The relationship between geology and rock weathering on the rock instability along Mugling-Narayanghat road corridor, Central Nepal Himalaya

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Abstract

The present study was conducted along the Mugling–Narayanghat road section and its surrounding region that is most affected by landslide and related mass-movement phenomena. The main rock types in the study area are limestone, dolomite, slate, phyllite, quartzite and amphibolites of Lesser Himalaya, sandstone, mudstone and conglomerates of Siwaliks and Holocene Deposits. Due to the important role of geology and rock weathering in the instabilities, an attempt has been made to understand the relationship between these phenomena. Consequently, landslides of the road section and its surrounding region have been assessed using remote sensing, Geographical information systems and multiple field visits. A landslide inventory map was prepared and comprising 275 landslides. Nine landslides representing the whole area were selected for detailed studies. Field surveys, integrated with laboratory tests, were used as the main criteria for determining the weathering zones in the landslide area. From the overall study, it is seen that large and complex landslides are related to deep rock weathering followed by the intervention of geological structures as faults, joints and fractures. Rotational types of landslides are observed in highly weathered rocks, where the dip direction of the foliation plane together with the rock weathering plays a principle role. Shallow landslides are developed in the slope covered by residual soil or colluviums. The rock is rather fresh below these covers. Some shallow landslides (rock topples) are related to the attitude of the foliation plane and are generally observed in fresh rocks. Debris slides and debris flows occur in colluviums or residual soil-covered slopes. In few instances, they are also related to the rock fall occurring at higher slopes. The materials from the rock fall are mixed with the colluviums and other materials lying on the slope downhill and flow as debris flow. Rock falls are mainly related to the joint pattern and the slope angle. They are found in less-weathered rocks. From all these, it is concluded that the rock weathering followed by geological structures has prominent role in the rock slope instability along Mugling–Narayanghat road section and its surrounding regions.

Key word: *Himalaya; Landslides; Weathering; Geographical information systems (GIS; Geological structures*

1. Introduction

Landslides are the most catastrophic natural hazard amongst the various land degradation process prevalent in the region (Ahmad and Joshi 2010). Globally, they cause hundreds of billions of dollars in damage and hundreds of thousands of deaths and injuries each year (Aleotti and Chowdhury 1999; Pradhan 2010). Nepal is located at the very heart of the Himalayan arc with nearly 83 % of its territory falling in the mountainous terrain, while the remaining 17 % in the south being occupied by alluvium plains. The inherently weak geological characteristics of rocks and soils have made the Himalaya fundamentally a very fragile mountain (Upreti 1999; Pradhan et al. 2006), which leads to the formation of several natural hazards including landslides. These landslides cause severe damage to the public and private properties; they also have had a significant effect on the lives of local people and been a cause of many socio-economic problems (Dwivedi et al. 2007). According to the data provided by the Ministry of Home (Nepal), more than 350 people lost their lives from landslides, floods, debris flows and related phenomena every year. Though landslides and related disasters occur frequently in the fragile and young Himalayan region of Nepal, only a few studies have been carried out so far. According to Gerrard (1994), phyllite rocks are the most susceptible to landsliding followed by shales, schists, poorly cemented sandstones, gneiss, granites and quartzite. Recently, some literatures have been published from Nepal Himalaya in the field of landslide hazard mapping (e.g. Brunsden et al. 1975; Wagner 1981; Kienholz et al. 1984; Deoja et al. 1991; Dhital et al. 1991, 2006; Dhital 2000; Dahal and Hasegawa 2008; Dahal et al. 2008, 2012; Devkota et al. 2012). In addition, some studies have been undertaken to understand the mechanism and process in landslide formation (e.g. Laban 1979; Ives and Messerli 1981; Caine and Mool 1982; Burbank et al. 1996; Upreti and Dhital 1996; Gerrard 1994; Gerrard and Gardner 2000a, b; Chalise and Khanal 2001). However, there exists only very few literature from Nepal focusing in the role of rock weathering and geological structures in landslide formation. Regmi et al. (2012) reported that there is a considerable effect of rock weathering and geological structures in the formation of large landslides. It is essential to make more rigorous studies in this aspect to get accurate information regarding the relationship between rock weathering and geological structures in landslide formation in the Himalaya. Thus, this study will be very helpful to know the main cause of landslide in the mountainous country like Nepal.

Weathering is the primary process in the landform development (Cortese 1895; Branner 1896; Falconer 1911; Jutson 1914; Walther 1915). Weathering significantly decreases the physical and mechanical properties of rocks, as it produces mineralogical and petrographical transformations of original rock, making the slope vulnerable for landsliding (Borrelli 2008; Borrelli et al. 2007; Brand et al. 1985; Calcaterra et al. 1996, 2004; Cascini et al. 1992, 1994; Critelli et al. 1991; Deere and Patton 1971; Gullà et al. 2004; Hencher et al. 1984; Lacerda and Santos 2000; Nishida and Aoyama 1985). Mugling–Narayanghat highway is the only trunk road connecting Terai with Kathmandu, the capital of Nepal. Landslides and related phenomenon have become regular issue along this highway. Heavy precipitation of July 29–30, 2003 created numerous landslides, slope failures, rock falls and debris flows along the highway and its surrounding region, severely damaging the highway and killing several people and livestocks. The precipitation recorded at Bharatpur Devghat and Shankher (Marsyandi Powerhouse) stations was 346 and 446 mm respectively during 24 h (Adhikari 2009). The situations become worsen during the monsoon of 2006 (DWIDP 2009). During the process of this study, 275 different types of landslides were identified and mapped along the road corridor and its surrounding area by using earlier reports, aerial photographs (taken after the monsoon of 2003), satellite images and from several field surveys. In this paper, an attempt has been made to understand the relationship between rock weathering and geological structures in the formation of landslides along the highway and its surrounding area. In addition, the causes of failure together with the mineralogical and geochemical characteristics of rocks and soils comprising the slide zone are described in this paper. The study involved detailed fieldwork followed by laboratory analysis of rock and soil samples collected from the landslide zone and its surrounding regions.

2. The study area

Mugling–Narayanghat road section is one of the main Highway of Nepal connecting the Terai plains with the capital and other central and western mountain districts. The road is very important to transport foods, commercial and industrial goods to the Kathmandu valley, where nearly 2.5 million people inhabit (as of the 2011 census). The road is also the main trade and transport route between Nepal and India. Thus, the day-to-day economy is governed by this important road. This highway is located in a mountain range between Narayanghat and Mugling of Chitwan Districts, Narayani Zone, Central Nepal and has been known as the most landslide prone area. The study area lies within longitude 84º 25' 00" E to 84º 32' 30" E and latitude 27º 45' 00" N to 27º 50' 00" N (Fig. 1a) that falls within the topographical map 2784-03C (Mugling) and 2784-02D (Jugedi Bajar) (Survey Department, Government of Nepal 1995). It covers an area of about 50 km^2. The study area consists of plane southern part, an area of gently rolling hills to the central part and a more rugged, hilly topography in the North. The altitude ranges in between 200 m near Jugadi Bazar and 1,380 m at the central part of the study area. The main rivers in the study area are Jugadi Khola, Khahare Khola, Das Khola and Rigdi Khola. These rivers along with their tributaries convene with Trishuli River below the highway (Fig. 1). The southern part of the study area is mostly covered by the alluvial terraces deposited by the Trishuli River and its tributaries. Steep slopes occur in the rocky outcrops of the Lesser Himalaya, while gentle slopes are found by the Siwaliks and Holocene deposits. The study area experiences sub-tropical to temperate climatic zone. In winter, temperature ranges from 6 to 25 ^{O}C while in summer, it varies from 25 to 40 ^{O}C.

The monthly maximum temperature and daily rainfall records from the nearby Bharatpur station during 2002–2006 have given a highest maximum temperature of 41.2 ^{O}C in May 2004 and a mean annual rainfall of 2,650 mm (DWIDP 2009). April, May and June are the hottest months with average maximum temperatures of 37.8, 39.3 and 38.6 ^{O}C, respectively (Regmi et al. 2012). Similar to other parts of Nepal, the summer monsoon is dominant from June to the end of September. The region receives approximately 80% of its annual rainfall during the monsoon period (June–September). Rainfall intensities vary throughout the basin, with maximum intensity occurring on south-facing slopes. During the monsoon period, relative humidity records its maximum value, whereas the temperatures are lower compared with the pre-monsoon period.

3. Geology of the study area

The tectonic structure of Nepal Himalaya can be subdivided into the five major belts: Fore Himalaya, Higher Himalaya, Lesser Himalaya, Sub Hiamalya (Siwaliks) and the Indo-gangatic plane. These five belts are separated by major thrust faults, namely South Tibetian Detachment System (STDS), Main Central Thrust (MCT), Main Boundary Thrust (MBT) and Himalayan Frontal Thrust (HFT). These tectonic features have created large amount of deformation in the rocks and soil, thus making them susceptible to landsliding. Mugling–Narayanghat road section and its surrounding region consists of rocks belonging to the Lesser Himalayan Precambrian rocks of Nawakot Complex (Stöcklin and Bhattarai 1978; Stöcklin 1980), Miocene Siwaliks and Holocene terrace deposits (Fig. 1a). The Lesser Himalayan rocks in this area are part of the Lower Nuwakot Group of the Nuwakot Complex, which include the Kunchha Formation, Fagfog Quartzite, Dandagaun Phyllite, Nourpul Fommation and Dhading Dolomite and Benighat Slate Formation belonging to Upper Nawakot Group (Fig. 1a). Stratigraphically, the Lower Nawakot Group is considered as an overturned sequence with the Kunchha Formation at the bottom and the Dhading Dolomite on the top. The Dandagaun Phyllites, Nourpul Formation and Dhading Dolomite appear repeatedly in some parts, due to folding and faulting. Benighat (Fig. 1a). The Siwalik Group in the study area consists of Lower Siwalik and Middle Siwalik (Ganser 1964). The Holocene deposits consist of river terraces of different ages. The main rock types are mudstones, sandstones, limestones, dolomites, slates, phyllites, quartzites and amphibolites (Table 1). The majority of instabilities are observed within the rocks of Nourpul Formation and Puribesi Quartzite. The main geological structure that demarcates the study area is the MBT (Main Boundary Thrust) that separates the Lesser Himalaya from the overlying

Siwaliks (Fig. 1a). It crosses the Mugling–Narayanghat road section near around 14 km, south of the Phwatar and runs east–west. The area has three other thrust in the north of the MBT (Fig. 1a) and one in the south of it. Kamalpur Thrust, Simaltal Thrust and Virkuna Thrust lie to the north of MBT, while Jugadi Thrust lies to the south of it. In addition, there are a large number of normal faults demarcating the study area. Simaltal Thrust and Virkuna Thrust have a common root zone. The area has also undergone local folding of different scales at places. Another major geological structure in the road section is the western closure of the Mahabharat Synclinorium. It is a huge syncline in the Mahabharat Range of the central Nepal and is locally known by the Jalbire Syncline (Fig. 1a).

4. Methods and techniques

This study was undertaken by using standard geological and geomorphological field techniques. Data about the lithology, morhometry and geological structures were obtained from the geological map of Central Nepal Himalaya (Stöcklin and Bhattarai 1978) and were modified by detailed fieldwork. Geological and lithotectonic units that might influence the distribution of the landslides were mapped separately. In addition to this, a large number of structural measurements such as, bedding and joint planes, thrusts and other minor faults were recorded. Common field techniques were implemented to map the landslides and to collect the rock and soil samples for laboratory analysis. Landslide inventory map was prepared using earlier reports, aerial photographs interpretation and multiple field surveys. From these, 275 landslides were identified and mapped. These landslides cover an area of about 1.67 km^2, which is 3.34 % of the entire study area. The smallest landslide observed in the study area is 107.56 m^2, while the largest one is 0.051 km^2. Out of the 275 landslides, 9 landslides representing the whole study area were selected for detailed studies (Fig. 1b). These landslides were mapped in detail. Different parameters such as slope angle, altitude, lithology, soil and rock types and the hydro-geological characteristics of each landslide zone were recorded during the field study. In addition, major geological structures were mapped, and representative soil and rock (fresh and weathered) samples were collected to determine their extent of weathering. The mineralogical composition of the collected rock and soil samples was studied by using optical microscope, X-ray powder diffraction of whole rock samples and by X-ray diffraction (XRD) of clay minerals separated by a density method. These techniques were used to trace mineral alterations leading to the evaluation of bulk changes in the whole rock during weathering. Thin sections were made from the collected rock and soil samples to decipher the general mineralogy of the rock outcrop that makes the landslides. In addition, the weathering intensity of rock was studied using these thin sections. XRD patterns were recorded with a Rigaku deffractometer (RDA IIIA) using graphite-mono- chromatized CuKa 40 kV and 40 mA. The diffractometer was calibrated using silicon as an external standard. XRD of the collected rock and soil samples were done in between 4^{O} and 40^{O} 2h steps size and 2 counting time per second. Clay samples were analysed by oriented aggregate method, after glycol treatment, heat treatment and HCL treatment.

5. Detailed Descriptions of landslides

From the 275 mapped landslides, 9 landslides were selected for further study that represents the entire study area. Out of these, 8 are from the Lesser Himalaya and one is from the Siwaliks (Fig. 1a). The location of the selected landslides in the study area is shown in Fig. 1b. The detailed description of each landslide is given below.

5.1 Dumre Besi Landslide

The Dumre Besi landslide is located at Dume Besi village near Simaltal and is one of the most active landslips in the Mugling–Narayanghat road section (Fig. 2). The landslide was initiated during the monsoon of 2003. Small landslide was formed below Dumre Besi, near the Simaltal village, which later expanded and delivered huge amount of debris obstructing the highway (Regmi et al. 2012). In the same year, several other landslips were initiated along this highway stretch resulting into its blockage for several days.

There are two large scarps in each of the tributary of the Dumre River in Dumre Besi landslide. These two scarps coalesce downstream to form a single complex failure (Fig. 2) involving several types of movement. The top of the slide reaches the Dumre village, situated above the road, while its toe lies at the cut bank of the Trishuli River, below the road (Regmi et al. 2012). The lower part of the landslide consists of light to dark grey phyllites and siltstones characterized by crenulation cleavage and abundant quartz veins. Dark grey phyllites are alternating with fine-grained sandstones. The phyllites and slates are fresh to slightly weathered, while the sandstones show no sign of weathering.

The rocks constituting the central part of the landslide are mainly light grey to dark grey phyllites alternating with a few thin metasandstone bands. The flanks of the landslide are covered by a residual soil with a thickness of 2–5 m. On the right bank of the gully, highly fractured, moderately weathered, light grey to white phyllites have cropped up, whereas the channel is covered by large (up to 7 m across) boulders. The landslide mass is made up of gravel, with grains ranging in size from 0.2 to 2 m and composed of greenish grey silt- stones and phyllites. There are also some highly fractured and weathered rock exposures. The second tributary of the Dumre River is situated about 40 m uphill side from the road and consists of alterations of light grey metasandstone and phyllite. The gully is narrow (ca. 3 m), and its depth is about 7 m. Its upper reach contains intensely folded and fractured light grey slates. Most of the rocks are highly weathered. This tributary consists of fewer landslides than the first one. As the rocks are much deformed, the foliation is variable and ranges between $165^{o}/39^{o}$ NE and $140^{o}/47^{o}$NE in the Nourpul Formation and between $250^{o}/78^{o}$ NW and $251^{o}/74^{o}$ NW in the Benighat Slates. There are two prominent joint sets (J1=$190^{o}/45^{o}$ SE and J2=$118^{o}/56^{o}$ SW) in the Nourpul Formation.

The Benighat Slates and the Nourpul Formation crop out in the upper part of the landslide. The Benighat slates consist of slightly weathered, light grey slates interbedded with light grey-laminated dolomites, highly jointed and fractured light grey phyllites and sandstones. The attitude of bedding is about $230^{o}/74^{o}$ NW. The Nourpul Formation is made up of slightly weathered light grey to white, laminated, shiny phyllites and metasandstones.

5.2 Maure Khola landslide

Most part of the Mguling–Narayanghat road passes through the gravitationally deformed zones. Maure Khola landslide is one of them. It is very active landslips in the Mugling– Narayanghat road section (Fig. 3). The rock debris generated by the landslides was mobilized into a disastrous debris flow in 2006 summer and damaged the

Highway Bridge. It is a big landslide, with more than 300 m in length, about 100 m in width and about 10 m deep. This landslide is characterized by a combination of rock topples, rockslides and debris slides. It is a complex type of landslide. The landslide is located in the rock formation belonging to Nourpul Formation, but there exists a body of amphibolite (metamorphosed basic igneous rock) in the valley and dominates the lithology.

