# Causes of large-scale landslides in the Lesser Himalaya of central Nepal

Netra Bhandary

*Environmental Geology*

Environ Geol
DOI 10.1007/s00254-008-1420-z

ORIGINAL ARTICLE

# Causes of large-scale landslides in the Lesser Himalaya of central Nepal

**Shuichi Hasegawa · Ranjan Kumar Dahal · Minoru Yamanaka · Netra Prakash Bhandary · Ryuichi Yatabe · Hideki Inagaki**

Received: 24 February 2008 / Accepted: 4 June 2008


**Abstract** Geologically and tectonically active Himalayan Range is characterized by highly elevated mountains and deep river valleys. Because of steep mountain slopes, and dynamic geological conditions, large-scale landslides are very common in Lesser and Higher Himalayan zones of Nepal Himalaya. Slopes along the major highways of central Nepal namely Prithvi Highway, Narayangadh-Mugling Road and Tribhuvan Highway are considered in this study of large-scale landslides. Geologically, the highways in consideration pass through crushed and jointed Kathmandu Nappe affected by numerous faults and folds. The relict large-scale landslides have been contributing to debris flows and slides along the highways. Most of the slope failures are mainly bechanced in geological formations consisting phyllite, schist and gneiss. Laboratory test on the soil samples collected from the failure zones and field investigation suggested significant hydrothermal alteration in the area. The substantial hydrothermal alteration in the Lesser Himalaya during advancement of the Main Central Thrust (MCT) and thereby clay mineralization in sliding zones of large-scale landslide are the main causes of large-scale landslides in the highways of central Nepal. This research also suggests that large-scale landslides are the major cause of slope failure during monsoon in the Lesser Himalaya of Nepal. Similarly, hydrothermal alteration is also significant in failure zone of the large-scale landslides. For the sustainable road maintenance in Nepal, it is of utmost importance to study the nature of sliding zones of large-scale landslides along the highways and their role to cause debris flows and slides during monsoon period.

**Keywords** Himalaya · Landslides · Clay minerals · Hydrothermal alteration

S. Hasegawa (✉) · R. K. Dahal · M. Yamanaka
Department of Safety Systems Construction Engineering,
Faculty of Engineering, Kagawa University, 2217-20,
Hayashi-cho, Takamatsu City 761-0396, Japan
e-mail: hasegawa@eng.kagawa-u.ac.jp

R. K. Dahal
Department of Geology, Tribhuvan University,
Tri-Chandra Multiple Campus,
Ghantaghar, Kathmandu, Nepal

N. P. Bhandary · R. Yatabe
Department of Civil and Environmental Engineering,
Graduate School of Science and Engineering,
Ehime University, Bunkyo-cho 3,
Matsuyama 790-8577, Japan

H. Inagaki
Kankyo Chishitsu Co. Ltd., Kaizuka,
1-4-5-203, Kawasaki-ku, Kawasaki City,
Kanagawa 210-0014, Japan

## Introduction

Nepal is a highly mountainous country located between China in the north and India in the south, east and west with an area of 147,181 sq. km (Fig. 1). It occupies about 800 km long central part of the Himalayan arc which has been formed by the collision of Indian and Eurasian plates. Nepal is mainly characterized by rugged topography, very high relief, variable climatic conditions, complex geological structures affected by active tectonic process and seismic activities. Topographic elevation changes from 60 m at the southern plains to 8,848 m at the Mt. Everest in the north within a horizontal distance of less than 200 km (Fig. 1). This kind of topography is prone to landslide and erosion in Nepal. The mountainous and hilly regions of the country occupy nearly 83% of the total area, whereas the

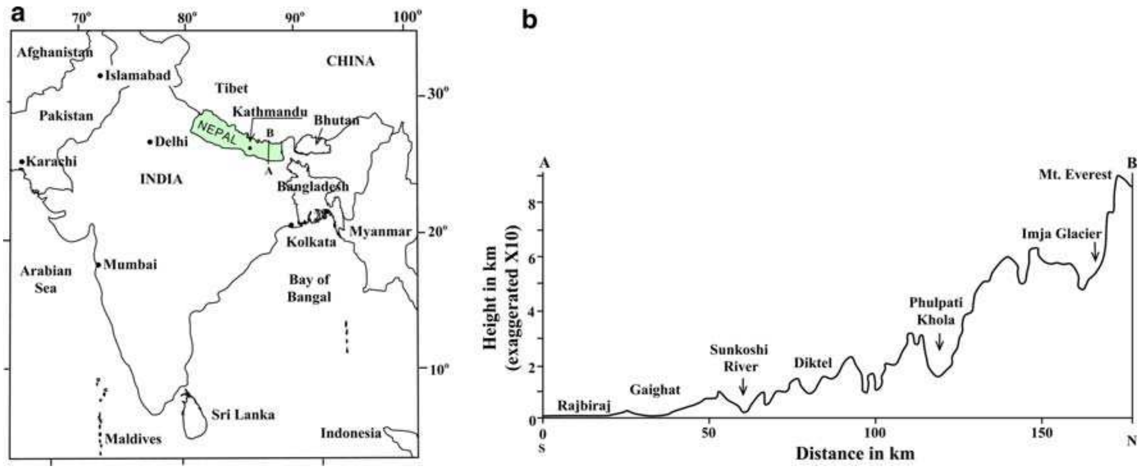



**Fig. 1** **a** Location map of Nepal, **b** S-N topographic profile (*line AB* in **a**) showing vast difference in elevation within short distance, height of the Mt Everest is 8,848 m

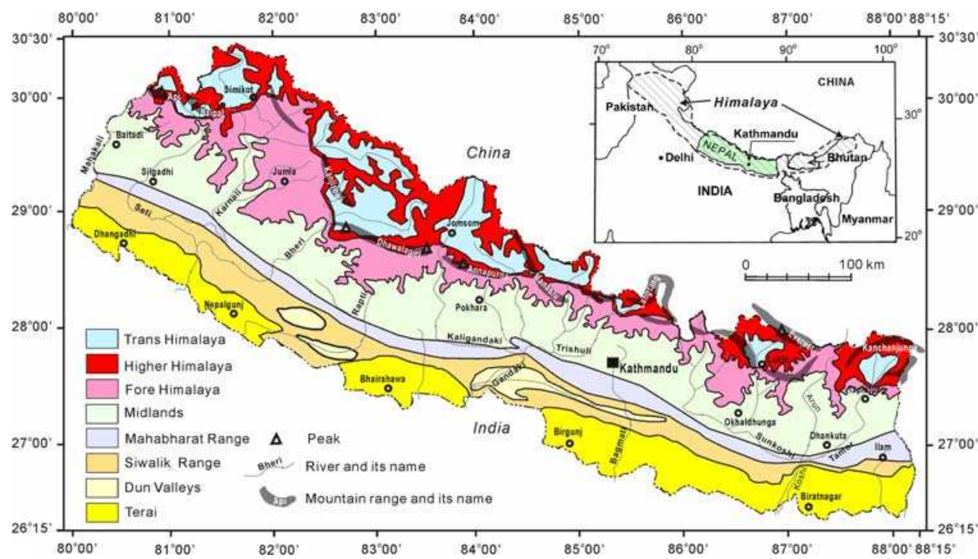



**Fig. 2** Digital elevation model (DEM) based geomorphologic map of Nepal (modified after Hagen 1969, Upreti 1999 and Dahal and Hasegawa 2008)

remaining 17% is flat land. The seasonal monsoon rains and intense but improper land use practices make the Nepalese Himalayas the most unstable landscapes in the world.

