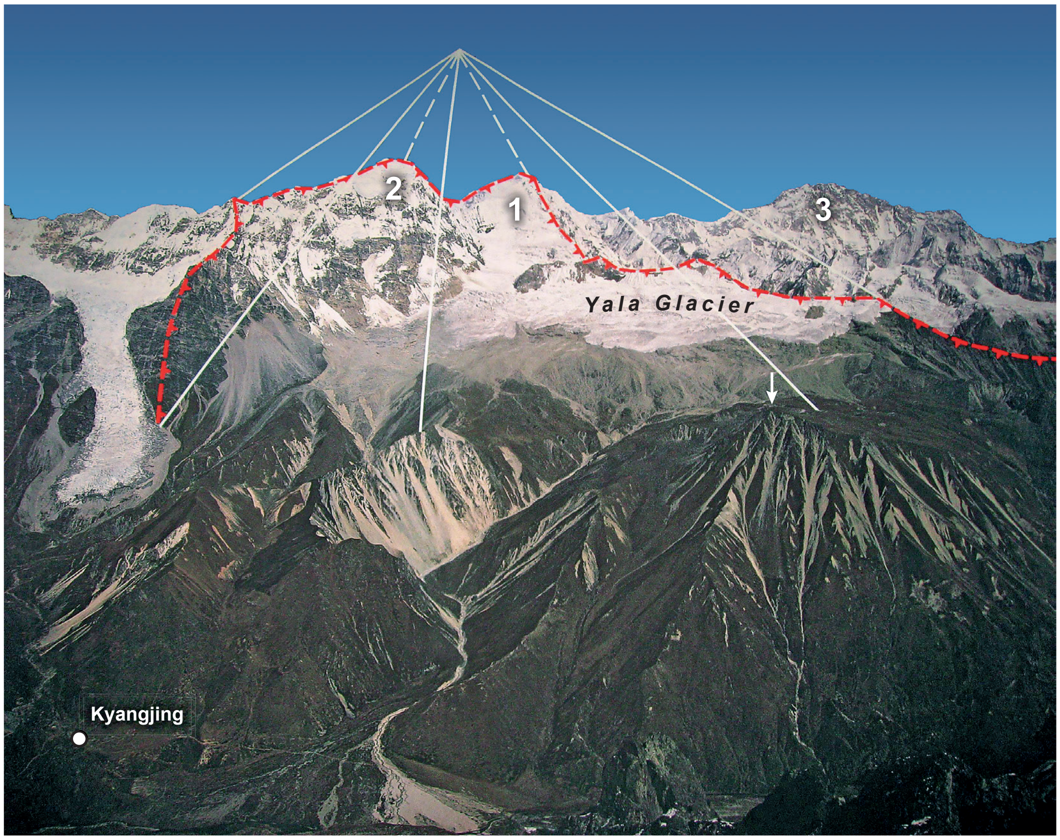


Fig. 6.4: Tsergo Ri (arrow) and Yala Plateau showing the massive rockslide (marked with the red line) which resulted in the destruction of an 8,000 m peak, leaving the peaks of Phrul Rangtshan Ri at 6,950 m (1) and Dragpoche at 6,562 m (2).The energy of the collapse was so great that migmatites, granites and gneisses were converted into frictionite at the sliding surface and easily eroded cataclasite towards its top (Weidinger *et al.*, 2014). Xixabangma (3; 8,027 m) is c. 30 km NE. 5,700 m, 28°10'N/85°33'E, November 1990. (HJI, JTW)

than 300 (Fig. 6.2a, b). Above Langtang village the northern rim of the valley includes the peaks of Langtang Lirung (7,234 m), Mera (6,958 m), Phagmogoldo (6,672 m) and Gengo Lirung (6,581 m) which forms a cirque with a 2.5 km long glacier extending towards the south, ending in a hanging valley at 4,400 m altitude. The profile from Mera Peak to the bottom of the valley at the village covers a vertical distance of 3,500 m and is similar in shape to a ski jump. It appears that the avalanche process may have been as follows:

1. Snow and ice sliding from the mountain slopes impacted on the glacier.
2. Moraine debris was incorporated.
3. The avalanche lost contact with the ground at 4,400 m as it hit the lip of the hanging valley.
4. The debris fell vertically to the bottom of the valley. This was accompanied by ice melting due to the friction and impact, and subsequent formation of debris flows.

6.1.2 Giant rockslides

Giant rockslides are another feature of the Himalayan disequilibrium. Their locally devastating impacts on biodiversity are obvious, but it is possible that they may explain disjunct populations of poorly dispersing species found on both sides of deep antecedent gorges (e.g., *Primula*, *Saxifraga*; Fig. 8.31). Giant rockslides or mixed avalanches of snow, soil and rock may have served as a vector during colder climates when altitudinal zones were lower. Such an effect has been suggested for minute soil-living wingless beetles (Schmidt, 2011).

Giant rockslides form eye-catching landmarks and dam rivers to form lakes (Weidinger, 2011). Their location and orientation are the result of weak tectonic structures leading to subsequent slope failure (Dortch *et al.*, 2009). Except for larger rock- and boulder-falls, large landslides are apparently not very often triggered by earthquakes or steepening of valley flanks through glacial erosion, but are more likely to result from saturation of rock by water, as shown by the frequency of major events during periods of intensified monsoon precipitation (Latamrang 5.4 ka BP, Pratt-Sitaula *et al.*, 2004; Kalopani 4.1 ka BP, R. Zech *et al.*, 2009). Most large rockslides are of granites or gneisses (Korup and Weidinger, 2011; Weidinger and Korup, 2009; Schramm *et al.*, 1998; Weidinger, 2006; Heuberger *et al.*, 1984; Heuberger and Weingartner, 1985). The Tsergo Ri rockslide in the upper Langtang Valley (Fig. 6.4) originated in a sulphidic mineralised ore structure within a discordant leucogranitic dyke along a tectonic fault, and the limestone rockfall which dammed Phoksundo Lake (Fig. 6.5a, b) originated in a huge fault formed by over-thrusting (Weidinger, 2011).

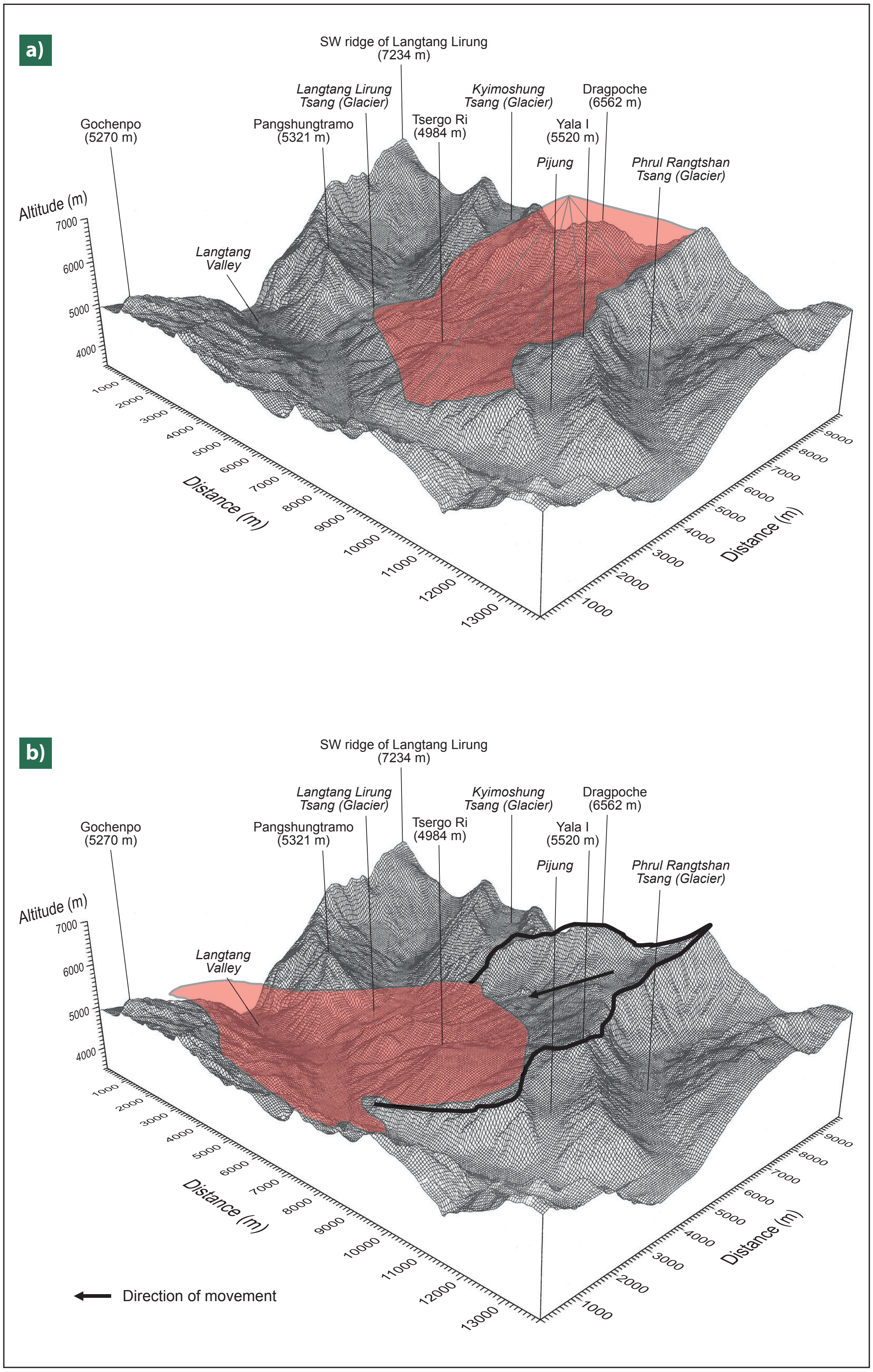
The Tsergo Ri rockslide, at 10×10^9 m^3, is one of the world's largest known rockslides and occurred at about 51 ±13 ka BP (Takagi *et al.*, 2007). It appears to have resulted from

