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Sliding of an old toppled block in the Chor Khola area, Siwalik Hills, Mid-Western Nepal

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ABSTRACT

An old toppled block was recognised near the confluence of the Surai Khola and Chor Khola in the Siwaliks of Mid-Western Nepal. The block occupies an area of about 17,000 m^2 and is represented by an interbedded sequence of sandstone and mudstone of late Miocene age. Most of the strata dip northwards, but some of them dip southwards as well. The strikes of the right-side-up and overturned strata are almost uniform, and the axis of toppling is essentially horizontal. The direction of toppling is N12°W with the rotation angle ranging between 74° and 118°. The toppling and sliding are closely related to rapid incision of the Surai Khola and the Chor Khola, and tilting of the strata due to faulting. The toppling may be as old as late Pleistocene, whereas the sliding is a recent phenomenon.

INTRODUCTION

Landslides and debris flows frequently occur in Nepal (Sharma 1981; Heuberger et al. 1984; Yagi et al. 1990; Dhital et al. 1993). They have contributed to a huge volume of sediments in southern hilly regions (Dangol 1998). The Siwaliks constitute the Himalayan foothills and range in altitude from 500 to 1,000 m. They are composed mainly of thick sedimentary sequences of sandstone, mudstone, and conglomerate of middle Miocene to early Pleistocene age (Tokuoka et al. 1986; Appel et al. 1991; Tokuoka 1992). An old toppled block was identified near the confluence of the Surai Khola and Chor Khola (Fig. 1) in the Siwaliks of Mid-Western Nepal (Fig. 2a and 2b). The landslide area was mapped in detail to obtain the information on causes and mechanism of failure.

PHYSIOGRAPHY AND GEOLOGY

The Surai Khola is an antecedent river and flows southwards dissecting the Siwalik Hills (Fig. 1). It has many tributaries, of which the Chor Khola flows from the east. The height of the upper river terraces along the Surai Khola gradually increases from 80 to 120 m (respectively from north to south), and is quite substantial around the Chor Khola (Tamrakar 1999). Most of the valley slopes of the Surai Khola, which seem to be controlled by bedding, face WSW, ESE, WNW, and ENE. The East–West Highway passes through the Siwaliks, and many people live in its vicinity. The cut slopes along the Highway are steep, contain thin vegetation cover, and are very susceptible to erosion.

The Siwalik Group in the Surai Khola area is divided into the Bankas, Chor Khola, Surai Khola, Dobata, and the Dhan Khola Formations in an ascending order (Dhital et al. 1995). Further, the Chor Khola Formation is subdivided into the Jungli Khola Member (lower) and the Shivgarhi Member (upper). The Group ranges in age from 13 Ma to less than 2.3 Ma (Appel et al. 1991) and attains a thickness of about 5,000 m in the Surai Khola area (Table 1).

The strata in the Chor Khola area belong to the lower part of the Shivgarhi Member. They contain coarse-grained 'salt-and-pepper' sandstone interbedded with sporadically variegated mudstone. Some medium- to fine-grained sandstone, shale, calcrete, and siltstone also intermittently occur. The coarse-grained sandstones are comparable with those of the Surai Khola Formation, but the latter are more micaceous and multi-storeyed (Corvinus 1992).

The uniaxial compressive strength of sandstones of the Surai Khola area ranges from 33 to 117 MPa, depending on their lithofacies and cement content (Tamrakar et al. 1999). The mudstones are significantly weaker and their strength is less than 10 MPa.

The Siwaliks in the study area form a monocline bounded between the Rangsing Thrust (RT) in the north and the Main Frontal Thrust (MFT) in the south. The MFT dips gently due north (Fig. 2a and 2b), and is recognised by the topographical break between the hills and alluvial fans. The strata strike roughly E–W and dip northwards constituting an imbricate slice (a hanging wall flat) riding over a footwall ramp (Dhital et al. 1995). The Siwaliks have been uplifting since early Pleistocene along the MFT (Kizaki 1994). In the Chor Khola area, the dip angles of the monocline gradually increase from south to north (Fig. 2b). This change indicates differential uplift of the Siwalik Group.