Steep slopes are the key features of the Himalayan geomorphology. Rapid uplift from Miocene, which continues even today, has created local relief measurable in kilometres from river valleys to peaks. As a result, large-scale valley slope creeping (large-scale landslides) due to gravity has been prolonging from the early upliftment of mountains, which is a common feature. Thus, landslides may be regarded as one end of the spectrum of slope modification processes in the Nepal Himalaya and adjacent regions.

Landslides in the Himalaya are scale-dependent, from massive extent of whole mountain ranges (gravity tectonics) through failure of single peaks to very minor slope failures (Shroder and Bishop 1998; Shang et al. 2003). However, only few studies have been done to understand the Nepal Himalayan landslide mechanisms and processes (e.g. Laban 1979; Selby 1988; Ives and Messerli 1981; Caine and Mool 1982; Wagner 1983; Heuberger et al. 1984; Burbank et al. 1996; Upreti and Dhital 1996; Gerrard 1994; Gerrard and Gardner 2000; Chalise and Khanal 2001) and there are still lack of research publications related to the mechanisms and processes of large-scale landsliding in the Lesser Himalaya. In this context, this paper deals with comprehensive information about the large-scale landslides observed in the major highways running through river valleys of central Nepal. The main objectives of this research include, (1) mapping of the large-scale landslides along the major highway of central Nepal, (2) investigating the failure zone of some of large scale landslides in terms of strength and clay mineralogy, and (3) discussing the role of hydrothermally altered clay in the origin of large-scale landslides.

## Geological setting

Geomorphologically, Nepal is divided into eight units running east–west (Table 1; Fig. 2), namely, Terai, Churia Range, Dun Valley, Mahabharat Range, Midland, Fore Himalaya, Higher Himalaya, Inner and Trans Himalaya (Hagen 1969; Upreti 1999). Likewise, geologically and tectonically, Nepal is divided into five major tectonic zones, namely, Terai, Sub-Himalaya (Siwaliks), Lesser Himalaya, Higher Himalaya and Tibetan-Tethys Himalaya (Ganser 1964; Upreti 1999). These tectonic zones are separated by major thrusts and faults of the Himalaya, namely from north to south (Fig. 3), South Tibetan Detachment System (STDS), Main Central Thrust (MCT), Main Boundary Thrust (MBT) and Main Frontal Thrust (MFT).

According to Bilham et al. (1997), the Indian Plate is moving northwards with an average rate of 1.5–5 cm per year and nearly half of this horizontal slip is being accommodated within the Himalaya. As a result, the rocks of the Himalaya are moving upwards as well as horizontally towards south along the major thrusts (Upreti 2001). The MCT was very active during the period between 25 and 19 million years ago, and the northern part of the Himalaya gained the present day height very quickly. Steep slopes and deeply eroded river valleys are the outcomes of such movement in the Higher Himalaya.

Many investigations have disclosed that movement along the MCT ceased by around 18 Ma (Copeland et al. 1991; Hodges et al. 1996). Such movement caused Higher Himalayan rocks to slide horizontally towards south about 120 km over the young Lesser Himalayan rocks. Thus, it is believed that once upon the geological time much of the Lesser Himalaya must have been covered by the rocks of the Higher Himalayan crystalline rocks like a bedspread. Evidences of such cover can be noticed very clearly in the geological map of Nepal (see Fig. 3). In eastern Nepal, MCT is still in south and only opens as window in the Arun River valley and Taplejung areas. But most of the parts of Higher Himalayan crystalline rocks are already eroded in other area. Although it is presumed that MCT became inactive and the movement along this thrust practically ceased by 18 Ma, it has been found that MCT was reactivated during a period 6–8 million years ago (Harrison et al.

**Table 1** Geomorphologic units of Nepal, modified after Hagen (1969), Upreti (1999) and Dahal (2006)

| SN | Geomorphic units | Width (km) | Altitudes (m) | Main rock types | Geological age | Main processes for landform development |
|---|---|---|---|---|---|---|
| 1 | Terai (northern edge of the Gangetic Plain) | 20–50 | 100–200 | Alluvium: coarse gravels in the north near the foot of the mountains, gradually becoming finer southwards | Recent | River deposition, erosion and tectonic upliftment |
| 2 | Churia range (Siwaliks) | 10–50 | 200–1,300 | Sandstone, mudstone, shale and conglomerate. | Mid-Miocene to Pleistocene | Tectonic upliftment, erosion, and slope failure |
| 3 | Dun Valleys | 5–30 | 200–300 | Valleys within the Churia Hills filled up by coarse to fine alluvial sediments | Recent | Tectonic upliftment, weathering, erosion, and slope failure |
| 4 | Mahabharat Range | 10–35 | 1,000–3,000 | Schist, phyllite, gneiss, quartzite, granite and limestone belonging to the Lesser Himalayan Zone | Precambrian and Paleozoic and some Cenozoic | Tectonic upliftment, weathering, erosion, and slope failure |
| 5 | Midlands | 40–60 | 300–2,000 | Schist, phyllite, gneiss, quartzite, granite and limestone geologically belonging to the Lesser Himalayan Zone | Precambrian and Paleozoic to mesozoic | Tectonic upliftment, weathering, erosion, and slope failure |
| 6 | Fore Himalaya | 20–70 | 2,000–5,000 | Gneisses, schists, phyllites and marbles mostly belonging to the northern edge of the Lesser Himalayan Zone | Precambrian | Tectonic upliftment, weathering, erosion, and slope failure |
| 7 | Higher Himalaya | 10–60 | >5,000 | Gneisses, schists, migmatites and marbles belonging to the Higher Himalayan Zone | Precambrian | Tectonic upliftment, weathering, erosion (rivers and glaciers), and slope failure |
| 8 | Inner and trans Himalaya | 5–50 | 2,500–4,500 | Gneisses, schists and marbles of the Higher Himalayan Zone and Tethyan sediments (limestones, shale, sandstone etc.) belonging to the Tibetan-Tethys Zone | Precambrian and Cambrian to Cretaceous | Tectonic upliftment, wind and glacial erosion, and slope degradation by rock disintegrations |

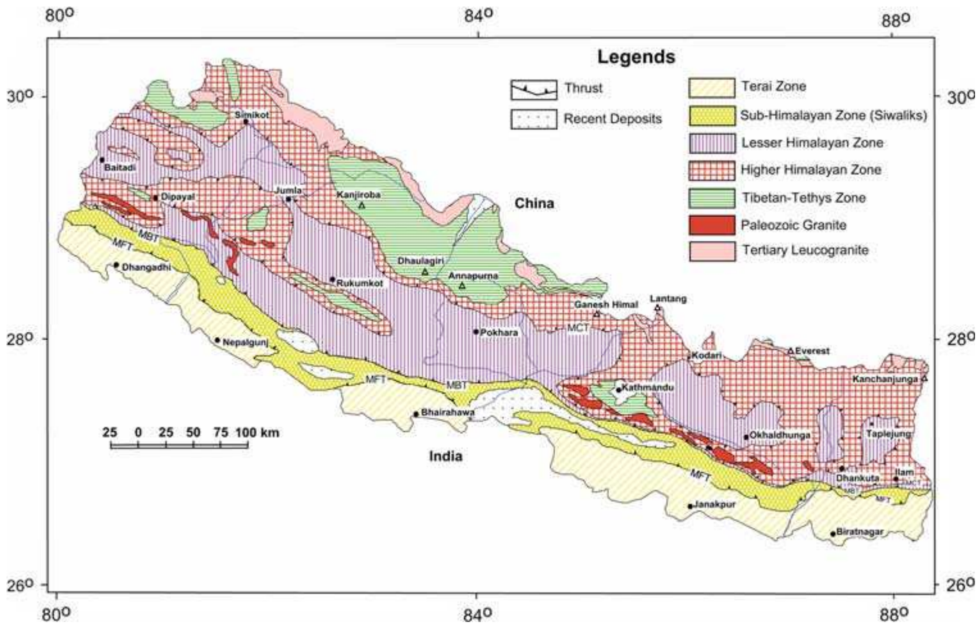



Fig. 3 Generalized geological map of Nepal (modified after Amatya and Jnawali 1994; Dahal 2006)

1997), and the Higher Himalaya again revitalized. Himalayas gain maximum topography around 17 Ma (Searle et al. 1997). As a result, normal fault system, STDS, developed as gravitational collapse structure, which is now considered as a tectonic boundary between the Tibetan-Tethys Zone and the Higher Himalayan Zone.