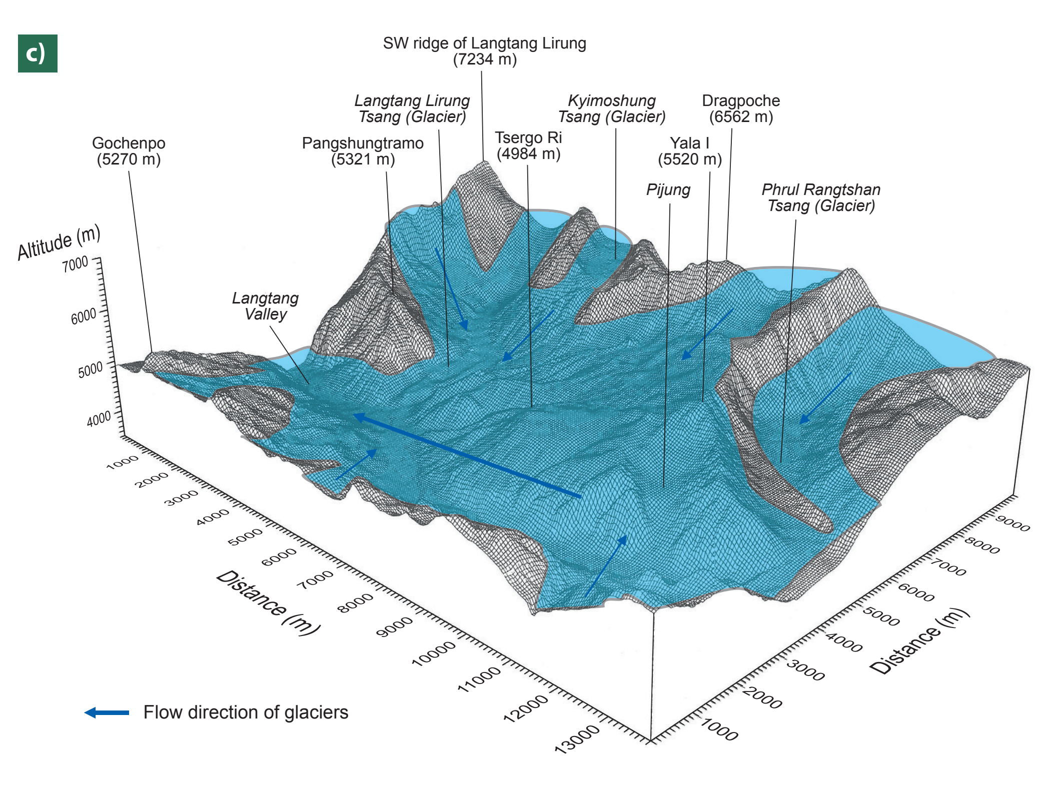
Fig. 6.5: (a) The Phoksundo Lake rockfall dammed a very steep valley. The deposition area is covered mainly with *Pinus wallichiana-Picea smithiana* forest, partly cleared for the fields of Ringmo village (arrow). 4,070 m, 29°12′N/82°56′E, June 1999. (SMi)
(b) Phoksundo Lake was dammed by a large prehistoric rockslide, whose direction of displacement was from east to west (red scarp and red arrow). Ringmo village (white line) is located on top of its cataclastic limestone material (dotted line) in a stable zone, whilst its southern part (frontal view) is subject to extensive backward erosion. The Suli Gad river formed a spillway as the lake overtopped the rockslide and it continues to follow this course. Possibly catastrophic historic flood events along this channel are marked by a chorten (Weidinger, 2002). The course of the river has been displaced towards the southwest by the rockslide and reaches the main valley over the highest waterfall in Nepal. Coarser boulders of a possibly younger rock avalanche (dashed line) form an elevated hilly area on top of the eastern part of the deposit. Modified from Google Earth, 17 March 2011.

the collapse of a former 8,000 m mountain (Weidinger *et al*., 2002), leaving only the peak of Dragpoche (6,562 m) (Fig. 6.6a–d). Other large mass-movements include the Kalopani rockslide (3×10^9 m^3; Fig. 6.7) in the Kali Gandaki Valley, the Khumjung rockslides (2.1×10^9 m^3; Fig. 6.8) in the Khumbu Himal north of Namche Bazar (Posch *et al.*, 2015; Götz *et al.*, 2015), the Lukla rockslide (c. 2×10^9 m^3) in the Dudh Koshi Valley, the Braga rockslide in the Manangbhot (5×10^9 m^3, Fig. 15.6) and the Latamrang rockslide in the Marsyangdi Gorge (5.5×10^9 m^3).

Sediments accumulate in the lakes behind dams caused by large rockslides and advancing glaciers, leaving evidence of their extent. The Palaeo-Thakkhola Lake was one of the largest, with a maximum length of 35 km from Kalopani to Tangbe and a depth of at least 360 m near Marpha (Kuhle, 1982; see Fig. 16.61 for localities). Sediments at its base have been dated to 55 ka BP (Baade *et al.*, 1988), but its duration is still unknown. Phoksundo Lake which formed behind the rockslide at the present location of Ringmo village (Fig. 6.5) has been dated to

Fig. 6.6: Tsergo Ri rockslide. (a) Reconstructed pre-slope failure topography of the collapsed 8,000 m peak in the Langtang Valley (Weidinger *et al.*, 2002). (b) Reconstruction of rockslide debris after the collapse. (c) Reconstructed extension of glaciation at the Last Glacial Maximum (LGM), mainly eroding rockslide material. (d) Rockslide debris after LGM and Late-glacial erosion. Surface plot from grid files generated from data obtained from Österreichischer Alpenverein, Cartography, Innsbruck using SURFER, Golden Software, Inc., Golden, CO.




c)
SW ridge of Langtang Lirung
(7234 m)
Langtang Lirung
Tsang (Glacier)
Kyimoshung
Tsang (Glacier)
Dragpoche
(6562 m)
Gochenpo
(5270 m)
Pangshungtramo
(5321 m)
Tsergo Ri
(4984 m)
Yala I
(5520 m)
Pijung
Phrul Rangtshan
Tsang (Glacier)
Altitude (m)
7000
6000
5000
4000
Langtang
Valley
Distance (m)
1000
2000
3000
4000
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6000
7000
8000
9000
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Distance (m)
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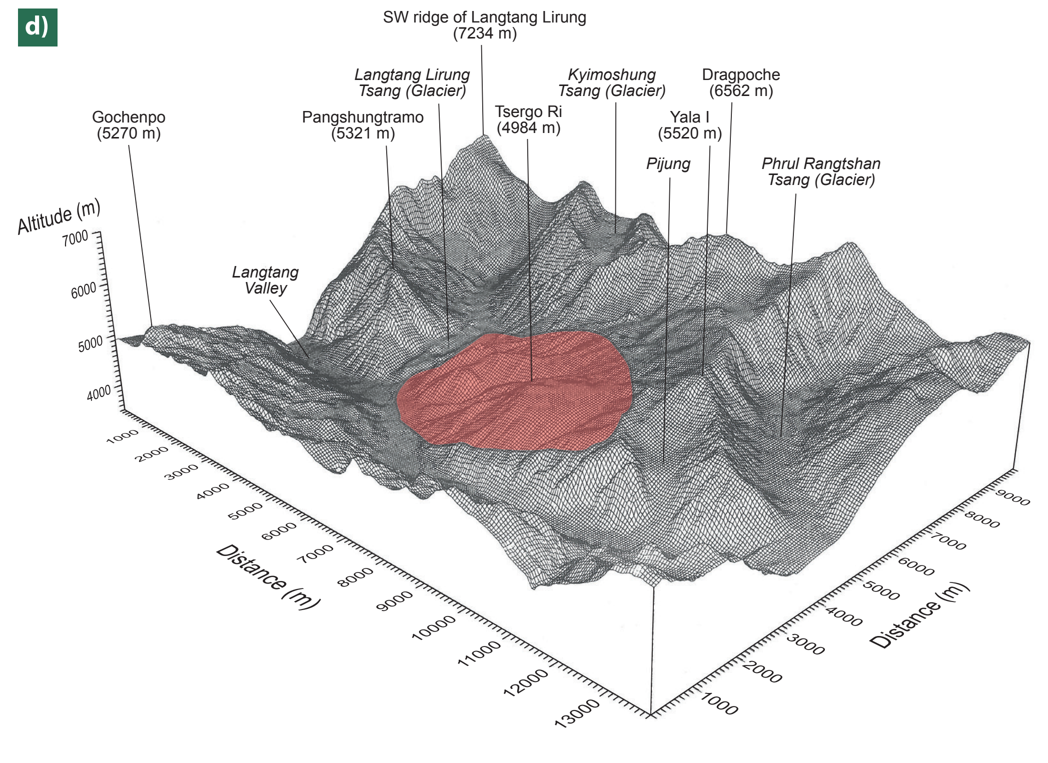
Flow direction of glaciers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Tsang (Glacier)
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Gochenpo
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Tsang (Glacier)
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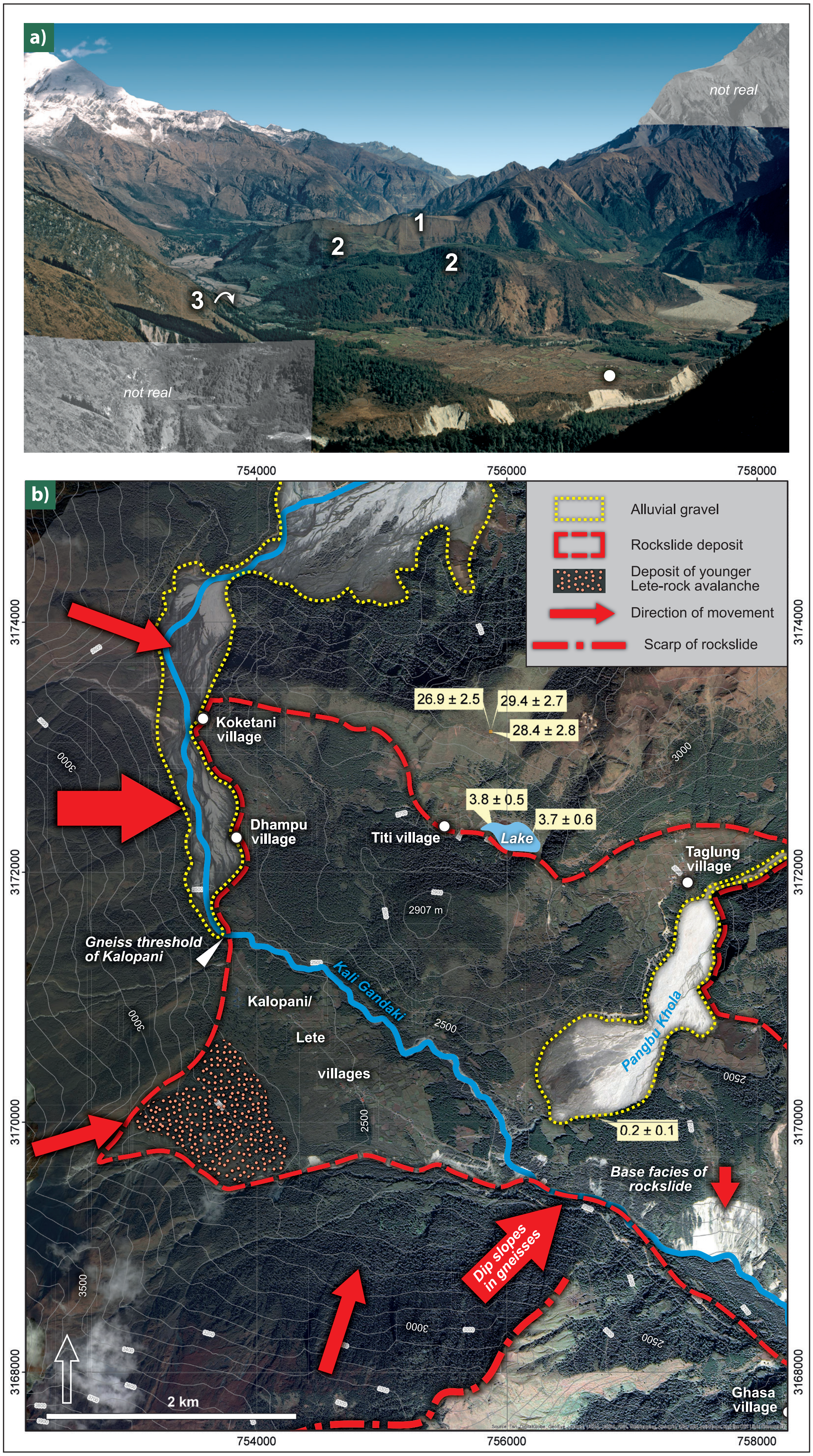


