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Effect of geological structures, rock weathering, and clay mineralogy in the formation of various landslides along Mugling-Narayanghat road section, Central Nepal Himalaya

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Abstract

The present study was conducted on the landslide prone area around Mugling-Narayanghat road section that consists of Lesser Himalayan and Siwaliks rocks. From more than 250 mapped landslides, ten were selected for detailed study that are supposed to the representative of the whole area. Detailed study showed that large and complex landslides are related to deep rock weathering followed by the intervention of geological structures as faults, joints, and fractures. Large landslides formed by gravitational deformation are related to the rock structures, while rock weathering plays a minor role. Rotational types of landslides are observed in weathered rocks, where the dip direction of the foliation plane plays a principle role. Shallow landslides are common in slopes covered by residual soil or colluviums. Some shallow landslides (rock topples) occur in less weathered rocks where the attitude of the foliation plays a major role, while others (rock plane failure) occur in cut slopes with less weathered rocks. Debris slides/flows occur in colluviums or residual soil covered slopes. In few instances, rock fall may occur on the upper slope, which then is mixed with the colluviums, residual soil, and other materials lying downhill and come down as debris flow. Rock falls are mainly related to the joint pattern and the slope angle and are found in less weathered rocks.

Introduction

Landslides are one of the most catastrophic natural hazards occurring in many areas of the world. Globally, they cause hundreds of billions of dollars in damage and hundreds of thousands of deaths and injuries each year (Aleotti and Chowdhury 1999). 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. Since Nepal occupies a major portion of the Himalaya, it has always been recognized as the area prone to natural hazards, e.g., earthquakes and landslides. In addition to the importance of these landslides for infrastructures and properties, they have had a marked effect on the lives of local people and have been a cause of many socio-economic problems including deforestation and intensive agricultural practices etc. (Dwivedi et al. 2007). Each year more than 350 people lost their lives from landslides, floods, debris flows, and related phenomena according to the data provided by the Ministry of Home.

Landslides and related disasters occur frequently in Nepal Himalaya. Recently many literatures have been published form Nepal Himalaya in the field of landslide hazard mapping (e.g. Brundsen et al., 1975 ; Kojan, 1978 ; Wagner, 1981 ; Kienholz et al., 1983 ; Kienholz et al., 1984 ; Deoja et al., 1991 ; Dhital et al., 1991, 2006 ; Dangol, 2000, Dahal et al. 2008a, 2008b, 2012 ; Regmi et al. 2010 ; Regmi et al. 2012, Devkota et al. 2012). Also, some studies have been undertaken to understand the mechanism and process in landslide formation (e.g. Laban 1979 ; Selby 1988 ; Ives and Messerli 1981 ; Caine and Mool 1982 ; Wagner 1981 ; Heuberger et al. 1984 ; Burbank et al. 1996 ; Upreti and Dhital 1996 ; Gerrard 1994 ; Gerrard and Gardner 2000 ; Chalise and Khanal 2001), but there exists only very few literatures from Nepal focusing on the role of rock weathering and geological structures in the formation of landslide. 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 is thought to be very helpful to know the main cause of landslide in the mountainous country like Nepal.

The Mugling-Narayanghat highway is the only road section connecting Terai and India with Kathmandu, the capital of Nepal. Landslides and related phenomena have become a regular issue along the road section. As most part of the road section runs through the right bank of the Trishuli River, river toe cutting and debris deposition by cross drains are the major issues making the road section very vulnerable (Adhikari 2009). Heavy precipitation during 29-30 July 2003 severely damaged the Highway, closing it for continuous six days, which have created numerous landslides, slope failures, rock falls and debris falls/flows killing several people and livestock. The 24 hour precipitation as recorded at Bharatpur, Devighat and Shankher (Marsyandi Powerhouse) stations were 346mm, 446mm, and 270mm respectively (Adhikari 2009). More than 250 different types of landslides were identified and mapped along the road

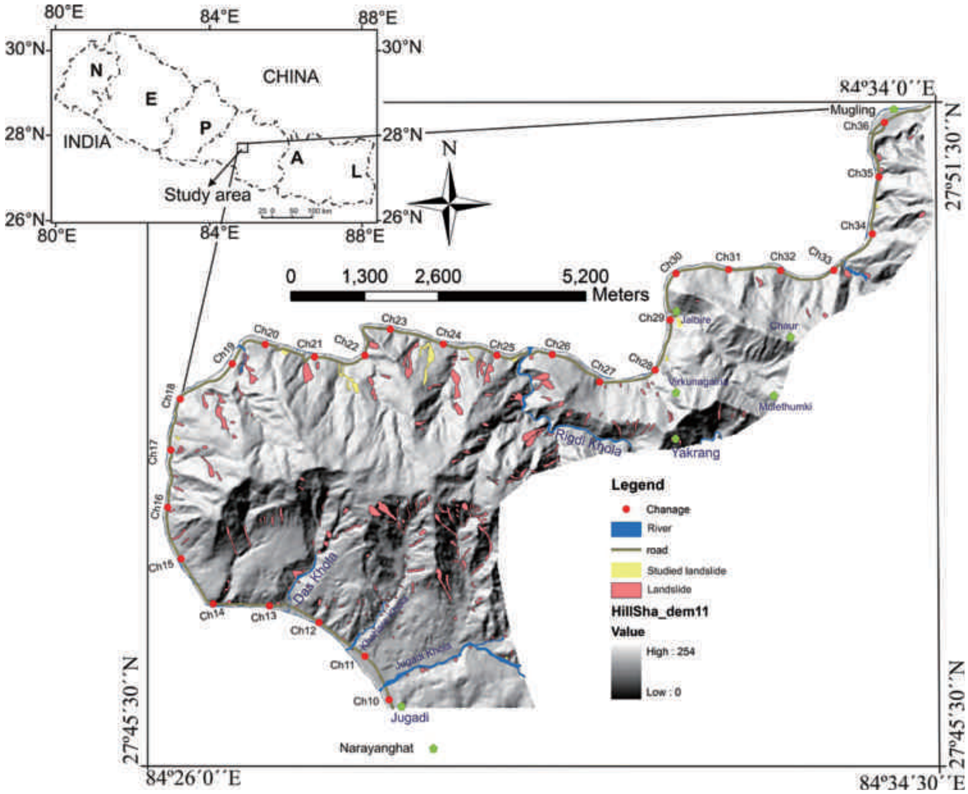


Fig.1 : Map showing the study area along with the distribution of landslides, including the landslides selected for detail investigation

corridor and its surrounding area.

The research problem was to produce a simple model that can effectively define the different types of landslides occurring along the road section and its surrounding regions in terms of general geological situation and rock weathering. These models are thought to be applicable in other parts of the Himalaya as well. For this, an attempt was made to know the relationship between rock weathering and geological structures in the formation of landslides along the highway and its adjoining region. It deals with the role of rock weathering and geological structures in the formation of different types of landslides and it describes the causes of failure together with the mineralogical and geochemical characteristics of rocks and soils comprising the landslide zone. The study involved detailed fieldwork and laboratory analysis of rock and soil samples collected from the landslide zone and its surrounding regions. A fivefold weathering grade scheme proposed by the Unified Rock Classification System (modified from Williamson, 1984 ; Geological Society Engineering Working Party 1997 ; and Hoek and Bray, 1997) was adopted to classify the degree of weathering of rocks

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 fresh rock
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	

in the landslide zone (Table 1).

The study area

Mugling-Narayanghat Highway, one of the major Highway of Nepal connects the Terai plains with the capital and other central and western mountain districts. This road is very essential in order to transport foods, commercial and industrial goods to the Kathmandu valley, where nearly 2.5 million people reside. It is also the main trade and transport rout between Nepal and India ; hence, this very important road governs the day-to-day economy. The Highway that is highly prone to landslides and is located in a mountain range between Narayanghat and Mugling of Chitwan Districts, Narayani Zone, Central Nepal. It is one of the vital links of the strategic road network of Nepal and lies within longitude 84°25' 00'' E to 84°32' 30'' E and latitude 27°45' 00'' N to 27°50' 00'' N (Fig. 1) and covers an area of about 45 km^2. It falls within the topographical map 2784-03C (Mugling) and 2784-02D (Jugedi Bajar) (Survey Department, Government of Nepal 1995).

Physiography

The area including Mugling-Narayanghat road corridor and its surrounding region consist 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 from 200 m at Jugedi Bazaar to 1380 m in between Chaur and Thulethumki. The drainage system in the area consists of Judedi Khola, Khahare Khola, Das Khola and Rigdi Khola. All these rivers, along with their tributaries confluences with the Trishuli River just below the highway (Fig. 1). The southern part of the study area is mostly covered by the river terraces formed by the Trishuli River and its tributaries (Fig. 2). Gentle slopes are

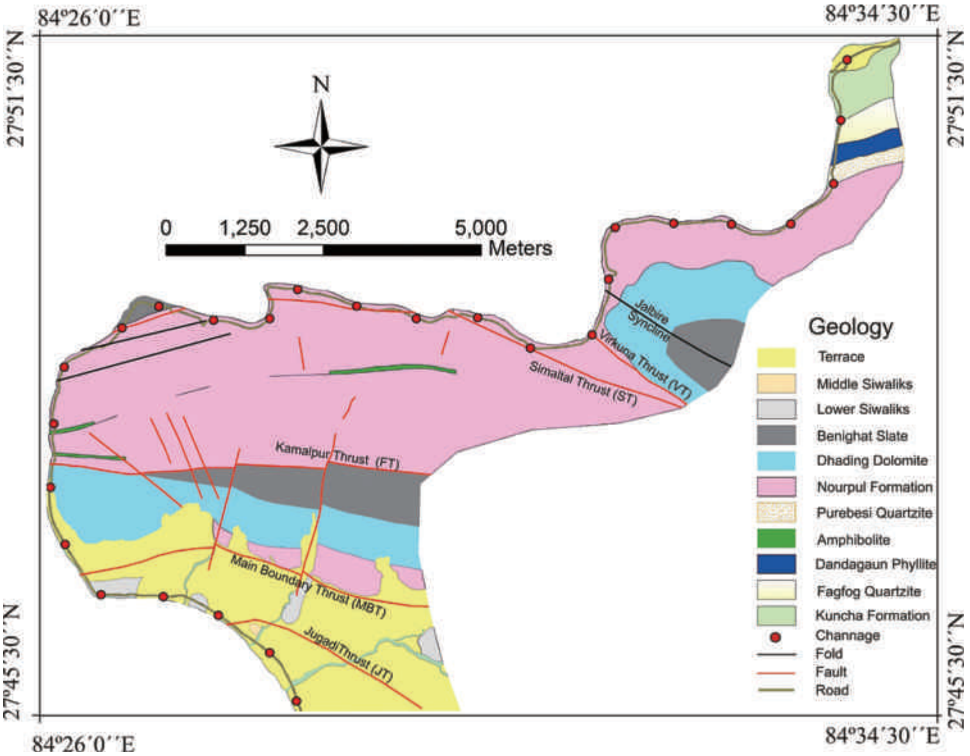


Fig. 2 : Geological map of the study area along with landslide distribution

created by the Siwaliks and the terraces, while steep slopes are observed in the rocky outcrops Lesser Himalaya. The study area belongs to sub-tropical to temperate climatic zone where the winter temperatures range from 6 to 25°C while in summer, they vary from 25°C to 40°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°C in May 2004 and a mean annual rainfall of 2650 mm (DWIDP 2009). April, May, and June are the hottest months, with average maximum temperatures of 37.8°C, 39.3°C, and 38.6°C, respectively. As in 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 too records its maximum value, whereas the temperatures are lower compared with the pre-monsoon period.

Geology

The Nepal Himalaya is located in the central part of the 2400 km long Himalaya and covers about one-third (800 km) of the whole Himalaya range. Like the other portions of the Himalaya, the Nepal Himalaya is also divided into the following five major tectonic zones from south to north, respectively (Gansser, 1964 ; Hagen, 1969).

Indo-Gangatic Plain (Terai)

…………… Himalayan Frontal Thrust (HFT)……………

Sub-Himalaya (siwaliks)

…………… Main Boundary Thrust (MBT)……………

Lesser Himalaya

…………… Main Central Thrust (MCT)……………

Higher Himalaya

…………… South Tibetan Detachment Fault System (STDFS)……………

Tibetan-Tethys Himalaya

These tectonic zones are separated from each other by thrust and fault boundaries. The thrust system in the Nepal Himalaya includes the Himalayan Frontal Thrust (HFT) between Siwaliks and Indo-Gangetic Plain, the Main Boundary Thrust (MBT) between the Lesser Himalaya and the Siwaliks, the Main Central Thrust (MCT) between the Higher Himalaya and the Lesser Himalaya, and the South Tibetan Detachment Fault System (STDFS), which is a gravity driven normal fault.