A thrust called MBT started in the south of the MCT about 10–11 million years ago and all the horizontal movement that had been occurring along the MCT shifted to the MBT (Meigs et al. 1995). This movement along the MBT effectively created high mountain range in the Lesser Himalaya known as the Mahabharat Range. The rivers flowing from the Higher Himalaya to south started to erode the elevated Mahabharat Range, resulting in development of deep and steep river valleys in the Lesser Himalayan Zone. The MBT is an active thrust system and the frontal part of the Lesser Himalaya is comparatively rising fast even today. But the MBT could not accommodate all strains due to northward displacement of the Indian Plate, which resulted in the development of another thrust MFT in the south at southern front of the Siwaliks. Nowadays, the MFT is more active than the MBT and is causing upliftment of the hills of Siwaliks.

Tertiary leucogranites are distributed around the highest peaks of the Himalaya along the border with China (see Fig. 3). They intrude the Higher Himalayan Gneiss and the Tibetan-Tethys Sediments. The radiometric age of the leucogranite is 9–24 million years, which indicates that the leucogranite intruded mainly in Miocene. The upheaval of Higher Himalaya, metamorphism, activity of the MCT and formation of the STDS occurred during the emplacement of the leucogranite (Deniel et al. 1987; Searle et al. 1997, 1999; Harrison et al. 1999; Upreti 1999).

The tectonic history of Nepal Himalaya largely supports the occurrence of deep and steep river valleys in central Nepal. These valleys have been extensively used to connect capital city Kathmandu with other cities by constructing two-lane national highways and consist of many large-scale landslides.

## The study area

Three highways of central Nepal, namely, Prithivi Highway (H4), Tribhuvan Highway (H2) and Narayangadh-Mugling Road (H5) were selected for this study (Fig. 4), because the present trend of prioritizing natural disasters in Nepal shows that landslide occurrences along the highways, especially the above-mentioned three routes are given much importance. It is also due to greater economic loss as well as a larger number of people affected, especially due to traffic disruption, during an event of roadside failure.

## Methodology

### Landslide mapping

Identification of large-scale creep on a steep mountain valley is a tedious work. To make it easy to recognize landslide spots along the selected road network, landslide inventory mapping was carried out with the help of aerial photo interpretation (API) and plotting the landslide shape and size on the topographic map (1:25,000 scale) based on the judgment from aerial photographs. During identification of

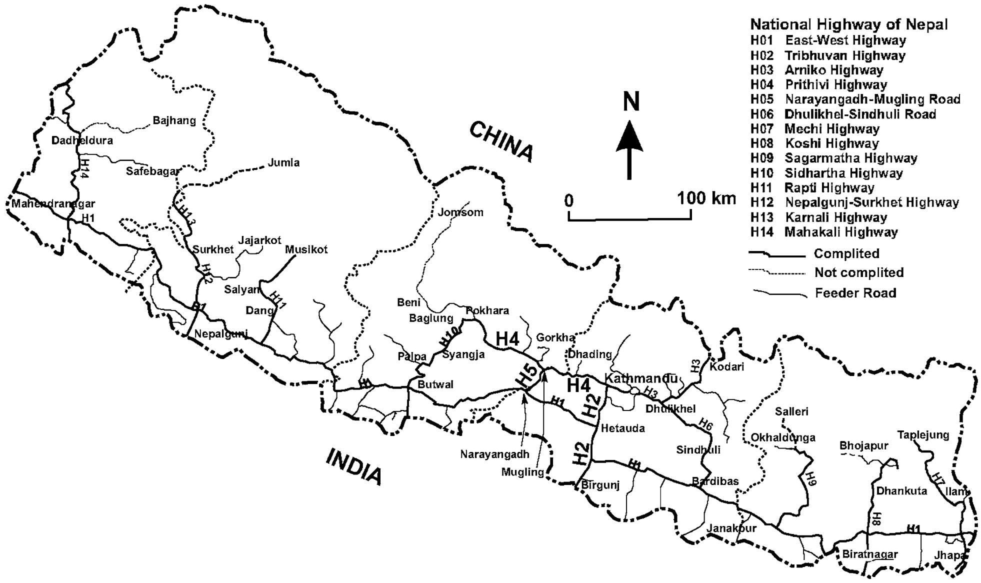



**Fig. 4** Major road network in Nepal and highways H2, H4 and H5 are selected for study

landslides, priority was given to already existing instabilities such as old landslides, colluvial deposits, and alluvial fans. The scale of aerial photographs used was about 1:50,000 and they were 12 years old. So, it was necessary to make field verification, especially for the failures that could have been missed in stereoscope viewing. For the field verification, six field visits were made from year 2003 to 2007. Moreover, the effect of vegetation cover is often high enough to hide slope failures measuring only a few hundred square meters. So, to avoid possibilities of mismatch between deskwork and field existence of landslides, the first field visit program was conducted along Prithvi Highway (Nagdhunga-Pokhara section) in July 2003; the second visit was made along Prithvi Highway (Nagdhunga-Pokhara section) and Narayangadh-Mugling Highway in November 2003; the third and fourth visits were carried out for Prithvi Highway (Naubise-Mugling section), Narayangadh-Mugling Road, and Tribhuvan Highway (Hetauda-Naubise Section) in November 2004 and November 2005. The fifth and sixth visits to for Prithvi Highway (Naubise-Mugling section) and Narayangadh-Mugling Road were carried out in June 2006 and December 2007. The activities carried out during the field visits included visual inspection, experience-based estimation of the failure type and associated geology, existence of vegetation cover and groundwater hydrology as well as examination of failure zones in uphill or downhill section of the roads.