Locally, beds are overturned between Dobata and Saddle Point along the Highway. On the right bank of the Surai

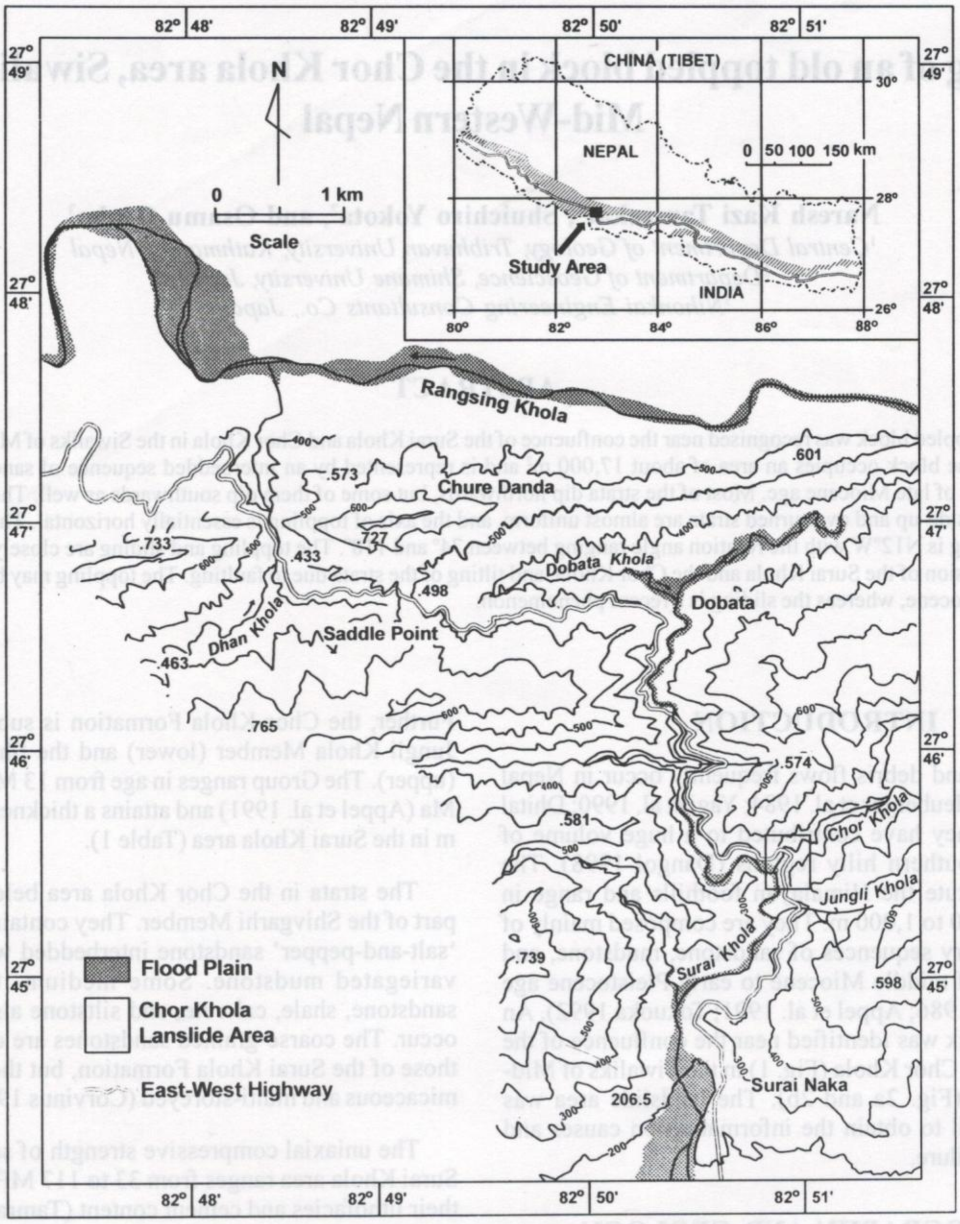


Fig. 1: Location of the Chor Khola Landslide area, Mid-Western Nepal

Khola (at Surai Naka), a northwestward plunging anticline is observed, which roughly follows the Surai Khola (Fig. 2a). The anticline is asymmetrical with its gentle southern limb (strikes N14°W and dips 10° SW) and relatively steep northern limb.