Fig. 6.7: (a) The Thakkhola Valley between the High Himalayas (near Lete; 2,380 m, white dot). High moraine ridges date from the Last Glacial Maximum (26 ka BP) (1), while the 3 × 10^9 m^3 Kalopani rockslide dates from only 4.1 ka BP (2). The gneiss threshold of Kalopani (2,490 m) dams the gravel bed of the Kali Gandaki (3). Above Lete, 4,060 m, 28°37'N/84°36'E, December 1976. (GM) (b) The Kalopani rockslide is composed of cataclastic material from at least one rockslide event, topped by a boulder carapace, both of which originated from the southwest, and it has geomorphologically strengthened a major knickpoint in the Kali Gandaki. Titi village in the northeast is at the rockslide's impact slope *brandung* or 'surge ridge', which created a natural lake. Boulders there were dated by Zech *et al.* (2009). The southeast part of the deposit is strongly influenced and geomorphologically overprinted by the Pangbu Khola and its glacial and alluvial sediments, which originate from Nilgiri. West of Kalopani, the Lete rock avalanche overlies the rockslide debris (Fort, 2000). This avalanche may have occurred in historical times and the nearby Kalopani Gompa could be a cultural-historic indicator for that event. Geological and geomorphological features have been interpreted from data contributed by W. Schwanghart.

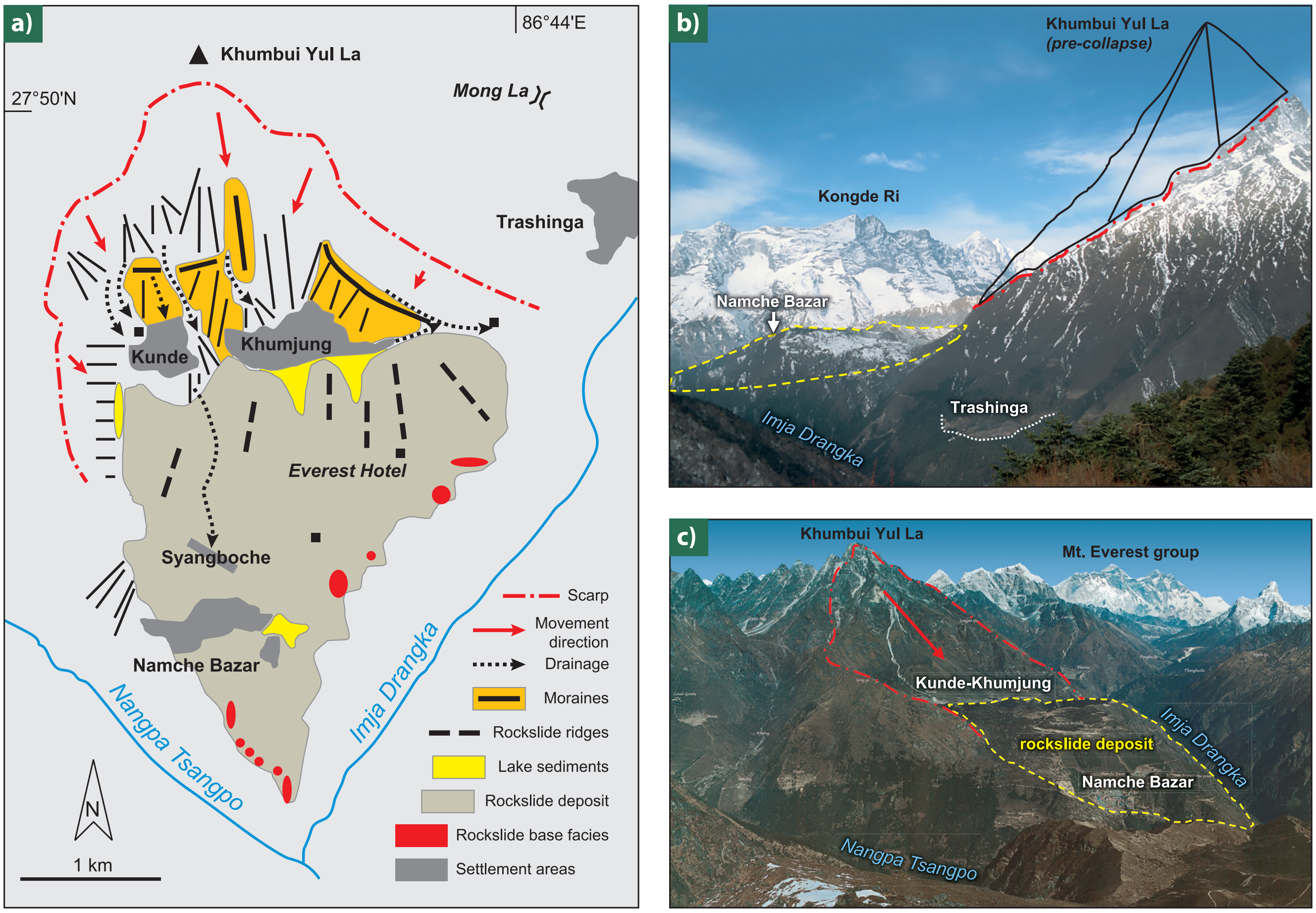


Fig. 6.8: (a) Geological sketch map of the Khumjung rockslide at the confluence of the Nangpo Tsangpo (Bhote Koshi) and the Imja Drangka (Imja Khola). The cataclastic rockslide material is susceptible to erosion and highly porous, so there is little surface flow of water across the area of deposition (Posch *et al.*, 2015; Götz *et al.*, 2015). Modified from Korup and Weidinger (2011). (b) Side view of the Khumjung rockslide towards the southwest showing the direction of movement from north (right) to south (left) and the reconstructed pre-slope failure topography of the collapsed Khumbui Yul La whose post failure elevation is 5,761 m. The red broken line shows the scarp and primary sliding surface of rockslide; the yellow dashed line the rockslide deposit with Namche Bazar, kame-terrace of Trashinga village (white dotted line). 3,600 m, 27°50′N/86°45′E, March 2007. (JTW). (c) Frontal view towards the northeast showing the water course on the face of its sliding surface. c. 4,000 m, 27°47′N/86°41′E, May 2013. (LSS)

30–40 ka BP (Yagi, 1997), ^{36}Cl dating revealed an age of 20,885 ±1675 BP (Fort *et al.*, 2013), which suggest that two rockslides occurred. The age of the rockslide which created the lake above Topke Gola in eastern Nepal (3,860 m, 27°39′N/87°34′E) is not yet known.

6.1.3 River captures

River captures are the third characteristic process of landscape history during mountain uplift and therefore an important component of disturbance ecology at the landscape scale. The pronounced asymmetry of the Himalayas with its southern foreland at 60 m and northern foreland at 5,000 m (Fig. 1.3) creates circumstances which permit river capture from the south. In all mountain areas modifications of the drainage pattern are indicated by sudden changes of the direction of valley in parallel with a change of the shape of the valley from a broad synclinal valley section into an anticlinal gorge. The occurrence of river gravel away from contemporary rivers is additional and necessary proof of an ancient river bed which has become dry following capture.

The first, and still most comprehensive, investigation of river capture is that of Toni Hagen, completed during the first geological survey of Nepal between 1950 and 1958 (Hagen, 1968/1969). None of the river captures have been dated so far. The following list summarises his account:

- In NW Nepal the Humla Karnali, after leaving the wide basin of Burang/Taklakot, bends sharply towards the northeast just inside the border with Tibet (Fig. 6.9:1). The Nara-La (4,500 m, 30°08′N/81°23′E) is the straight prolongation of the original course of the river.