From the structural and geological points of view, the Mugling-Narayanghat road passes through the Precambrian Lesser Himalayan rocks of Nawakot Complex (Stöcklin and Bhattarai 1978, Stöcklin 1980), the Miocene Siwaliks and Holocene alluvial deposits (Fig. 2). The Nawakot Complex is divided into the Lower and Upper Nawakot Group, and along this road section, the rocks from both groups are exposed. The Kunchha Formation, Fagfog Quartzite, Dandagaun Phyllite, Nourpul Fommation, and Dhading Dolomite are from the Lower Nawakot Group, while the Benighat Slate represents the Upper Nawakot Group. The Purebesi Quartzite Member is a distinct quartzite zone, overlying the phyllites of the Dandagaun Formation and forms the basal part of the Nourpul Formation. Besides these, some amphibolites bands are also observed within the Nourpul Formation. The Siwalik Group in the study area consists of Lower and Middle Siwaliks. The Holocene deposit consists of the river terraces of different ages (Table 2). The main rock types are mudstone, sandstone, limestone, dolomite, slate, phyllite, quartzite and amphibolites (Table 2). The majority of instabilities were observed within the Nourpul Formation and the Puribesi quartzite. The highway between km 23 to km 28 lies within thrust affected weak zone, where thick colluvial soil along its slope and plenty of seepage is observed.

The main geological structure that demarcates the study area is the MBT (Main Boundary Thrust). It separates the Lesser Himalaya and the Siwaliks (Fig. 2). It crosses the highway near around Km 14, south of the Phwatar and runs east-west. As the MBT is one of the major thrusts in the Himalaya, it plays the major role on slope instabilities. The area has three other thrust faults in the north of the MBT (Fig. 1) and one in the south of it. In this study area, they are named as the Kamalpur Thrust (KT), which crosses the highway at Ch16+700, the Simaltal Thrust (ST), which crosses the highway at Ch23+00 and the Virkuna Thrust (VT), which crosses the highway at Ch27+600 and passes to the south-east along the Virkunagaira and meets the ST somewhere south of Yakrang. Jugedi Thrust (JT) is the only thrust lying to the south of MBT, which passes from Jugedi village. ST and VT have a common root zone (Devkota et al. 2012). In addition, there are a large number of normal faults, which are in local and regional in extent. ST and VT 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. 2).

Methods and techniques

Standard geological and geomorphologic field techniques were implemented for the present study. The geological map of Central Nepal (by Stocklin and Bhattrai, 1978) was used to collect the data relating the lithology, morphometry and geological structures. They were modified where needed by detailed field work. 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. The landslide inventory map was prepared using earlier reports, aerial photograph interpretation and field surveys. Form this more than 400 landslides were identified and mapped, out of which 10 landslides representing the whole study area were selected for detail studies. These landslides were mapped in detail. Arc GIS 9.3 was used to know the number of landslides and their density within each lithological unit, also the number and density of landslide within certain fault distance was calculated using Arc GIS and Microsoft excel. Different parameters as slope angle, altitude, lithology, soil and rock types and the hydrogeological characteristics of each landslide zone was 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, X-ray diffraction (XRD) of clay minerals separated by a density method, X-ray fluorescence (XRF), and various other analytical techniques. These techniques were used to trace mineral alterations leading to the evaluation of bulk changes in the whole rock during

Table 2 Table showing the different formation observed along Mugling-Narayanghat road section and its surrounding area

		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 black slate.
		Nourpul Formation	Late Pre Cambrian	Predominantly phyllitic, but contains a variable amount of quartzitic and calcareous intercalations and dolomites and dolomitic quartzites
		Purebesi Quartzite	Late Pre Cambrian	Purple quartzite
		Amphibolits		Thin beds of greenish amphibolites
		Dandagaun Phyllites	Late Pre Cambrian	Uniform argillaceous to finely quartzitic phyllites of dark blue-green color
		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 are present in quartzite.
		Kuncha Formation	Late Pre Cambrian	Alternation of phyllites, phyllitic quartzites and phyllitic gritstones resembling greywakes

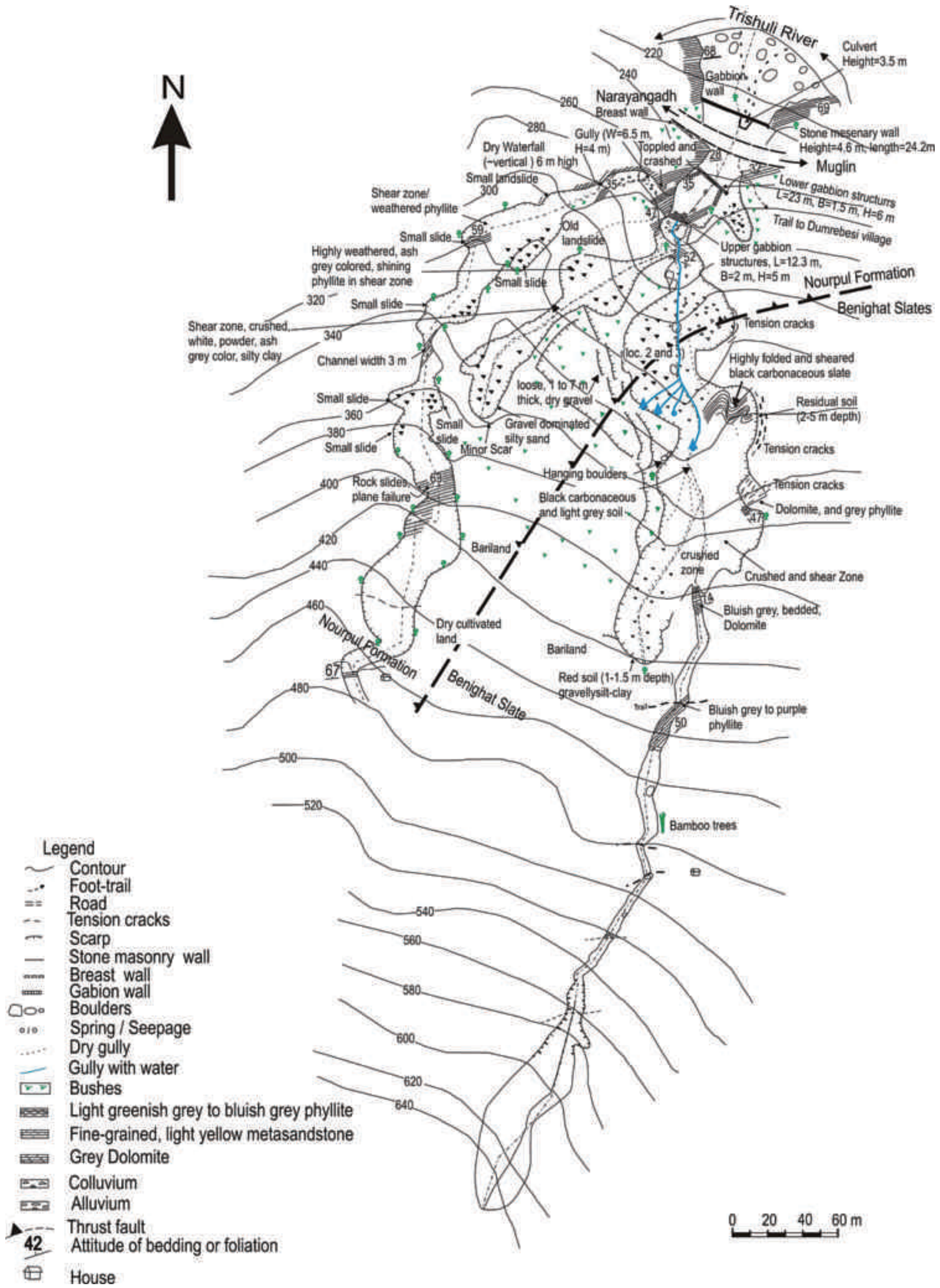


Fig. 3 : Map showing the detailed features of the landslide of Dumre Besi

its weathering. Thin sections were made from all the collected rock and soil samples. These thin sections were then carefully observed under the optical microscope in order to know the general mineralogy of the samples. 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-monochromatised 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°to 40°2θ steps size and 2 counting time per second. Various methods were adopted to know the mineralogy of the rock as well as to know the different types of clay minerals present within the rock and soil samples. Clay samples were analyzed by oriented aggregate method, after glycol treatment, after HCl treatment, and heat treatment.

Detailed Descriptions of landslide

From all the mapped landslides, 10 landslides representing the whole study area were selected for further studies. Out of the 10 landslides, 9 are from the Lesser Himalaya and one is from the Siwaliks. The location of the selected landslides in the study area is shown in fig. 2. Detailed description of each landslide is given below.

Dumrebesi Landslide

The Dumre Besi landslide is one of the most active landslips in the Mugling-Narayanghat road section (Fig. 3). It was first recognized during the 2003 monsoon rainfall. At first a small landslide developed below Dumre Besi, near the Simaltal village, and the debris from the failure obstructed the highway. In the same year, many more landslips were initiated in this highway stretch resulting into its blockage for several days. Since then, the road has been experiencing partial closures (from a few hours to several days) in every monsoon season due to the Dumre Besi and other instabilities.

The Dumre Besi landslide has two large scarps developed in each of the tributaries of the Dumre River and they coalesce downstream to form a single complex failure (Fig. 3) 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. Its upper part is covered by soil with some sparse vegetation, whereas the central zone, from where the thrust passes, contains thick landslide debris with sporadic exposures of severely weathered rock, and the lower portion includes some rock outcrops exhibiting slight weathering.

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. These sandstones commonly contain tension cracks filled with quartz veins. The phyllites and slates are fresh to slightly weathered, while the sandstones show no sign of weathering. The rocks

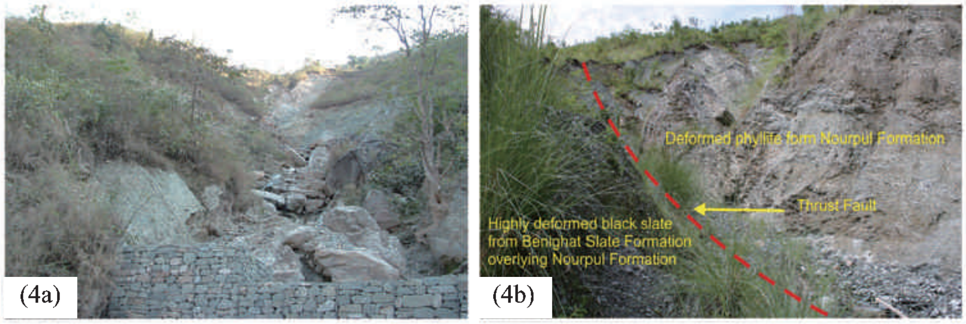


Fig. 4 : (a) Large boulders (up to 7 m in diameter) observed in the debris along the channel draining the landslide (View towards south) (b) Thick crushed zone developed along the thrust, view towards south

constituting the central part of the landslide are mainly light grey to dark grey phyllites alternating with a few thin metasandstone bands.

About 130 m uphill from the road, on the left bank of the stream, highly sheared light to dark grey phyllites are observed. The sporadic boulders lying in the gully are composed of highly weathered, fine-grained, greenish grey sandstones and folded black carbonaceous shales. 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 crop up whereas the channel is covered by large (up to 7 m across) boulders (Fig. 4a).

The area is wet and there are many springs and seeps. Most of the boulders are of coarse-gained grey sandstone. The matrix between the large boulders is composed of highly weathered greenish grey siltstone and black carbonaceous shale. About 7 m deep colluvial slide occupies the right bank of the gulley. The landslide mass is made up of gravel, with grains ranging in size from 0.2 to 2 m and composed of greenish grey siltstones and phyllites. There are also some highly fractured and weathered rock exposures (Fig. 4b). The second tributary of the Dumre River, situated about 40 m uphill side from the road, 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°/39° NE and 140°/47°NE in the Nourpul Formation and between 250°/78° NW and 251°/74° NW in the Benighat Slates. There are two prominent joint sets (J1=190°/45°SE and J2=118°/56° SW) in the Nourpul Formation.