The lower part of the landslide body is mostly covered by thick deposit of debris that was derived from the main landslide as well as from the sides of the landslide (Fig. 4a). It is mainly the depositional zone of the landslide. The thickness of the debris is about 5 m, and it covers the entire valley. The volume of this debris is about 60,268 m3. The debris consists of materials ranging in size from boulders to clay. The channel slope is 22.5^{o} and the width of the channel is > 30m. The main material bordering the debris is the terrace deposits. Dense forest is observed along the valley wall. No water is observed along the channel in this part; however, the water is present in the channel below the road. Water here flows as sub-surface water flow. Several gabion walls have been constructed here to protect the road and the bridge downstream (Fig. 4b). The first gabion wall is constructed at a distance of 15 m from the road section, and others are located at a distance of 10–15 m from each other (Fig. 4b).

The central part of the landslide mainly consists of debris deposits in the channel while small debris slides and rockslides occur in the valley walls (Fig. 4c). Here, highly fractured, moderately weathered black slates with some quartz veins are observed. Moderately weathered greenish phyllite is observed above the black slate. The groundwater is high in this part. Moderately weathered, highly fractured pink quartzite with phyllite parting is absorbed about 10 m upstream from the greenish phyllite. Here, rock topple is observed (Fig. 4d). The attitude of the foliation plane is $270^{O}/74^{O}$N while that of the joints are J1=$350^{O}/75^{O}$NE, J2=$145^{O}/57^{O}$SW. The joint spacing is from few cm to 10 cm. These joints are responsible for the rockslide in this part. Massive amphibolite is observed above this. This amphibolite is also highly fractured and jointed. Many big boulders of amphibolite are observed in the channel (Fig. 4e). The fractured and jointed nature of the amphibolite is the reason for the presence of these boulders. There are many slickensides in the rocks showing some kind of movement. Many gabion walls have been constructed here to stop the debris flow. Rock topples are observed in most of the rock exposure.

The main landslide is located in the upper rich of the slope (Fig. 4f). Here, mainly rock topple is observed in the slate (Fig. 4f) at the western part as well as in the quartzite lying in the southeastern part (Fig. 4f). Slate show moderate weathering, while quartzite and amphibolite is not much weathered. 2 m thick, residual soil occurs at the top part of the landslide. Here, the width of the landslide is about 70 m. The slope is up to 45^{o}. Much of the debris in the channel is the product of this part. The quartzite is highly jointed and fractured producing huge rock failure. Steep slope is created by the failed material of the quartzite. These materials are in the critical stage (Fig. 4e), when condition favours, there is a chance of huge debris slide from here. There are no any control measures applied in this part to control the landslide. Above the crown of the landslide, there are cultivation lands and a small village.

A landslide characterized by a combination of debris slide, rockslides and rock topple has wrecked the area. As the amphibolite is heavily fractured and jointed, the valley walls are prone to rock failure. Pour water pressure in the discontinuities can easily trigger failures. Besides the occurrence of discontinuities described above, there are minor faults within the landslide. In addition, the landslide is situated in just above the Simaltal Thrust (Figs. 1, 3). This thrust and the fault must have created the incipient weakness and instabilities in the area. The field observations suggest that the area is prone to future landslide and debris flow.

5.3. Gaighat Landslide

The Gaighat landslide is a rotational type of rockslide along Mugling Narayanghat road section. The landslide is 80 m wide and 100 m long and about 5–6 m deep (Fig. 5a). It is also an active landslide that was developed during the 2003 monsoon rainfall. The landslide is mainly characterized by rotational type of rockslide. The landslide is located in Gaighat, and the rock types along the landslide are slate and phyllite belonging to Nourpul Formation.

This landslide is mainly divided into 3 parts (Fig. 5a, b), source area, transportation zone and depositional zone. The source area, from where all the debris is derived, is located at an altitude of 385 m. The top 2 m is covered by residual soil. Here, the main scarp of the landslide is observed. The slope of the main scarp is 60°. Severely to completely weathered, highly crumbled slate and phyllite are observed here. Only the quartz veins present in the rocks seems to be in good condition. The sliding surface can be seen here. As the rocks are highly deformed here, the attitude of the foliation plane cannot be obtained. However, the rocks are dipping towards north.

Below the zone of source area, transportation zone lies (Fig. 5a, b). Here, the rocks are moderately to severely weathered. It is rather steep zone with only thin deposit of colluvial materials. Rocks are observed at the flank of the landslide, and these are highly deformed. The undisturbed outcrops dip parallel to the hill slope with an attitude of $190^{\circ}/55^{\circ}$W.

The lower portion of the landslide is mostly covered by thick deposit of debris material (Fig. 5a). These debris are derived from the upper part of the landslide. This is the zone of deposition. Here, no rock exposure is found. This landslide does not contain any stream, and hence, there is no any role of running water. The landslide is mainly caused by the weathering of rocks.

5.4. Jugadi Khola Landslide

Jugadi Khola is a river that passes through Jugadi Village along Mugling–Narayanghat road section. Several landslides and debris flow originated in the upstream part of this river during the monsoon of 2003 and 2006 killing many peoples and destroying huge amount of property downstream. The bridge over the river is also in critical stage due to the above mentioned phenomenon. Thus, to know the main cause of the landslide and debris flow in the river basin, this landslide was studied. It is a translational type of shallow rockslide about 1 km upstream from the Bridge of Judagi Khola. The landslide is 30 m wide and 50 m long and about 50–80 cm deep. It is an active landslide. The main trigger of the landslide is rainfall and river under cutting by Jugadi Khola; however, rock weathering has also a prominent role in the formation of this landslide.

The main rock types are interbedding of fine-grained, light grey sandstone and variegated red to purple mudstone. The upper part of the landslide consists of yellow mudstone. The sandstone is thickly bedded. The beds are up to 4 m in thickness, but are highly jointed, making them susceptible to failure. The attitude of foliation plane and the joints are, F = $250^{O}/40^{O}$N, J1 = $110^{O}/76^{O}$NE, J2 = $219^{O}/69^{O}$NW. The landslide is dissected by several gullies. These gullies are eroding the rocks very rapidly. Talus cone is observed at the lower portion of the landslide mass. There are many similar landslides at the upstream part of the channel. All these landslides are delivering huge amount of debris in the channel, which flow downstream during the monsoon season.

5.5. Jalbire Landslide

This landslide is located at the uphill side of the road section near the temple of Jalbire, along Mugling–Narayanghat road corridor (Fig. 6a). The rock types in the Jalbire area are dolomites and some phyllite of Dhading Dolomite Formation of Pre Cambrian age along the main scarp, while the lower portion, from where the maximum debris is derived, belongs to the Nourpul Formation. However, the thick debris and residual soil covers the underlying rocks, so no rock exposures are seen here (Fig. 6a, b). The attitude of the foliation plane is 245^{O} /38^{O} N, while that of joints are J1 = 24^{O} /84^{O} NW and 317^{Oo} / 55^{O}NE.

This landslide was triggered by the heavy rainfall of 2003. The landslide is translation type slide, but develops into debris flow along the lower rich of the mountain. Several houses were destroyed, and 4 people were killed by this landslide. The slope is mostly covered by vegetation and soil. The slope varies in between 20^{O} to 60^{O}. The lowest slope gradient is observed near the road section and the highest at the cliff, from where the rock failure occurred.

This landslide is located at the uphill side of the road section near the temple of Jalbire, along Mugling-Narayanghat road corridor (Fig.6a). The rock types in the Jalbire area are dolomites and some phyllite of Dhading Dolomite Formation of Pre-Cambrian age along the main scarp, while the lower portion, form where the maximum debris is derived belongs to the Nourpul Formation. However, the thick debris and residual soil covers the underlying rocks, so no rock exposures are seen here (Fig. 6a, 6b). The attitude of the foliation plane is 245^{O} /38^{O} N, while that of joints are J1=24^{O} /84^{O} NW and 317^{O} /55^{O} NE.

5.6. Kalikholagaun landslide

The road section in between CH 29 to CH 36 is suffered from shallow rock topples. Here, the rocks belonging to Kuncha Formation, Fagfog Quartzite Formation Dandagau For- mation and Nourpul Formation are distributed. Kalikholagaun landslide is one of them. It lies at Kalikholagaun and is located at the Nourpul Formation. The landslide is about 20 m wide and 10 m high (Fig. 7a).

The outcrop is dominated by slightly weathered slate and few quartzites. The attitude of foliation plane at the lower slope is $233^{O}/78^{O}$SE, while that at the upper slope is $233^{O}/45^{O}$SE (Fig. 7a). The rocks are well bedded, and the thickness of the bed ranges from 5 cm to 30 cm. The rock is light grey and is very hard. The dip amount of the foliation plane decreases as the altitude increases, due to toppling. The opening of cracks between the overlying rocks and the rocks below is few cm. Also, it is seen that the rocks are dipping away from the slope, but due to the higher amount of dip angle of the rocks, they are toppled in the upper slope.

5.7. Landslide at CH28 km

The rock unit around the landslide belongs to the Nourpul Formation, which consists of alternate beds of quartzite, phyllites and some carbonate beds with general attitude of $130^{O}/ 30^{O}$NW. It forms the southern limb of the Jalbire Syncline. This landslide is located to the north of the Virkuna Thrust (VT) (Fig. 1a). The upper part of the landslide consists of colluvium deposits (Fig. 8a). Below this rock exposure is seen (Fig. 8a). The rocks are fresh to highly weathered and are intensely fractured, jointed and deformed. Two prominent joint sets (J1 = $345^{O}/30^{O}$SW and J2 = EW/45^{O}S) are developed in the rocks that make it very unstable due to the random fracturing of the rocks. The lower part of the landslide is mantled by thick (>5 m) collapsed deposits consisting of coarse soil with domination of boulders and blocks and younger colluviums on the top (Fig. 8a). Figure 9b shows the cross-section of the landslide. From this, it is seen that the average slope of the landslide is 27.5°. Also, it is seen that both the top and lower portion of the landslide are covered by debris. The central part consists of the rock exposure (Fig. 8b). Moat part of the landslide is seen to be covered by debris (Fig. 8). The material in the debris ranges from clay to boulder size particles.

5.8 Landslide at CH 23.760 km

The rock types encountered at the present landslide consist of interbeded quartzite, phyllites and slate of the Nourpul Formation. The quartzite is highly jointed and fractured, and the phyllites are weathered and crushed into soils. On the lower left side of the landslide, quartzite is intensely fractured, separating the outcrops into the number of unstable blocks. Phyllite is exposed on the right side, which is highly weathered and behaves either like a soil or unusually fractured and jointed when it is fresh. In the lower part, soils are sandy gravel with lots of fines and some boulders and blocks, and the thickness varies from <1 m to >5 m. The attitude of the foliation in undisturbed outcrop is dominantly $270^{\circ}/72^{\circ}$NW, and the attitude of the major joint is $220^{\circ}/63^{\circ}$NW. Some folded structures are also seen on the slate and phyllite. Huge quartzite boulder is observed in the lower part of the landslide (Fig. 4g). The upper part of the landslide is covered by 2–3 m thick soil. Below this, highly weathered rocks are observed, and the lower part of the landslide is consisting of decomposed rocks and debris deposits (Fig. 4h). Although some engineering structures are constructed for the protection of the slope failure to some extent (Fig. 4g), the landslide still seems active and highly hazardous for the villages located up slope and road below.

5.9 Ghumaune Rock Fall

Rock fall is a relatively small landslide confined to the removal of individual and superficial rocks from a cliff face (Selby 1982). The term ‘‘rock fall’’ is commonly used, if the numbers of rock blocks are countable. This phenomenon is dangerous and may cause lose of human lives and damage of the infrastructures. Several parts of the road section suffer from rock falls. One such rock fall occurred at the Ghumaune are of Mugling Narayanghat road section. This rock fall (27°49’ 02’ ’ N, 84°28’ 05’ ’ E) crosses Mugling–Narayanghat Highway along the south of Ghumaune.

This rock fall consists of rocks belonging to Dhading Dolomite Formation of the Nawakot Complex (Stöcklin 1980). The bedrock in the rock fall zone consists of dolomites and dolomitic quartzite and alternation of phyllite and quartzic dolomite. The rocky outcrop have made nearly vertical cliff (Fig. 9a, b). The dolomites are highly jointed, and the phyllites intercalated with the dolomites are weathered. These phenomena have made the slope vulnerable to rock fall. Figure 9b shows the cross-section of this rock fall. It is seen that the rock fall occurs at the upper slope. The rocks come down-slope as free falling, rolling and sliding (Fig. 9b).

The rocks are dipping towards north east (60^{O}–80^{O}) with dip amount ranging from 46^{O} to 84^{O}. Two major joint sets are present in the rock fall site. They are J1 = $120^{O}/38^{O}$ and $88^{O}/56^{O}$, and the cut slope is almost vertical. The spacing of the joints varies from few cm to 12 cm, and the joint surface is planner rough with clayey infillings, joints are continuous and persistence of the joints is about 1 m. The wedges are formed by these joints. Also, it is clear that the wedge joint formed by intersection of foliation and joints is unstable. The rockslide is occurring at the contact between dolomite and phyllite. The dolomite is rather fresh while the phyllite is weathered. Figure 4i shows the area suffered from rock fall, and the boulder that had fallen in 2006 is shown in Fig. 4j. This boulder is of dolomite and is rather fresh.

6. Laboratory studies

Laboratory analyses were used to determine the mineralogy of the materials from each landslide so as to know the extent of weathering in the landslide. Thin section and XRD analysis was performed to know the mineralogy of rocks and soil along with the distribution of clay minerals in these landslides and to know the formative mechanism of these clay minerals.

The main mineralogical constituents of the rocks and soil samples within each landslide zone were determined by the study of thin sections made from fresh and weathered rock samples and confirmed using XRD (Fig. 10). Randomly oriented samples were analysed by XRD in order to know the general distribution of minerals in different parts of landslides. After this, oriented specimens were analysed by XRD in order to facilitate clay-mineral identification. For this, the bulk samples were powdered and then centrifuged after suspension in water to obtain clay fractions <2 μm lm in size. The bulk and oriented specimens were analysed with graphite–monochromatized CuKα 40 kV and 40 mA. The diffractometer was calibrated using silicon as an external standard.

Table 2 gives the general distribution of minerals in each landslide zone. From the table, it is seen that the deep-seated landslides are rich in clay minerals, while rock fall are lacking the clay minerals. It is seen that these deep-seated landslides are rich in smectite, a kind of clay mineral that expands when wet (Fig. 10a). Also, it is clear that large-scale landslides formed by gradational deformation are related to the geological structures and the rock weathering has less effect here. From the detailed study, it is also seen that shallow landslides are of two distinct types. Basically rock topples are controlled by the attitude of the foliation plane and the natural or cut slope. Here, the rock weathering plays a very minor role. On the other hand, rock weathering plays a major role in shallow landslides found in colluvium-covered slopes. These landslides are found in highly weathered rocks, and the weathering depth is very less. Here, mainly smectite, chlorite, vermiculite and kaolinite are found as the weathering product (Fig. 10b). In the case of landslide from Siwaliks, the XRD analysis shows that only chlorite is seen to be weathered (Fig. 10c), while the other minerals are not weathered at all. From the overall XRD analysis of rock and soil from different landslides, it is clear that the rock weathering plays a significant role in forming most of the landslides along the road section and its surrounding region (Table 3).

7. Results and Discussion

Although mass movements are widespread throughout the Mugling–Narayanghat road section and its surrounding regions, this paper discusses about the selected 9 landslides that are representative of the whole study area. These landslides are from the very big complex slide to a smaller one, from rotational type to simple slide. This section was chosen because of the considerable number of active mass movements. In this section, 275 mass movements have been identified through remote sensing, from earlier reports and field surveying. The field survey was of crucial importance in order to confirm the collected landslides during the desk work. The role of geology and geological structures in individual landslide as well as in the whole is given below. Also, the role of rock weathering in each landslide is described. Finally, some models are prescribed that is thought to be applicable in the landslide occurrence along this road section.

7.1 Landslides and geology

Geology of an area is a major factor in the formation of landslide in that area. In geology, mainly lithological factor and structural factors are considered. In the present study too, the relationship between geology and landslide formation along Mugling–Narayanghat road section is tried to understand. In the geology, lithology and geological structures are considered.