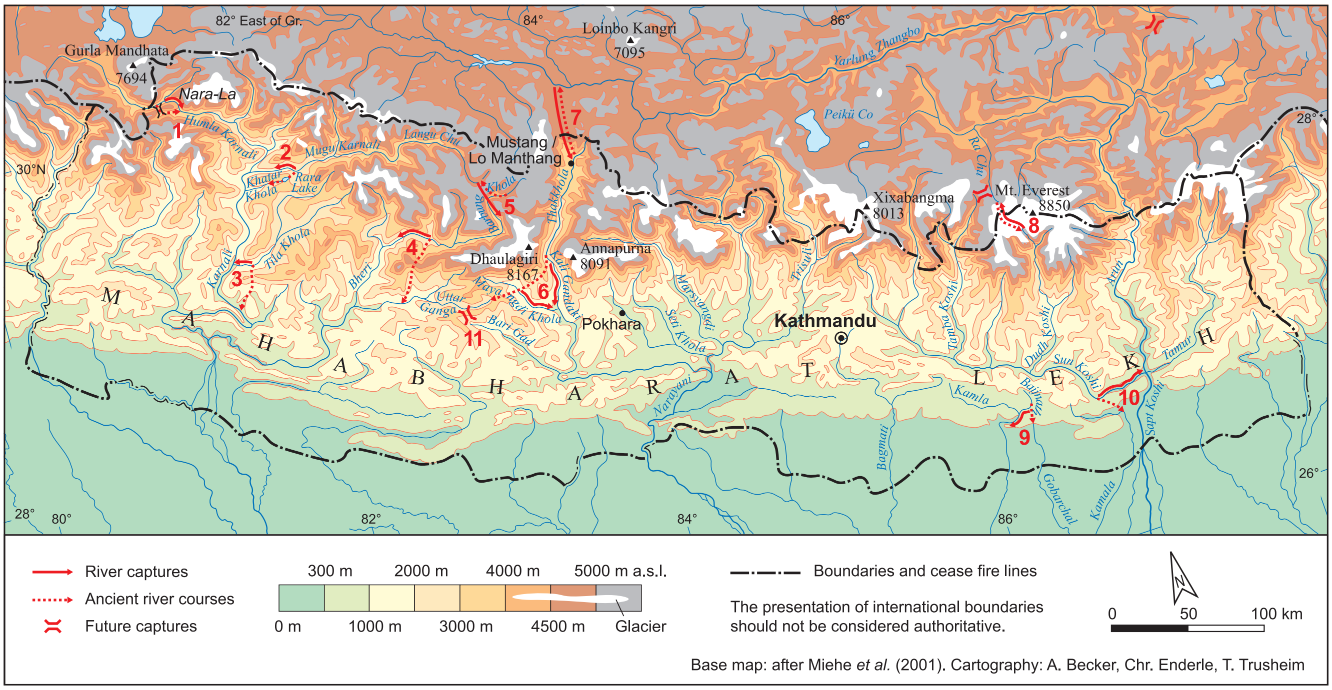


Fig. 6.9: River captures in Nepal – 1: Humla Karnali capture; 2: Mugu Karnali capture; 3: Tila Khola capture; 4: Barbung-Bheri capture; 5: Barbung-Langu Chu capture; 6: Mayangdi-Uttar Ganga capture; 7: Upper Mustangbhot capture; 8: Nangpa-La capture; 9: Muksar capture; 10: Sun Koshi capture. Modified from Hagen (1969).

- Rara Lake (Figs 6.9:2, 6.10a, b) is in a curious situation, as it rises to a 20 m lip at its eastern end, beyond which the ground falls away steeply for over 1,300 m to the deeply incised gorge of the Mugu Karnali only 5 km away. The lake's basin and its drainage into the Kathar Khola are part of the ancient course of the Mugu Karnali. An eastern tributary of the Humla Karnali, deeply incised into the Galwa anticline, captured the Mugu Karnali from the northwest in the area of Ruga.
- Traces of the ancient river bed of the Tila Khola in Jumla (Fig. 6.9:3) can be seen in ancient gravel terraces which dip strongly northwards on the northern slope of the Mabu-La (2,160 m, 29°06′N/81°47′E) and the Bartha-La (3,120 m, 29°02′N/81°42′E). The Tila Khola was captured by a steep western tributary of the deeply incised Karnali.
- The lower Barbung Khola (Fig. 6.9:4) drained towards the southwest over the Jangla Bhanjyang (4,530 m, 28°49′N/82°55′E) and was captured laterally from the Bheri.
- The upper Barbung Khola (Fig. 6.9:5) has a suspicious bend west of Charka. The upper southwest to northeast oriented valley once was the upper part of the Langu Chu, but was captured due to the steeper gradient from the south (Molha-La, 5,020 m, 29°08′N/83°20′E).
- The Myagdi-Uttar Ganga capture (Fig. 6.9:6) took place in the upper Bheri Valley and can best be seen in the wide valley around Dhorpatan and the plateau-like Jalja-La (3,460 m, 28°30′N/83°13′E) between Dhorpatan and Lumsung. The wide valley of Dhorpatan was not shaped by the present small river, but was part of a larger valley which was captured by the western tributary of the Mayangdi Khola. The mature shape of the Uttar Ganga indicates that it may once have drained into the Kali Gandaki towards the southwest.
- The steep gorge of the Kali Gandaki between Tatopani and Beni is probably a capture from the southeast.
- In upper Mustangbhot (Fig. 6.9:7) a drainage reversal towards the south occurred (Adhikari and Wagreich, 2011). Upper Mustang was once part of the Yarlung Zhangbo drainage towards the north over the Karo-La (4,550 m, 29°17′N/83°57′E), but was captured from the south by the deep Thakkhola Graben.
- In the Khumbu Himal (Fig. 6.9:8) a reverse change can be detected with a shift of the northward watershed due to the deeply eroded Arun Gorge draining this part of southern Tibet. The extraordinarily broad upper Bhote Koshi possibly drained northwards to the Tingri Dzong area, but was then captured from the east by the Phung Chu as part of the Arun catchment.
- In the eastern Duns, the Gobarchal Khola (Fig. 6.9:9) had its ancient origin much further north in the Mahabharat Lekh, as shown by

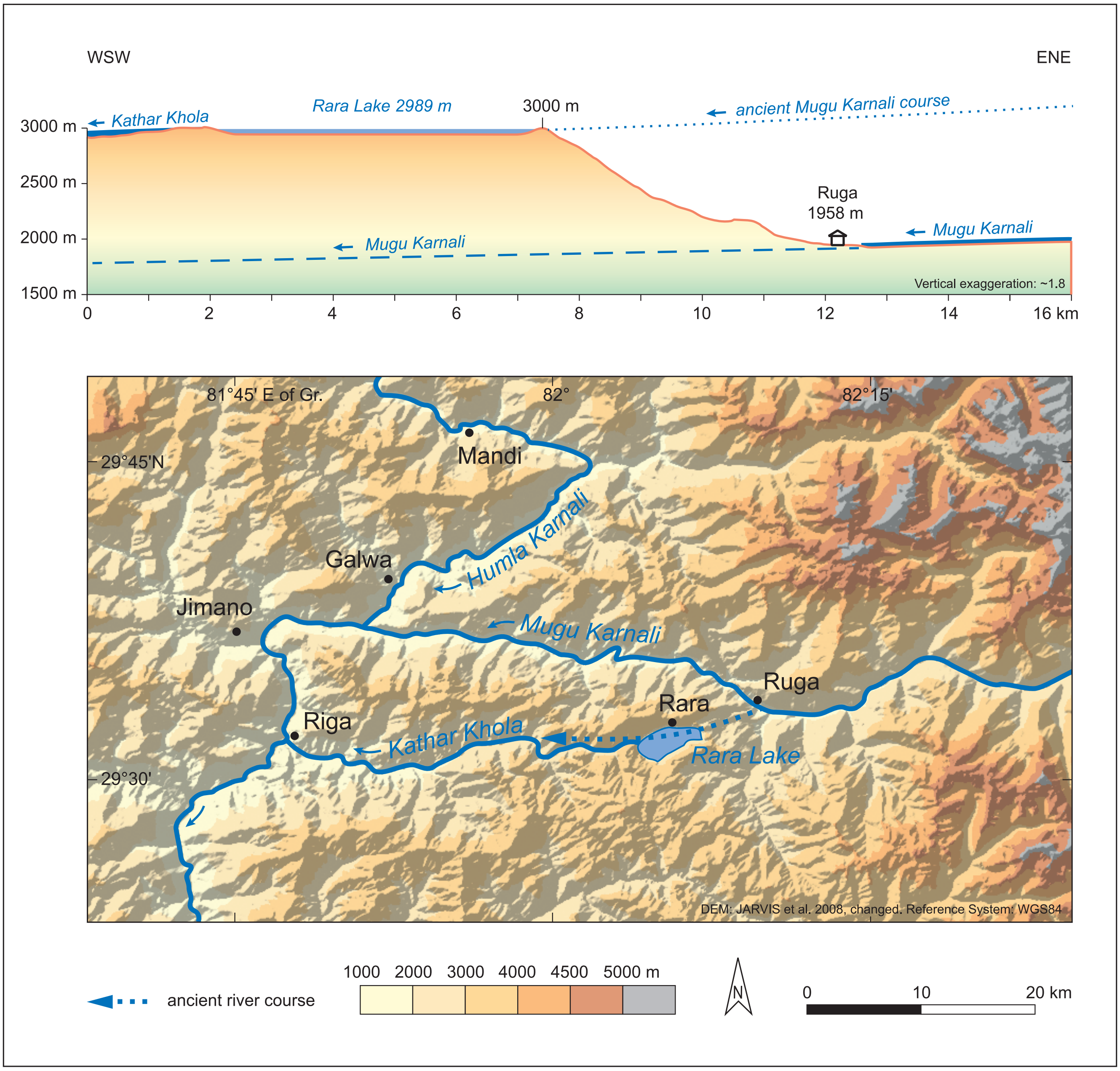


Fig. 6.10: Cross-section and survey map of Rara Lake with the ancient and current course of the Mugu Karnali. The watershed between the Rara Lake and the Mugu Karnali is only 20 m above the lake level, but over 1,300 m above the Mugu Karnali. The lake's basin and its drainage into the Kathar Khola are part of the ancient course of the Mugu Karnali. An eastern tributary of the Humla Karnali, deeply incised into the Galwa anticline, captured the Mugu Karnali from the northwest in the area of Ruga. Modified from Hagen (1969).

ancient granitic gravels near Muksar (200 m, 26°50'N/86°23'E). It was then captured by the Baijnath Khola, an eastern tributary of the Kamla Khola.

- The Sun Koshi (Fig. 6.9:10) once had a straight southeastern drainage into the valley of the Triyuga Khola, but was captured in a sharp bend (26°53'N/86°46'E) from the east and now flows into the Arun/Sapt Koshi.

In the geologically near future the Kali Gandaki is likely to capture the upper Yarlung Zhangbo near Zhongba (4,550 m, 29°36'N/84°02'E) as it erodes northwards into soft Spiti shales through the ridge which is today the Karo-La. A similar capture is expected to happen in the upper tributaries of the Arun with the middle reaches of the Yarlung Zhangbo then becoming a part of the Ganges catchment.