The Benighat Slates and the Nourpul Formation crop out in the upper part of landslide. The Benighat slates consist of slightly weathered, light grey slates interbedded with light grey laminated dolomites, highly jointed and fractured light

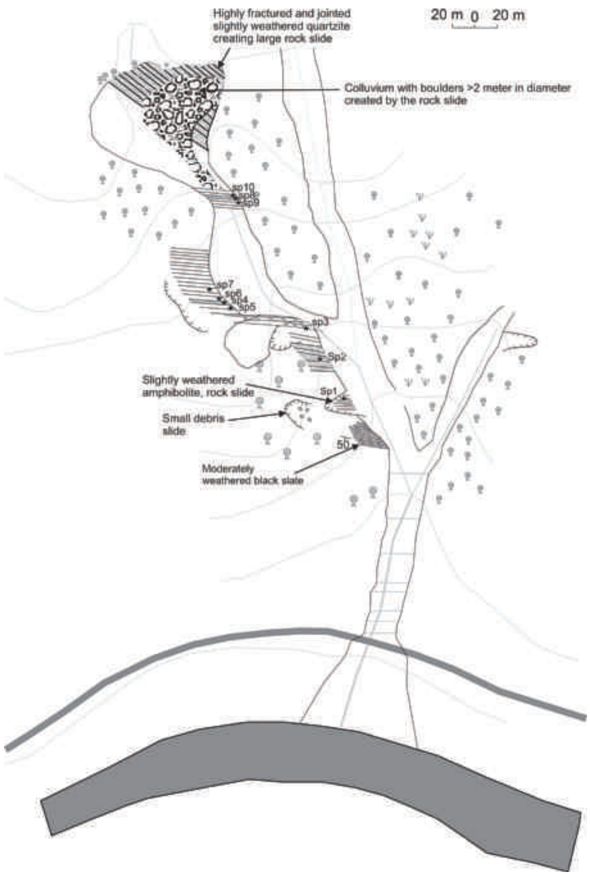


Fig. 5 : Map showing the detailed features of Maure Khola landslide

grey phyllites and sandstones. The attitude of bedding is about 230°/74° NW. The Nourpul Formation is made up of slightly weathered light grey to white, laminated, shiny phyllites and metasandstones.

The thrust fault that passes through the central part of the landslide has created a thick (more than 15 m) crush and shear zone (Fig. 4b). Since the rocks are much deformed in the fault zone, tightly folded to sheared black carbonaceous slates can be seen near the thrust (Fig. 3). This is the major source of debris in the stream. The rocks around the thrust are mainly light grey to white deformed phyllites and black carbonaceous slates. As these rocks are almost completely disintegrated to yield white clay-rich powdery mass, the water flowing through them is always turbid.

Maure Khola landslide

Among several gravitationally deformed zones observed along Mugling-Narayanghat road section, the Maure Khola landslide is the most active one (Fig. 5). The rock debris that was generated by the landslide mobilized into a disastrous debris flow in the summer of 2006 damaging the Highway Bridge, and creating many problems. It is a big landslide (Length ≥ 300 m, breadth = 100 m and depth = 8 m), characterized by a combination of rock topple and debris flow. 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 deposits of debris that were brought form the upper part (Fig. 6a). It is mainly the depositional zone of the landslide. Here the debris is more than 5 meters thick and it covers the entire valley. The volume of this debris is about 60,268 m^3. 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. The average slope of the channel here is about 22.5°and it is about 30 m wide. Many gabion walls have been constructed here to protect the road and the bridge downstream. The first gabion wall is constructed at a distance of 15 m form the road section. Many gabion walls have been constructed here to protect the road and the bridge downstream (Fig. 6b). The first gabion wall is constructed at a distance of 15 m from the Highway and others are located at a distance of 10–15 m from each other (Fig. 6b).

The central part of the landslide mainly consists of debris deposits in the channel while small landslides in the valley walls (Fig. 6c). Here, highly fractured, moderately weathered black slates with some quartz veins are observed. Moderately weathered greenish phyllite is observed above the black slate. The water is observed in the stream here. Moderately weathered, highly fractured pink quartzite with phyllite parting is absorbed about 10 m upstream from the greenish phyllite (Fig. 5). There is a small rotational slide and a wedge type of failure in the valley wall (Fig. 5). The attitude of the foliation plane is 270°/74°N while that of the joints are J1 = 350°/75°NE, J2 = 145°/57°SW. The joint spacing is from 20 cm to more than 1 m. These joints are responsible for the rock slide 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. The fractured and jointed nature of the amphibolite is the reason for the presence of these boulders. There are several sheared zones in these amphibolites and quartzite, making them susceptible for toppling. These sheared zones are the most unstable zone here and landslides are occurred in such zones. There are many slicken sides in the rocks showing some kind of movement. Many gabion walls have been constructed here to stop the debris flow.

The main landslide is located in the upper rich of the slope (Fig. 5). Here mainly rock topple is observed in the amphibolites and slate/phyllite (Fig. 6d) at the western part as well as in the quartzite lying in the in the southeastern part (Fig. 6e). Slate show moderate weathering, while quartzite and amphibolites is not much weathered. 2 m

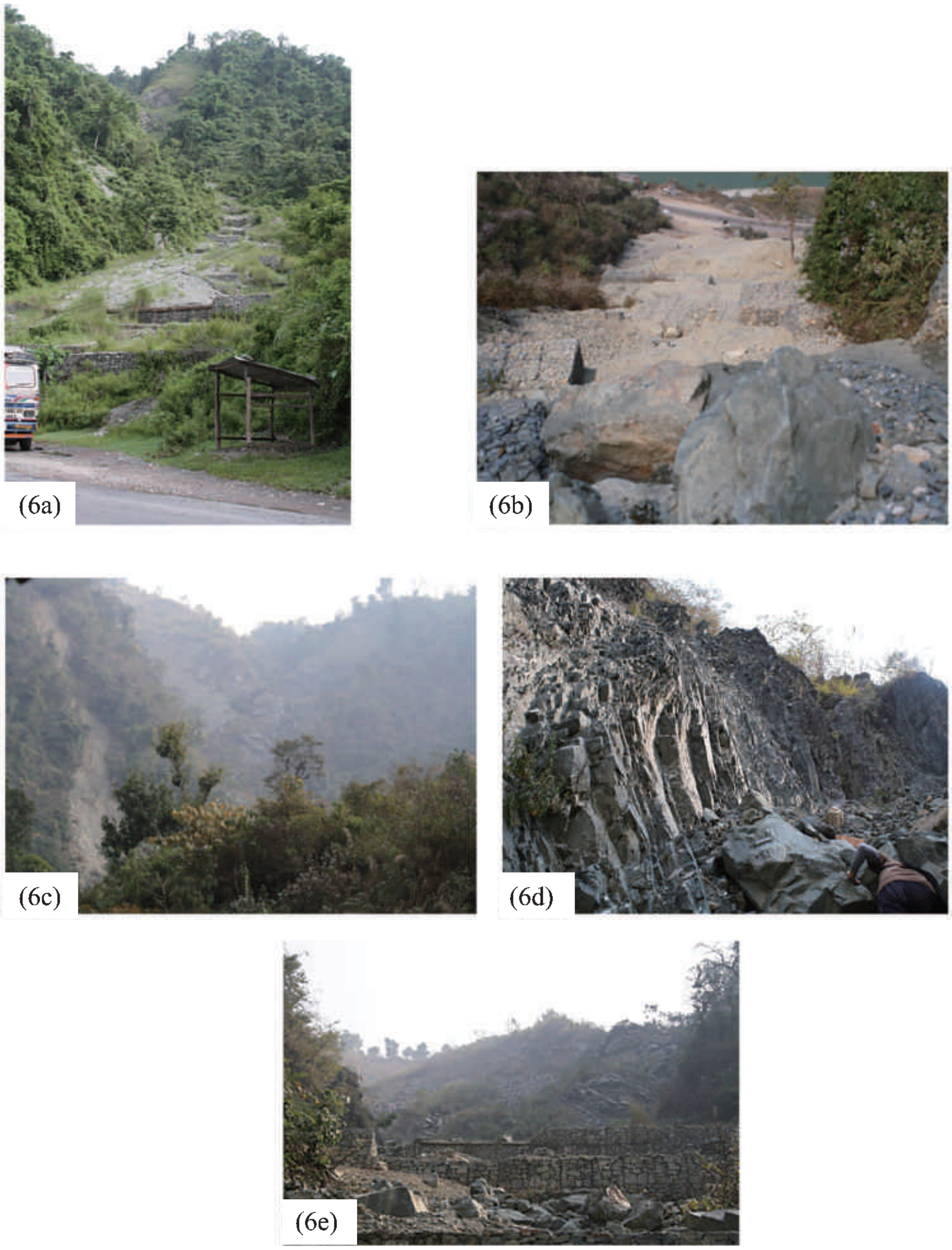


Fig. 6 : (a) The debris fan in the bottom part of the landslide just above the highway, (b) several gabion walls used to control the debris, (c) small landslides observed in the wall of the main landslide, (d) toppled rocks observed in the upper part of the landslide, (e) General view of the top part of the landslide

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°degree. 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, when condition favors, 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. The rocks in the landslide zone are highly ruptured and shear zone is developed in several places. These shear zones are very critical as the landslide develops in such zones. In addition, some minor faults are developed in these share zones. Several small-scale faults are encountered within the sliding rocks of both the slate and amphibolites. These faults act as the sliding surface. The attitude of foliation plane at this shear zone is 140°/55°E. Soft clay like material is developed in the sliding surface and its thickness is about 5 cm. This clayey substance in the sliding surface is very soft and it forms weak or permeable zones, where a favorable condition for the rock toppling occurs.

A landslide characterized by a combination of debris slide/flow, rock slide and rock topple has wrecked the area. It is about 500 m long, 70 m wide and the depth varies from 4-8 m. 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. In addition to the occurrence of discontinuities described above, there are several minor faults within the landslide, and the Simaltal Thrust (ST) passes just below it. These thrusts 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.

Gaighat Landslide

The Gaighat landslide (80 m wide, 100 m long and 5-6 m wide) is a rotational type of rock slide observed along Mugling-Narayanghat road section at Gaighat (Fig. 7a). Geologically, it consists of slate and phyllite of the Nourpul Formation. It was initiated during the monsoon of 2003 and is an active landslide. It is a medium scale landslide along the road section.

This landslide is mainly divided into 3 zones; initiation zone (source area), transportation zone and depositional zone (Fig. 7a). The source area, from where all the debris are derived is located at an altitude of 385 m. The top 2 meter is covered by residual soil. Here, the main scarp of the landslide is observed and it consists of severely to completely weathered, highly crumbled slate and phyllite. Corestone mainly composed of quartz are seen in good condition. The slope of the main scarp is 60°. The slip surface can be seen here. The altitude is variable as the rocks are highly deformed here. However the general trend of foliation plane is EW with north dip direction.

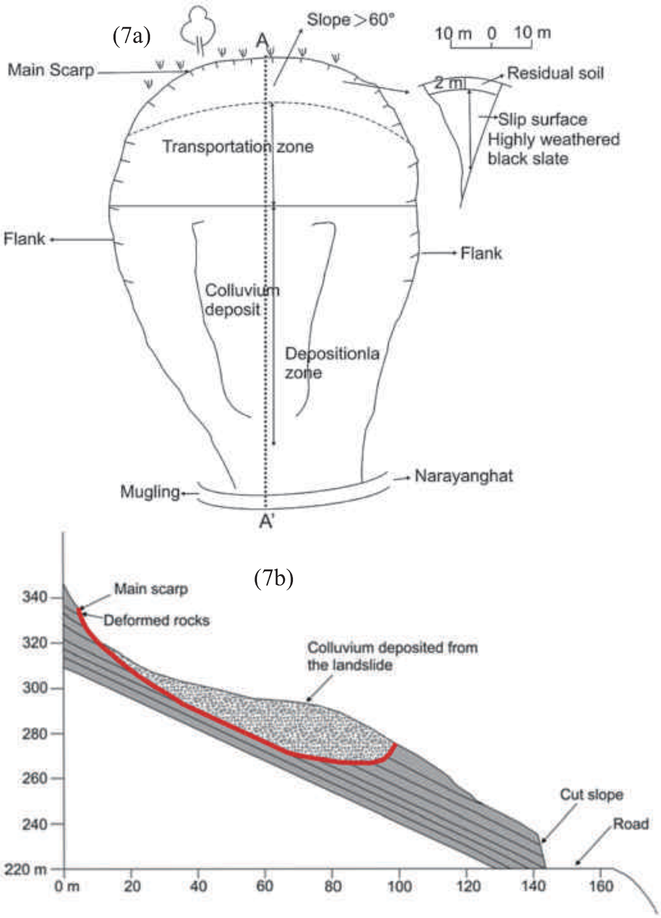


Fig. 7 : (a) Detailed view of the landslide, (b) Cross-section along A-A'

Moderately to severely weathered rocks are observed in the transportation zone that lies below the zone of source area. It is rather steep zone with only thin deposit of colluvium material. Rocks are observed at the flank of the landslide, and they are slightly to highly deformed (Fig. 7a). The undisturbed outcrops dip parallel to the hill slope with an attitude of 190°/55° N.

The lower portion of the landslide is mostly covered by thick deposit of debris material (Fig. 7a). These debris are derived from the upper slope. This is the zone of deposition. Here, no rocks are exposed. There is no role of any running water in this landslide, as there is no any stream here. The landslide is mainly caused by the rock weathering.

The cross-section of the landslide (Fig. 7b) shows that the upper part, i.e. the main scarp consists of deformed rocks. From the figure, it is clear that the landslide is related to the dip direction of the beds. Thick colluvium is observed in the lower part of the landslide. Below the landslide, cut-slope is observed from where the Mugling-Narayanghat road section passes. Also, it is seen that the slope is very unstable as the dip of the beds are parallel to the slope and the road cut has worsened the situation.