7.1.1 Lithology and landslides

Lithology is one of those parameters known to influence landslides in some regions because certain geological conditions accelerate weathering and prepare the rock for mass movements (Goretti 2010). There are numerous associations of mass movements with particular rocks which demonstrate the importance of lithology and mass movements (Sidle et al. 1985). The lithology in Mugling–Narayanghat road section and its surrounding area consists of the rocks belonging to Holocene Terrace deposits, Siwaliks rocks and Lesser Himalayan rocks. The distribution of landslides along different frock formation is shown in Fig. 1a. In order to understand which class in the lithology has more influence in the landslide formation, landslide inventory map was combined with the lithological map of the study area. From this, it is seen that the geologic units with the majority of the recent landslides were the Nourpul Formation (~130 landslides), Terrace Deposits (~40), the Benighat Slate Formation (~44), the Dhading Dolomite Formation (~30), the Lower Siwaliks Formation (~10), the Purebesi Quartzite Member(~11), the Amphibolit Formation (~3), the Dandagau Formation (~2) and the Kuncha Formation (~5) (Fig. 11a). Also, from the laboratory analysis of the collected rock and soil samples, it was seen that the rocks belonging to Nourpul Formation are highly weathered.

The geologic unit in the study area with the most landslides per unit area of exposure is the Amphibolite followed by Nourpul Formation and Benighat Slate Formation (Fig. 11b). The Amphibolite is intruded within the Nourpul Formation (Fig. 1a). The slates, phyllite are highly weathered while amphibolites are highly fractured and jointed. The rocks in the Purebesi Quartzite member and Dhading Dolomite Formation are highly jointed and fractured making them vulnerable to rock fall and rockslide. This finding agrees with the general agreement of Gerrard (1994) according to whom phyllite rocks are the most susceptible to landsliding followed by shales, schists, poorly cemented sandstones, gneiss, granites and quartzite.

7.1.1 Geological structures and landslides

Geological structures have prominent role in the rock slope instabilities as the presence of these tectonic structures breaks the rock mass reducing its strength (Donati and Turrini 2002). The geological structures in the study area can be divided into major geological structures and minor geological structures. Both the major and minor geological structures have a significant role in the slope instability. There are four major thrust faults crossing the study area along east west axis. The Main Boundary Thrust (MBT) crosses the Narayanghar–Mugling road near around 14 km, south of Phwatar and runs east–west (Fig. 1a). As the MBT is one of the major thrusts in the Himalaya, it plays an important role on slope instabilities. In the Narayanghar–Mugling section, instabilities along the Das Khola, Khahare Khola and Jugedi Khola valleys are mostly located in the MBT zone, Jugadi Thrust zone and immediately north of these faults (Fig. 1a). The area has three other thrust in the north of the MBT (Fig. 1a). They are the Kamalpur Thrust (KT), the Simaltal Thrust (ST) and the Virkuna Thrust (VT) (Fig. 1a). There are also several normal faults in the study area (Fig. 1). Most of the instabilities on the road side and in the stream catchment areas between 10 and 28 km are largely, directly or indirectly, due to the thrust faults and the normal faults mentioned above. Mugling–Narayanghat road corridor and its surrounding region have also undergone local folding of different scales at places, which have locally controlled slope stability. Another major geological structure in the road section is the Jalbire Syncline, which crosses the road section at around Ch 28 km. It has also some roles in the stability of the slope along the road section around Jalbire area. Several researchers have reported the occurrence of large-scale landslides on both the limbs of the syncline. Similar situation is observed around the Jalbire Syncline. Several large-scale landslides are observed around the syncline. The brittle rocks, especially dolomite, quartzite and amphibolite, are jointed and intensely fractured, making the slope vulnerable to rock falls and slides. Phyllites and slates have undergone high degree of weathering and have some ductile deformation at places.

Figure 11c shows the distribution of landslides with the increasing distance from the fault. From this figure, it is seen that the landslide distribution is higher within the distance of 50–100 m from the fault. Also, it is seen that higher amount of landslides is located at a distance greater than 250 m from the fault. In Fig. 11d, it is seen that the landslide density is higher within the distance of 0–200 m from the fault. As the distance increases, the density decreases. From this, it is clear that the faults play greater role in the landslide formation along Mugling–Narayanghat road section and its surrounding regions. Also, as stated in the case of individual landslides, geological structures as fault, joints and fractures play great role in their formation and further enlargement of these landslides. Thus, it is seen that the geological structures have a prominent role in the slope instability in the regional scale as well as in individual landslides along the road section and its surrounding area.

7.2 Landslides and rock weathering

Rock weathering has a prominent role in the formation of landslides along Mugling–Narayanghat road corridor and its surrounding region. Effect of rock weathering in different types of landslides along the road section is described below.

Rock weathering plays a key role in the formation of Dumre Besi landslide. The lower portion of the landslide consists of fresh rocks to slightly weathered rocks. A thrust passes through the center of the landslide making the area susceptible to weathering. The rocks are highly and complexly weathered around this thrust. Thick debris is distributed around the thrust. The upper part consists of less-weathered rocks, and the tope is covered by residual soil (Regmi et al. 2012). Here, the weathering is of complex type. Thin section and XRD analyses of the collected rock samples show that smectite and vermiculite were formed during weathering.

Maurekhola landslide is a large landslide formed by gravitational deformation of rocks. The slate and phyllite are seen to be weathered, while quartzite and amphibolites what covers most part of the landslide is less weathered. Due to the gravitational deformation of the rocks, several small scale faults are seen here. Also, the rocks are dipping at high angle making them susceptible for rock topples. Thus, from the overall stud, it is concluded that this rock weathering is less effective in these types of landslides, while geological structures play a significant role.

Gaighat landslide is mainly triggered by high rainfall; however, rock weathering has played a key role in its initiation and further aggravation. The top part of the landslide, that is the main scarp, consists of 2-m-thick residual soil followed by severely to completely weathered, highly crumbled slate and phyllite. Fresh rocks contain large amount of quartz, with some calcite, sericite and some feldspar, while the weathered rocks are rich in clay minerals and some opaque minerals. The slip surface of the landslide was investigated, and it was observed that thick deposits of clay minerals occur here. Here, few smectite group clay minerals and some weathered chlorite occur. These clay-rich layer helped in forming an impermeable layer; thus, the upper weathered materials that is relatively weaker and fully saturated with water slided downhill due to decrease in the resisting force.

Jugadi Khola landslide lies at the left bank of Jugadi Khola, so the river under cutting is the primary cause of the landslide. However, the rocks from the landslide zone also show weathering phenomenon with the development of some of clay minerals. Mainly few weathered chlorite as well as original chlorite are the clay minerals observed, while quartz, feldspar, muscovite are the primary minerals. Also, the sandstones are highly fractured and jointed. The rainfall together with the rock structures and river undercutting have acted together to generate this landslide. There is also some role of rock weathering in the formation of this landslide.

The main scar of the Jalbire landslide is located about at an altitude of 640 m. Here, rock fall in the dolomite occurred, which along with the colluviums and residual soil covering the down-slope flowed downhill as a debris flow killing 4 peoples and destroying several houses. The XRD analysis of the collected rock samples from the landslide zone indicated that they are fresh and lack any clay minerals. The main minerals observed at the rock outcrop consist of mainly dolomite, with some quartz and minor amount of mica minerals. The steep upper slope, followed by the jointed rock mass, the dip direction of the beds and the rainfall all combined to generate the rock fall at the upslope and debris flow down-slope at Jalbire. Here, the rock weathering is not affective in the formation of the landslide.

Kalikholagau landslide lies at the northern limb of the Jalbire syncline. Here, the main rock types are slate and quartzite. The rocks are dipping at very steep angle and are less weathered. Also, the road cut has created very steep slope. Due to the steep slope and higher dip angle of the foliation plane, rock toppling is observed here. Here, the rock weathering is less effective. Similar types of landslides occur in most part of the road section at the northern limb of the syncline.

The lithological units comprising the landslide at Ch28 are from the Nourpul Formation and consist mainly quartzite, phyllites and some carbonate beds. The rocks are fresh to highly weathered and are intensely fractured, jointed and deformed. Large amount of quartz, mica minerals and some feldspar constitute the min mineralogy of the collected rock and soil sample from the landslide zone. The collected rock and soil samples consist of chlorite and mica as the main clay mineral. In the formation of this landslide, both the chemical weathering and physical weathering have played a significant role. The occurrence of weathered rocks, thick debris cover in the dip slope followed by the presence of numerous joints and fractures and heavy rainfall all combined together to generate this landslide.

This landslide is observed at Ch23.760, and it consists of interbeded quartzite, phyllites and slate of the Nourpul Formation. The quartzite is highly jointed and fractured, and the phyllites are crushed into soils. The XRD analysis of collected rock and soil sample shows that the fresh rocks are rich in quartzite, muscovite, feldspar and chlorite, while their weathered products are rich in chlorite, smectite, vermiculite and kaolinite. From the analysis, it is seen that rock weathering have a major impact in the formation of this landslide. The weathered rocks with a significant amount of joints and fractures; thick colluvium cover followed by heavy rainfall is responsible for the formation of this landslide.

The outcrop comprising the Ghumaune rockfall are mainly dolomite and dolomitic quartzite with some phyllite partings belonging to Nurpul Formation of the Nawakot Complex. Nearly vertical cliff persists in the vicinity of the landslides. From the thin section and XRD analysis of the collected rock samples, it is seen that quartz, dolomite and mica minerals constitute the main mineralogy with some minor amount of feldspar. No clay minerals are found in the rocks sample collected from this landslide. Even though the phyllite seems to be weathered, no clay minerals could be detected. The high dip amount and highly jointed nature of the dolomite, followed by very steep slope (nearly vertical), are combined together to generate the present rock fall.

7. 3 Models relating to the landslide types, geology and weathering along Mugling–Narayanghat road section

Despite the high frequency of landslides and erosional phenomena that occur in weathered rocks, very little is known about the direct and indirect relationship between these phe- nomena (Calcaterra and Parise 2010). In this regard, Deere and Patton (1971) divided the rocks into 3 zones and 6 subzones based on the severity of the weathering and also discussed the types of instabilities occurring in different types of weathered rocks. According to him, rotational and translational slides occur in the upper residual soil, that is in IA and IB horizons; translational slide (planar, wedge failure) occur in IC, IIA, IIB and III horizons. Similarly, rockfall occur in IIA and IIB horizons and rotational and translational slide occur in colluvial-covered slope. The first, simplified attempts to classify slides in natural slopes of residual soils (e.g. Morgenstern and de Matos 1975; Vargas and Pichler 1975), Durgin (1977) provided a comprehensive scheme of the relationships existing between landslides and weathering. According to Durgin (1977), rotational types of slides occur in thoroughly decomposed rocks; debris flows, debris avalanches and debris slides are found in rocks where <15 % of fresh rocks are found; rock fall avalanches, rolling rocks are found where the fresh rock ranges in between 15 and 85 %; and rock falls, rockslides, block glides; debris avalanches and slides over sheeting surfaces occur where <15 % of weathered material occurs along the joints.

Most of these studies were carried out for granite, granodiorite and gneiss (Oyagi 1968; Durgin 1977; Chigira and Yokoyama 2005; Duzgoren-Aydin and Aydin 2006; Borrelli et al. 2012). These studies are not applicable in the present study area, as the area consists of low-grade metamorphic and sedimentary rocks. Hence, in the present study, we have attempted to show the relationship between rock weathering, general geology and landslide formation along one of the most landslide-affected road sections of Nepal Himalaya. These relationships are also thought to be applicable in other parts of the Himalaya with similar geological settings. For this extensive fieldwork followed by laboratory work and literature review have been carried out.

Several landslides are located at Mugling–Narayanghat road section and its surrounding region. However, some factors like the shape/size, type, material involved are common to all the landslides analysed. Two models can effectively define large and complex land- slides. One of them is common in deeply weathered rocks, which are consisting of different lithological units. In addition, geological structures as fault, joints and fractures play a prominent role in creating deep weathering in such landslides (Regmi et al. 2012). The landslide extends up to slightly weathered rocks from completely weathered in these landslide types (Fig. 12a). In the other type of landslides, geological structures as attitude of foliation plane, faults and slope angle have a prominent role, while rock weathering have less effect (Fig. 12b). From Fig. 12c, it is seen that most of the rotational types of land- slides are located in the deep slope, where the rock is also considerably weathered. These types of landslides are mostly found in the slope with uniform lithology. Rock is completely to highly weathered in these landslides (Fig. 12c). Shallow landslides are of two types. One of them is observed in slightly weathered to fresh rocks, where the attitudes of foliation plane and slope angle are very high (Fig. 12d). Several small-scales, very shallow landslides are located in slopes covered by thick colluviums or residual soil. The rock is rather fresh below the colluviums (Fig. 12e). Debris slides and debris flow are the dominant types of landslides occurring in Mugling–Narayanghat road section and its surrounding area. Most part of the area is covered by thick colluviums or residual soils. Rock is also highly weathered below these cover. Thus, in every monsoon, they flow down as debris flow or debris slide. In some case, there is frock fall at the upper slope. The materials from the rock fall get mixed with the colluviums and other materials lying on the slope downhill and flow as debris flow (Fig. 12f). Rock fall is encountered in on steep slopes. The rocks are not much weathered in these steep slopes; however, they are highly jointed and fractured (Fig. 12g).

8. Conclusion

A detailed study was carried out at Mugling–Narayanghat road section and its surrounding area to assess the relationship between geology, rock weathering and mass movement. The major triggering factor for all the landslides is the rainfall; however, several conditioning factors as geological structures, rock weathering, clay mineral formation and river undercutting have operated over a long time making the area susceptible for landslides. The complexity of both the regional and local geological setting makes it extremely difficult to draw a straightforward relationship between landslides and rock weathering. However, from the detailed study of the region, it is seen that large and complex landslides are related to deep rock weathering followed by the intervention of geological structures as faults, joints and fractures. Large landslide formed by gravitational deformation is related to the rock structures and while the rock weathering play a minor role. Rotational types of landslides are observed in weathered rocks, where the geological structures as the dip direction of the foliation plane play a fundamental role. Some shallow landslides are developed in the slope covered by residual soil or colluviums and the rock is rather fresh below these covers, while some are found in rocks with high dip angles that are less weathered. Debris slides and debris flows occur in colluviums or residual soil covered slopes. In few instances, they are also related to the rock fall occurring at higher slopes. The materials from the rock fall get mixed with the colluviums and other materials lying on the slope downhill and flow as debris flow. Rock falls are mainly related to the joint pattern and the slope angle. They are found in less-weathered rocks.

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References

Adhikari TL (2009) Disaster mitigation works along Narayanghat Mugling Highway. In: International seminar on hazard management for sustainable development

Ahmad R, Joshi MN (2010) Assessment of landslide susceptibility on land degradation processes in Chamoli and surrounding area using RS and GIS technique. Int Geoinf Res Dev J 1(3):1

Aleotti P, Chowdhury R (1999) Landslide hazard assessment: summary review and new perspectives. Bull Eng Geol Environ 58:21–44

Borrelli L (2008) Categorie di frane ed elementi caratteristici nei profili di alterazione. PhD thesis, Uni- versity of Calabria, 395 pp

Borrelli L, Greco R, Gullà G (2007) Weathering grade of rock masses as a predisposing factor to slope instabilities: reconnaissance and control procedure. Geomorphology 87:158–175

Borrelli L, Perri F, Critelli S, Gullà G (2012) Minero-petrographical features of weathering profiles in Calabria, southern Italy. Catena 92:196–207

Brand EW, Phillipson HB, Southeast Asian Geotechnical Society, International Society of Soil Mechanics and Foundation Engineering. Technical Committee on Sampling and Testing of Residual Soils (1985) Sampling and testing of residual soils: a review of international practice. Scorpion Press, Hong Kong 194 pp

Branner JC (1896) Decomposition of rocks in Brazil. Geol Soc Am Bull 7:255–314

Brunsden D, Doornkamp JC, Fookes PG, Jones DKC, Kelly JMH (1975) Large-scale geotechnical mapping and highway engineering design. Q J Eng Geol 8:227–253

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. Mt Res Dev 2:157–173

Calcaterra D, Parise M (2010) Weathering as a predisposing factor to slope movements. Geological Society, London, Engineering Geology Special Publication, vol 23, pp 1–4

Calcaterra D, Parise M, Dattola L (1996) Caratteristiche dell'alterazione e franosita ` di rocce granitoidi nel bacino del Torrente Alaco (Massiccio delle Serre, Calabria). B Soc Geol Ital 115:3–28

Calcaterra D, Bruno DE, Parise M, Silvestri F, Capparelli G (2004) Effects of weathering on slope instability in gneissic rocks at Luzzi (Calabria, Italy). Proceedings of the IX international symposium on land- slides, Rio de Janeiro

Cascini E, Cascini L, Gullà G (1992) A back-analysis based on piezometer response. In: Bell DH (ed) Proceeding of the Sixth International Symposium on Landslides. A.A. Balkema, Rotterdam, pp 565–1128

Cascini L, Critelli S, Di Nocera S, Gullà G, Matano F (1994) Weathering and landsliding in Sila Massif gneiss (Northern Calabria, Italy). In: Oliverira R, Rodrigues LF, Coelho AG, Cunha AP (eds) Pro- ceedings Seventh International Congress

International Association of Engineering Geology, IAEG, Lisboa/Portugal, pp 1613–1622

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

Chigira M, Yokoyama O (2005) Weathering profile of non-welded ignimbrite and the water infiltration behavior within it in relation to the generation of shallow landslides. Eng Geol 78:187–207

Cortese E (1895) Geologic description of Calabria (Regio Ufficio Geologico d'ltalia, Rome [in Italian])

Critelli S, Di Nocera S, Le Pera E (1991) Approccio metodologico per la valutazione petrografica del grado di alterazione degli gneiss del Massiccio Silano (Calabria settentrionale). Geología Applicata e Idrogeología 26, 41–70.