Fig. 6.11: Steep crests of unconsolidated gravel and sands of the Siwaliks with broad gravel beds of the Duns, flooded during the monsoon and then undercutting the slopes by lateral erosion. North of Chandigarh, India, 850 m, December 1983. (GM)

6.2 Characteristic landforms

Here we outline the characteristic landforms of the Himalayas and their predominant processes according to the major landscape units, from the tropical altitudes of the Siwaliks, to the subtropical Midlands, the temperate-to-cold High Himalayas and the Arid Zone.

The **Tarai** and **Bhabar** are the most recently formed alluvial plains and fans in the foreland of the Siwaliks. The Tarai is the Nepalese part of the Gangetic plain and rises from 60 m in the east to 200 m in the west. The Bhabar is a zone of alluvial fans between the Tarai/Gangetic plain and the Siwaliks at altitudes from 100 to 300 m. They consist of finer sands and gravels and are rapidly and easily eroded and reaccumulated by intense rainfall during the monsoon. Gullies are small because the landscape is flat or rises only gently.

The **Siwaliks** are built of accretions of sand, gravel and pebbles, with increasing grain size towards the north. These sediments have been thrusted and folded into syncline and anticline crests between the MFT in the south and the MBT in the north (Fig. 3.3). Valley bottoms rise from 160 m in the east to 600 m in the west, while the crests are at 600 to 1,300 m. Sand and gravels are mostly unconsolidated, and strong uplift

Fig. 6.12: Whaleback ridges and crests of the Midlands with convex slope angles show intensified uplift. South of Dhaulagiri I, 4,200 m, 28°35′N/83°32′E, January 1977. (GM)

Fig. 6.13: Frontal views of Dharbang landslide scarp and its deposits, which have been partially eroded by the Myagdi Khola. 20 years later vegetation has recolonised the slide area except for the steepest rock wall. 1,100 m, 28°24'N/83°23'E, (a) May 1994 and (b) April 2014. (JTW)

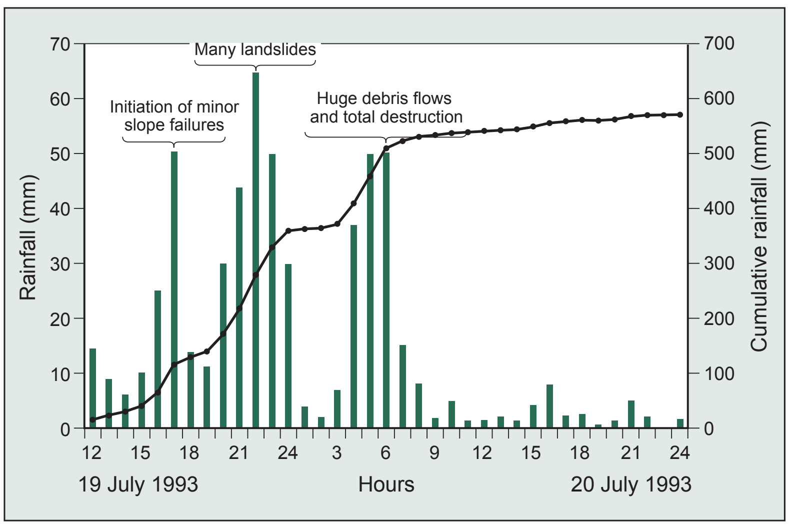
rates of 10–15 mm yr^{-1} and heavy monsoonal precipitation lead to pronounced gully erosion, and the formation of deeply incised V-shaped valleys with steep, unstable sides subject to mass wasting and the creation of steep cones of avalanche debris.

The **Duns** are broad valleys with steep flanks (Fig. 6.11), stretching between the crests of the Siwaliks. Braiding rivers flow along the very gently falling valley bottoms which lie parallel to the ridges of the Siwaliks, and then cut southwards through the ridges in steep V-shaped canyons. These peculiarly convoluted river courses originated in the uplift of the Mahabharat Lekh and the Siwaliks (Figs 3.5, 3.6). At the height of the monsoon their gravel beds are completely flooded, causing strong lateral erosion of the valley flanks.

The **Midlands** (or **Lesser Himalayas**) are also located between two tectonic boundaries, the MBT with the Mahabharat Lekh in the south and the MCT in the north (Fig. 3.3), where a break in slope marks the front of the High Himalayas. The morphology of the broad main valleys whose floors are at 300–400 m in the south and 700–800 m close to the southern face of the High Himalayas contrasts sharply with that of the steep, deeply incised side valleys. The relief of the Midlands largely follows the tectonic structure of the low-angled, north-dipping rocks, resulting in a pattern of asymmetrical escarpments with steep southern faces which give way to gently sloping northern aspects. The bedrock of the Midlands is mostly very old and deeply weathered sandstone, quartzite, shale and mica-schist. The broad main valleys have huge staircase-like terraces of several hundred metres of gravel, whereas the side valleys are narrowly V-shaped, rising steeply with many rapids or waterfalls. Slopes are mostly convex, with moderate angles on the upper slopes and

Fig. 6.14: A debris slide after heavy rainfall briefly dammed the Kali Gandaki below Tatopani. 1,200 m, 28°39′N/83°37′E, July 1999. (GM)

Fig. 6.15: Rainfall at Tistung, Central Nepal on 19 and 20 July 1993, and the landslide disaster associated with this extreme rainfall – the highest one-day precipitation (541.4 mm) ever recorded in Nepal (Department of Soil Conservation and Watershed Management, Kathmandu). Modified from Dahal and Hasegawa (2008).



increasing angles lower down. This slope angle pattern is an indication of accelerated uplift, and the ratio of floor width to valley height has been used as a morphometric parameter for mountain landscape dynamics (Whipple and Tucker, 1999). The contrast between the mature topographies of soft, undulating whaleback ridges and steeply incised convex side valleys (Fig. 6.12) suggests a relief pattern consistent with an advanced stage of peneplanation during eras of tectonic stability and a more rapid recent uplift associated with increasing rates of incision during which fluvial incision proceeds more rapidly than the denudation of slopes (Fig. 6.1).

Steep slopes of deeply weathered bedrock in a climate of high seasonal rainfall are prone to landslides (Fig. 6.13), and areas like the southern slopes of Ganesh Himal suffer small to medium-sized landslides every monsoon season (Thouret, 1983). Plants which establish quickly on open soil are therefore widespread and slopes show a pattern of succession stages of different ages (Figs 6.13, 6.14). Large debris slides follow long periods of heavy monsoon rainfall lasting up to 90 days, whilst shallow landslides are caused by extreme events of short duration (Fig. 6.15). The steepness of the slopes largely depends on the bedrock, with quartzite forming steep rock walls, whilst landslides in deeply weathered shale and gneisses lead to gentler slopes. Thus, the widespread contrast between steep escarpments and wide, gentle slopes may also result from the chemical properties and weathering of the bedrock. Slopes of mica-schist are in an almost continuous state of flux (Fig. 6.16) and are a threat to cultivation (Kienholz *et al.*, 1984) and road construction (e.g. 'Friendship Bridge', Kathmandu-Lhasa Highway, 27°58′N/85°58′E).

The **High Himalayas** are clearly distinguished from the Midlands by their greater altitudes and their glaciers, ancient moraines and large landslides. The High Himalayas are dissected by the deeply incised transverse valleys into a chain of isolated archipelago-like mountain massifs (Fig. 1.2). Three valleys follow tectonic grabens (Thakkhola Graben, Gyirong Graben of the Trisuli Valley and Pum Qu Graben of the Arun Valley) and are antecedent (Chapter 3). These transverse canyons have their river knickpoints just in the axis of the High Himalayas (Fig. 6.7a:3; Kalopani gneiss threshold/ rockslide deposit; Hagen, 1969; Kuhle, 1982; Korup *et al.*, 2006), where the gradients of the rivers become steeper by an order of magnitude (Fig. 6.1; Lavé and Avouac, 2001). Uplift and incision rates of approximately 4 to 8 mm yr^{-1} (Lavé and Avouac, 2001) have resulted in the world's deepest valleys and steepest vertical distances (Fig. 15.2a). Rock and ice avalanches are relief-specific and generate characteristic landforms depending on the geological structure and lithologies, such as the summits of the Nilgiri peaks with their extraordinary steep western flanks (Kuhle, 1982; Fort, 2000) and Annapurna I where the northerly-dipping Higher Himalayan Crystallines are exposed over 2,100 m and overtopped by Palaeozoic limestones (Fig. 6.17) (Armatya *et al.*, 1994).

The main valleys in the rain shadow of the High Himalayas (including the Khumbu Himal) are broad and U-shaped, with their valley floors at elevations ranging from 2,500 m (Thakkhola) to 3,500 m (Manangbhot: Fig. 15.6, Langtang: Fig. 15.10) or higher than 4,000 m (Khumbu Himal: Fig. 15.29). Steep, unconsolidated moraines cover the lower slopes up to several hundred metres, and are dissected by highly active debris flow channels and morainic pinnacles (Fig. 6.19).

Melting of glaciers leads to glacial lakes dammed by terminal moraines (Fig. 6.19), and minor weakening of the moraines or lake-level disturbances can lead to disastrous outburst floods (Chapter 5; Figs 5.11, 5.12) (Korup and Tweed, 2007). The terminal moraines of the Dhaulagiri Glacier have been dated to 25 to 28 ka BP (Fig. 6.7a: 1; R. Zech *et al.*, 2009) and the undated outflow from its glacial lake had major effects downstream. A more recent outburst along the Seti Khola led to huge accumulations of clastic sediments in the Pokhara Basin around 500–1,000 years ago (Hormann, 1974; Fort, 2000; Schwanghart *et al.*, 2014). The huge erratic boulders of Paleozoic limestone and Higher Himalayan gneisses (such as the holy Bim Kali (37 m in diameter) at Pokhara University campus) originating from that flood can be traced back to moraines and/or rockslide material on the southern slopes of Annapurna III, 25 km away (Hagen, 1969). The dramatic flood in the valley of the Seti Khola on 5 May 2012 was caused by a large avalanche in the Sabche glacial cirque which temporarily blocked the river. The force of this relatively minor flood event gives an idea of the scale of floods which could have occurred in (pre-)historic times (Fig. 6.20a, b; Bhandary *et al.*, 2012).