Judedi Khola Landslide

Judedi Khola (River) passes through Judedi Village along Mugling-Narayanghat road section. The monsoon of 2003 and 2006 developed several landslides and debris flow d in the upstream part of this river causing several deaths and destroying huge amount of property downstream. The bridge over the river is also in critical situation 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 rock slide about 1 km upstream from the Bridge of Jugedi Khola (Fig. 8a). The landslide is 30 m wide, 50 m high and about 50-80 cm deep. It is an active landslide. The main trigger of the landslide is rainfall and river under cutting by Judedi Khola; however, rock weathering have also a prominent role in the formation of this landslide.

It lies in the rocks belonging to the Lower Siwaliks. The main rock types are interbedding of fine-grained, light gray sandstone and variegated red to purple mudstone (Fig. 8a). 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°/40°N, J1=110°/76°NE, J2=219°/69°NW. The landslide is dissected by several gullies (Fig. 8a). These gullies are eroding the rocks very rapidly. Talus cone is observed at the lower portion of the landslide mass (Fig. 8a). 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.

The cross-section of the landslide is shown in Fig. 8b. From the cross-section, it is seen that the top part of the landslide consists of residual soil. Sandstone and mudstone are dipping at high angle. Also, it is seen that the beds are crumbled at the top part. Also, it is seen that the sandstone is highly fractured and jointed. The undercutting action of the river is also seen in the cross-section. Thus, the river undercutting followed by high dip amount of the beds, highly jointed and fractured nature of the sandstone and rock weathering all coupled to generate the present landslide.

Jalbire Landslide

Jalbire landslide is located at the uphill side of the road section near the temple of Jalbire, along Mugling-Narayanghat road corridor (Fig. 9a). Geologically the landslide belongs to the Precambrain Dhading Dolomite and Nourpul Formation. The main scarp consists of dolomites and some phyllite of the Dhading Dolomite Formation, while the lower portion, form where the maximum debris is derived belongs to the

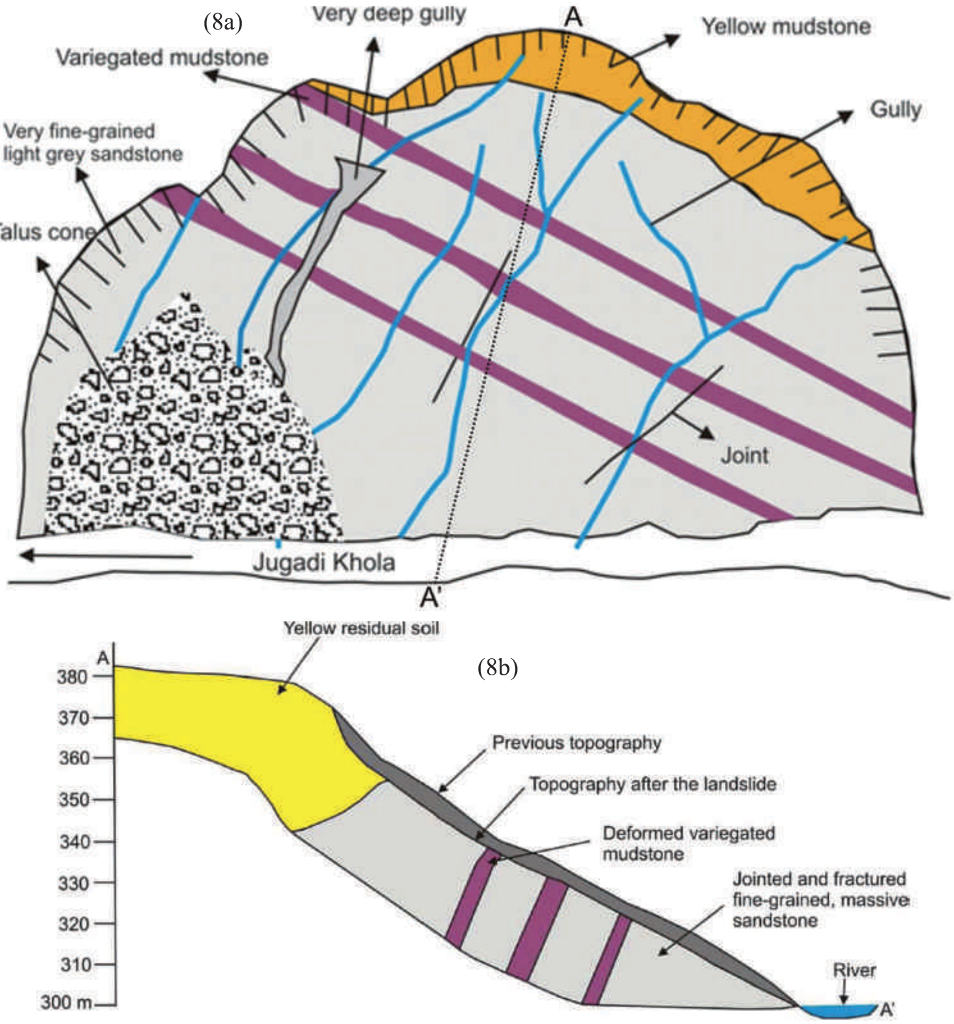


Fig. 8 : (a) Sketch showing the Jugedi Khola landslide, (b) Cross-section of the landslide along A-A'

Nourpul Formation. However, the thick debris and residual soil covers the underlying rocks, so no rock exposures are seen here. The attitude of the foliation plane is 245°/38°N, while that of joints are J1=24°/84°NW and 317°/55°NE. The cross-section shows that the upper part of the landslide consists of dark-gray to light-gray dolomite, where the rock fall occurred. The central and lower part is completely covered by the colluviums and the debris from the above landslide (Fig. 9b).

This landslide was triggered by the heavy rainfall of 2003. It is a translational type of rock slide, but develops into debris flow along the lower rich of the mountain, where several houses were destroyed (Fig. 10) and 5 peoples were killed by this landslide. The

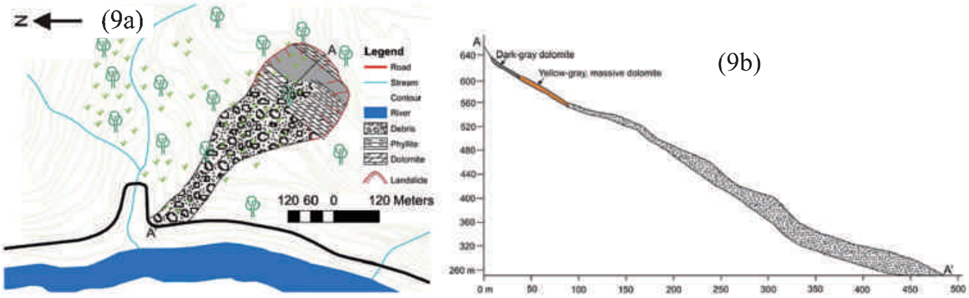


Fig. 9 : (a) Plan view of the Jalbire landslide. (b) Schematic cross-section of the Jalbire landslide

Fig. 10 : Photograph showing the damaged houses by the debris flow that occurred in 2003 at Jalbire

slope is mostly covered by vegetation and soil. The slope varies in between 20° to 60°. The lowest slope gradient is observed near the road section and the highest at the cliff, form where the rock failure occurred.

Ch28 landslide

The rock unit around the landslide belongs to the the Nourpul Formation, which consists of alternate beds of quartzite, phyllites and some carbonate beds with general attitude of 130°/30°NW. It forms the southern limb of the Jalbire Syncline. The Virkuna Thrust is located few meters south of the landslide (Fig. 2). Colluviums are distributed at the upper part of the landslide (Fig. 11a), below which rocks are exposed. The rocks are fresh to highly weathered, and are intensely fractured, jointed and deformed. Two prominent joint sets (J1=345°/30°SW and J2=EW/45°S) are developed in the rocks making it very unstable due to the random fracturing of the rocks (Fig.

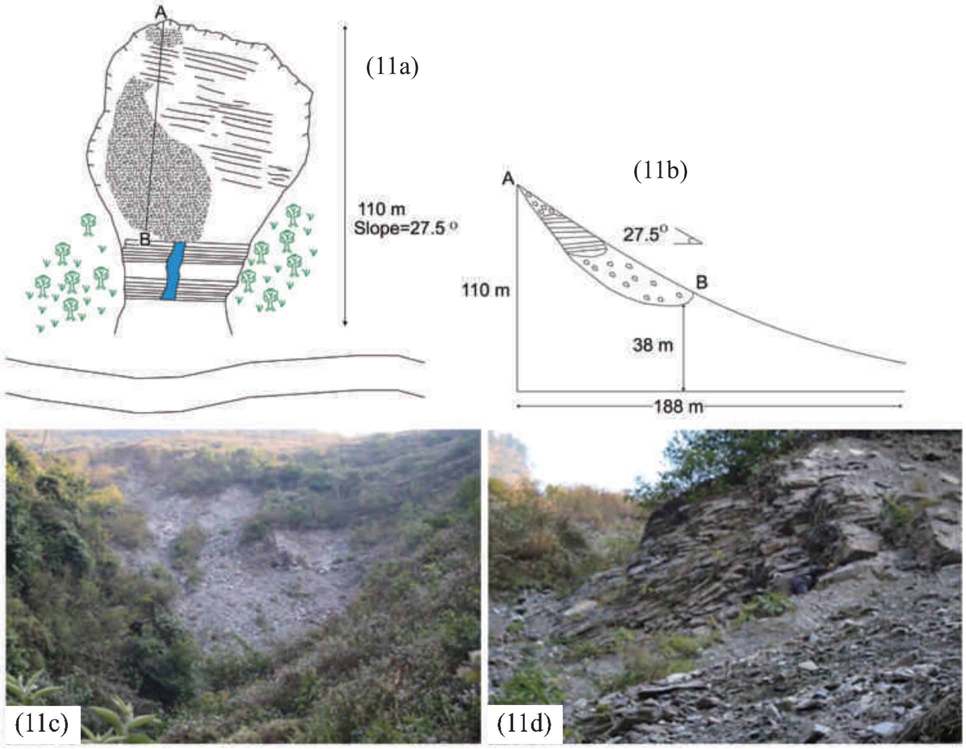


Fig. 11 : (a) Landslide observed at Ch 28 km, (b) Cross-section along A-B. (c) General view of the landslide at Ch 28 km (d) Rock exposure at the central part of the landslide

11a). The lower slope is mantled by thick (>5m) collapsed deposits consisting of coarse soil with domination of boulders and blocks and younger colluviums on the top (Fig. 11b). The collapsed deposit is believed to have formed during or following the formation of the VF. Fig. 11b shows the cross-section of the landslide. From this, it is seen that the average slope of the landslide is 27.5°. In addition, it is seen that both the top and lower portion of the landslide is covered by debris. Moat part of the landslide is seen to be covered by debris (Fig. 11c), while there exists some rock exposure at the central part consists of the rock exposure (Fig. 11d). The material in the debris ranges from clay to boulder size.

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 number of unstable blocks (Fig. 12a, b). Phyllite is exposed on the right side, which is highly weathered and behaves either like a soil or unusually fractured and jointed when

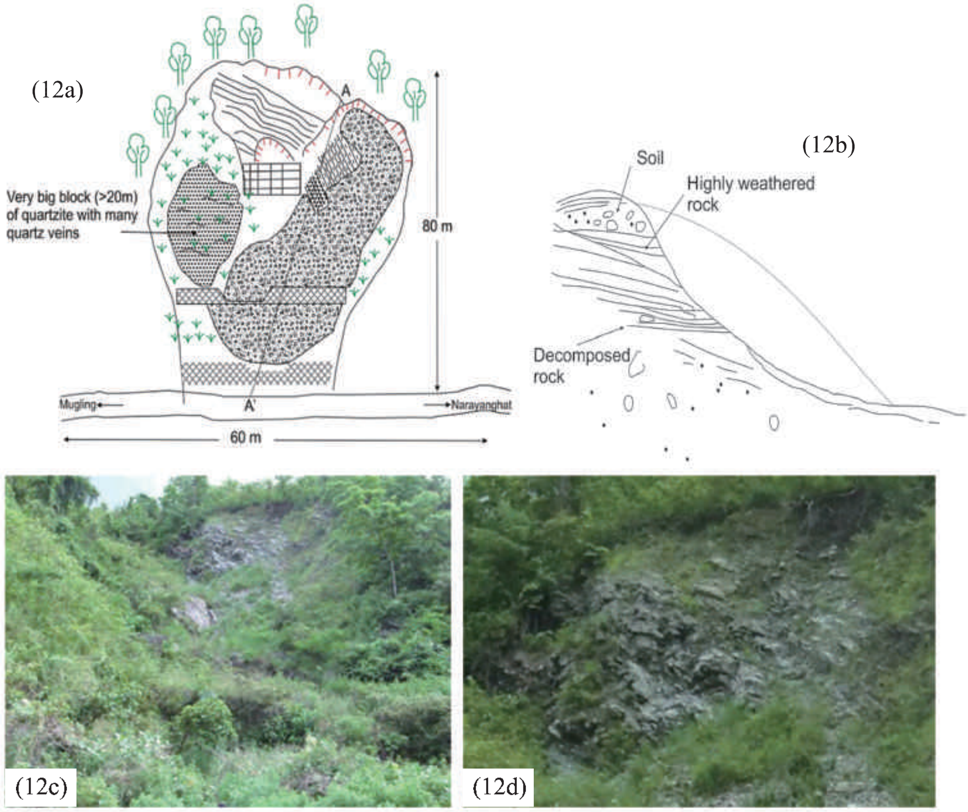


Fig. 12 : (a) Sketch showing the detailed view of the landslide observed at Ch 23.760 km, (b) Cross-section of the landslide, (c) Photographic view of the landslide at Ch 23.760 km (View NW) ; (d) Fractured and decomposed rocks observed in the landslide of Ch 23.760.