Dahal RK, Hasegawa S (2008) Representative rainfall thresholds for landslides in the Nepal Himalaya. Geomorphology 100:429–443

Dahal RK, Hasegawa S, Nonomura A, Yamanaka M, Dhakal S, Paudyal P (2008) Predictive modelling of rainfall-induced landslide hazard in the Lesser Himalaya of Nepal based on weights-of evidence. Geomorphology 102(3–4):496–510

Dahal RK, Hasegawa S, Bhandary NP, Poudel PP, Nonomurac A, Yatabe Y (2012) A replication of landslide hazard mapping at catchment scale. Geomat Nat Hazards Risk. doi:10.1080/19475705. 2011.629007

Deere DU, Patton FD (1971) Slope stability in residual soils. In: Proceedings of the fourth Pan American conference on soil mechanics and foundation engineering, San Juan, Puerto Rico, American Society of Civil Engineers, New York, vol 1, pp 87–170

Deoja B, Dhital MR, Thapa B, Wagner A (1991) Mountain risk engineering handbook. ICIMOD, Kath- mandu 857 pp

Devkota K, Regmi AD, Pourghasemi HR, Yishida K, Pradhan B, Ryu IC, Dhital MR, Althuwaynee OF (2012) Landslide susceptibility mapping using certainty factor, index of entropy and logistic regression models in GIS and their comparison at Mugling–Narayanghat road section in Nepal Himalaya. Nat Hazards. doi:10.1007/s11069-012-0347-6

Dhital MR (2000) An overview of landslide hazard mapping and rating systems in Nepal. J Nepal Geol Soc 22:533–538

Dhital MR, Upreti BN, Dangol V, Bhandari AN, Bhattarai TN (1991) Geological engineering methods applied in mountain road survey: an example from Baitadi-Darchula Road Project (Nepal). J Nepal Geol Soc 7:49–67

Dhital MR, Shrestha R, Ghimire M, Shrestha GB, Tripathi D (2006) Hydrological hazard mapping in Rupandehi district, West Nepal. J Nepal Geol Soc 31:59–66

Donati L, Turrini MC (2002) An objective method to rank the importance of the factors predisposing to landslides with the GIS methodology: application to an area of the Apennines (Valnerina; Perugia, Italy). Eng Geol 63:277–289

Durgin PB (1977) Landslides and the weathering of granitic rocks: reviews. Eng Geol 3:127–131

Duzgoren-Aydin NS, Aydin A (2006) Chemical and mineralogical heterogeneities of weathered profiles: implications for landslide investigation. Nat Hazards Earth Syst 6:315–2006

DWIDP (2009) The study on disaster risk management for Narayanghar–Mugling Highway. Unpublished report

Dwivedi SK, Dwivedi S, Joshi GR (2007) Slope stability of the Pawati Landslide, Dolkha District, Central Nepal. In: Yin ZZ, Yuan JP, Chiu ACF (eds) Proceedings of 3rd Asian conference on unsaturated soils, Nanjing, China. Science Press, Beijing, pp 625–630

Falconer JD (1911) The geology and geography of Northern Nigeria. Macmillan, London

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 AJ, Gardner RAM (2000a) The role of landsliding in shaping the landscape of the middle hills, Nepal. Z Geomorphol Suppl Bd 122:47–62

Gerrard AJ, Gardner RAM (2000b) The nature and management implications of landsliding on irrigated terraces in the Middle Hills of Nepal. Int J Sust Dev World 7:229–236

Goretti KKM (2010) Landslide occurrence in the hilly areas of Bududa Districts in Eastern Uganda and their causes. Unpublished PhD thesis, Makerere University, 106 pp

Gullà G, Borrelli L, Greco R (2004) Weathering of rock-mass as possible characterizing factor of predisposition to slope instabilities. Proceedings of the IX international symposium on landslides, Rio de Janeiro, pp 103–108

Hencher SR, Massey JB, Brand EW (1984) Application of back analysis to some Hong Kong landslides. Proceedings of the IV international symposium on landslides, Toronto, pp 631–638

Hoek E, Bray JW (1997) Rock slope engineering. Institute of Mining and Metallurgy, London, pp 402

Ives JD, Messerli B (1981) Mountain hazards mapping in Nepal; introduction to an applied mountain research project, vol 1. Mountain Research and Development, University of California Press, Berkeley, pp 223–230

Jutson JT (1914) An outline of the physiographic geology (physiography) of Western Australia. Geol Sur Western Australia Bull 61, 249 p

Kienholz H, Schneider G, Bichsel M, Grunder M, Mool P (1984) Mapping of mountain hazards and slope stability. Mt Res Dev 4(3):247–266

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

Lacerda WA, Santos JR (2000) Water table fluctuation–a cause of slide initiation in residual and colluvial soils in tropical regions. Proceedings of the VII international symposium on landslides, Cardiff, pp 877–880

Morgenstern RN, De Matos M (1975) Stability of slopes in residual soils. In: Proceedings of the 5th Panamerican conference on Soil Mechanics and Foundation Engineering, Bueno Aires. (3):369–384

Nishida K, Aoyama C (1985) Weathered residual soil properties and failure mechanism of slope. Pro- ceedings of the IV international conference and field workshop on landslides, Tokyo, pp 289–294

Oyagi N (1968) Weathering-zone structure and landslides of the area of granitic rocks in Kamo-Daito, Shimane Prefecture. Reports of cooperative research for disaster prevention, National Research Center for Disaster Prevention, vol 14, pp 113–127

Pradhan B (2010) Landslide susceptibility mapping of a catchment area using frequency ratio, fuzzy logic and multivariate logistic regression approaches. J Indian Soc Remote Sens 38(2):301–320

Pradhan B, Singh RP, Buchroithner MF (2006) Estimation of stress and its use in evaluation of landslide prone regions using remote sensing data. Adv Space Res 37(4):698–709

Regmi AD, Yoshida K, Dhital MR, Devkota K (2012) Effect of rock weathering, clay mineralogy, and geological structures in the formation of large landslide, a case study from Dumre Besei landslide, Lesser Himalaya Nepal. Landslides. doi:10.1007/s10346-011-0311-7

Selby MJ (1982) Controls on the stability and inclinations of hillslopes formed on hard rock. Earth Surf Proc Land 7:449–467

Sidle RC, Pearce AJ, O'loughlin CL (1985) Hillslope stability and land use. Water Resources Monograph 11, 140 pp

Stöcklin J (1980) Geology of Nepal and its regional frame. J Geol Soc Lond 137:1–34
Stöcklin J, Bhattarai KD (1978) Geology of the Kathmandu area and central Mahabharat range. Report of Department of Mines and Geology/UNDP (unpublished), Nepal Himalaya 86 pp
Upreti BN (1999) An overview of the stratigraphy and tectonics of the Nepal Himalaya. J Asian Earth Sci 17(5–6):577–606
Upreti BN, Dhital MR (1996) Landslide studies and management in Nepal. ICIMOD, Nepal 87 pp Vargas M, Pichler E (1975) Residual soil and rockslides in Santos, Brazil. In: Proceedings of the 4th international conference of the soil mechanics and foundation engineering, London, vol 2, pp 394–398
Wagner A (1981) Rock structure and slope stability study of Waling area, central west Nepal. J Nepal Geol Soc 1(2):37–43 Walther J (1915) Laterites in Western Australia. Zeitschrift fu ¨r Geologische Gesellschaft 67B:113–140 [in German] Williamson DA (1984) Unified rock classification system: bulletin of the association of engineering geol- ogists, XXI(3):345–354

Table 1 Table showing the weathering degree of rocks
(modified from Williamson 1984; Geological Society Engineering Working Party 1997; and Hoek and Bray 1997)

State	Definition	Description
		Degree of Weathering
1	None	No visible sign of weathering
2	Slight	Discoloration on major discontinuity surfaces; rock material may be discolored and somewhat weaker than
3	Moderate	Less than half of the rock is present either as a continuous framework or as corestones
4	Severe	Most of rock material is decomposed; disintegrated to a soil, or both; original mass structure is largely intact
5	Complete	

Table 2: Table showing the different formation observed along Mugling–Narayanghat road section and its surrounding are

		Formation	Geological Age	Rock type
		Quaternary Deposit	Recent	Mainly river terraces
Siwaliks		Middle Siwaliks	Mesozoic	Coarse grained, salt and pepper like massive sandstone
		Lower Siwaliks	Mesozoic	Variegated mudstone, with some thick bedded, light grey, fine grained sandstones
MBT (Main Boundary Thrust)				
NAWAKOT COMPLEX	Upper Nawakot Group	Benighat Slate Formation	Palaeozoic	Dark bluish grey to nearly black, soft-weathering slates and phyllites; many are argillaceous, and subordinately siliceous or finely quartzitic.
	ST (Simaltal Thrust)			
	LOWER NAWAKOT GROUP	Dhading Dolomite	Late Pre Cambrian	Dolomite consisting of fine crystalline or dense and light blue-grey in color. It is thinly bedded and platy in the basal part and the beds are thick to massive with common occurrence of columnar stromatolite in some parts. Frequent intercalation of
		Nourpul Formation	Late Pre Cambrian	Predominantly phyllitic, but contains a variable amount of quartzitic and calcareous intercalations and dolomites and
		Purebesi Quartzite	Late Pre	Purple quartzite
		Amphibolits		Thin beds of greenish amphibolites
		Dandagaun Phyllites	Late Pre	Uniform argillaceous to finely quartzitic phyllites of dark blue
		Fagfog Quartzite	Late Pre Cambrian	White quartzite made up of colloidal fine-grained chert to impure coarse orthoquartzite, with occasional reddish to pale orange tints, with some intercalation of phyllite. Ripple marks
		Kuncha Formation	Late Pre Cambrian	Alternation of phyllites, phyllitic quartzites and phyllitic gritstones resembling greywakes

Table 3: Semi-quantitative abundances of minerals of the rocks and soil form the landslide zones indicated by thin-section and XRD method

	Rock type	Weathering degree	Original Minerals						Derived Minerals			
			Quartz	Feldspar	Mica minerals	Amphiboles (Hornblende)	Dolomite	Chlorite	Smectite	Chlorite	Vermiculite	Kaolinite
Dumre Besi landslide	Quartzite and Phyllite	Fresh to slight	++++	++	++	–	–	–	–	–	–	–
	Phyllite and slate	Moderate to complete	++	–	–	–	–	+	+++	++	+	–
Maure Khola landslide	Quartzite and amphibolite	Slight	++++	++	++	+++	–	+	–	–	–	–
	Phyllite and slate	Moderate to severe	++	–	+	–	–	++	-	++	+	–
Ch 31 landslide	Phyllite and slate	Fresh to slight	+++	–	++	–	–	++	–	–	–	–
	Phyllite	complete	+		++			++	+	+	+	–
Kalikholagaun landslide	Slate and quartzite	Slight										
Jugadi khola landslide	Sandstone	Slight	++++	++	++	–	–	++	–	–	–	–
	Mudstone	Severe	+	–	+	–	–	+	–	++	–	–
Jalbire landslide	Dolomite	Fresh	+++	++	++	–	++++	–	–	–	–	–
	Dolomite	Moderate	+++	++	++		+++	–	–	–	–	–
28 landslide	Phyllite/Slate/Quartzite	Moderate	+++	+	++	–	–	++	–	++	–	–
	Phyllite	Severe	+	+++	+	–	–	++	–	++	+	++
23.600 landslide	Quartzite	Sight	+++	++	++	–	–	+	–	–	–	–
	Phyllite	Severe	+	–	++	–	–	+	–	++	–	–
Ghumaune rock fall	Dolomite	Fresh	+++	++	++	–	++	–	–	–	–	–
	Dolomite	Slight	+++	+	++	–	++	–	–	–	–	–

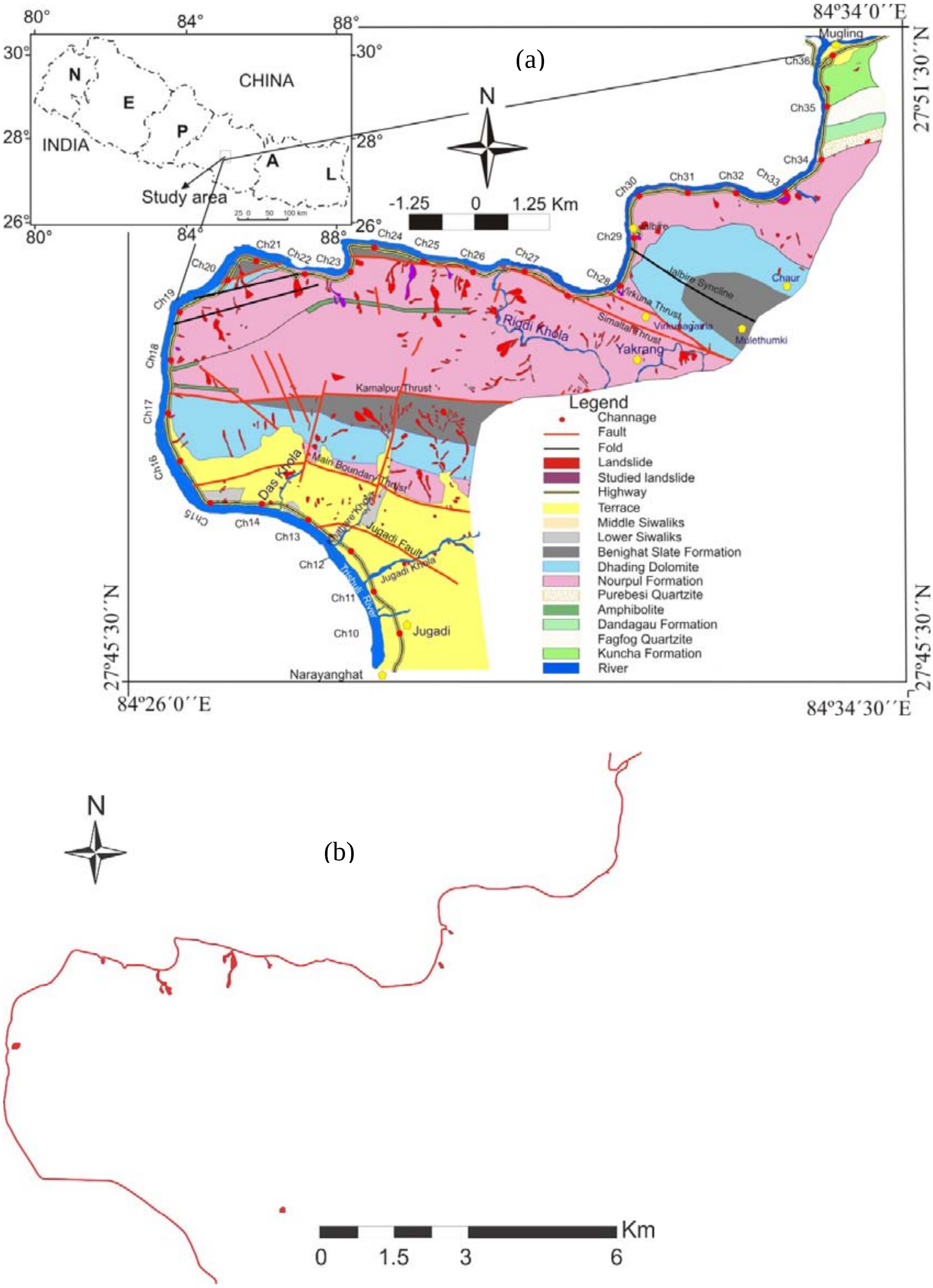


Fig. 1 a Map showing the study area, geological map along with the distribution of landslides, including the landslides selected for detailed investigation, b Map showing just the landslides under investigation in this study