CHOR KHOLA LANDSLIDE

The Chor Khola Landslide (Fig. 3 and 4) is located on the lower reaches (250–330 m) of the Chor Khola along the East-West Highway southeast of the Chor Khola Bridge. In this area, the southward-dipping beds are observed resting on the northward dipping beds on a west-facing excavated slope. Interbedded sandstones and mudstones dip southwards in the upper portion of the slope, whereas they dip northwards in the lower portion (Fig. 3). The fining-upward sequences indicate that the north-dipping beds are facing right-side-up, whereas the south-dipping ones are overturned. It shows that the upper portion of the slope was rotated northwards. The boundary between the right-side-up and overturned beds was traced for more than 70 m (Fig. 3).

The landslide is facing westwards as well as northwards, and its slope angle varies significantly. Two gentle surfaces are recognised on the original hill slope at an altitude of 320–340 m and 290–315 m, respectively (Fig. 4). Two large concave slopes truncate these gentle geomorphic surfaces. One of the concave slopes is wide and rectangular, and is facing N10°W (i.e. towards the Chor Khola). The other is also wide, but is facing N50°W with a relatively steep toe

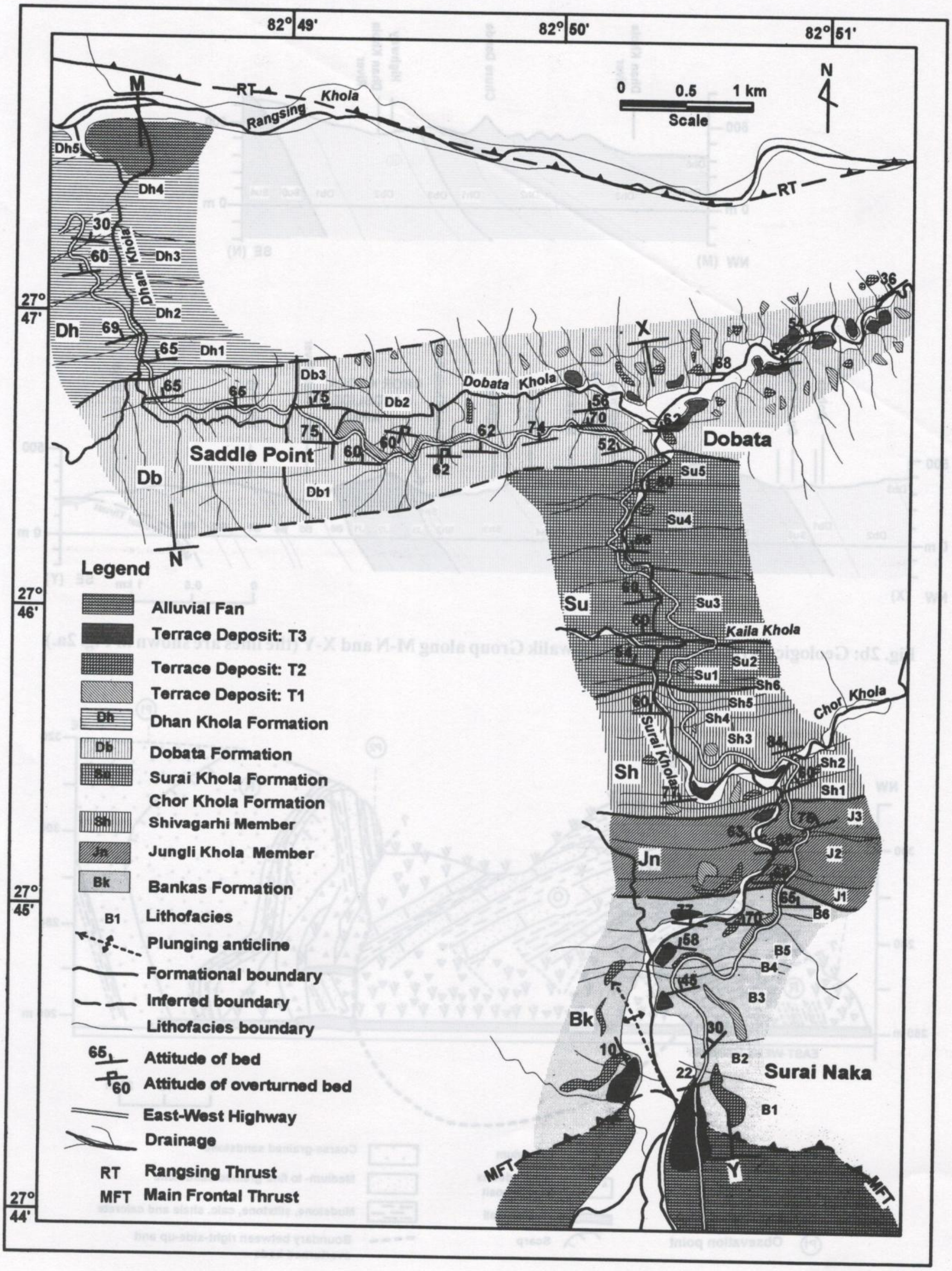


Fig. 2a: Geological map of the Siwalik Group along the Surai Khola

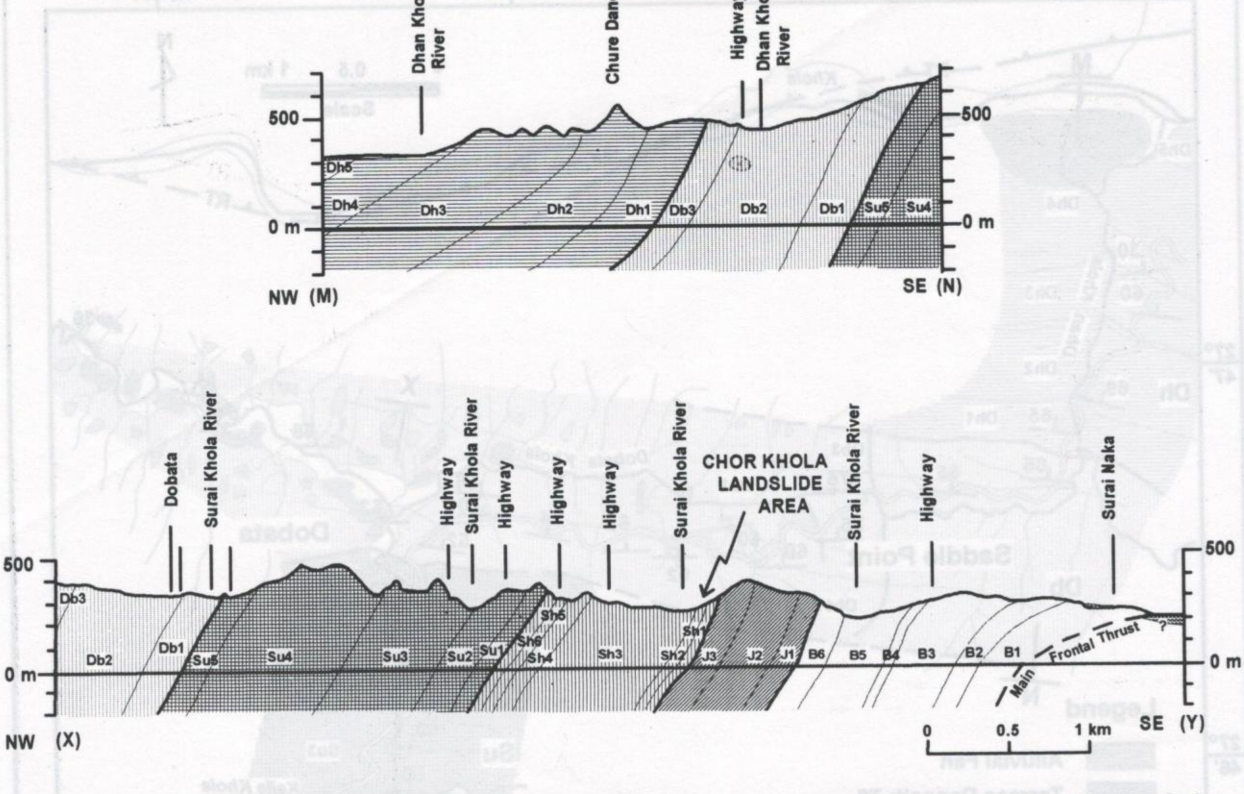


Fig. 2b: Geological cross-sections of the Siwalik Group along M-N and X-Y (the lines are shown in Fig. 2a.)