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 (Fig. 12a).The attitude of the foliation in undisturbed outcrop is dominantly 270°/72°NW and the attitude of the major joint is 220°/63°NW. Some fold structures are also seen on the slate and phyllite.

Here, mainly rock slide is observed at the upper slope of the valley and soil slides both the banks of the river (Fig. 12 c, d). As the dip slope is mantled by thick collapsed deposits consisting of coarse soil with domination of boulders and blocks and younger colluviums on the top, the failed rock along with these debris flow down as a debris flow in every monsoon season. Although some engineering structures are constructed (Fig. 12c), and are protecting the slope from failure to some extent in some parts, the landslide still seems active and highly hazardous both for the village located up slope and road below.

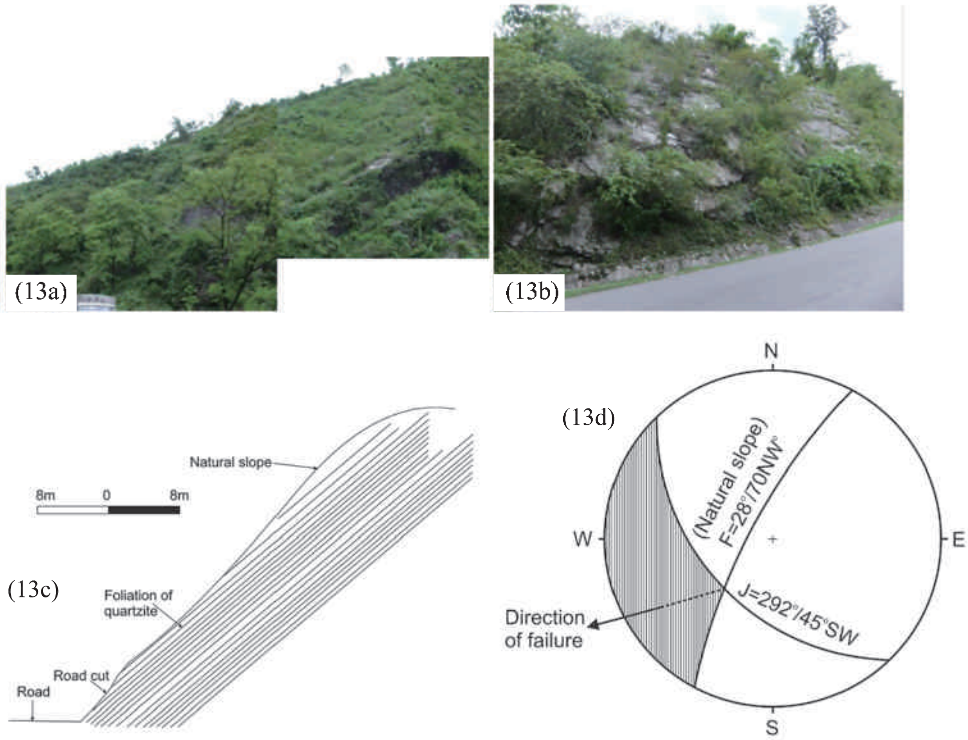


Fig. 13 (a) Photograph of the unstable rock mass at the right bank of Rigdi Khola near the bride site, (b) Photograph of the unstable rock mass at the right bank of Rigdi Khola at the bride site, (c) Sketch of the failure surface, (d) Serigraphic projection of the joint and foliation plane showing the failure surface.

Rigdi Khola rockslide

Rigdi Khola is one of the major tributaries of Trishuli River along Mugling-Narayanghat road section. Both banks of the river near the highway are in very unstable stage due to rock plane failure. The road cut along the right bank of Rigdi Khola has created unstable areas around Rigdi Khola (Fig. 13a). Here the rocks are dipping towards the road section with the similar angle as that of the natural slope. In addition the rock mass is suffered from wide opened joints (Fig. 13b). Here one gabion wall has been built to control the rock failure ; however, the foundation of the wall is very unstable (Fig. 13b). Due to the presence of these open cracks, there is a great possibility of failure of rock block including the wall.

As stated earlier, the left bank of the Rigdi Khola near the highway is also in very critical stage due to regular rock plane failure. Fig. 13c shows the rock slope that is very much suffered from rock plane failure. The main rock type is quartzite and potentially daylighted bedding conditions occur on the cut-slope making the area very susceptible for rock failure (Fig. 13c). The attitude of foliation plane is 28/74N, while

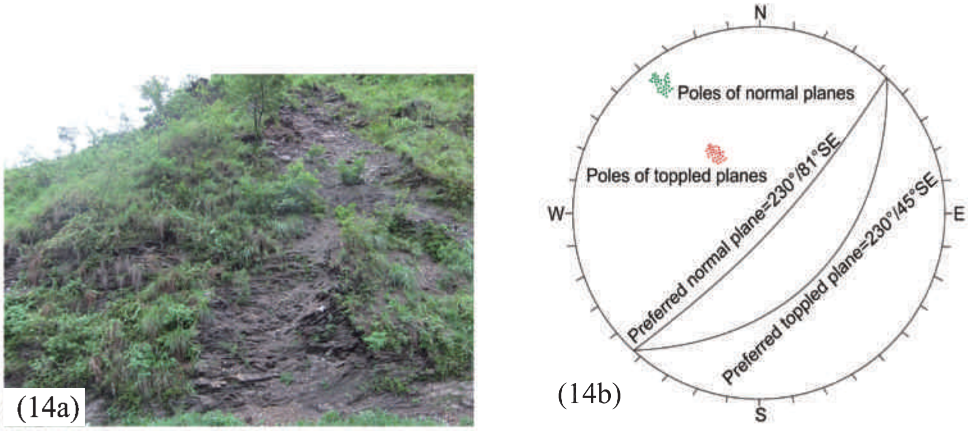


Fig. 14 (a) Photograph showing the landslide (View NW), (b) Serigraphic projection of the poles of the normal beds as well as the toppled beds and the normal and toppled planes

that of joints are ; J1=317/35SW and J2=298/44. Here, the rocks are rather fresh. Fig. 13d is the cross-section of the rock slide. Here it is seen that the rocks are dipping towards the road, and the road cut has created unstable zone.

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 Formation, and Nourpul Formation are distributed. Kalikholagaun landslide is one of them. It is lies at Kalikholagaun and is located at the Nourpul Formation. The landslide is about 20 m wide and 10 m high (Fig. 14a).

The outcrop is dominated by slightly weathered slate/phylite and few quartzites. The attitude of foliation plane at the lower slope is 233°/78°SE, while at the upper slope it is 233°/45°SE (Fig. 14b). The rocks are well bedded and the thickness of the bed ranges from 55 cm to 20 cm. The rock is light gray 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 more than 20 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. Fig. 14b shows the serigraphic projection of both the normal and toppled rocks.)

Ghaumaune 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 loss of human lives and damage of the infrastructures. Several part of the road section suffers from rock falls. One such rock fall occurred at the Ghumaune are of

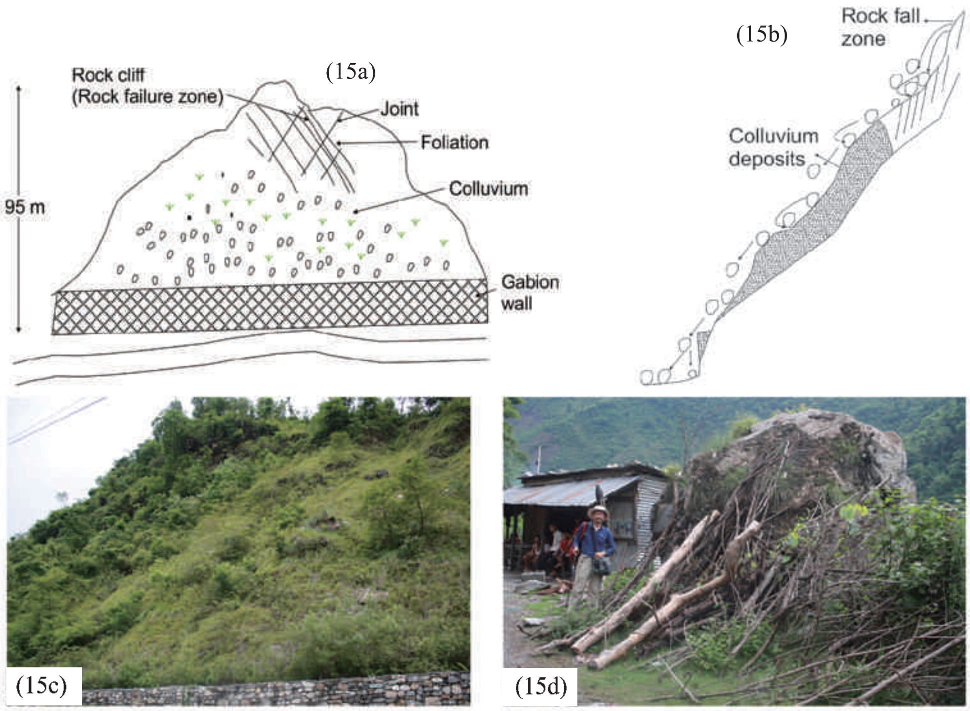


Fig. 15 : (a) Sketch showing the rock fall zone near Ghumaune of 2006, (b) Cross-section of the rock fall area, (c) Road section showing the steep cliff at Ghumaune, where rock failure occurred during the monsoon of 2006, (d) Large boulder of dolomite formed by the rock failure during the monsoon of 2006 lying on the road side.

Mugling-Narayanghat road section. This rock fall (27°49'0''N, 84°27'30''E) crosses Mugling-Narayanghat Highway along the south of Ghumaune.

This rock fall consists of rocks belonging to Dhading Dolomite 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. 15a, 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. Fig. 15b 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. 15b).

The rocks are dipping towards north east (60°-80°) with dip amount ranging from 46°to 84°. Two major joint sets are present in the rock fall site. They are J1=120°/38° and 88°/56°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 are unstable. The rockslide is occurring at the contact between dolomite and phyllite. The dolomite is rather fresh while the phyllite is weathered. Fig. 15c shows the area suffered from rock fall and the boulder that had fallen in 2006 is shown in Fig. 15d. This boulder is of dolomite and is rather fresh.

Laboratory studies

All the rock and soil samples collected in the field were analyzed in the laboratory in order to know the main mineralogical constituents, as well as the extent of weathering in the landslides. Thin section and XRD analysis of the collected rock and soil samples were performed in order to know the mineralogy of rocks and soil along with the distribution of clay minerals in these landslides and to know the formation mechanism of these clay minerals.

The main mineralogical constituents of the rocks and soil samples within each landslide zone were determined from thin section made from fresh and weathered rock samples and confirmed using XRD. Randomly oriented samples were analysed by XRD in order to know the general distribution of minerals in different parts of landslides. After this oriented specimen 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 in size. The bulk and oriented specimens were analysed with graphite-monochromatised CuKa 40 kV and 40 mA. The diffractometer was calibrated using silicon as an external standard.

Table 3 gives the general distribution of minerals in each landslide zone. From the table it is seen that most of the large landslide are rich in clay minerals, while rock fall, rock slides and rock topple are lacking any clay minerals. It is seen that the large landslides are rich in smectite, a kind of clay mineral that expands when wet (Fig. 16a). From the XRD analysis, it is also seen that many sallow landslides are rich in chlorite that is a weathered product of primary chlorite or other minerals (Fig. 16b). Also, it is seen that the sallow landslide are fond in highly weathered rocks and the weathering depth is very small. Here mainly smectite, vermiculite, kaolinite and chlorite are found (Fig. 16c). From the overall XRD analysis of rocks and soil from different landslides, it is clear that they have a prominent role in forming the landslides along the road section and its surrounding area.