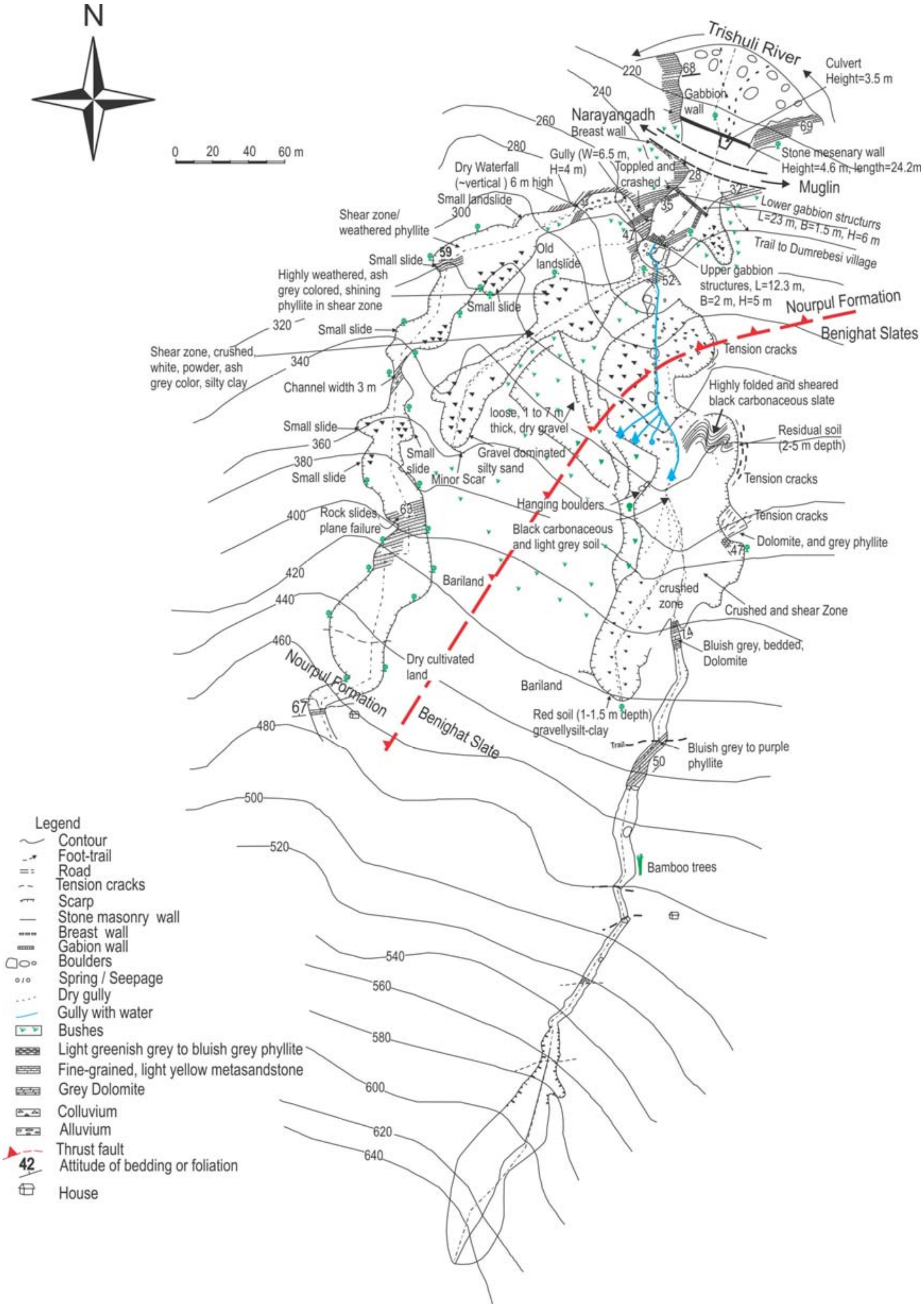


Fig. 2 Map showing the detailed features of the landslide of Dumre Besi

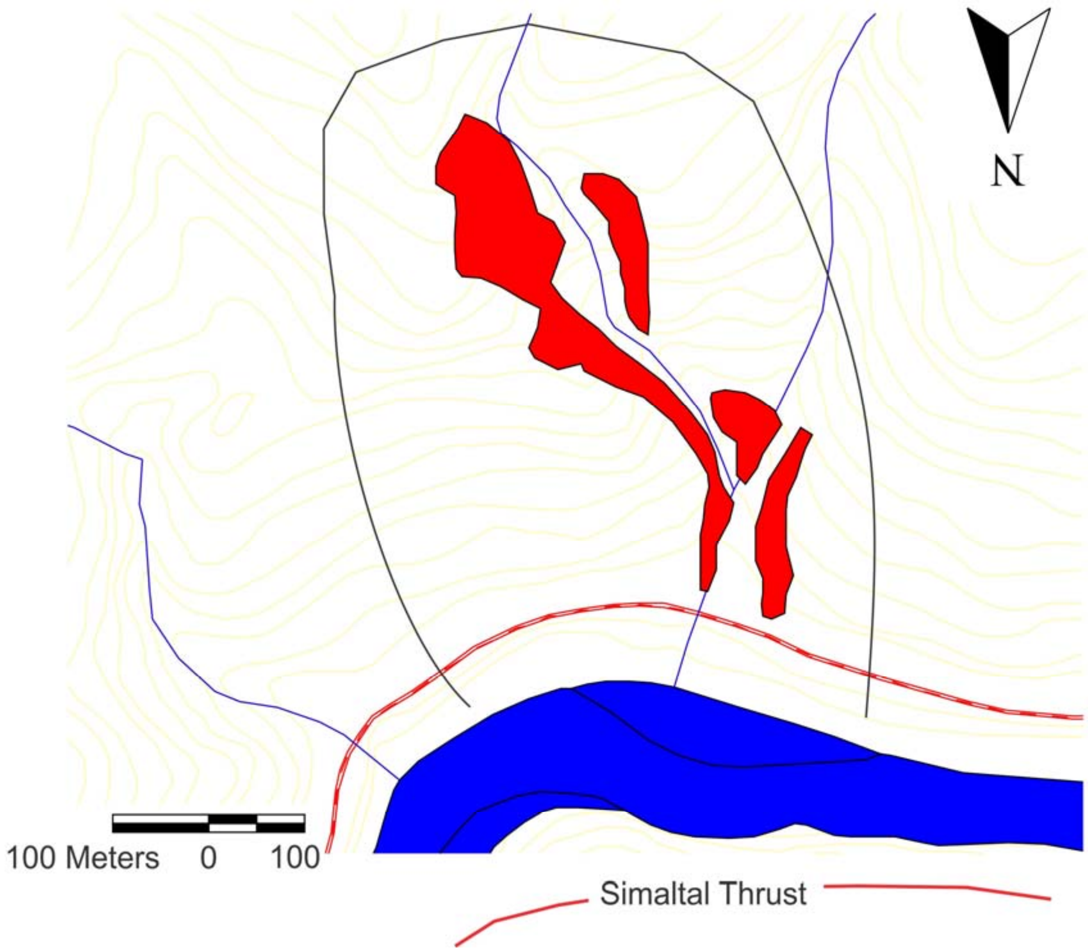


Fig. 3 Plan view of the Maure Khola landslide. Red polygons indicating the active landslides, blue boundary indicates the gravitationally deformed surface

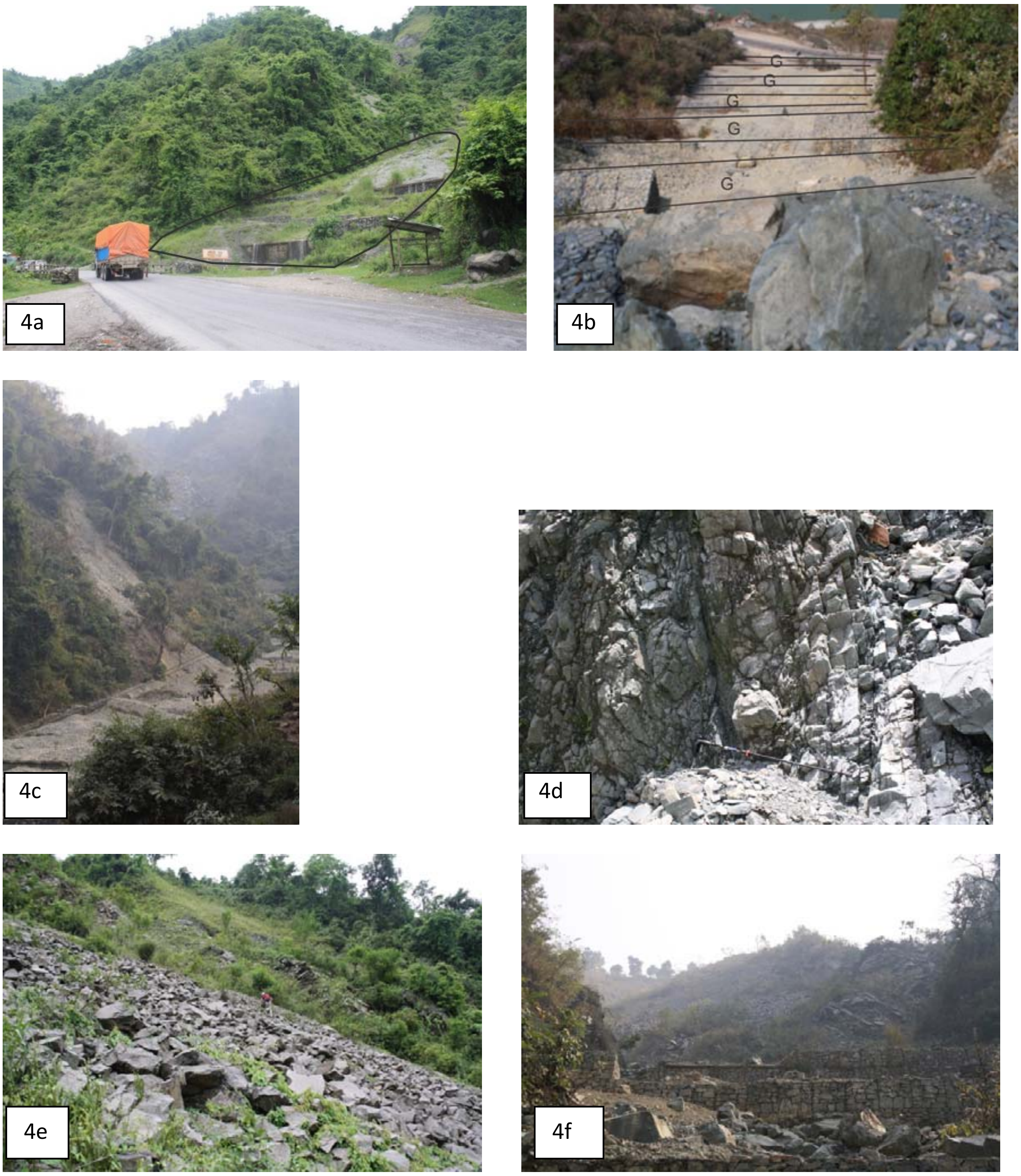


Fig. 4 (a) The debris fan {indicated by black line} in the bottom part of the landslide just above the highway. (b) Several gabion walls {indicated by black box (G)} used to control the debris. (c) Debris observed in the channel at the central part of the channel and small debris slide in the valley walls. (d) Moderately weathered, highly fractured amphibolites and pink quartzite showing rock toppling. (e) Channel covered by several big boulders of amphibolites. (f) The upper part of the landslide consisting of rock topple is dominated by quartzite and slate. (g) General view of the landslide at Ch 23.760 km. (h) Fractured and decomposed rocks observed in the landslide of Ch 23.760. (i) Road section showing the steep cliff at Ghumaune, where rock failure occurred during the monsoon of 2006. (j) Large boulder of dolomite formed by the rock failure in Ghumaune during the monsoon of 2006 lying along the road side

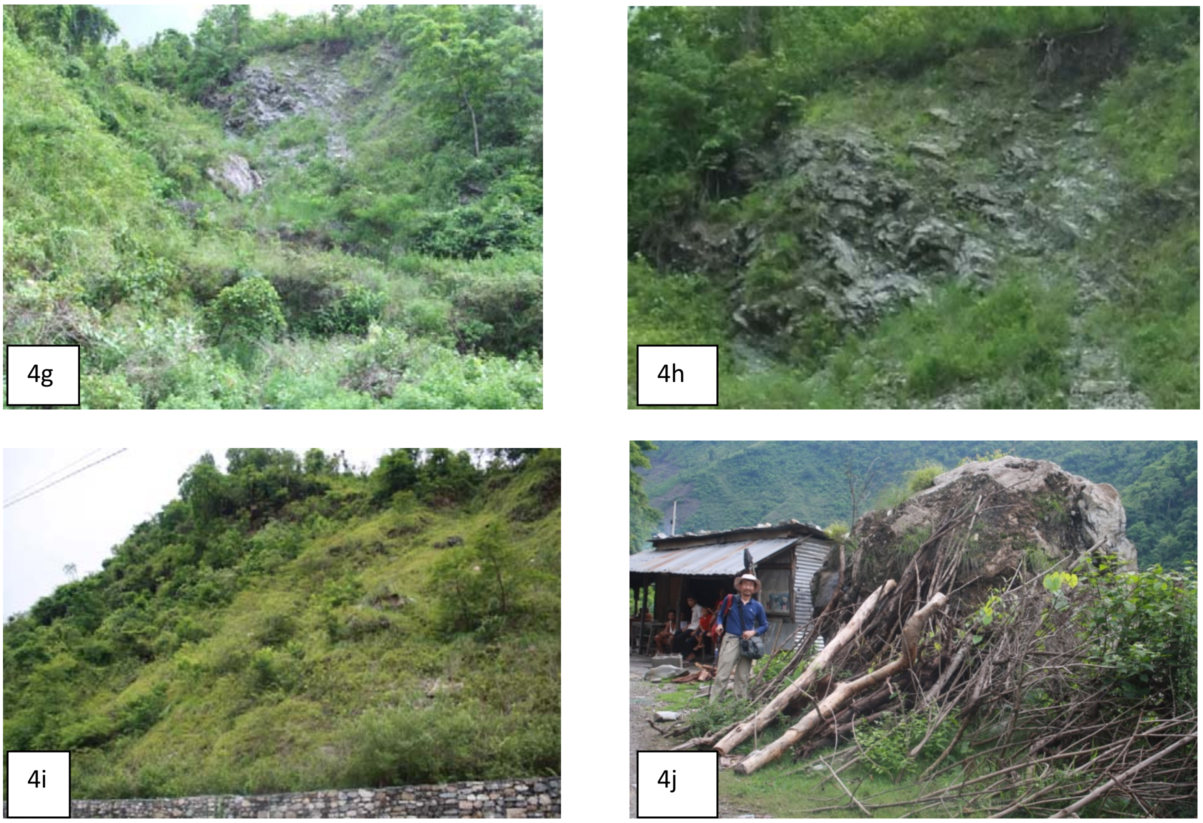


Fig.4: Continued

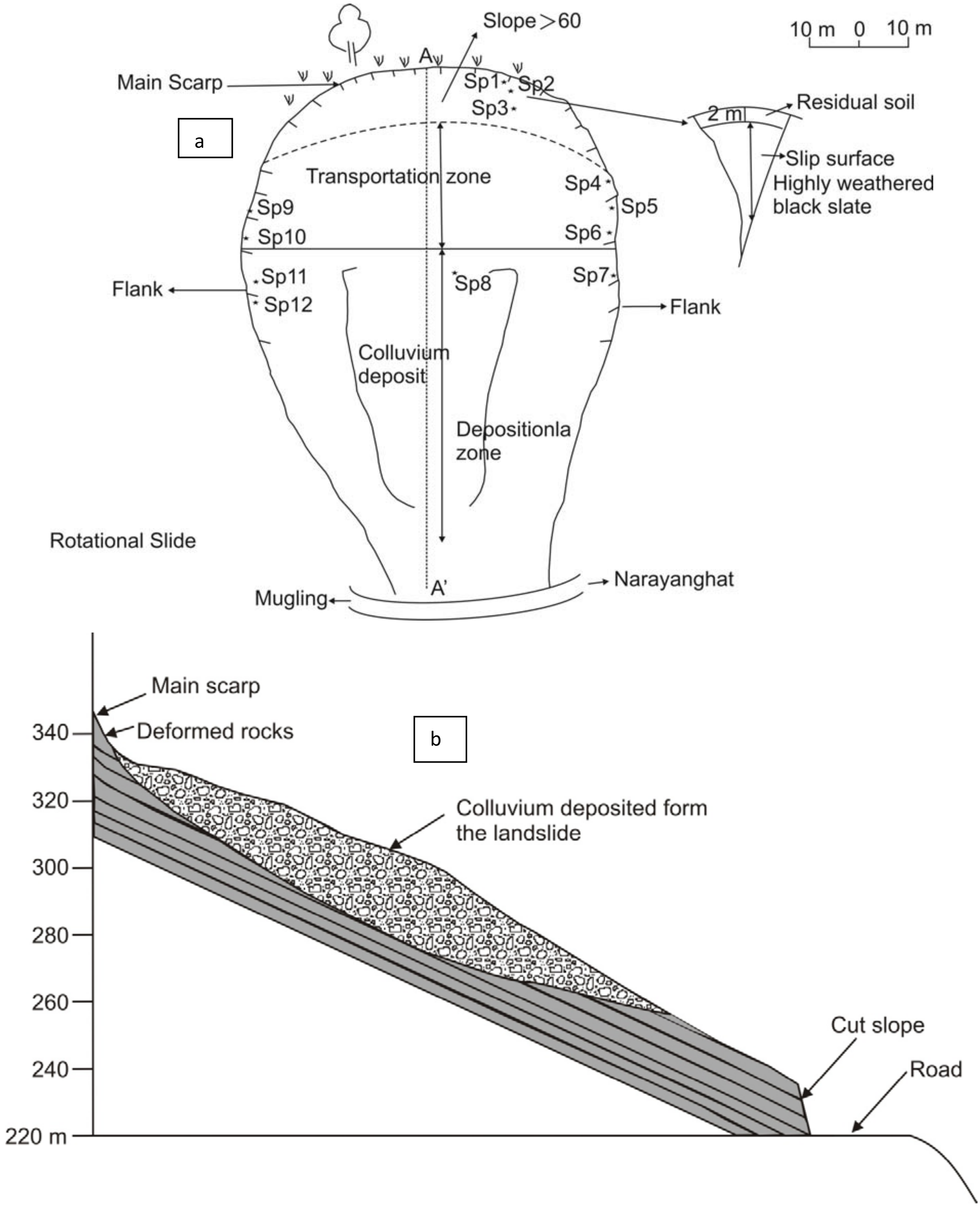


Fig. 5: (a) Detailed view of the landslide. (b) Cross-section along A-A'