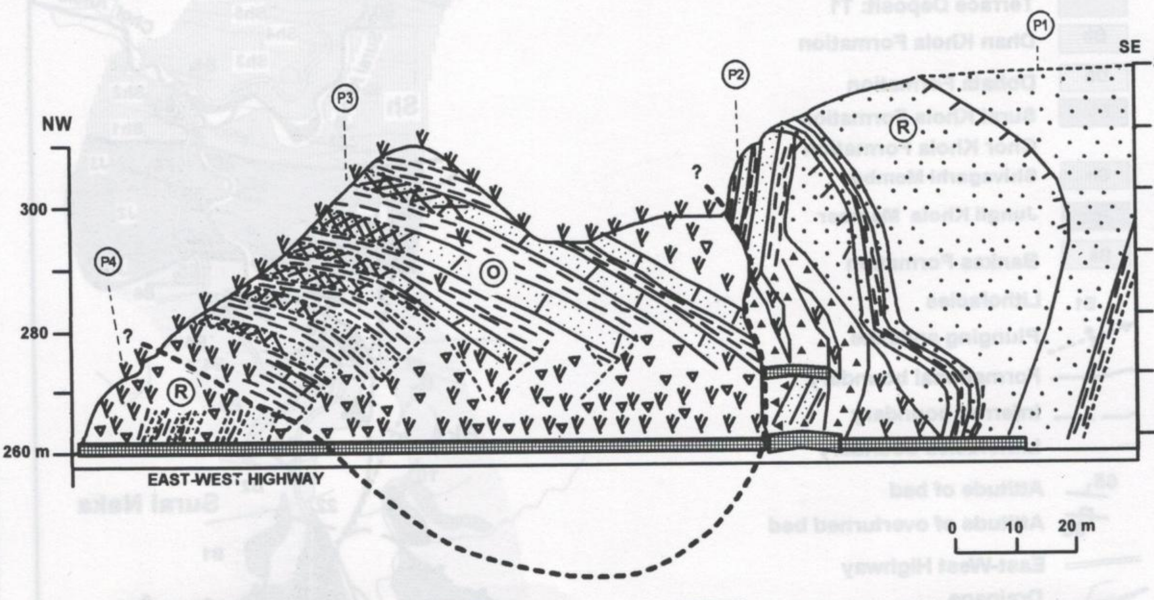
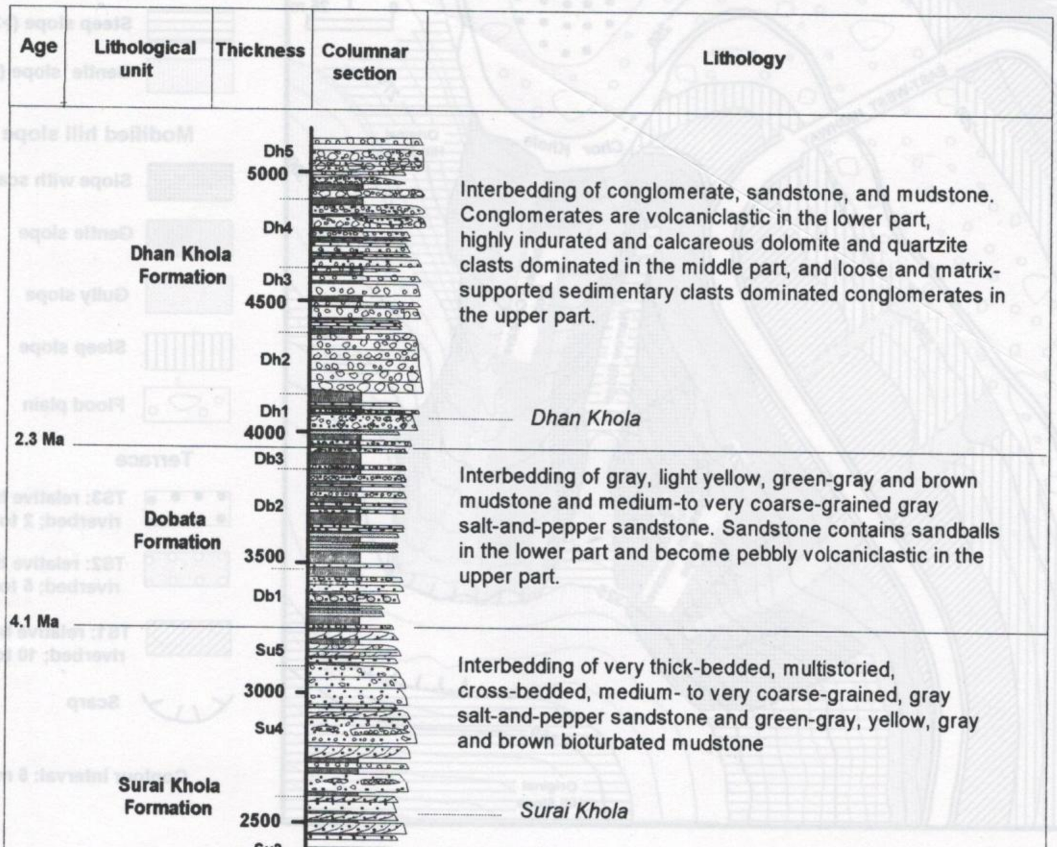