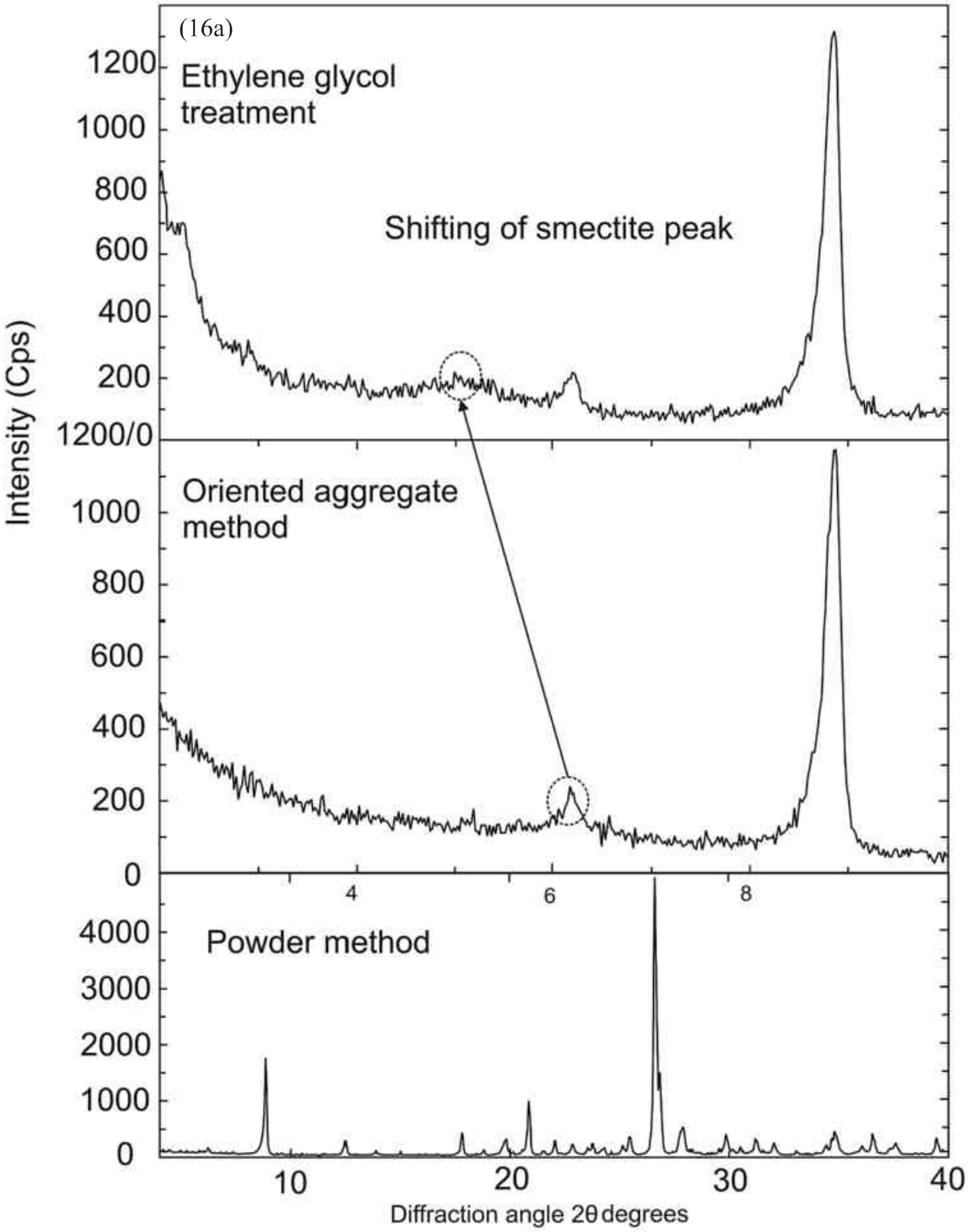
Results and Discussion

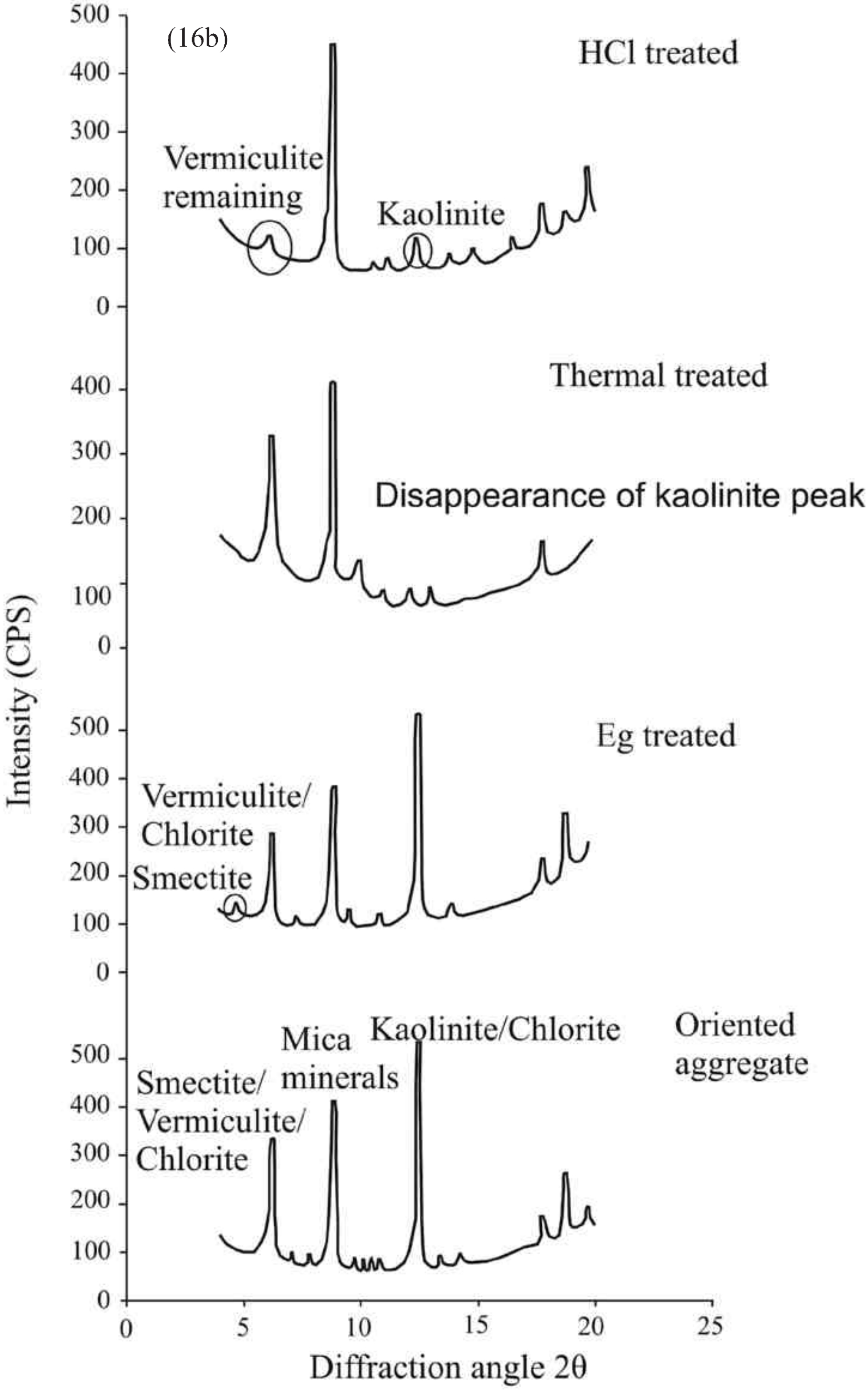
Among several landslides occurring along the Mugling-Narayanghat road section, 10 selected landslides that are representative of the whole study area are discussed in the present study. These landslides are from the very big complex slide to a smaller one, from rotational type to simple slide; from rock topple to rock fall. The present road section was selected, as it consists of a considerable number of active landslides.

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	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	++++	++	++	+++	–	+	–	–	–	–
	Slate and phyllite	Moderate to severe	++	–	+	–	–	++	–	++	–	–
Gaighat landslide	Phyllite and slate	Fresh to slight	+++	–	++	–	–	++	–	–	–	–
	Phyllite	Complete	+	–	++	–	–	++	+	+	+	–
Jugedi Khola landslide	Sandstone	Slight	++++	++	++	–	–	++	–	–	–	–
	Mudstone	severe	+	–	+	–	–	+	–	++	–	–
Jalbire landslide	Dolomite	Fresh	+++	++	++	–	++++	–	–	–	–	–
	Dolomite	Moderate	+++	++	++	–	+++	–	–	–	–	–
Ch28 landslide	Phyllite/slate and quartzite	Moderate	+++	+	++	–	–	++	–	++	–	–
	Phyllite	severe	+	+	+	–	–	++	–	++	–	–
Ch23.760 landslide	Quartzite	Slight	+++	++	++	–	–	+	–	+	–	–
	Phyllite	severe	+	–	++	–	–	++	+	++	+	++
Rigdi Khola landslide	Quartzite	Fresh to slight	++++	–	++	–	–	–	–	–	–	–
Kalikholagaun landslide	Slate and quartzite	Slight	++++	++	+	–	–	+	–	–	–	–
Ghumaune rock fall	Dolomite	Fresh	+++	++	++	–	++	–	–	–	–	–
	Dolomite	Slight	+++			–	++	–	–	–	–	–

+ Sign indicates increasing amount


(16a)
Ethylene glycol treatment
Shifting of smectite peak
Oriented aggregate method
Powder method
Intensity (Cps)
1200
1000
800
600
400
200
1200/0
0
4000
3000
2000
4
6
8
10
20
30
40
Diffraction angle 2θ degrees


(16b)
HCl treated
Vermiculite remaining
Kaolinite
Thermal treated
Disappearance of kaolinite peak
Eg treated
Vermiculite/ Chlorite
Smectite
Mica minerals
Kaolinite/Chlorite
Oriented aggregate
Smectite/ Vermiculite/ Chlorite
Intensity (CPS)
Diffraction angle 2θ
0
100
200
300
400
500
0
5
10
15
20
25

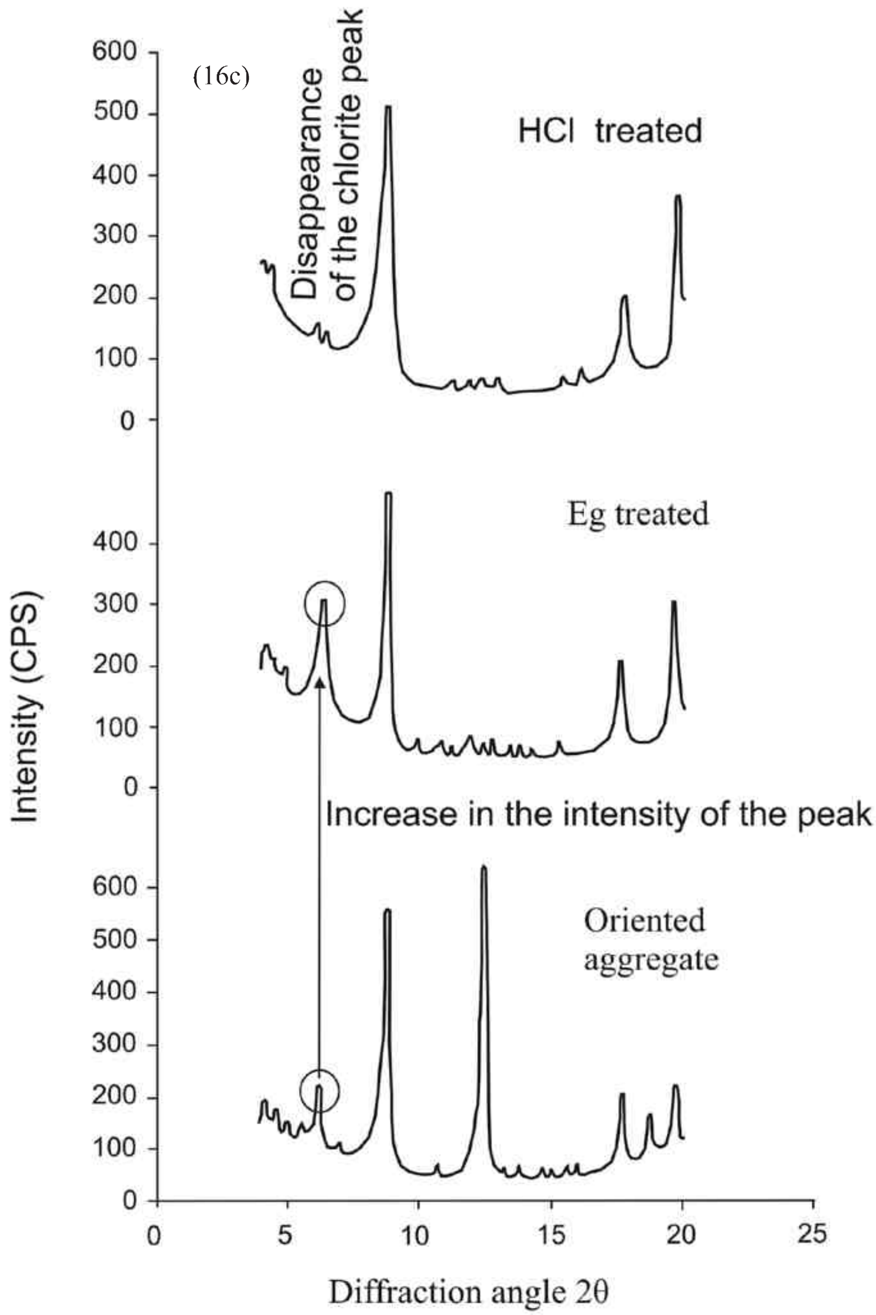


Fig. 16 : (a) Shifting of smectite peak shown by the XRD pattern of the rock sample from Dumre Besi landslide (b) Smectite, vermiculite and kaolinite shown in the XRD pattern of rock sample from 23.600 km landslide (c) XRD pattern of rocks from Jugedi Khola landslide, showing the weathering of chlorite mineral, here it is seen that the chlorite peak intensity increases due to the EG treatment.