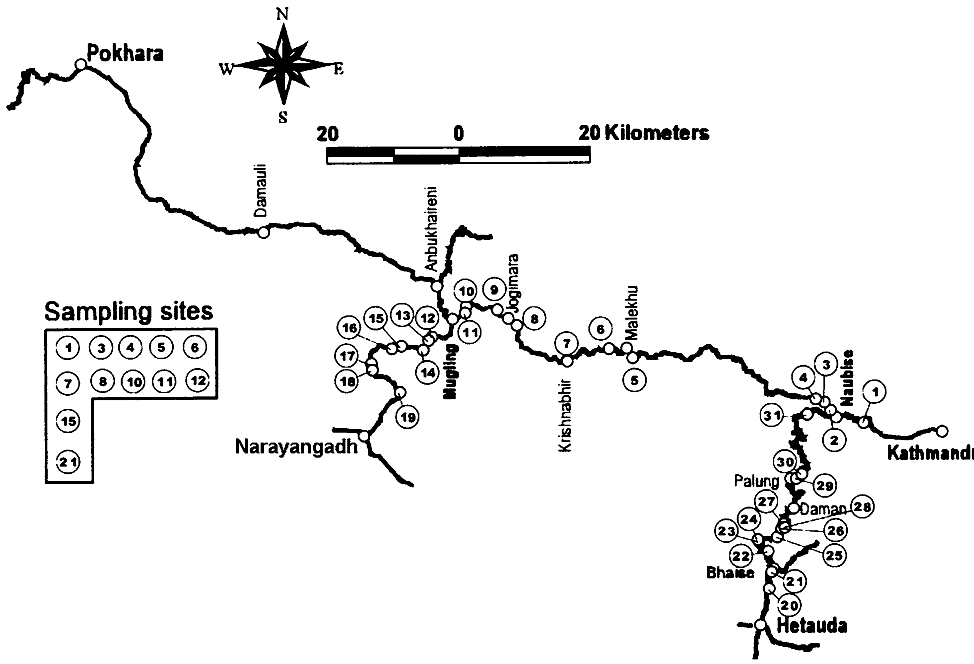
## Soil sampling and laboratory test

During field verification, failure zone materials were observed in some landslides along the Prithivi Highway, Narayangadh-Mugling Road and Tribhuvan Highway. It was noticed that the failure zone soils consist of significant amount of clay mineralization. Considerable amount of coarse rock fragments (granule to pebble size) were also present in failure zone. As a result, study of stress–strain behaviour and hydrological characteristics (Dai et al. 1999; Frattini et al. 2004; Shakoor and Smithmyer 2005; Yilmaz and Karacan 2002; Yilmaz and Yildirim 2006) of failure zone soil are not possible in undisturbed soil sample. So, disturbed soil samples were collected from the failure zones for laboratory tests in order to interpret residual shear strength parameters and clay mineral composition. Moreover, in some locations, non-clayey materials such as sand and gravel were also noticed in the failure zones. Although 31 sites were taken into consideration as problematic large scale landslide sites, only 12 sites (Fig. 5) were selected for the soil sampling because of availability of clay materials.

Strain-controlled and constant normal stress type direct ring shear apparatus (Bishop et al. 1971) was used to measure shear strength of clayey soils under three effective pressures (1, 2, and 3 kgf/cm$^2$; i.e. 98.07, 196.14 and 294.21 kN/m$^2$, respectively). The results obtained from the ring shear tests were interpreted in terms of stress–strain curves and strength envelopes. A total of ten soil samples from the landslides along the highways were used for ring shear test.

The method for the detection of clay minerals in this study is based on X-ray diffraction patterns in (1) powder method, (2) oriented aggregate method, and (3) ethylene glycol treatment method of clay mineralogical analysis. However, the latter two methods were carried out only to confirm the minerals detected in powder method, which often results in an overall representation of minerals in a sample.

Fig. 5 Vulnerable landslide spots and soil sampling sites




Review of the models of Himalayan tectonics

Observations in the clay-rich zones below the thick rock successions distinctly suggested that there were specific roles of fluid movements along the fractures of rockmass. Thus, in this research, special attentions were given to the available previous study about mechanism and model of the MCT, MBT and Tertiary volcanism in Himalaya.

## Findings of mapping and laboratory test

### Relation between large-scale landslide and rainfall triggered landslide

Basic measurements (length, breadth, slope angle and so forth) of failed slopes, study of geological characteristics (rock types, attitudes of joints, foliation and bedding and so forth) of sites and soil sampling were carried out during field visits, and it was noticed that mainly geological formations having phyllite, schist and gneiss are having the instability problem. In total, 31 vulnerable sites were identified after inventory mapping. The inventory maps of all three selected highway stretches were prepared in GIS (ArcGIS 9.0) environment. The inventory maps suggested a quite surprising relation between landslide and road alignment. Almost whole Narayangadh-Mugling Road section was found to be run through the landslide terrains (Fig. 6). Similarly, in 2003, a huge landslide disaster occurred in this road (Dahal et al. 2006; Dahal and Hasegawa 2008) and caused damages to many bridges and hundreds of meters of road stretch. Almost all rainfall-triggered landslides that occurred in 2003 were observed in large-scale landslide material.

### Clay minerals of sliding surface material

From the X-ray diffraction patterns of the tested soil samples, it is clearly understood that the main constituent minerals of the collected samples (Table 2) are chlorites, illites, muscovite, actinolite, feldspar and quartz with occasional appearance of smectite, talc and metahalloysite. In Sample 1 of the Prithivi Highway at Khatripauwa village, some traces of montmorillonite (smectite) were observed and confirmed by conducting oriented aggregate analysis and ethylene glycol treatment analysis (Fig. 7). Metasandstone with alternate bands of slates is the main unit in the site. A marked presence and significantly high intensity of X-rays corresponding to illites (along with muscovite) in almost all samples indicates that the landslide materials consist of a higher percentage of illites. High content of quartz in soil samples also gives a clear significance of high value of peak and residual shear resistance (>30°).

### Shear strength of sliding surface material

The shear strength results indicate that there is no significant difference in peak strength and residual strength of almost all tested samples because all shear tests were conducted on remolded saturated samples under normally consolidated conditions, which often exhibit insignificant drop in strength in post peak state of shear. Figure 8 shows a comparison of angles of peak and residual shear resistances. Although the number of samples collected was not