Fig. 3: A sketch showing reverse and normal strata exposed on the western concave slope along the East-West Highway

Table 1. Lithostratigraphic column of the Siwalik Group in the Surai Khola area, Mid Western Nepal. Columnar section and age are based respectively on Dhital et al. (1995) and Appel et al. (1991).



Age	Lithological unit	Thickness	Columnar section	Lithology
2.3 Ma	Dhan Khola Formation	5000 4500 4000	Dh5 Dh4 Dh3 Dh2 Dh1	Interbedding of conglomerate, sandstone, and mudstone. Conglomerates are volcaniclastic in the lower part, highly indurated and calcareous dolomite and quartzite clasts dominated in the middle part, and loose and matrix-supported sedimentary clasts dominated conglomerates in the upper part. *Dhan Khola*
4.1 Ma	Dobata Formation	3500	Db3 Db2 Db1	Interbedding of gray, light yellow, green-gray and brown mudstone and medium-to very coarse-grained gray salt-and-pepper sandstone. Sandstone contains sandballs in the lower part and become pebbly volcaniclastic in the upper part.
7 Ma	Surai Khola Formation	3000 2500 2000	Su5 Su4 Su3 Su2 Su1	Interbedding of very thick-bedded, multistoried, cross-bedded, medium- to very coarse-grained, gray salt-and-pepper sandstone and green-gray, yellow, gray and brown bioturbated mudstone *Surai Khola* *Kaila Khola*
9 Ma	Chor Khola Formation Shivgarhi Member	1500	Sh6 Sh5 Sh4 Sh3 Sh2 Sh1	Sequences of very thick-bedded, medium- to very coarse-grained, gray salt-and-pepper sandstone, fine-grained sandstone, and gray, brown and yellow bioturbated mudstone. *Chor Khola* Marl occurs in the lower and the upper parts of the member.
11 Ma	Jungli Khola Member	1000	J3 J2 J1	Interbedding of fine- to medium-grained gray bitoturbated sandstones and variegated (yellow, brown, green-gray, red-purple mottled) mudstone
13 Ma	Bankas Formation	500 0 m	B6 B5 B4 B3 B2 B1	*Paira Khola* Interbedding of fine-grained green-gray sandstones and maroon, yellow, brown, orange, and purple variegated mudstones. Calcrete beds occur frequently.

Conglomerate; Coarse-grained sandstone; Fine- to medium-grained sandstone; Mudstone, siltstone and claystone; Marl