In this section, more than 250 landslides have been identified through remote sensing, from earlier reports and field surveying. The role of geology, geological structures and rock weathering in individual landslide as well as in the whole area is given below. From this some models are prescribed that are thought to be applicable in the landslide occurrence along this road section.

Landslides and geology

Geology plays an important role in the landslide formation of that area. In the present study too, the relationship between geology and the landslide formation along Mugling-Narayanghat road section and its surrounding area is tried to understand. In the geology, lithology and geological structures are considered.

Lithology and landslide

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. 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 Precambrian Lesser Himalayan rocks, Miocene Siwaliks rocks and Holocene Terrace deposits. The distribution of landslides along different rock formation is shown in Fig. 17a. In order to understand which class in the lithology has more influence in the landslide formation, the 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 (118), Terrace Deposits (60), the Benighat Slate Formation (40), the Dhading Dolomite Formation (31), the Lower Siwaliks Formation (8), the Kuncha Formation=5, the Amphibolite Formation=3, and the Purebesi Quartzite Formation (2) (Fig. 17a). 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 (Table 2) followed by the Lower Siwaliks, the Middle Siwaliks, and the Benighat Slate Formation (Fig 17b). The Amphibolite is intruded within the Nourpul Formation (Fig. 2). The slates, phyllite are highly weathered while amphibolites is 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 Gerrad et al. (1994) according to whom phyllite rocks are the most susceptible to landsliding followed by shales, schists, poorly cemented sandstones, gneiss, granites and quartzites.

Geological structures and landslide

Geological structures have prominent role in the rock slope instabilities as the

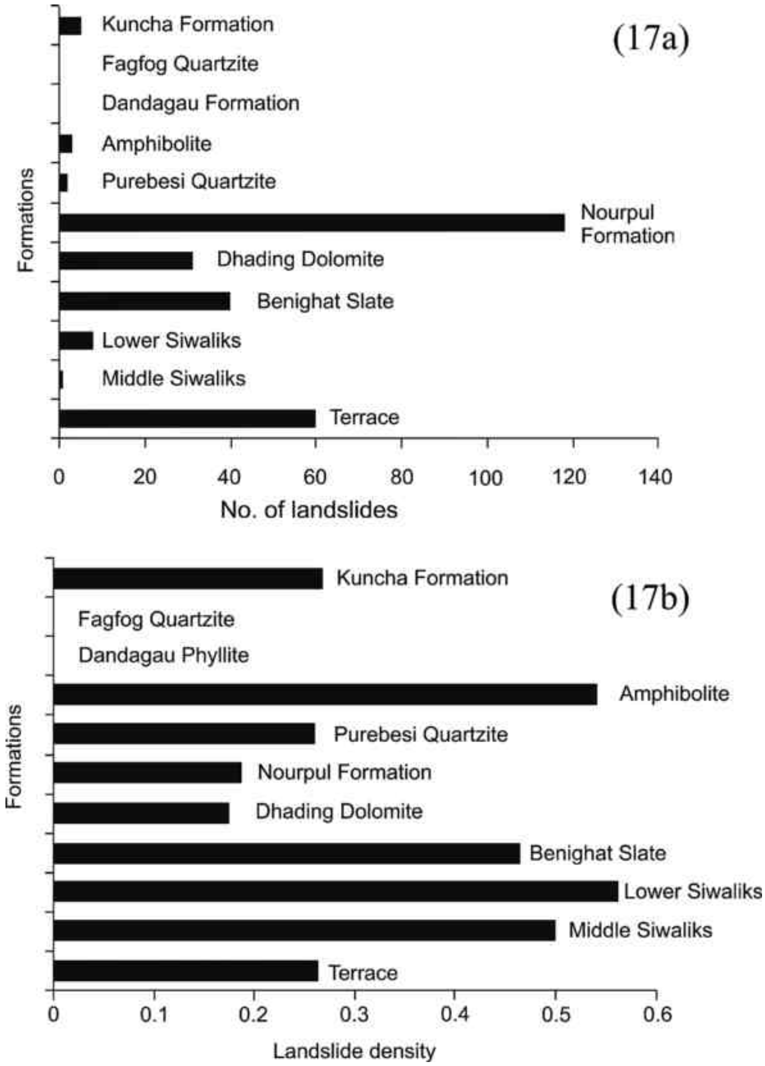


Fig. 17 : (a) Distribution of landslides in each lithological unit, (b) Landslide density in lithological unit

presence of these tectonic structures breaks the rock mass reducing its strength. The geological structures in the study area are considered as major and minor geological structures. There are four major thrusts crossing the study area along east west axis. The Main Boundary Thrust (MBT) crosses the road section at Km 14, south of Phwatar and runs east west (Fig. 2). As the MBT is one of the major thrusts in the Himalaya, it plays an important role on slope instabilities. In the Mugling-Narayanghat road section, instabilities along the Das Khola, Khahare Khola and Jugedi Khola valleys are mostly related to the MBT and JT (Fig. 2). In addition to the

KT, ST and VT, there are several normal faults in the study area (Fig. 2). Most of the instabilities on the roadside and in the stream catchment areas between Ch10 to Ch28 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. It has also some roles in the stability of the slope along the road section around Jalbire area. 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.

Fig. 18a 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 are located at a distance greater than 250 m from the fault. In Fig. 18b, it is seen that the landslide density is higher within the distance of 0 to 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.

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 to slightly weathered rocks. A thrust passes through the centre 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 top is covered by residual soil (Regmi et al. 2012). Thin section and XRD analysis of the collected rock samples showed 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,

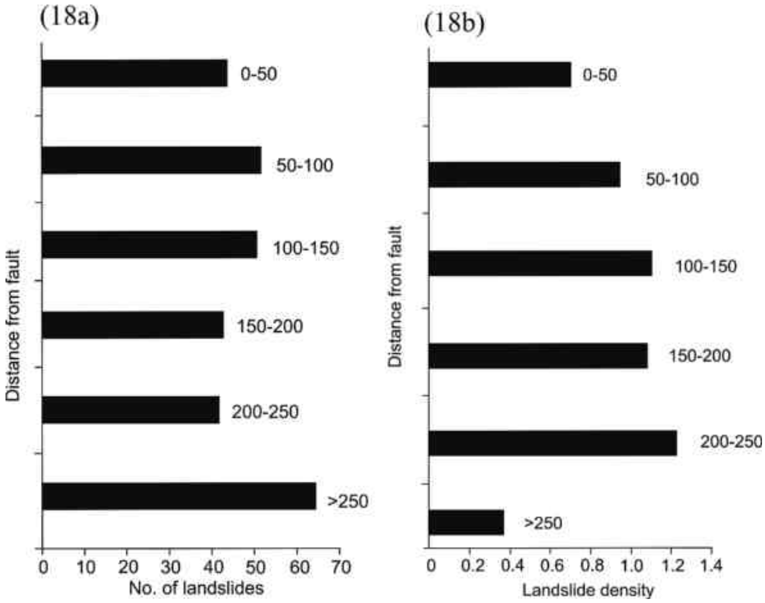


Fig. 18 : (a) Distribution of landslides with the increasing fault distance along the Highway and its surrounding region, (b) Landslide density in each fault distance zone

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 have played a key role in its initiation and further aggravation. The top part of the landslide, i.e. 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.

Jugedi Khola landslide lies at the left bank of Jugedi 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.

The lithological units comprising the landslide at Ch28 are from the Nourpul Formation and consists 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 show that the fresh rocks are rich in quartzite, muscovite, feldspar and chlorite, while their weathered product are rich in chlorite, semectite, 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 are responsible for the formation of this landslide.

Both the banks of Rigdi Khola at the Highway suffer from rock plane failure. Here the main rock type is quartzite. The rocks are dipping towards the road and the dip amount is almost equal to the natural slope. The rocks are almost fresh. The road cut has daylighted the rocks making them very unstable and several rock plane failure occur each year.

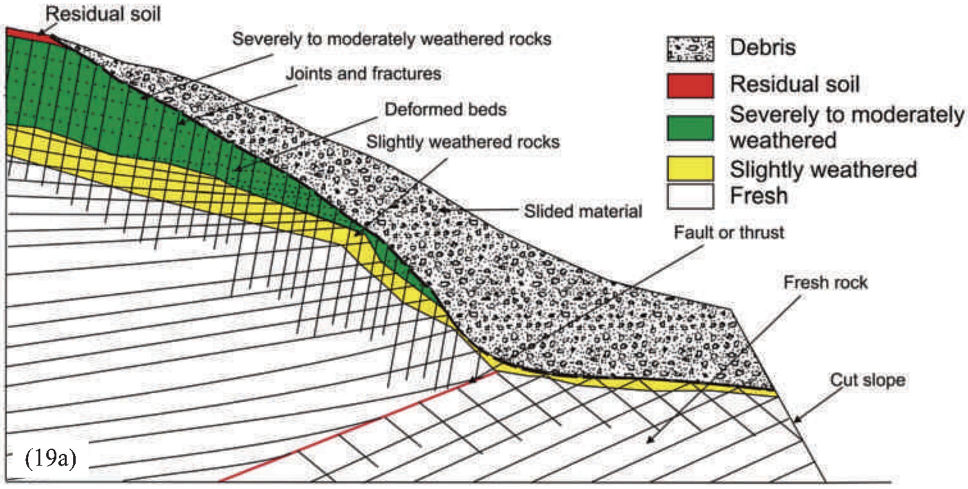
Kalikholagau landslide lies at the northern limb of the Jalbire syncline. Here the main rock types are slate and quartzite. The rocks are dipping at very steep angle and are less weathered. Also, the road cut has created very steep slope. Due to the steep slope and higher dip angle of the foliation plane, 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 outcrop comprising the Ghumaune rock fall are mainly dolomite and dolomitic quartzite with some phyllite partings belonging to Dhading Dolomite 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.

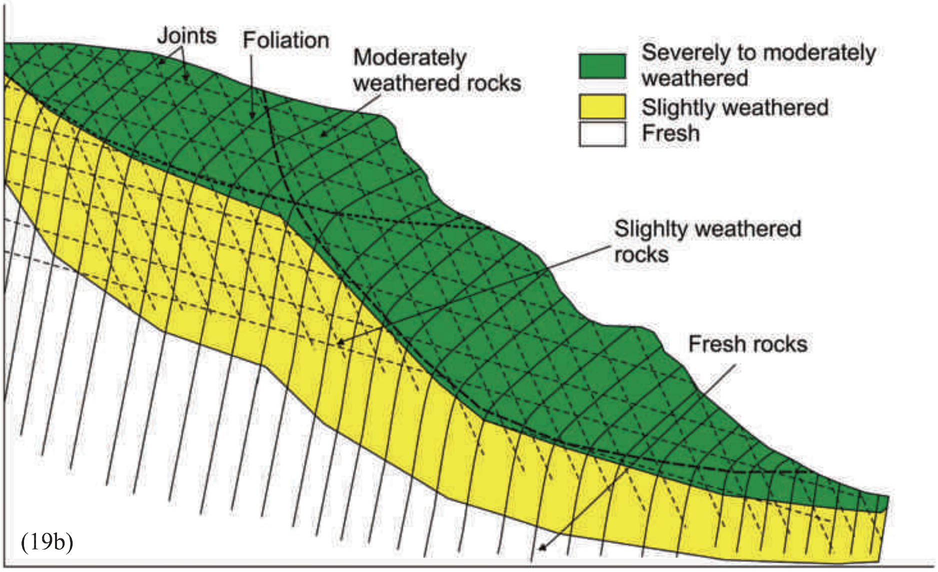
Models relating to the landslide types, geology and rock weathering along Mugling –Narayanghat road section

Different types of models exist relating to the geology, rock weathering and landslide formation. Deere and Patton (1971) divided the rocks into 3 zones and 6 subzones based on the severity of the weathering. He gave a very simple model relating to the landslides and rock weathering as ; shallow slides occur in upper residual soil, i.e. in IA and IB horizons ; block or wedge slide occur in the lower part of residual soil and weathered rocks, i.e. IC, IIA and IIB horizons ; shallow slides occur in colluviums covered slope, i.e. in Zone I, and slide of colluviums along deep - seated planes of weakness occur in Zone I in the weathered rocks. 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 him, rotational types of slides occur in thoroughly decomposed rocks ; debris flows, debris avalanches, 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%–85% ; and rock falls, rockslides, block glides ; debris avalanches and slides over sheeting surfaces occur where <15% of weathered material occurs along the joints.