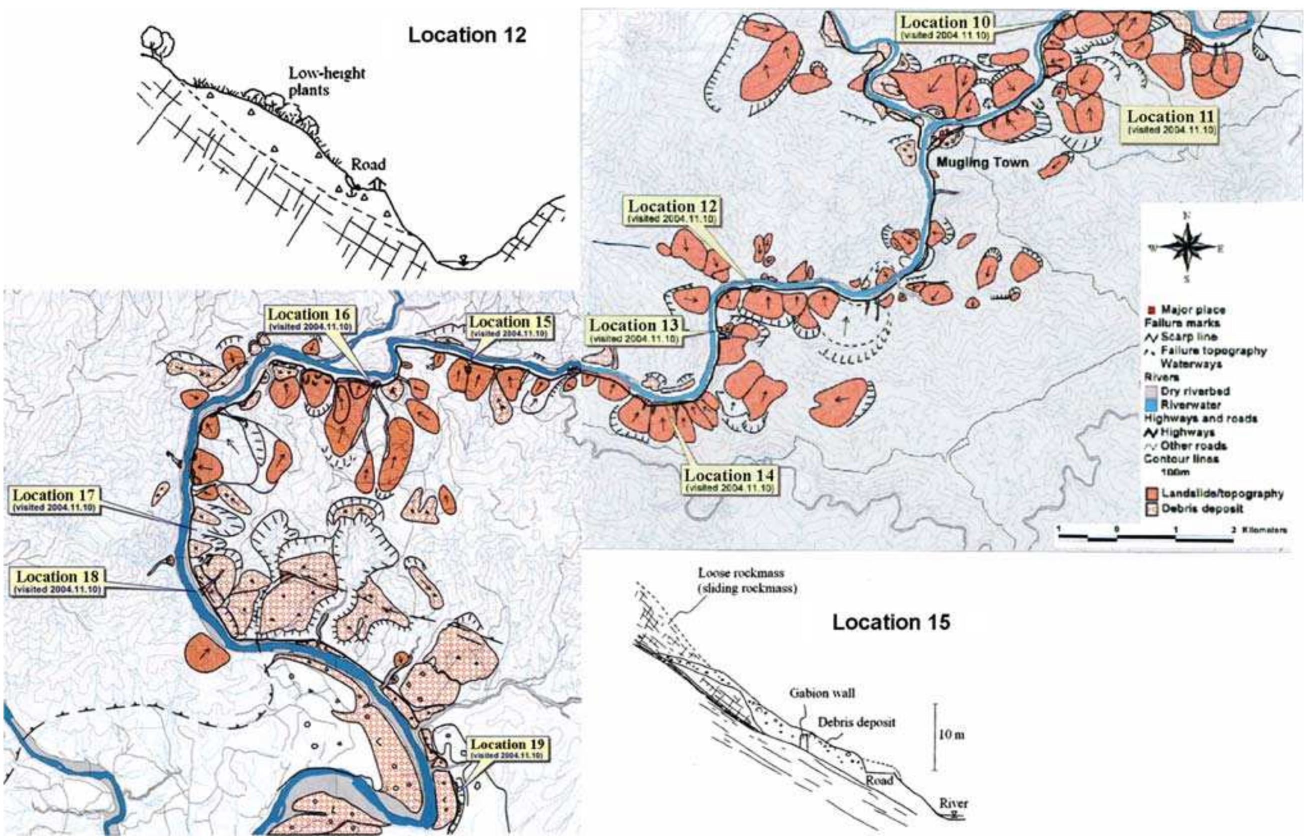



**Fig. 6** Example of landslide inventory map, some section of Prithivi Highway and Narayangadh-Mugling road

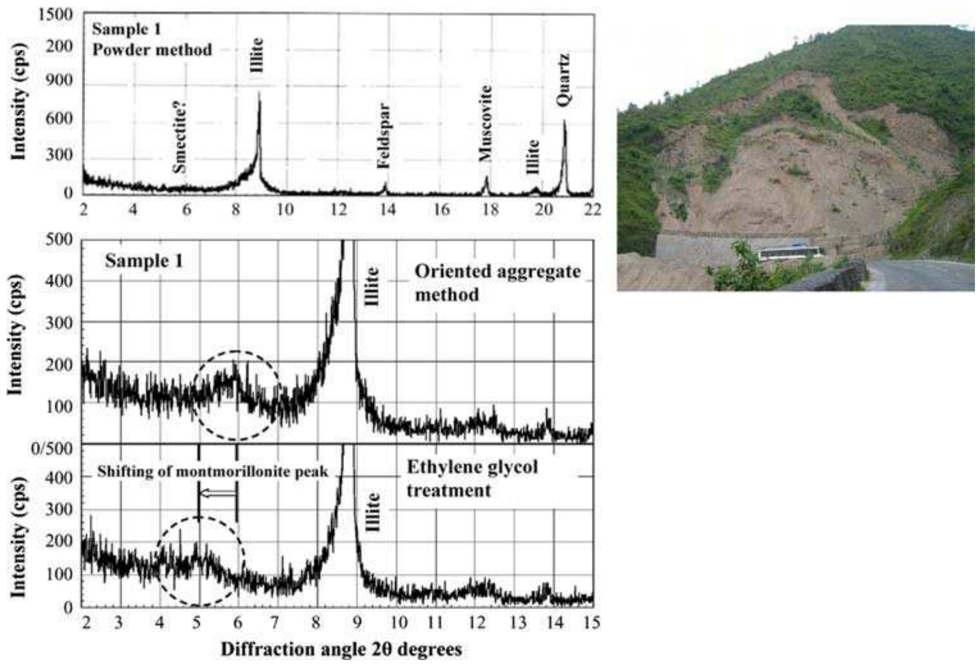
**Table 2** Relative occurrences of clay minerals in some of investigated sites

| Loc. | Occurence | Minerals | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | Quartz | Albite | K-felspars | Chlorite | Illite | Actinolite | Smectite | Muscovite |
| No. 1 | Weathered metasandtone | ++ | + | − | − | +++ | − | + | + |
| No. 6 | Weathered landslide materials | +++ | − | − | ++ | ++++ | − | − | +++ |
| No. 10 | Weathered landslide materials | ++ | − | − | ++ | +++ | − | − | ++ |
| No. 15 | Phyllite (bedrock) | ++++ | +++ | − | +++ | ++ | − | − | − |
| | Sliding zone materials (micro-breccia) | ++++ | +++ | − | +++ | ++ | − | − | − |
| | Coarse breccia | ++++ | ++ | − | +++ | +++ | − | − | − |
| No. 16 | Amphobolite (bedrock) | +++ | +++ | − | ++++ | ++ | ++++ | − | − |
| | Sliding zone materials (micro-breccia) | +++ | ++ | − | +++++ | + | ++++ | − | − |
| | Coarse breccia | +++ | +++ | − | ++++ | ++ | ++++ | − | − |
| No. 25 | Granite (bedrock) | +++++ | +++ | +++ | − | +++ | +++ | − | − |
| | Granite powder | ++++ | +++ | +++ | − | +++ | +++ | − | − |

Abundant +++++◄——————► + Poor

significant enough to give an interpretation for the range of internal friction angles representing all landslide and slope failure soils along the highways, it is believed that the range marked in the figure more or less represents a greater part of their shear strength parameters. The marked ranges show that the peak angle of shear resistance varies between 22° and 36°, whereas the residual angle varies between 21° and 34°. This indicates that the landslides and failure zone materials of the study area do not possess a general average value of angle of shearing resistance, which is necessary for stability of slopes of study area, having average slope angle of 30°. Likewise, this site consists of slate and green phyllite and shows relatively less value of residual shear resistance than that of quartzite, limestone and granite.

Fig. 7 X-ray diffraction of landslide materials from location 1 (see Fig. 5) of the Prithivi Highway



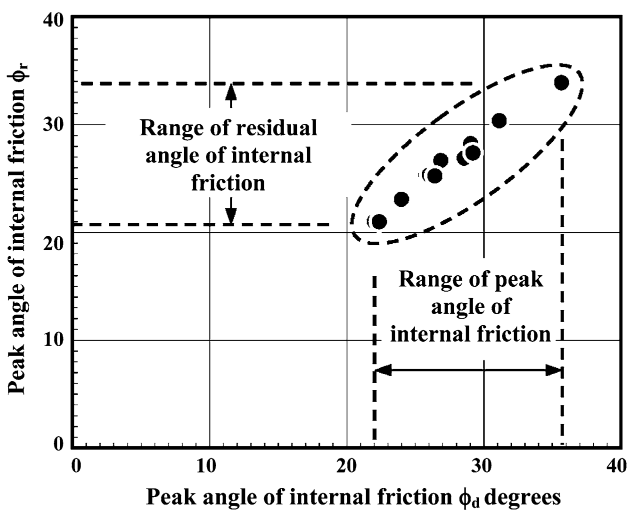




**Fig. 8** Comparison of peak and residual angles of internal friction for representative soil samples along the Prithivi Highway, Narayangadh-Mugling Road, and Tribhuvan Highway

## Hydrothermal alteration and landsliding

Hydrothermal alteration is a process in which mineralogical changes take place as a result of interaction of rocks with hot water solutions, often known as hydrothermal fluids. These fluids carry various metallic ions in solution, either from a nearby igneous source, or from leaching out of some nearby rocks. Hydrothermal alteration is common in a wide variety of geological environments, including thrust and batholith zones. The study of sheared and crushed zones in various geological units suggested that there were significant hydrothermal alterations in the Himalayan rockmass.