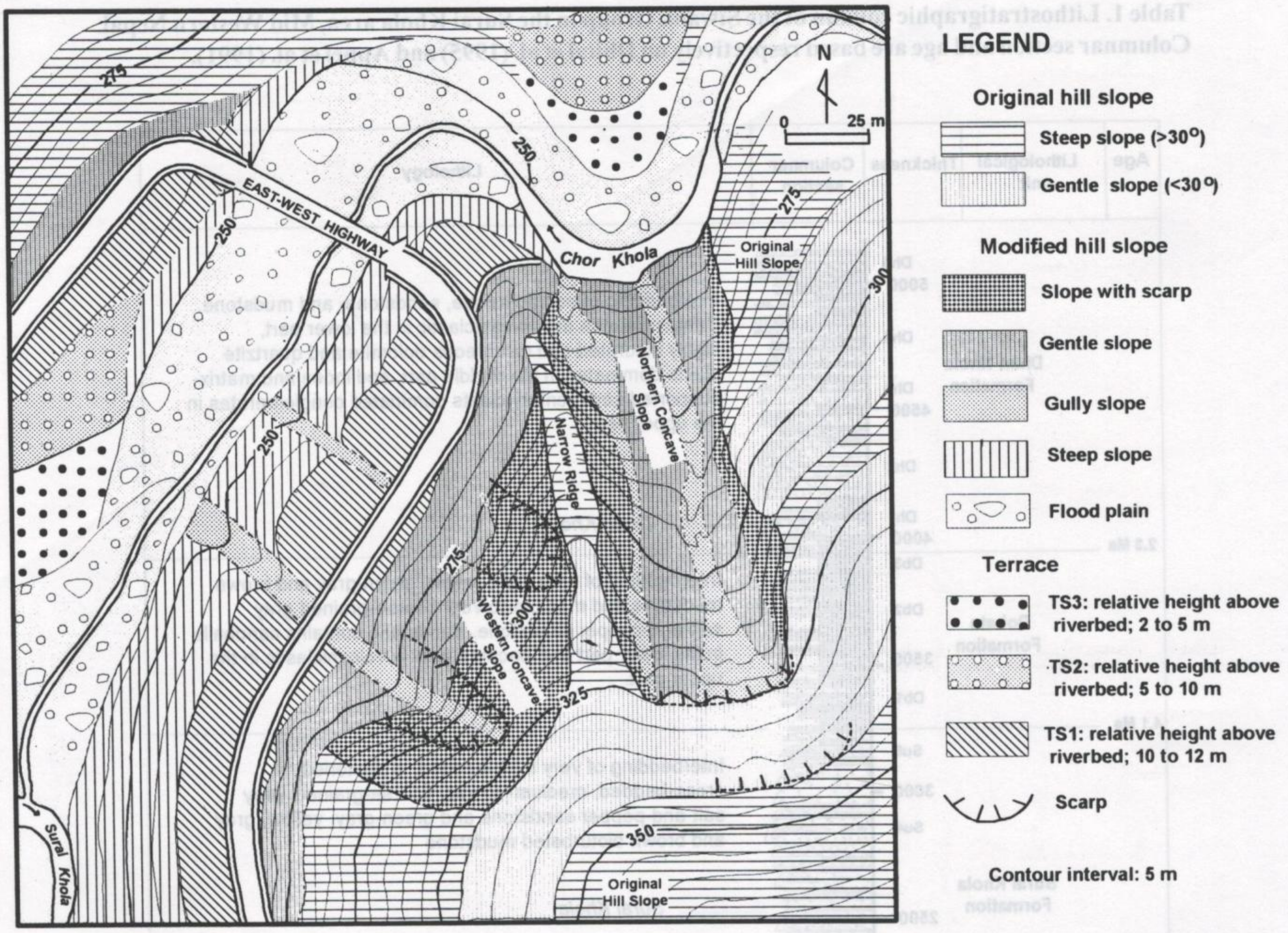


Fig. 4: Geomorphological map of the Chor Khola Landslide area

(Fig. 4). They are termed here as the northern concave slope (NCS) and western concave slope (WCS), respectively. A small and narrow ridge extending N–S separates them (Fig. 4). The NCS, WCS, and the narrow ridge constitute the major portion of the landslide.

Rock structure

The rocks of the Shivgarhi Member make up the landslide zone (Fig. 3 and 5). A summary of rock types and their attitude in the landslide zone is given in Table 2. The medium- to coarse-grained sandstones are 1–2 m thick, whereas the mudstones are thick-bedded and range from massive to laminated types. Though the sandstones predominate in the Shivgarhi Member as a whole, there is a higher proportion of mudstone in the landslide zone (Fig. 3).