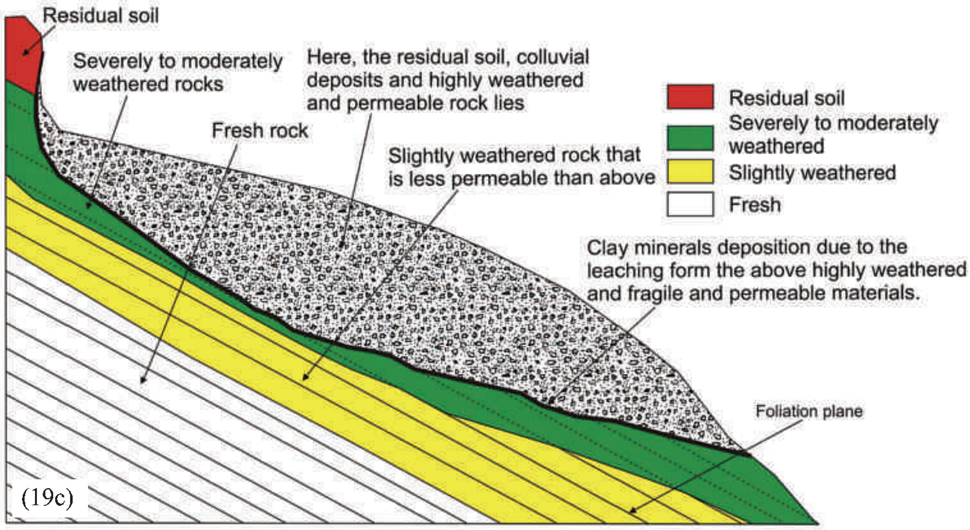
Most of these models are not applicable in the landslides observed in the Himalayan rocks. In this situation, an attempt has been made to develop some models relating to the general geology, rock weathering and landslide formation along one of the most landslide affected road sections of Nepal Himalaya. These models 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.



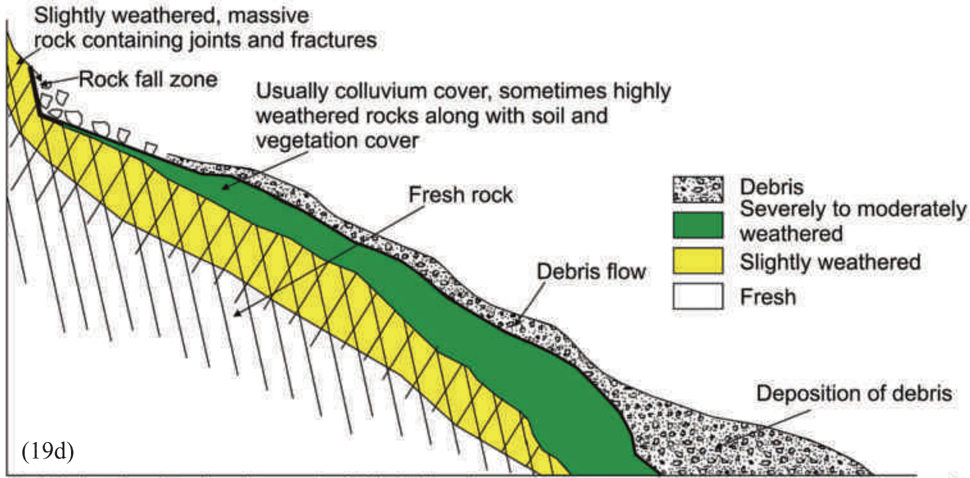
Model showing the development of large complex landslide



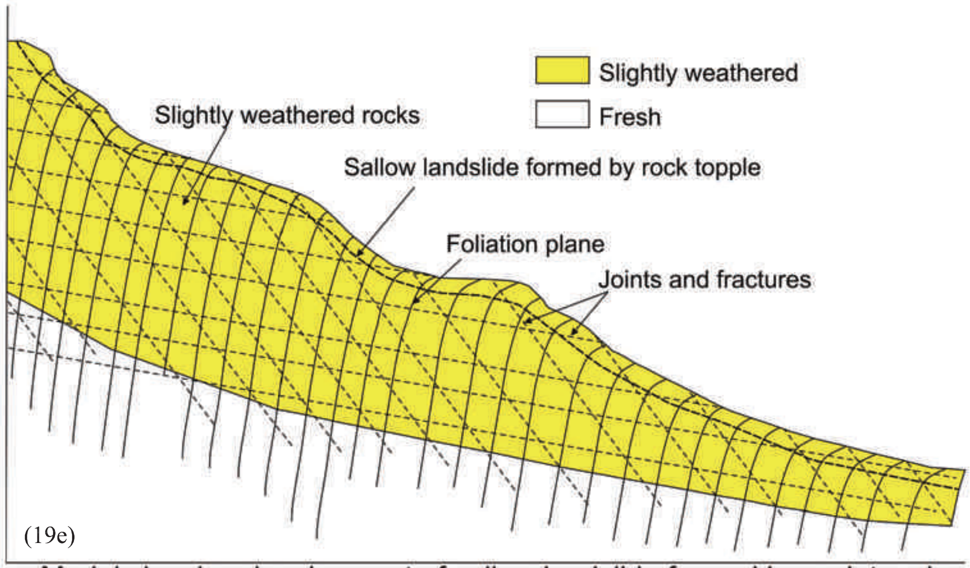
Model showing gravitationally induced complex landslide



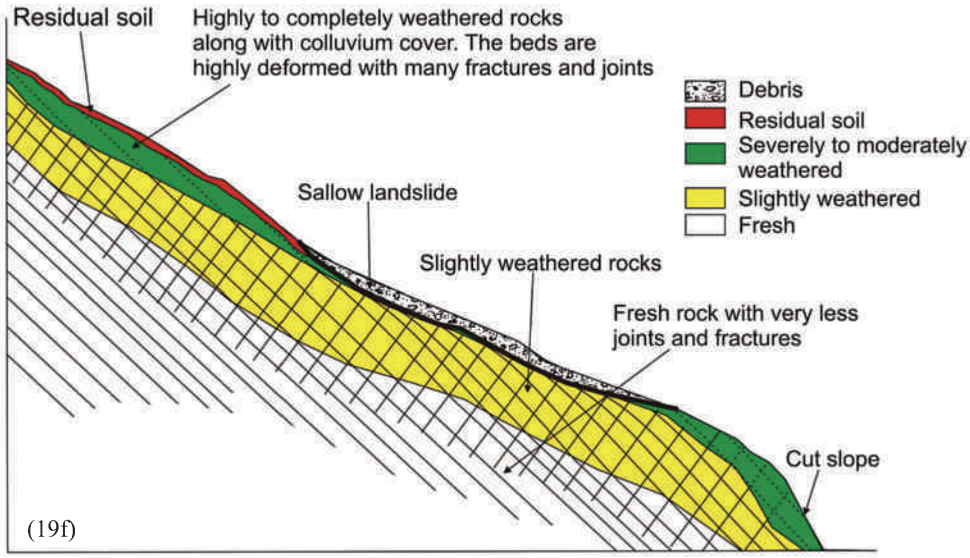
Model showing the development of rotational type of landslide



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



Model showing development of sallow landslide formed by rock topple



Model showing the development of sallow landslide

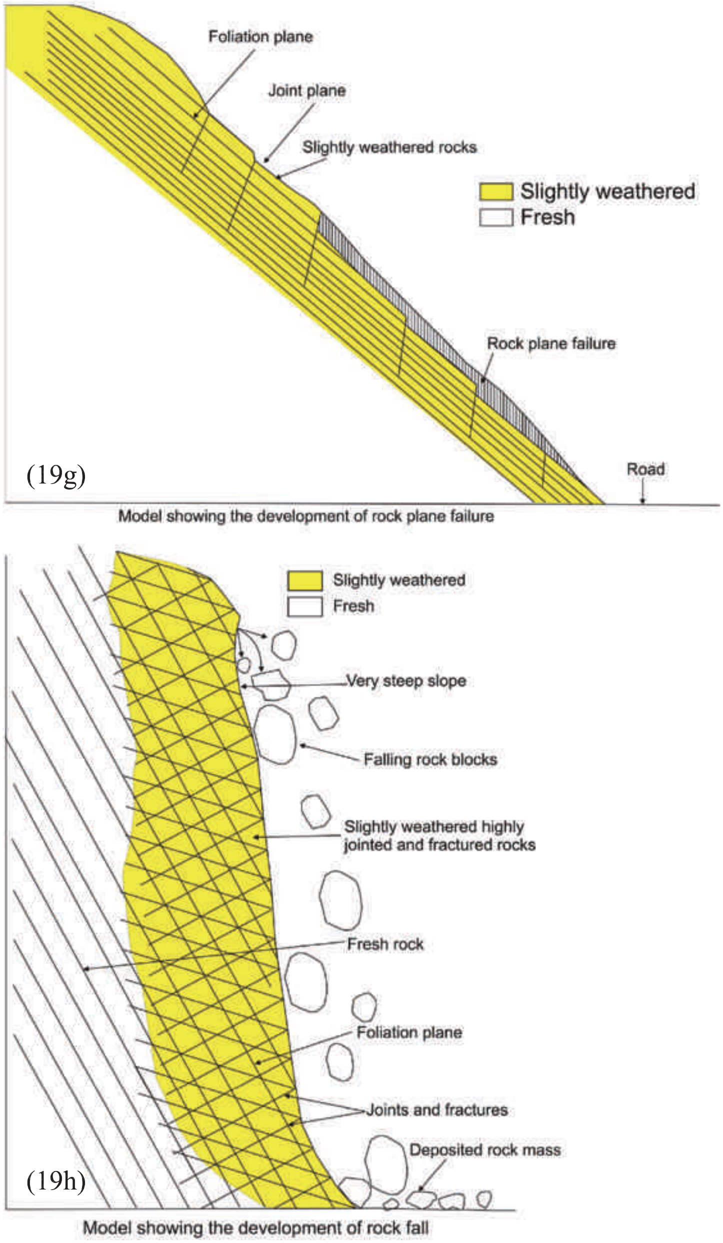


Fig. 19 : Models showing different types of landslides occurring at Mugling–Narayanghat road section and its surrounding area and their relationship with general geology and rock weathering. (a) Large scale complex landslide, (b) Large and complex landslide formed due to gravitational deformation, (c) Rotational type of landslide, (d) Shallow landslide formed by rock topple, (e) Shallow landslide in colluviums covered slope, (f) Rock fall at the upper slope and debris flow down–slope, (g) Rock plane failure occurring in slightly weathered rocks, and (h) Rock fall in very steep slope.

Mugling-Narayanghat road section consists of different types of landslides. However, some factors were common to all the landslides analysed. For example, large scale complex landslides are common in deeply weathered rocks, where different lithological units are found. Also, geological structures as fault, joints and fractures play a prominent role in creating deep weathering in such landslides (Fig. 19a). The weathering degree ranges from fresh to completely weathering degree in these landslides. In the other type of large landslides, geological structures as attitude of foliation plane, faults and slope angle have a prominent role, while rock weathering have less effect (Fig. 19b). Much of the medium scale rotational types of landslides are located 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. 19c). Debris slides and debris flow are the dominant types of landslides occurring along the Mugling-Narayanghat road section and its surrounding region. 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 may be rock 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. 19d). Shallow landslides are of three types. 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. 19e). Some part of the road section is suffered from some shallow rock plane failure. The rocks dipping towards the natural slope with similar angle to that of the slope and where the road cut has daylighted the foliation plane suffers from such failure (Fig. 19f). The rock is rather fresh in such slides. The other one, i.e. rock topple is observed in slightly weathered to fresh rocks, where the attitudes of foliation plane and slope angle are very high (Fig. 19g). Rock fall is encountered on steep slopes. The rocks are highly jointed and fractured and are not much weathered in these steep slopes (Fig. 19h).

Conclusions

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 main rock types are limestone, dolomite, slate, phyllite, quartzite, and amphibolites of the Lesser Himalaya, sandstone, mudstone and conglomerate of the Siwaliks and Holocene river terraces. The major triggering factor for all the landslides along the road section and its surrounding region 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 geomorphic parameter if the region as steep slope angles and rugged topography followed by the groundwater along the slope were also responsible for the formation of the 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 (rock topples) are found in rocks with high dip angles that are less weathered. Some shallow rock slides (rock plane failure) occur in fresh rocks, where the dip angle and the dip direction play a major role. 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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