Strings of linked paternoster lakes in glacial cirques (see Fig. 5.3) are a feature of the Late Glacial landforms on the broad ridges extending south from the High Himalayas, from Dhaulagiri Himal eastwards. Many of these localities, such as Gosain Kund or Panch Pokhari in E Nepal, are sacred sites and destinations for pilgrims.

The **Arid Zone** in the rain shadow of the High Himalayas (Northern Himalaya, Chapter 3) has vertical relief distances almost comparable with those of the High Himalayas. Valley floors are between 2,800 and 3,000 m (Mustangbhot), 3,500 to 4,200 m (Nar and Phu), 2,800 to 4,400 m (Barbung Khola) and 4,000 to 4,800 m (upper Dolpa), while summits range between 5,500 and 7,000 m. Bedrock diversity is far higher than in the High Himalayas or in the Midlands and sedimentary rocks such as limestone, marl and claystone are common. In Mustangbhot, Spiti shales are interbedded with multi-coloured sandstone and marly limestones (Hagen, 1968).

These Tertiary sediments, overlain by moraines and alongside the gravel terraces and sediments of the Palaeo-Thakkhola Lake, have the appearance typical of a desert. However, marls and black slate (Spiti shales; Upreti and Yoshida, 2005) have moved by slumps and earth flow (Figs 6.21, 6.22), presumably during times of higher rainfall. Moraines and gravel terraces up to 350 m in height have been incised by the main rivers and glacier-fed minor streams.

Fig. 6.16: Quasi-permanent debris flow of mica-schist in the Midlands with *Alnus nepalensis* (Chapter 16.2.10). South of Tatopani, 1,200 m, 28°27′N/83°36′E, August 1995. (SMi)

Fig. 6.17: The geological structure of the northerly dipping Higher Himalayan Crystallines, which determines the relief with its leucogranites. The vertical distance between the summit of Annapurna I (8,091 m, arrow) and the Kali Gandaki near Ghasa is 6,000 m, with a horizontal distance of only 17 km. Pass west above Lete, 4,600 m, 28°35′N/83°35′E, 1 January 1977. (GM)

Fig. 6.18: Glacial lake (1) of the basin of the Gangapurna North Glacier (2). The terminal moraine (3) is undercut by the river (4). Outer slopes of side moraines (5) are at an early stage of succession, with partial colonisation by *Pinus wallichiana*, 4,000 m, 28°39′N/84°05′E, September 1977. (GM)

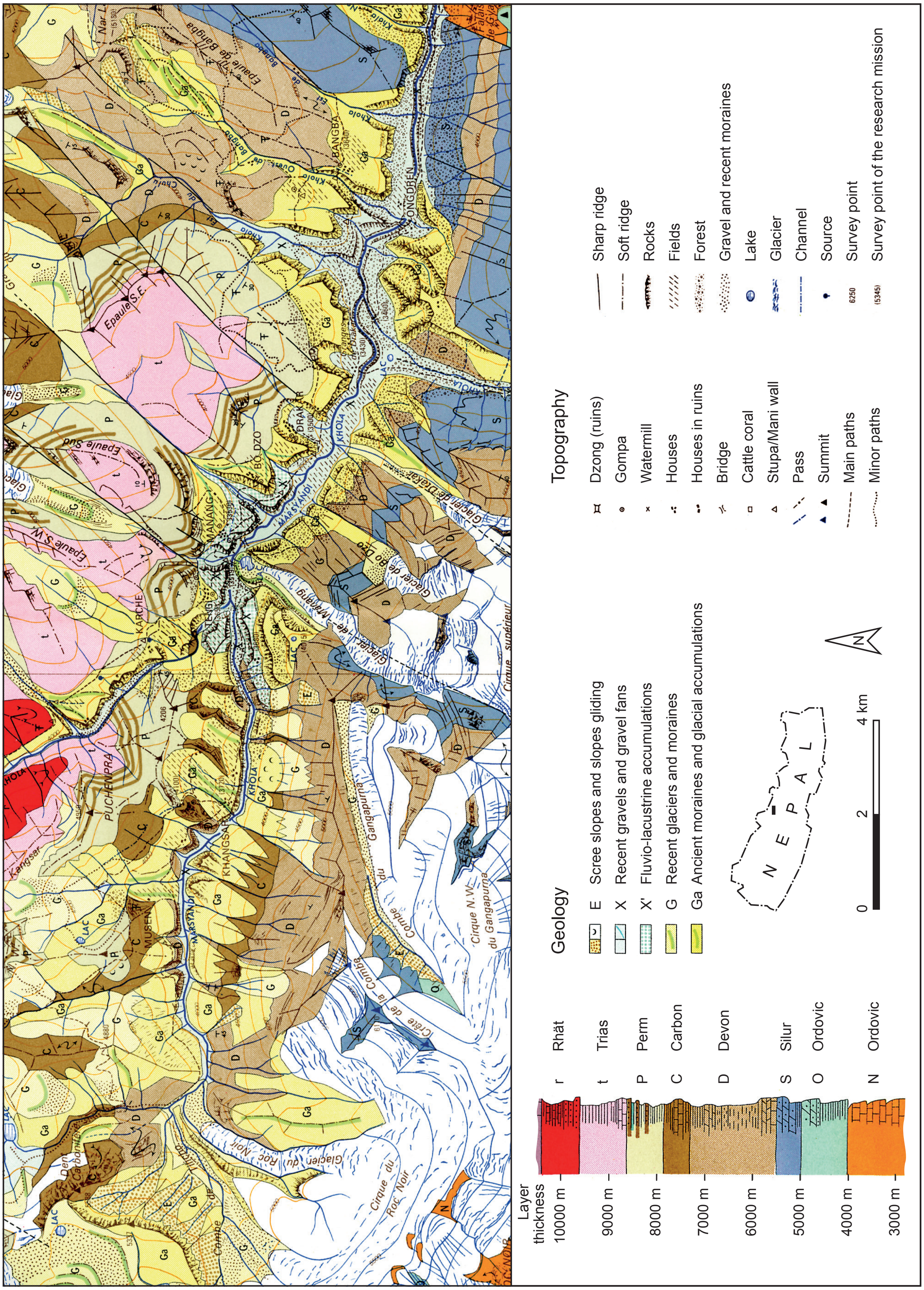
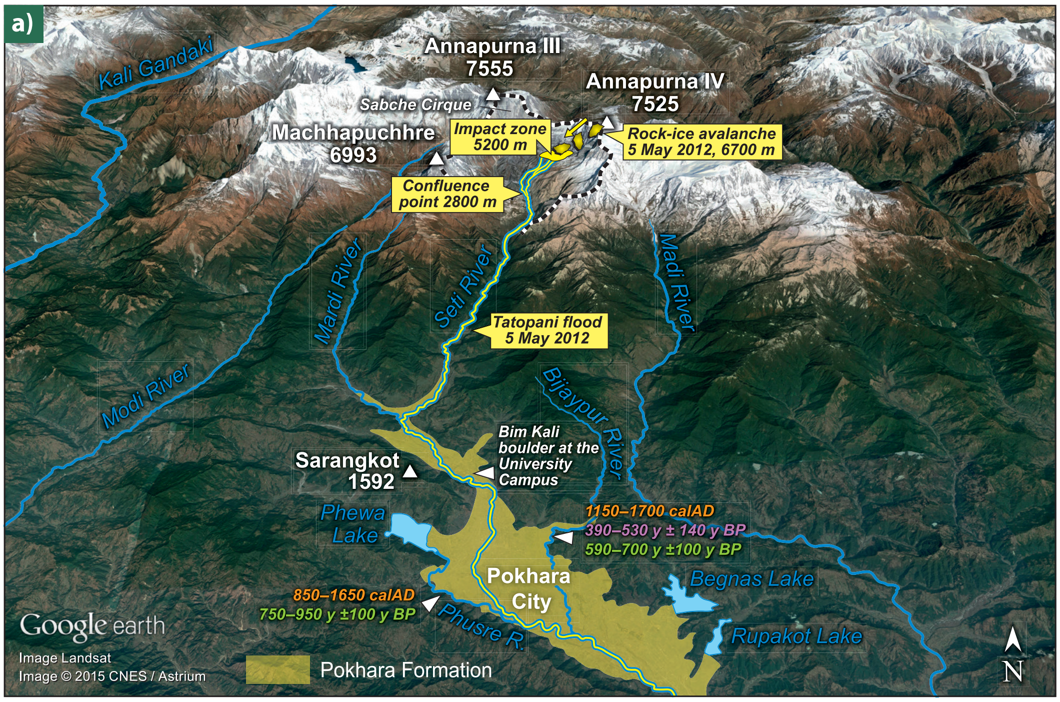


Fig. 6.19: Geological map of Manangbhot showing the vast extension of moraines and fluvio-glacial sediments. Modified from geological sketch map of Nyi Shang (Bordet *et al.*, 1975). More recent work (Weidinger, 2006) has shown that the origin of the majority of this material is a large rockslide which is partially overlain by moraines.