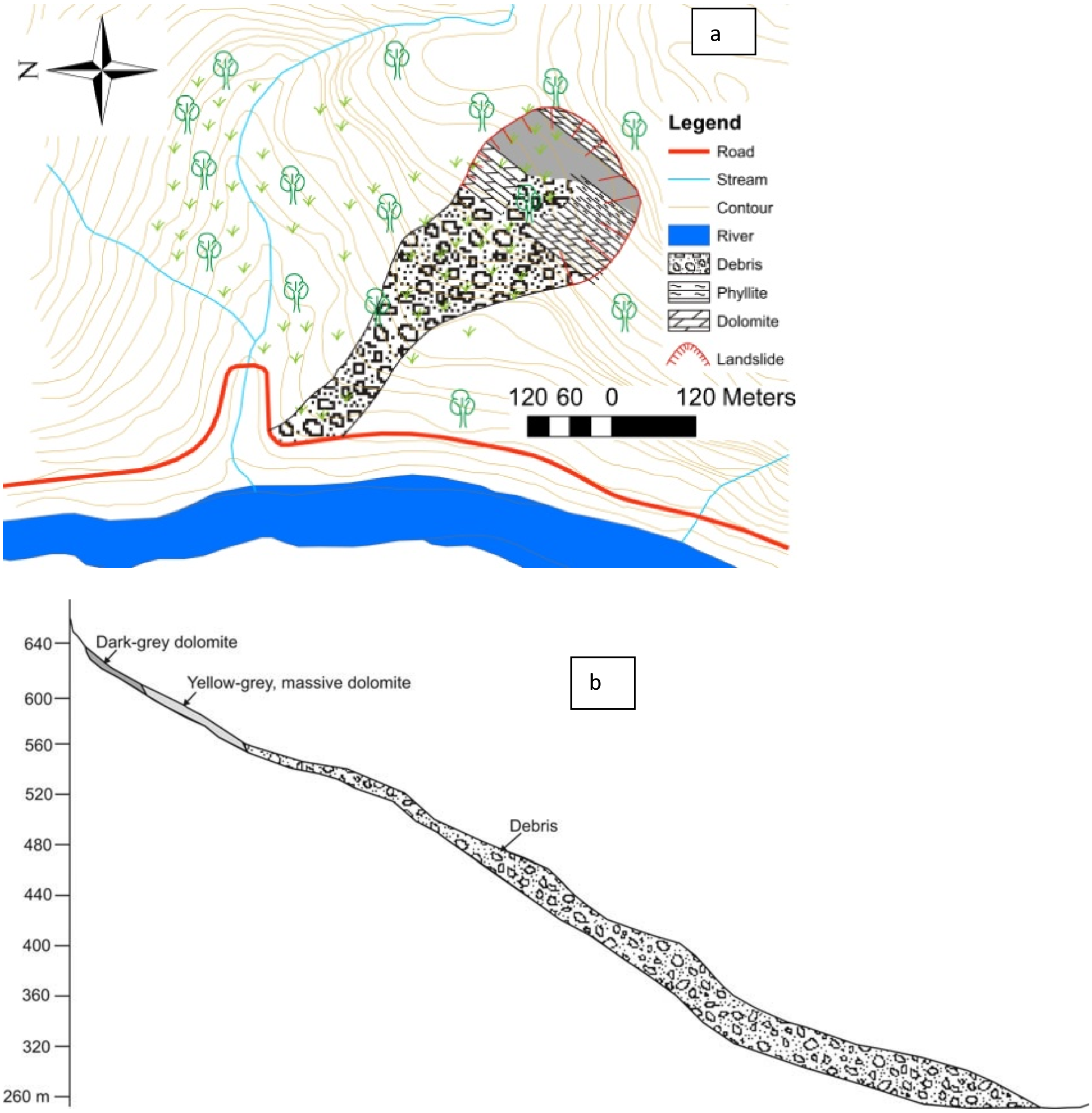


Fig. 6: (a) Plan view of the Jalbire landslide. (b) Schematic cross-section of the Jalbire landslide

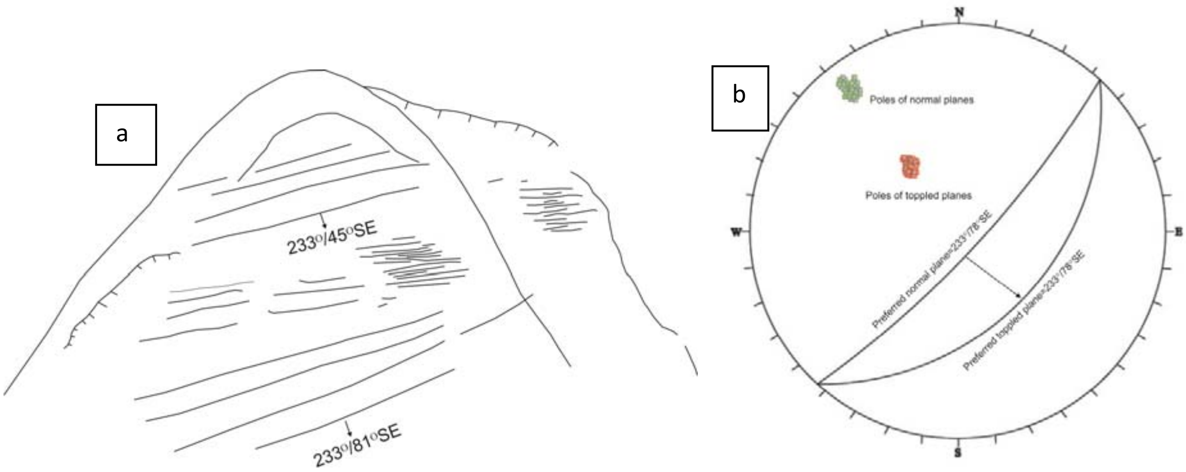


Fig.7: (a) Sketch showing the rock topple at Kalikholagau (b) Serigraphic projection of the poles of the normal beds as well as the toppled beds and the normal and toppled planes.

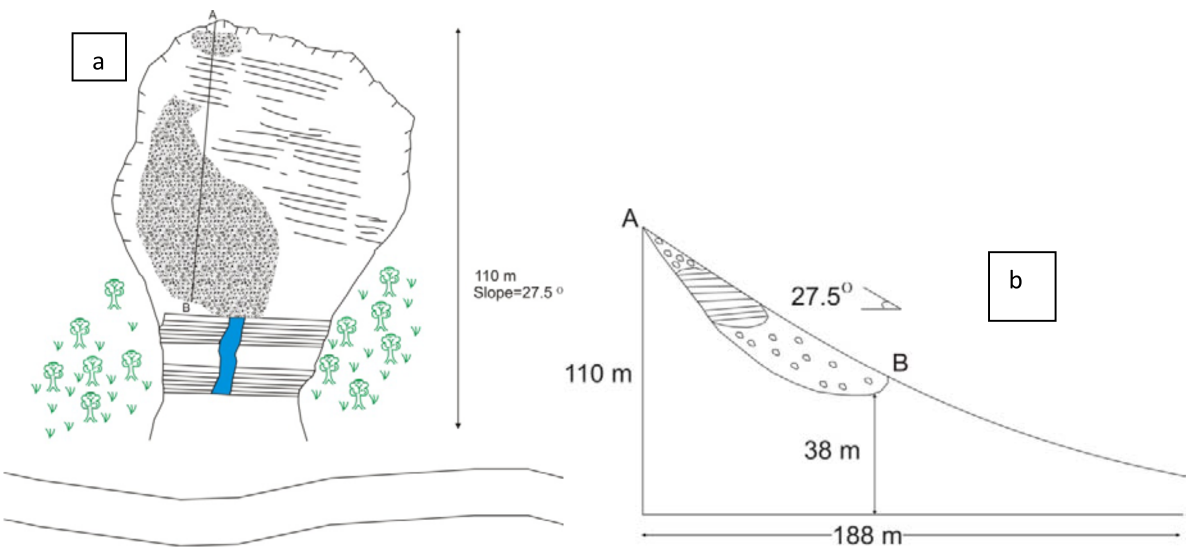


Fig. 8: (a) Landslide observed at Ch 28 km, (b) Cross-section along AB.

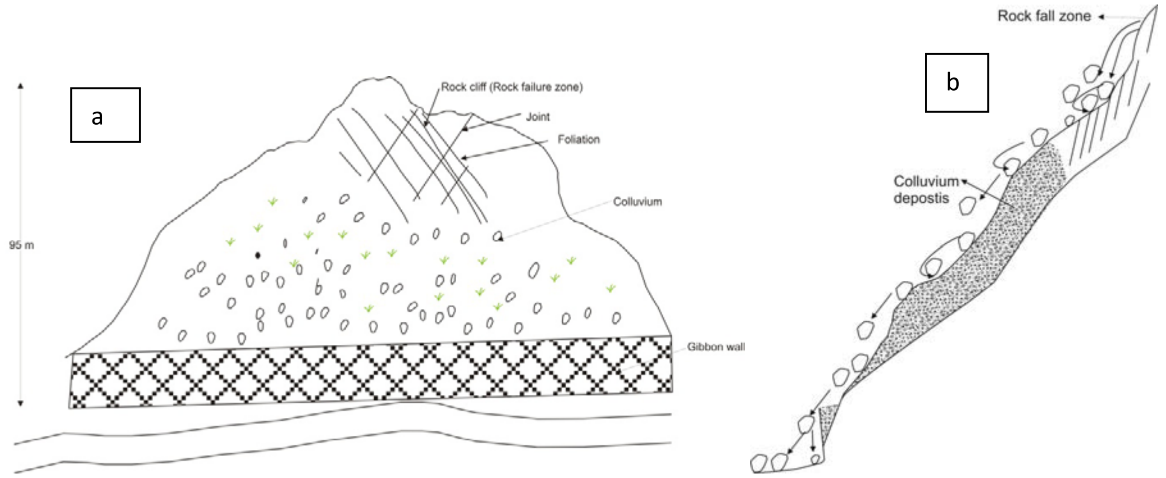
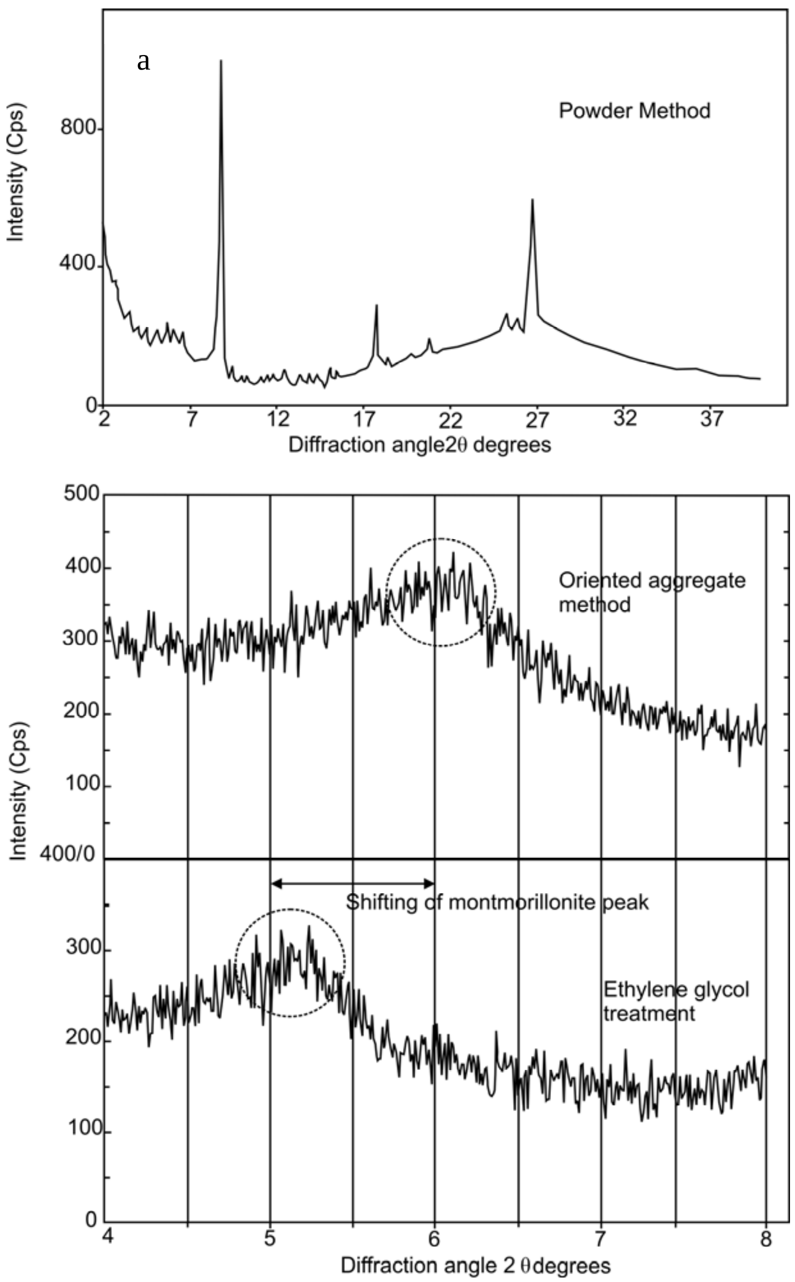
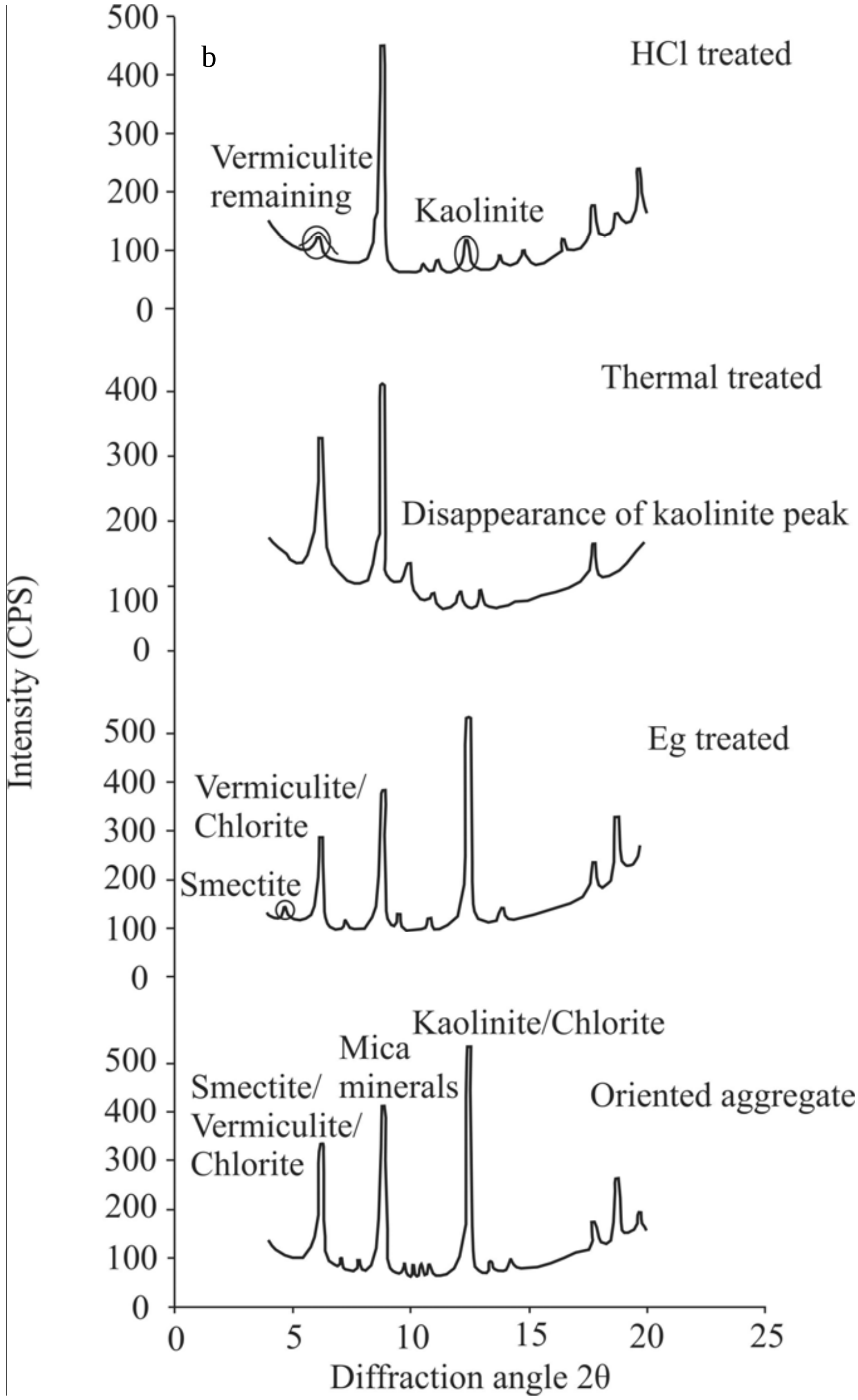