The hydrothermal outflow can occur most commonly at the tip of individual fault (Curewitz and Karson 1997). Heat sources for hydrothermal systems usually include igneous bodies, such as plutons (Wohletz and Heiken 1992; Embley and Chadwick 1994) and frictional heating due to fault slip (Lachenbrunch 1980; Scholz 1980; Ander and Wiltschko 1994). Both these conditions are very favourable in Himalaya and many researchers have pointed out hydrothermal fluid movement along the MCT (Le Fort 1988; Copeland et al. 1991; Evans et al. 2001). Thus, the authors believe that the possible source of hydrothermal fluids in the Lesser Himalayan rockmass should have strong link with the emplacement of the Miocene leucogranite of Higher Himalaya (Harris et al. 1993) and during the cooling of leucogranite, surging of fluids have taken place through the MCT to the under-plated Lesser Himalayan rocks. The process of surging is illustrated in Fig. 9. It can be assumed that the surging started from 22 to 20 Ma. Still the movement of the hydrothermal fluids in Himalaya is continuing and hot springs are found in the tip of the MCT (Bhattarai 1980; Evans et al. 2001). The deformation and partial melting of hanging wall of the MCT in the geological past (Le fort 1988; Hodges et al. 1996) should have also modulated the movement of hydrothermal solution. Hydrothermal fluids had started to circulate in crushed, porous and permeable Lesser Himalayan rocks during and after the advancement of the MCT. As a result, the circulations of fluid have taken place in the shear zones and fractures. Finally, following the regular erosion and abrupt upliftment, the large scale valley collapsing occurred along the hydrothermally altered zones which had remarkable clay mineralization.

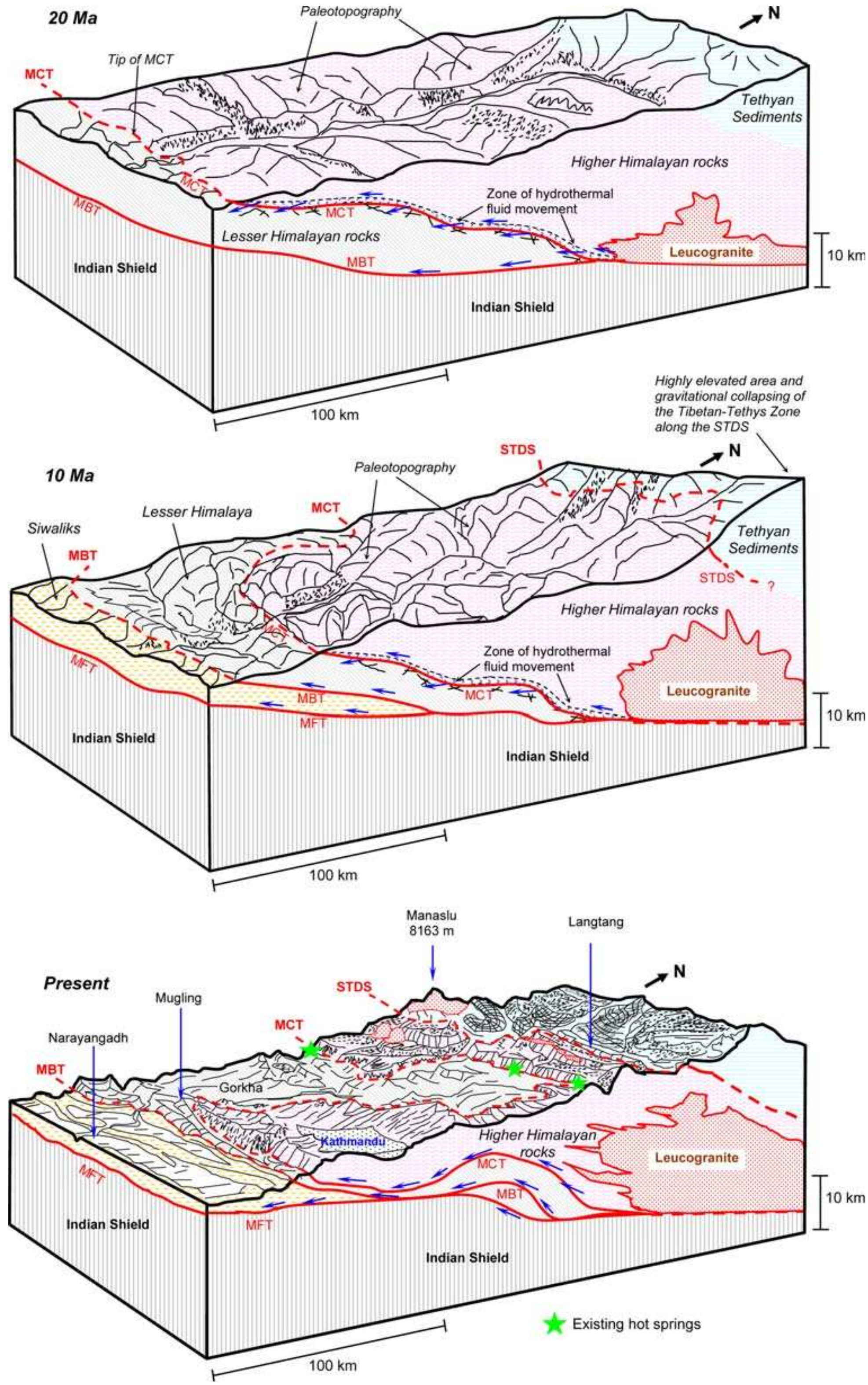



**Fig. 9** Conceptual model of surging of hydrothermal solution in central Nepal Himalaya. The surging of fluids in geological past attributed to the clay mineralization in Lesser Himalayan rockmass. Geology and topography adopted from Hagen (1969), Brunel (1986), Le fort (1988) and Schelling (1992)

Hydrothermally altered zones or clay mineralizations along fractures were well observed in sliding zones of large-scale landslides at various locations and illustrations of such zones are provided in Fig. 10 (location 15) and Fig. 11 (location 16). At location 15 (see Fig. 6), the sliding surface of the large-scale landslide consists of more

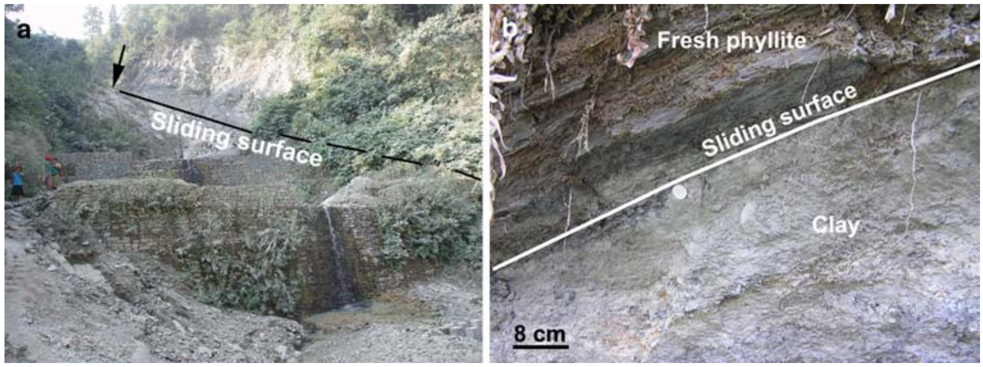



**Fig. 10** Large-scale landslide at Location 15 along Narayangadh-Mugling Road and a close view of slip surface and altered clay zone. *Arrow* in **a** shows the location of **b**

than 1-m-thick gray clay layer (Fig. 10). The overlaying rock is fresh phyllite, but it has abundant open joints and fracture. The boundary between sliding surface and overlaying phyllite is very sharp and phyllite does not have shear structure. These observations indicated that the sliding surface which resembles fault gouge was formed by hydrothermal alteration. Similarly, at location 16 (see Fig. 6), the sliding surface of the large-scale landslide consists of more than 1-m-thick greenish grey clay and breccia layer (Fig. 11). The overlaying rock is amphibolite and it is also fresh as in location 15.