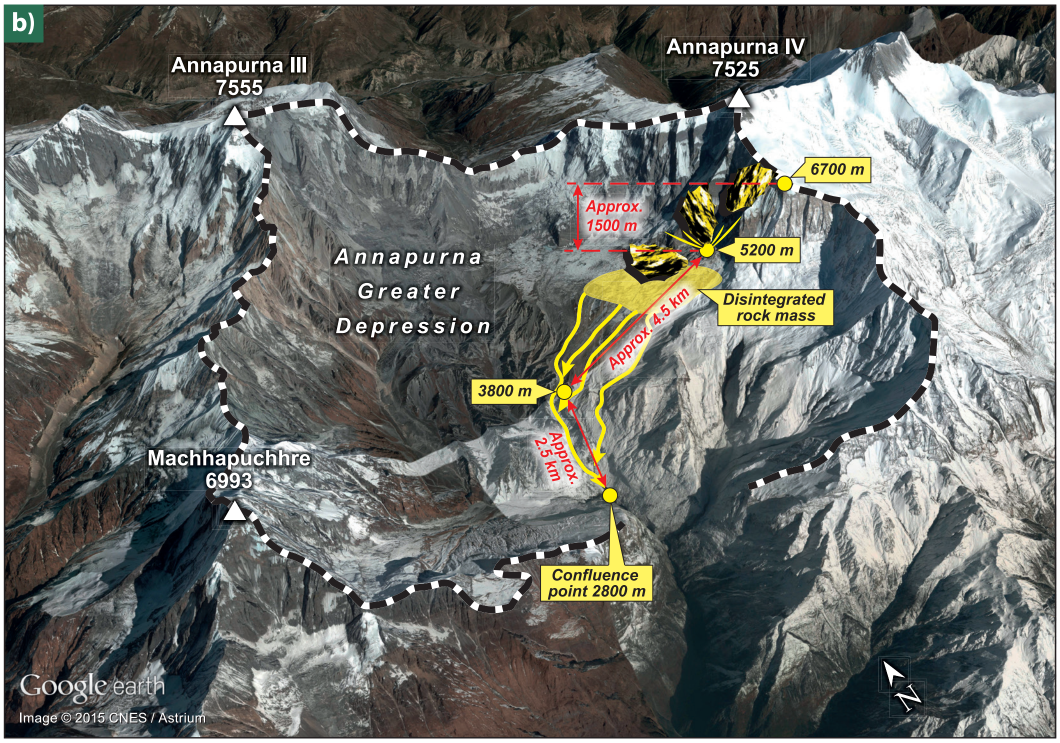


Fig. 6.20: (a) The Pokhara formation of sediment accumulations originated as rock and ice avalanches from the peaks of Annapurna III and IV which impacted on glacial and/or rockslide material in the Sabche cirque, descended the Seti Khola as catastrophic mud and debris flows and accumulated in the valley bottom, creating the Phewa Tal. This process appears to have occurred continually from historic to recent times according to sediments dated by Yamanaka *et al.* (1982), Fort (1987) and Schwanghart *et al.* (2013, 2014). (Features compiled by JTW 2015 on a Google Earth panoramic view, 30 December 2014). (b) The Sabche cirque is framed by Machhapuchhre (6,993 m), Annapurna III (7,555 m) and Annapurna IV (7,525 m). On 5 May 2012 a large avalanche of ice and rock from the southwest flank of Annapurna IV fell 1,500 m into the cirque, disintegrated and descended another 2,400 m in altitude to the confluence point, temporarily damming the river and subsequently causing a serious flood in the valley of the Seti Khola (Google Earth, Imagery, 30 December 2014, interpreted and edited by Bhandary *et al.*, 2012).

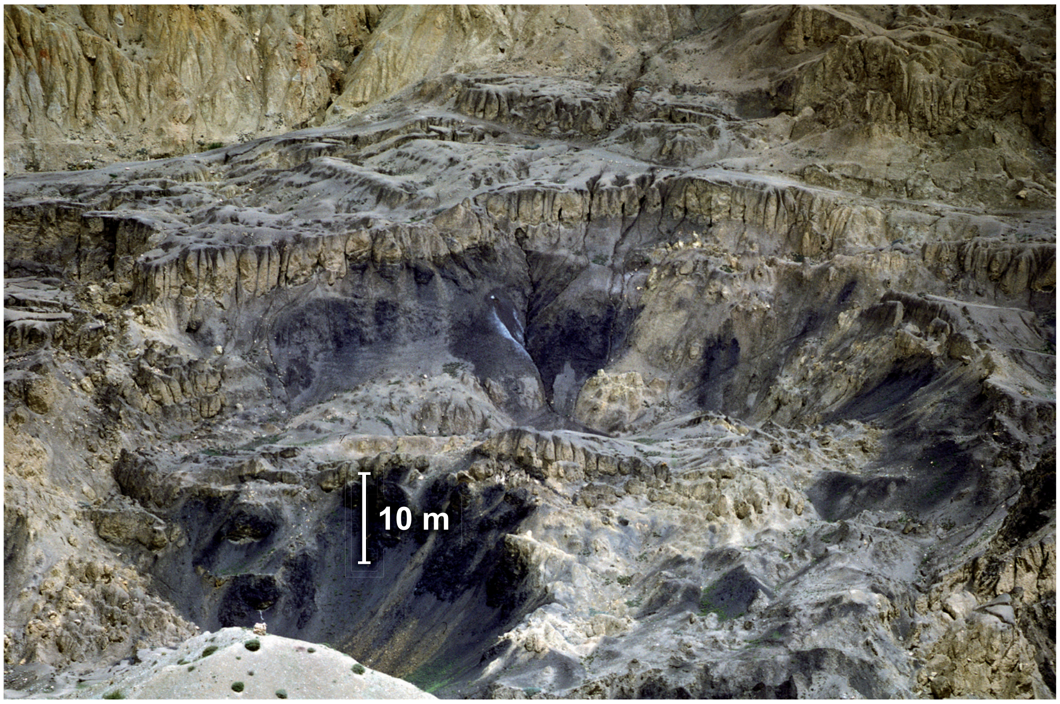


Fig. 6.21: Marl and black slate (Spiti shales) move in slumps and earth flow during times of higher rainfall. Mustangbhot near Yara, 3,720 m, 29°06'N/84°80'E, August 2001. (GM)

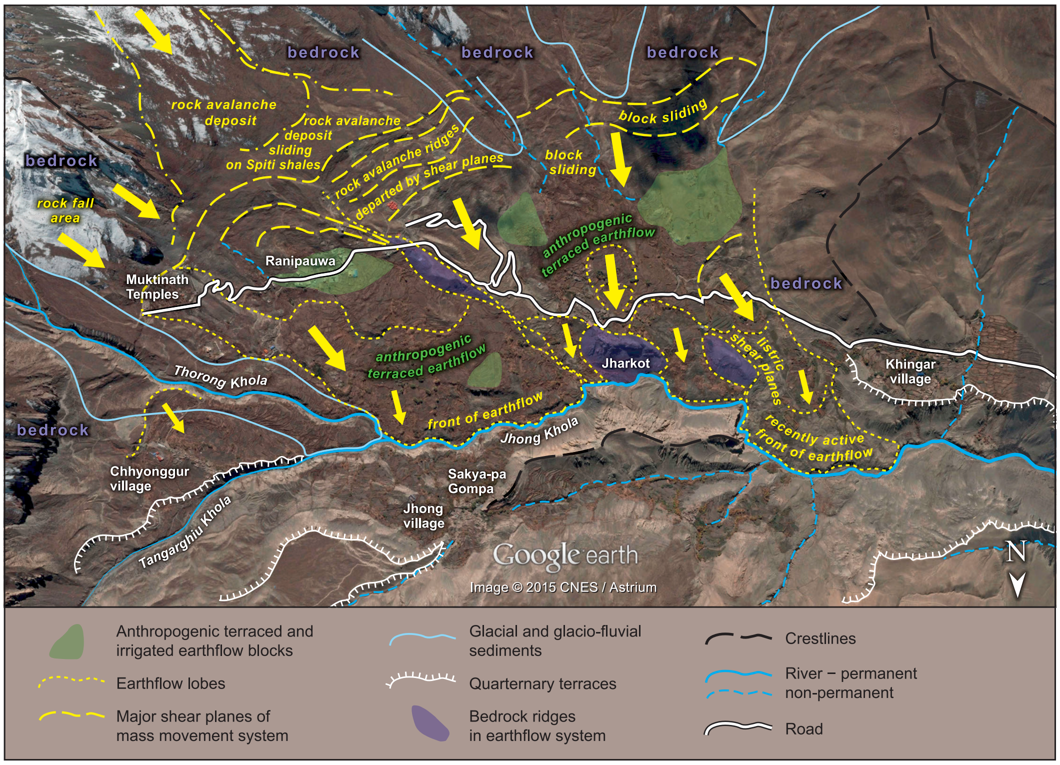


Fig. 6.22: Geomorphological sketch map of the rock avalanche and earth-flow system around the villages of the Muktinath Valley. The farmers live in a 'symbiotic' relationship with the mass-movement, using the tops of sliding blocks as agricultural land and irrigating them not only with water from precipitation but also spring water originating from the landslide's active shearing planes. However such activities may possibly trigger new sliding processes (compiled by Weidinger, with contributions by Attems, Bell, Fort, Götz, Korup, Google Earth, Imagery, 27 October 2014).

Fig. 6.23: Rock glaciers are indicative of permafrost in arid high mountains. The rock glacier (arrow) is of Late Glacial or Holocene age. The dashed line marks the probable height of the valley glacier at the Last Glacial Maximum. Upper Dolpa, east of Yang-La, 4,830 m, 6 km south of the Nepal-Tibet border, 29°38'N/82° 50'E. Modified from Google Earth, 10 January 2011.

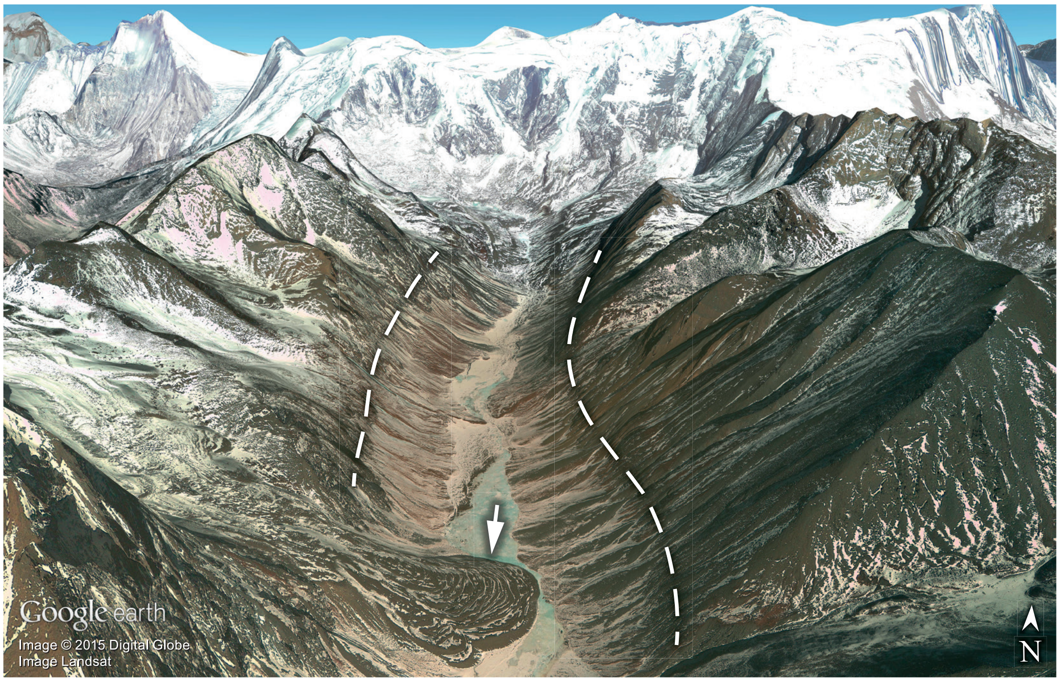


Fig. 6.24: Periglacial environment with frost-creeping scree colonised by *Eriophyton wallichii* (1). *Urtica hyperborea* (2) and *Rhodiola* sp. (3) grow in the shelter of large, immobile boulders which are partly covered with crustose lichens (4). Ice axe 85 cm long. Upper Cha Lungpa, 5,250 m, 28°54'N/83°35'E, August 1977. (GM)