Fig. 9: (a) Sketch showing the rock fall zone near Ghumaune of 2006, (b) Cross-section of the rock fall area.


a
Powder Method
Intensity (Cps)
800
400
0
2
7
12
17
22
27
32
37
Diffraction angle2θ degrees
500
400
300
200
100
400/0
Oriented aggregate method
Shifting of montmorillonite peak
Ethylene glycol treatment
4
5
6
7
8
Diffraction angle 2 θdegrees


b
HCl treated
Vermiculite
remaining
Kaolinite
Thermal treated
Disappearance of kaolinite peak
Eg treated
Vermiculite/
Chlorite
Smectite
Kaolinite/Chlorite
Mica
minerals
Smectite/
Vermiculite/
Chlorite
Oriented aggregate
Intensity (CPS)
Diffraction angle 2θ
0
5
10
15
20
25
0
100
200
300
400
500

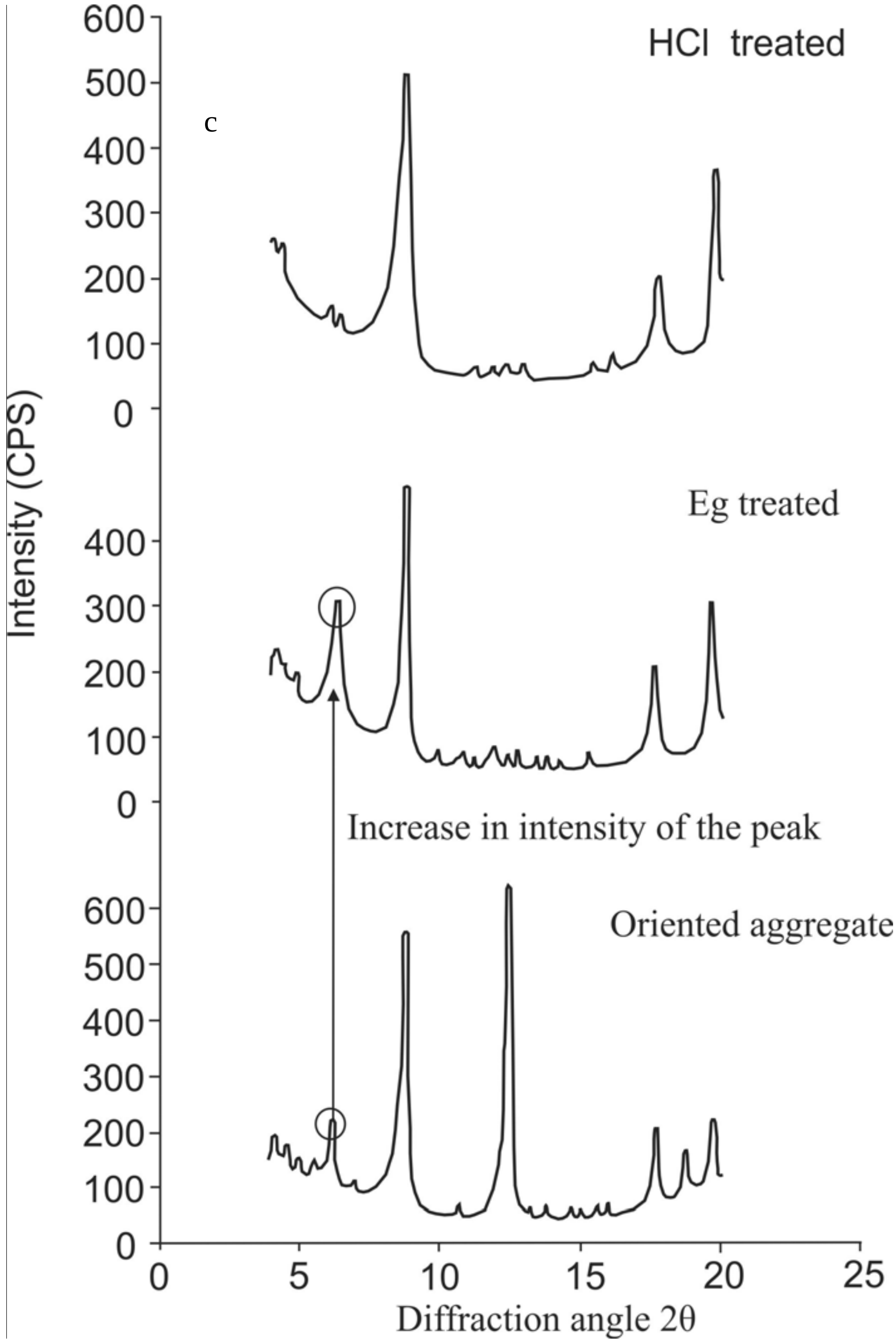
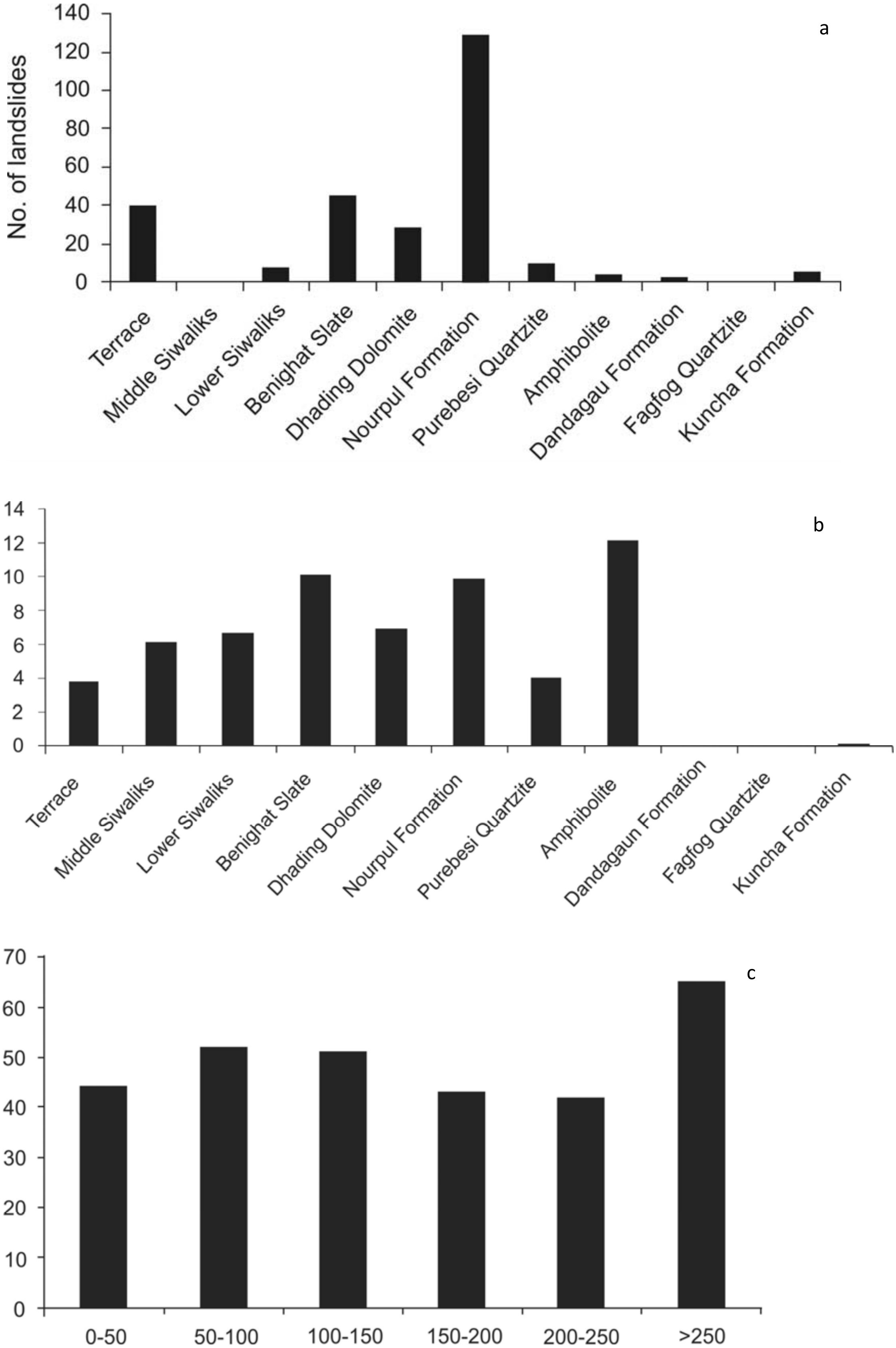


Fig. 10 (a) XRD pattern of the rock sample from Dumre Besi landslide showing the shifting of smectite peak. (b) XRD pattern of rock sample from Ch23.600 landslide, showing the presence of smectite, vermiculite and kaolinite clay minerals. (c) XRD pattern of rocks from Jugadi Khola landslide, showing the weathering of chlorite mineral, here it is seen that the chlorite peak intensity increases due to the EG treatment


a
No. of landslides
0
20
40
60
80
100
120
140
Terrace
Middle Siwaliks
Lower Siwaliks
Benighat Slate
Dhading Dolomite
Nourpul Formation
Purebesi Quartzite
Amphibolite
Dandagau Formation
Fagfog Quartzite
Kuncha Formation
b
0
2
4
6
8
10
12
14
Terrace
Middle Siwaliks
Lower Siwaliks
Benighat Slate
Dhading Dolomite
Nourpul Formation
Purebesi Quartzite
Amphibolite
Dandagaun Formation
Fagfog Quartzite
Kuncha Formation
c
0
10
20
30
40
50
60
70
0-50
50-100
100-150
150-200
200-250
>250

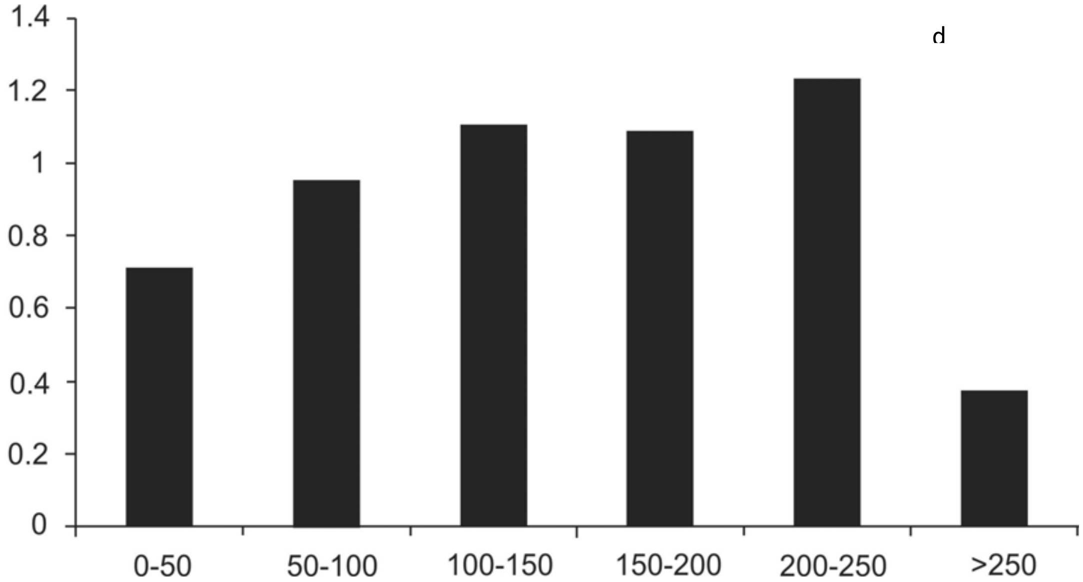
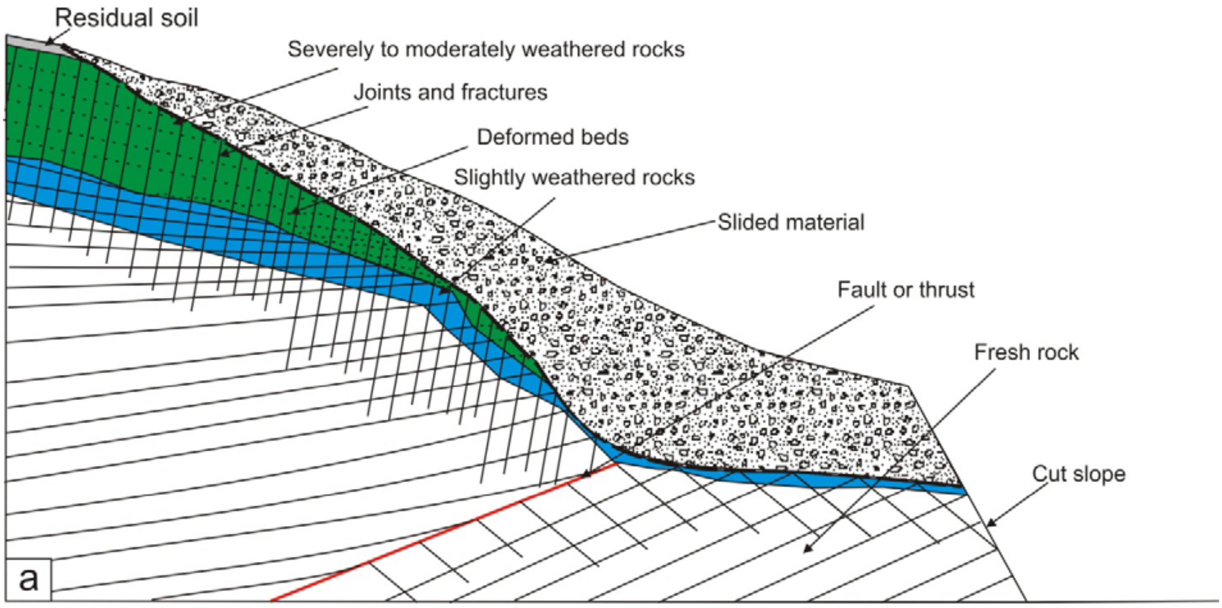
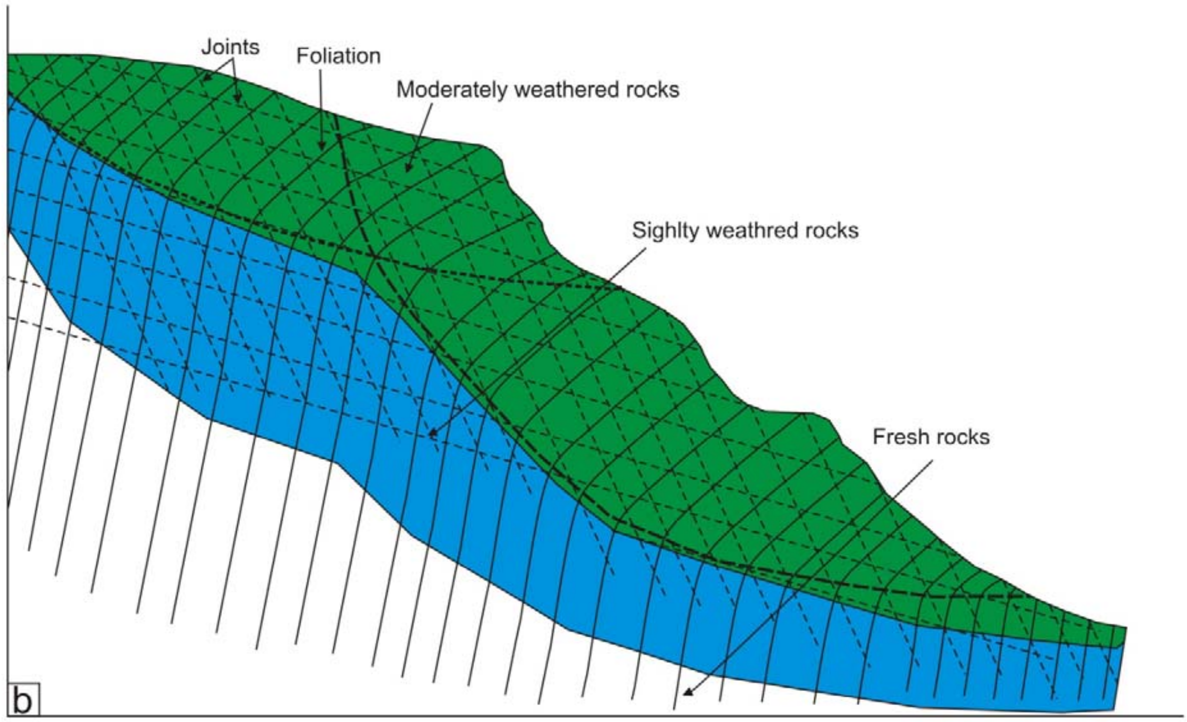