The rockmass of amphibolite also has abundant open joints and fractures. The boundary between sliding surface and overlaying amphibolite is very sharp and clay and breccia layer does not have shear structure (Fig. 11). This emplacement also indicates that the sliding surface which has many similarities to fault breccia was previously formed by hydrothermal alteration.

The clay mineralization in the failure zones noticed in this study and the existence of many hot water springs along the vicinity of MCT (Bhattarai 1980) are the main supporting evidences to the hydrothermal alteration in the Lesser Himalayan Zone. Strength of the clay materials estimated from ring shear is also supporting the overlain rockmass creeping along the zone of clay mineralization.

Typical large-scale landslide terrain of the Lesser Himalaya is illustrated in Fig. 12. The landslide terrain of Nepal usually has three stage of landslide activation. The first stage (Fig. 12) corresponds to the large scale failure along the zone of clay mineralization whereas small scale slope failures are found in same huge landslide body as III stage of landslide incidence. In the roadside slope of Nepal, mostly III stage landslides were mitigated from low cost mitigation measures and were still noticed to be ineffective because of disturbed mass owing to the stage I and II landslides. The schematic model illustrated in Fig. 12 is perfectly observed in field and examples from locations 6 and 10 are given in Figs. 13a, b.

## Concluding remarks

Landslide mapping of selected highways (H2, H4, and H5) in Nepal shows that more than 50% of the road alignment passes through large-scale landslide areas. Thus, most of the stretches have severe landslides and debris flow problems. The results of X-ray diffraction analysis of soils revealed that large-scale landslides along the highways have significant clay mineralization in sliding zones. The substantial hydrothermal alteration in the Lesser Himalaya during and after the advancement of the MCT and thereby clay mineralization in sliding zones of large-scale landslide are the main causes of large-scale landslides in the highways of central Nepal.


**Fig. 11** Large-scale landslide at Location 16 along Narayangadh-Mugling Road and close view of slip surface and altered clay zone. *Arrow* in **a** shows the location of **b**

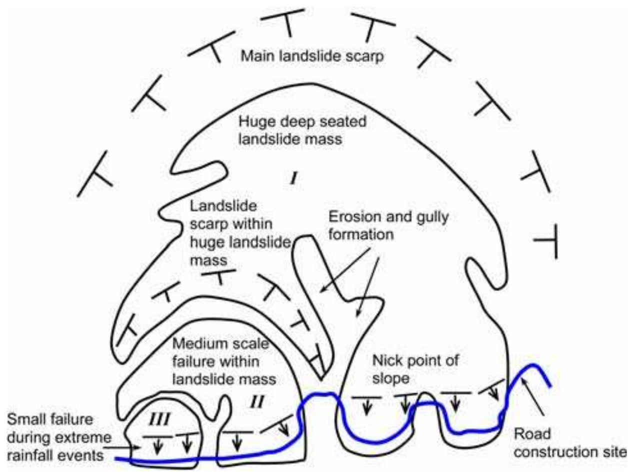



**Fig. 12** Schematic model of valley creeping type landslide terrain in mountains of central Nepal. The road is found to be constructed on toe of large-scale landslides having clay mineralization in failure zone as shown in Fig. 10 and 11. Stage III is associated with the monsoon rainfall related landsliding process

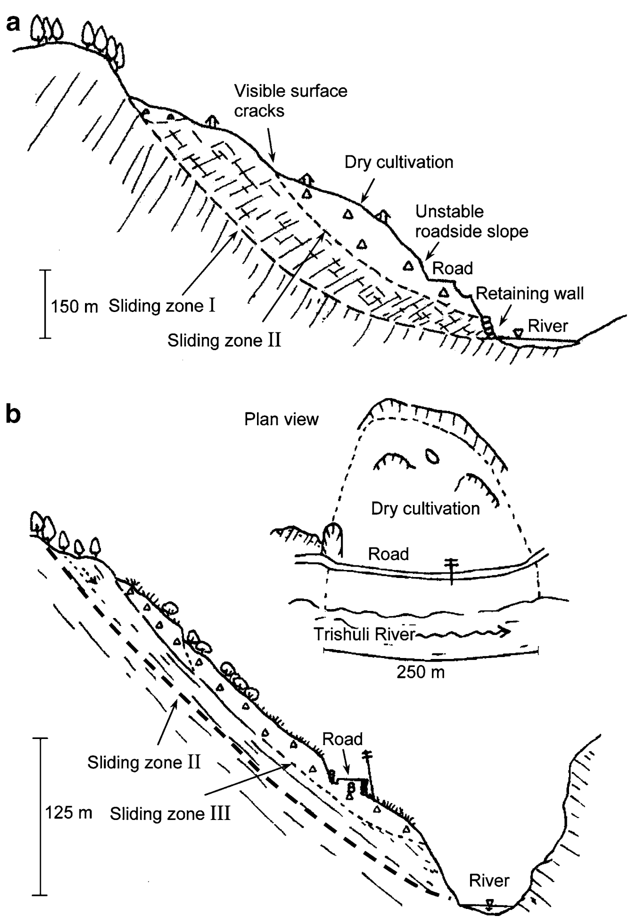



**Fig. 13** **a** Longitudinal section of valley creeping landslide at location 6 (see Fig. 5) and **b** Both plan and section view of landslide terrain and valley collapsing features at location 10 (see Fig. 5)

Similarly, the alignment investigation of roads in the Lesser Himalaya of Nepal should be inevitably accommodated with the wide range of surface and subsurface exploration techniques. The selected highways in this study are the main routes to the capital city of Kathmandu from the rest of the country, and the investigation suggested that for the sustainable road maintenance, it is of utmost importance to study the nature of sliding zones of large-scale landslides along the highways and their role to cause debris flows and slides during monsoon period. Likewise, the large-scale landslides also need to be considered during construction of roadside cut slopes, tunnels and mitigation measures.

**Acknowledgments** This research was partly support by "Grant-in-Aid for Overseas Scientific Research and Investigation" of the Ministry of Education, Culture, Science and Technology, Japan. Mr. Anjan Kumar Dahal and Ms. Seiko Tsuruta are sincerely acknowledged for their technical support during the preparation of this paper.