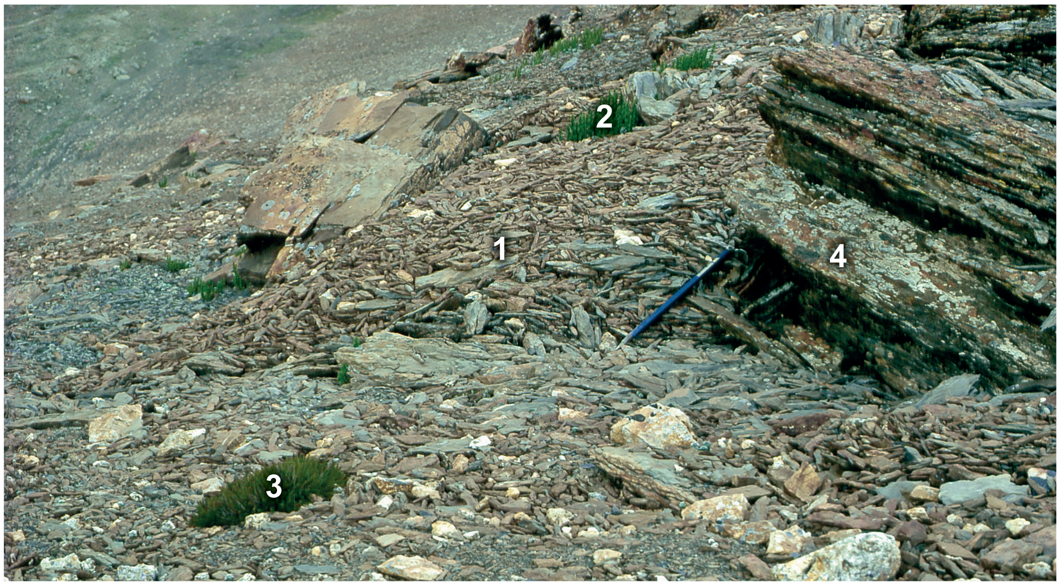
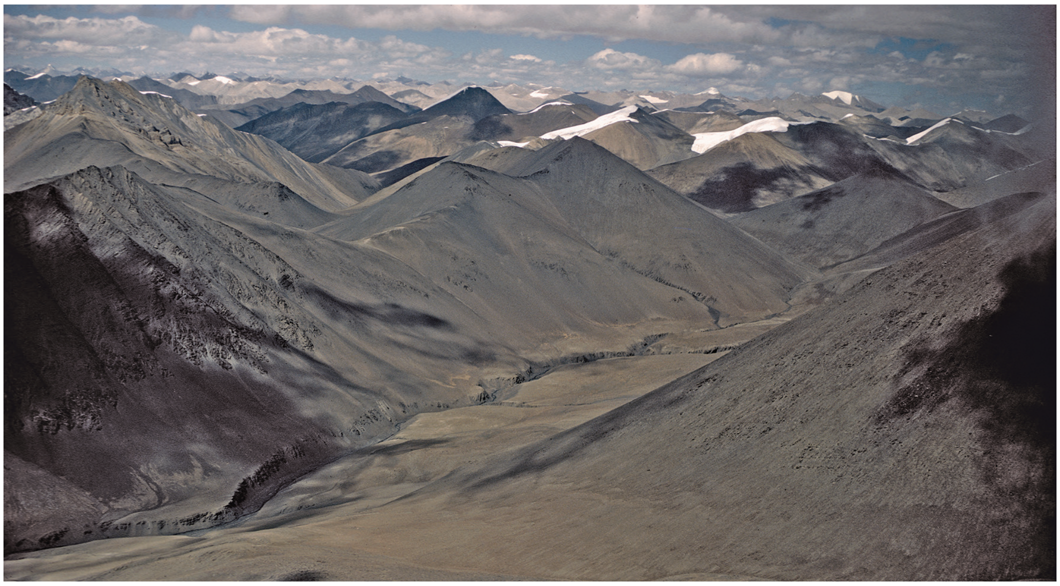


Fig. 6.25: Periglacial valleys with braided streams (5,000 m) and scree-covered slopes of the rolling hills in the watershed area between Kali Gandaki (Cha Lungpa) and Barbung Khola. Ice wedges indicate the presence of permafrost. 6,052 m, 28°56'N/83°36'E, towards the west, October 1977. (GM)



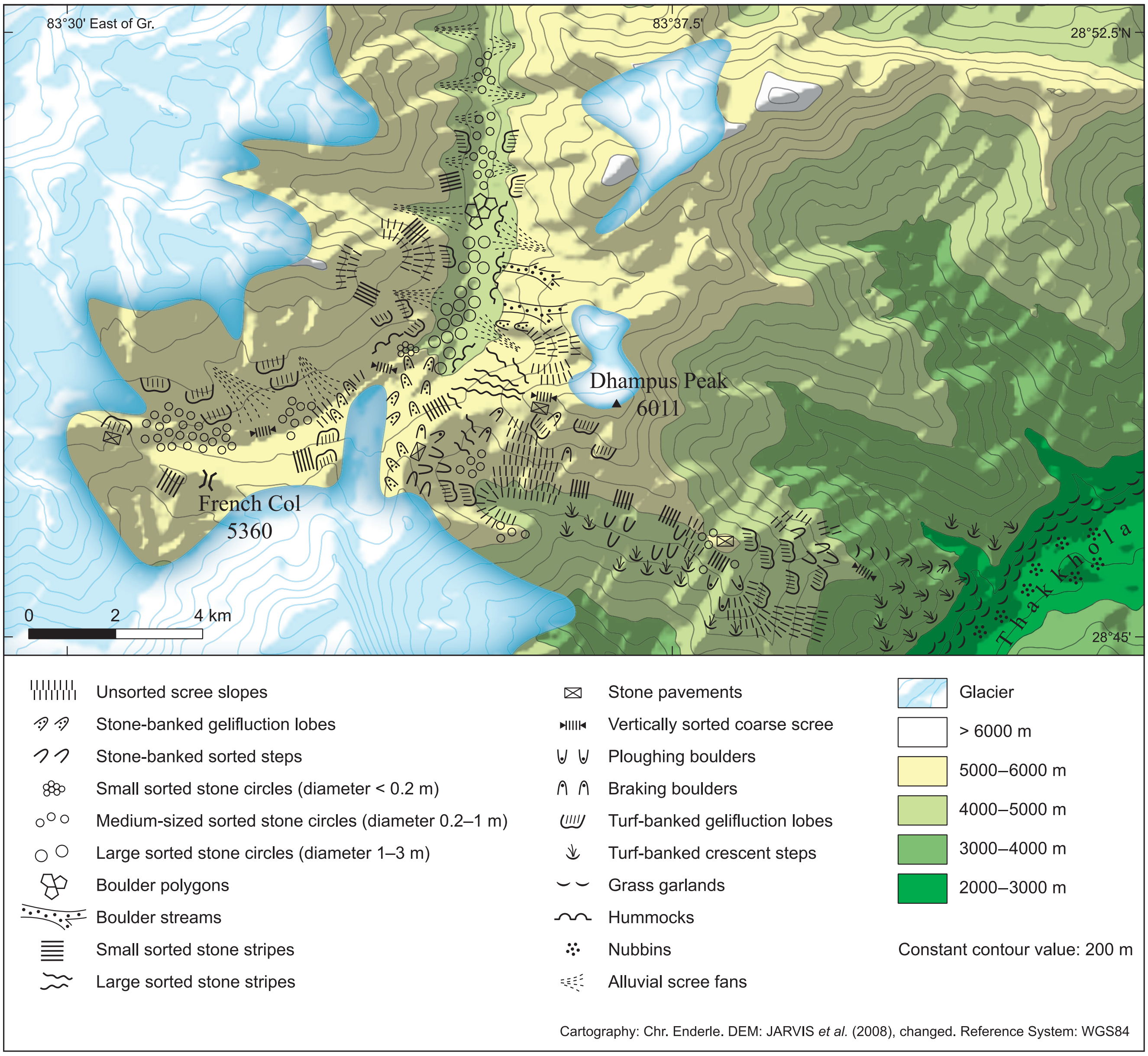


Fig. 6.26: Periglacial landforms in a high-altitude valley in the Inner Himalayas indicate conditions analagous to lowland climates in the Arctic. Hidden Valley, north of Dhaulagiri I. Modified from Kuhle (1982), nomenclature modified after Washburn (1979).

In some places sediments have eroded into pinnacles. Watershed areas between 4,800 and 5,500 m are not thus dissected and have rolling hills. Rock glaciers are a feature of this cold, arid, high-altitude environment and indicate the presence of discontinuous alpine permafrost (Fig. 6.23). The lower limit of active rock glaciers corresponds to a mean annual temperature of -1°C (Washburn, 1979) and there are numerous such ice-cored glacier-like permafrost forms in the high side valleys of upper Dolpa. Their substrate originates mostly from supraglacial debris. They are usually more than 1 km in length, are broader than 100 m and more than 15 m thick (Owen and Dortch, 2014). Owen and England (1998) suggested that rock glaciers record the advance of ice-cored moraines following the retreat of glaciers since the Little Ice Age.

Periglacial and permafrost landforms typical of high Arctic latitudes can be seen at these altitudes, including frost shattering, periglacial creep of scree, tallus cones, patterned ground, ice wedges and gravel fans in broad valleys (Figs 6.24–6.26; Kuhle, 1982).

The abandoned village of Phudzeling (3,060 m), with its deserted fields and caves excavated in glacial deposits (see 14.4.3). Muktinath Valley, Mustang, 3,300 m, 28°50'N/83°49'E, 2006. (CP)