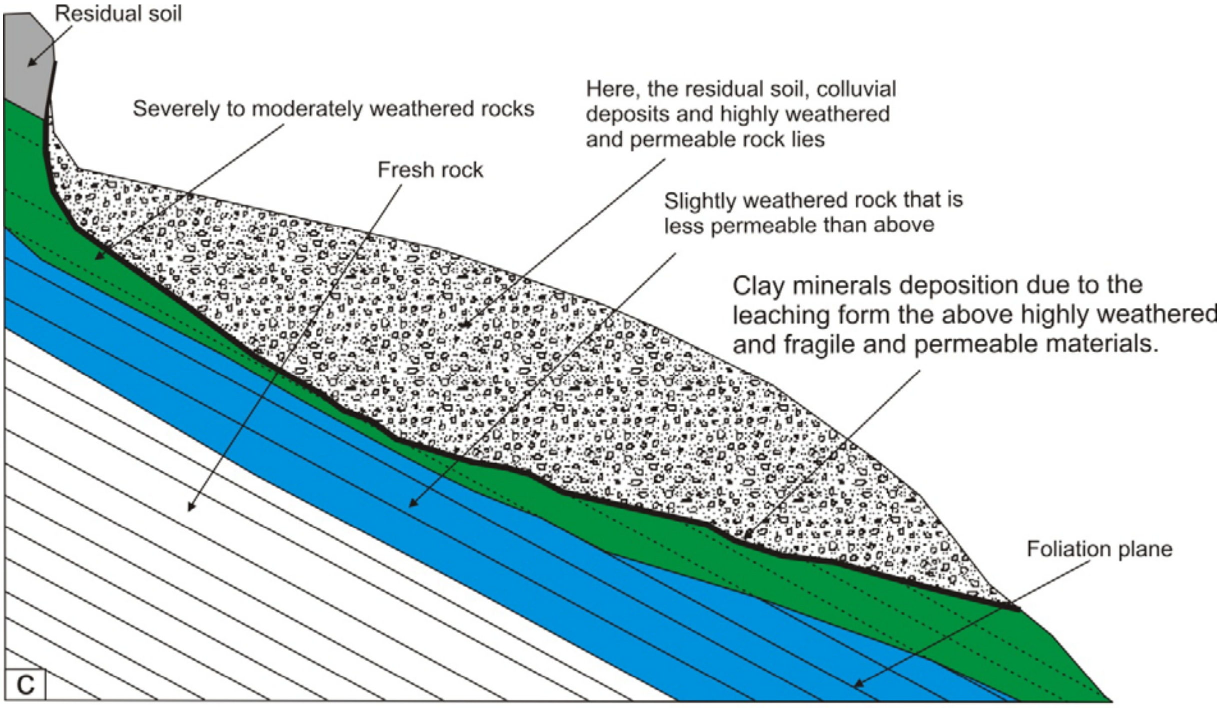
Fig. 11: (a) Distribution of landslides in each lithological unit (b) Landslide density in each lithological unit. (c) Distribution of landslides with the increasing fault distance in Mugling-Narayanghat road corridor and its surrounding area (d) Landslide density in every fault distance zone.



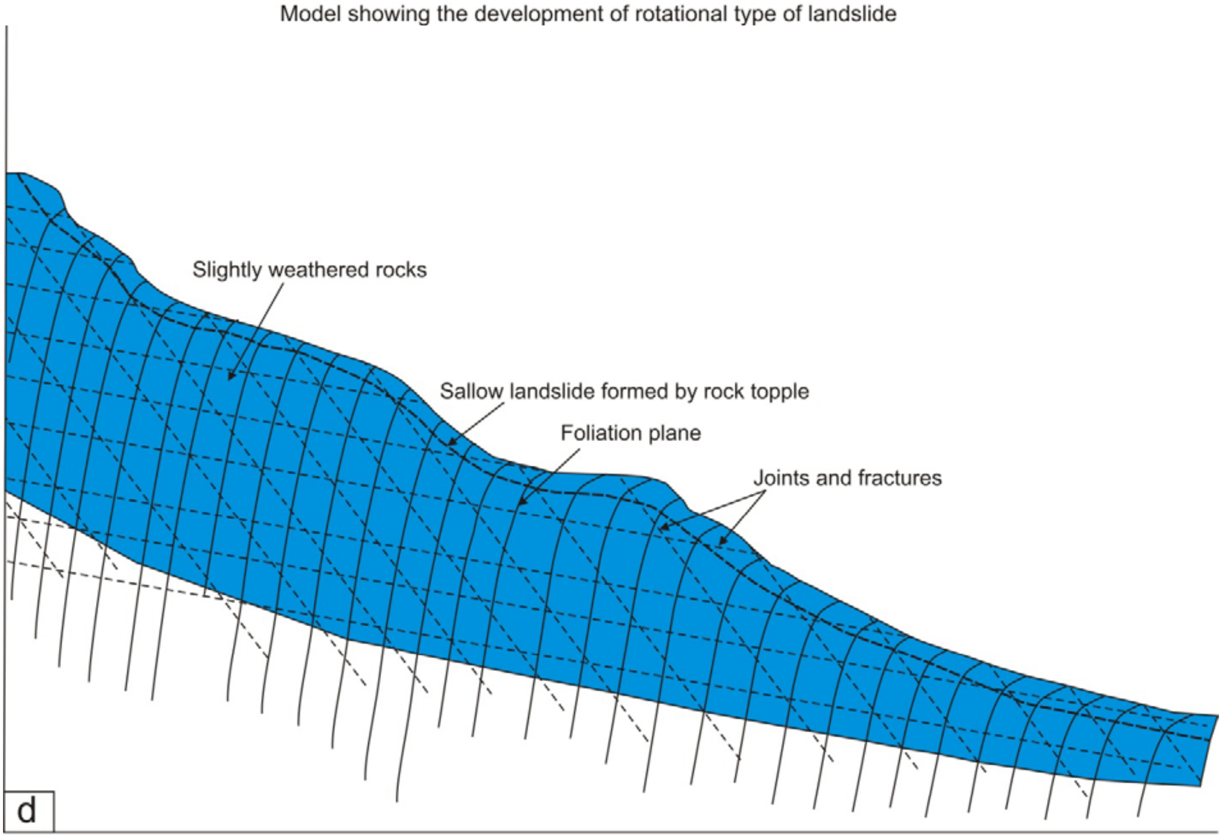
Model showing the development of large complex landslide



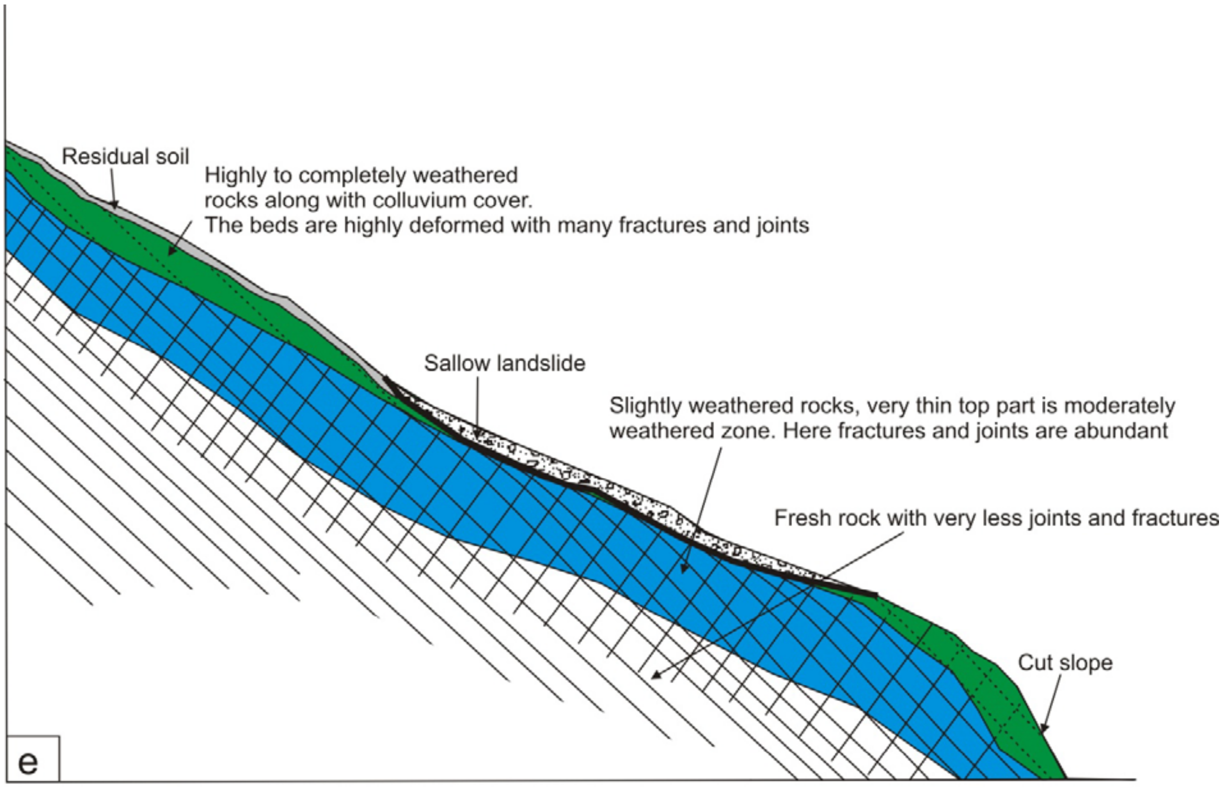
Model showing gravitationally induced complex landslide



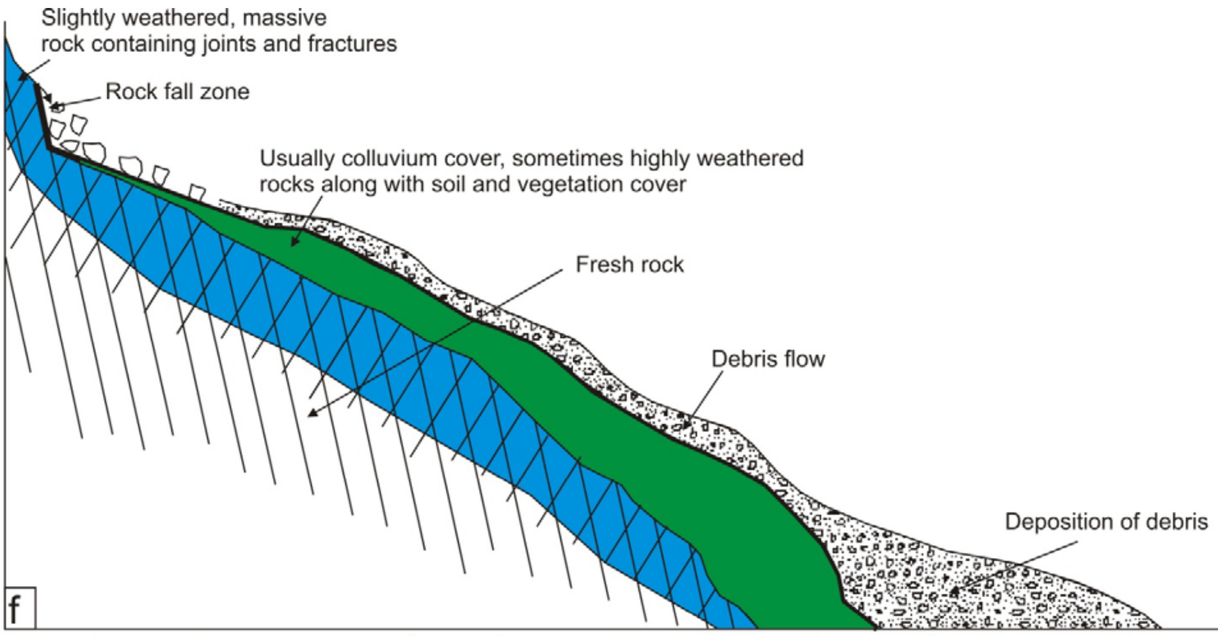
Model showing the development of rotational type of landslide



Model showing development of sallow landslide formed by rock topple



Model showing the development of sallow landslide



Model showing the development of debris flow, in some cases, except the rock fall at the top part, all other features are similar

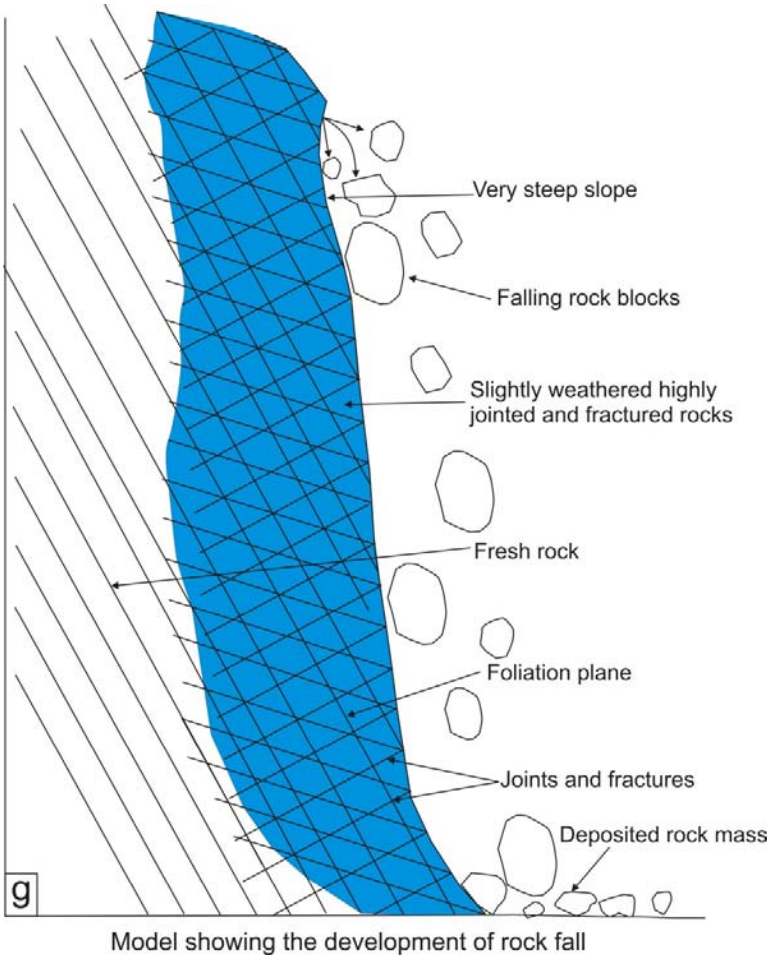


Fig. 12: Models showing different types of landslides occurring at Mugling–Narayanghat road section and its surrounding area and their relationship with general geology and rock weathering (a) Large scale complex landslide, (b) Large and complex landslide formed due to gravitational deformation, (c) Rotational type of landslide, (d) Sallow landslide formed by rock topple, (e) Sallow landslide in colluviums covered slope, (f) Rock fall at the upper slope and debris flow down-slope, and (g) Rock-fall in very steep slope