## References


Amatya KM, Jnawali BM (1994) Geological map of Nepal. Scale: 1:1,000,000. Kathmandu, Nepal

Anders MH, Wiltschko DV (1994) Microfracturing, paleostress and growth of faults. J Struct Geol 16(6):795–815

Bhattarai DR (1980) Some geothermal spring of Nepal. Tectonophysics 62:7–11

Bilham RK, Larson JF, Project Idylhim Members (1997) GPS measurements of present-day convergence across the Nepal Himalaya. Nature 386:61–64

Bishop AW, Green GE, Garga VK, Andresen A, Brown JD (1971) A new ring shear apparatus and its application to the measurement of residual strength. Geotechnique 21(4):273–328

Brunel M (1986) Ductile thrusting in the Himalayas: shear sense criteria and stretching lineations. Tectonics 5:247–265

Burbank DW, Leland J, Brozovic EN, Reid MR, Duncan C (1996) Bedrock incision, rock uplift and threshold hillslopes in the northwestern Himalayas. Nature 379(6565):505–510

Caine N, Mool PK (1982) Landslides in the Kolpu Khola drainage, Middle Mountains, Nepal. Mountain Res Dev 2:157–173

Chalise SR, Khanal NR (2001) Rainfall and related natural disasters in Nepal. In: Li Tianchi, Chalise SR, Upreti BN (eds) Landslide hazards, mitigation to the Hindukush-Himalayas. ICIMOD, Kathmandu, pp 63–70

Copeland P, Harrison TM, Hodges KV, Mareujol P, Le Fort P, Pecher A (1991) An early Pliocene thermal perturbation of the main central thrust, central Nepal: implications for Himalayan tectonics. J Geophys Res 96:8475–8500

Curewitz D, Karson JA (1997) Structural settings of hydrothermal outflow: fracture permeability maintained by fault propagation and interaction. J Volcanol Geotherm Res 79:149–168

Dahal RK (2006) Geology for technical students. Bhrikuti Academic Publication, Kathmandu, p 756

Dahal RK, Hasegawa S (2008) Representative rainfall thresholds for landslides in the Nepal Himalaya, Geomorphology, doi: 10.1016/j.geomorph.2008.01.014, p 15 (in press)

Dahal RK, Hasegawa S, Masuda T, Yamanaka M (2006) Roadside slope failures in Nepal during torrential rainfall and their mitigation, In: Marui et al. (eds) Disaster mitigation of debris flow, slope failures and landslides, (Interpraevent 2007), Universal Academy Press, Tokyo, vol 2, pp 503–514

Dai F, Lee CF, Wang S, Yuyong F (1999) Stress-strain behaviour of a loosely compacted volcanic derived soil and its significance to rainfall-induced fill slope failures. Eng Geol 53(3–4):359–370

Deniel C, Vidal P, Fernandez A, Le Fort P, Peucat J-J (1987) Isotopic study of the Manaslu granite (Himalaya Nepal): inferences on the age and source of Himalayan leucogranites. Contrib Mineral Petrol 96:78–92

Embley EW, Chadwick WW (1994) Volcanic and hydrothermal processes associated with a recent phase of seafloor spreading at the northern Cleft segment: Juan de Fuca Ridge. J Geophys Res 99:4741–4760

Evans MJ, Derry LA, Anderson SP, France-Lanord C (2001) Hydrothermal source of radiogenic Sr to Himalayan rivers. Geology 29:803–806

Frattini P, Crosta GB, Fusi N, Negro PD (2004) Shallow landslides in pyroclastic soils: a distributed modelling approach for hazard assessment. Eng Geol 73:277–295

Ganser A (1964) Geology of the Himalaya. Inter Science John Wiley, London

Gerrard J (1994) The landslide hazard in the Himalayas: geological control and human action. Geomorphology 10:221–230

Gerrard J, Gardner RAM (2000) Relationships between rainfall and landsliding in the Middle hills. Nepal Norsk geogr Tidsskr 54:74–81

Hagen T (1969) Report on the geological survey of Nepal preliminary reconnaissance: Zürich, Mémoires de la soc. Helvétique des sci. naturelles, p 185

Harris N, Inger S, Massey J (1993) The role of fluids in the formation of High Himalayan Leucogranites. In: Treloar PJ, Searle MP (eds) Himalayan tectonics, geological society special publication No 74, pp 391–400

Harrison TM, Ryerson FJ, LeFort P, Yin A, Lovera O, Catlos EJ (1997) A late Miocene-Pliocene origin for the central Himalayan inverted metamorphism. Earth Planet Sci Lett 146:E1–E7

Harrison TM, Grove M, McKeegan KD, Coath CD, Lovera OM, Le Fort P (1999) Origin and episodic emplacement of the Manaslu intrusive complex, central Himalaya. J Petrol 40(1):3–19

Heuberger H, Masch L, Preuss E, Schrocker A (1984) Quaternary landslides and rock fusion in central Nepal and in the Tyrolean Alps. Mt Res Dev 4:345–362

Hodges KV, Parrish RR, Searle MP (1996) Tectonic evolution of the central Annapurna Range, Nepalese Himalaya. Tectonics 15:1264–1291

Ives JD, Messerli B (1981) Mountain hazards mapping in Nepal; introduction to an applied mountain research project. Mt Res Dev 1:223–230

Laban P (1979) Landslide occurrence in Nepal. HMG/FAO and UNDP, Ministry of Forest, Department of Soil Conservation, Integrated Watershed Management, Kathmandu, pp 27

Lachenbrunch AH (1980) Frictional heating, fluid pressure, and the resistance to fault motion. J Geophys Res 85:6097–6112

Le fort P (1988) Granite in the tectonic evolution of the Himalaya, Karakoram and Southern Tibet. Philos Trans R Soc Lond Ser 326(A):281–298

Meigs AJ, Burbank DW, Beck RA (1995) Middle–Late Miocene (>10 Ma) formation of the main boundary thrust in the western Himalaya. Geology 23(5):423–426

Schelling D (1992) The tectonostratigraphy and structure of the eastern Nepal Himalaya. Tectonics 11:925–943

Scholz CH (1980) Shear heating and the state of stress on faults. J Geophys Res 85:6174–6184

Searle MP, Parrish RR, Hodges KV, Hurford A, Ayres MW, Whitehouse MJ (1997) Shisha Pangma Leucogranite, South Tibetan Himalaya: field relations, geochemistry, age, origin, and emplacement. J Geol 105:295–318

Searle MP, Noble SR, Hurford AJ, Rex DC (1999) Age of crustal melting, emplacemet and exhumation history of the Shivling leucograpnite, Garhwal Himalaya. Geol Mag 136(5):513–525

Selby MJ (1988) Landforms and denudation of the High Himalaya of Nepal: results of continental collision. Z Geomorphol Neue Folge 69:133–152 Supplementeband

Shakoor A, Smithmyer AJ (2005) An analysis of storm-induced landslides in colluvial soils overlying mudrock sequences, southeastern Ohio, USA. Eng Geol 78:257–274

Shang Y, Yang Z, Li L, Liu D, Liao Q, Wang Y (2003) A super large landslide in Tibet in 2000: background, occurrence, disaster, and origin. Eng Geol 54:225–243

Shroder JF, Bishop MP (1998) Mass movement in the Himalaya: new insights and research directions. Geomorphology 26:13–35

Upreti BN (1999) An overview of the stratigraphy and tectonics of the Nepal Himalaya. J Asian Earth Sci 17:577–606

Upreti BN (2001) The Physiography and geology of Nepal and landslide hazards. In: Tianchi L, Chalise SR, Upreti BN (eds) Landslide problem mitigation to the Hindukush-Himalayas, ICIMOD, p 312

Upreti BN, Dhital MR (1996) Landslide studies and management in Nepal. ICIMOD, Nepal, p 87

Wagner A (1983) The principal geological factors leading to landslides in the foothills of Nepal: a statistical study of 100 landslides—steps for mapping the risk of landslides. HELVETAS–Swiss Technical Cooperation and ITECO–Company for International Cooperation and Development, unpublished, pp 58

Wohletz K, Heiken G (1992) Volcanology and geothermal energy. University California Press, CA, p 432

Yilmaz I, Karacan E (2002) A landslide occured in clayey soils: an example from Kýzýldag region of Sivas-Erzincan highway (Sivas-Turkey). AAPG Div Environ Geosci 9(1):35–42

Yilmaz I, Yildirim M (2006) Structural and geomorphological aspects of the Kat landslides (Tokat-Turkey), and susceptibility mapping by means of GIS. Environ Geol 50(4):461–472