The boundary between the right-side-facing and overturned strata was confirmed at P2, P4, P7, and P8. The distribution of overturned beds was traced eastwards from the WCS as shown by the dashed line in Fig. 5. They extend over 17, 000 m^2 following essentially the E-W trend, which is roughly parallel to the strike of beds. The western margin of the overturned block is the left bank of the Chor Khola. The northern boundary of the failed surface (which dips southwards) lies at an altitude of 270–280 m. The southern boundary is covered by colluvium and is inferred to lie at an altitude of 340–350 m, near the top of the NCS where numerous tension cracks (tens of metres long and tens of centimetres wide) are observed.

Fig. 6 shows the geological structure of the landslide zone. A-A′ and B-B′ are cross-sections along the steepest portions of the NCS and the WCS, respectively. In the former, the thickness of the overturned block is 10 m, whereas in the latter it ranges from 20 to 30 m. Most of the overturned beds might have been eroded away. The loosely consolidated debris flow deposits cover the overturned as well as right-side-up beds in the lower portion of the NCS (Fig. 5 and 6). The landslide toe at the WCS is covered by the terrace gravel and fill material.

Table 2: Description of rock type and structure in the landslide zone (The observation points are shown in Fig. 5)

Obs. point	Location	Rock type	Strike/dip	Description
P1	South of the WCS	Sandstone and mudstone	N65°–85°E/ 55°–60°W	Sandstone is massive, coarse-grained, and of 'salt-and-pepper' type.
P2	Southern scarp of the WCS	Sandstone, mudstone, calcrete, calcareous siltstone	N80°W–N70°E/ 45°NE–50° NW	Sandstones are medium- to thin-bedded, medium-grained, and grey.
P3	Scarp of the WCS	Sandstone, mudstone and calcrete	N85°–89°E/ 45°–80°SE	Sandstone is thick- to medium-bedded, fine-grained, and clacareous. Mudstone is yellow, green-grey, and maroon.
P4	Gentle slope of the WCS	Sandstone and mudstone	N70°–75°E/ 70°– 64°N	Sandstone is thick- to medium-bedded, fine-grained, and calcareous. Mudstone is yellow, green-grey, and maroon.
P5	Scarp of the NCS	Sandstone and mudstone	N89°E–N60°W/ 22°SE–4°SW	Sandstones are thick-bedded, fine-grained, and calcareous.
P6	Gully slope of the NCS	Sandstone and mudstone	N85°E/ 42°SE	A sequence of coarse-grained sandstone and mudstone is exposed
P7	Left flank of the NCS at an altitude of 285 m	Sandstone, mudstone and shale	N85°E/ 55°NW	Interbedded fine-grained sandstone, mudstone, and shale are exposed.
P8	Right flank of the NCS at an altitude of 275 m	Sandstone and mudstone	N85°W/ 45°SW	Fine-grained laminated sandstones are interbedded with mudstones.
P9	Left flank of the NCS, between 255 and 265m	Sandstone and mudstone	N64°–55°E/ 62°–72°NW	Sandstone is thick- to medium-bedded, fine-grained, and calcareous. Mudstone is yellow, green-grey, and maroon.
P10	Right bank of the Chor Khola,	Sandstone and mudstone	N75°–80°E/ 80°–82°NW	Thick to massive, coarse- to medium-grained sandstone and mudstone are interbedded. The sandstone beds are as massive and coarse as those cropping out at P1.
P11	On the uphill side of the Highway, west of the Chor Khola Bridge	Sandstone and mudstone	N75°E/ 60°NW	Massive, coarse- to medium-grained sandstone and mudstone are interbedded. The sandstone beds are as massive and coarse as those cropping out at P1.

Table 3: Description of joint sets measured on sandstone beds

Joint set	Attitude	Spacing	Aperture	Roughness
Bedding joint (J1)	N75°E/60°NW	0.5 to 2 m	1 to 2 cm	Smooth to wavy
Cross-joint (J2)	N68°E/42°SE	<1 m	2 to 5 cm	Very smooth (polished)
Vertical joint (J3)	N83°W/83°NE	<1 m	0.2 to 1 cm	Rough; clayey infilling
Diagonal joint (J4)	E-W/20°N	3 to 10 m	Variable	Smooth

The sandstones contain four prominent joint sets (Table 3; Fig. 7). The cross-joints are very smooth and often display slickensides. The bedding joints are also well developed and more closely spaced in fine- to medium-grained sandstones than in medium- to thick- bedded ones.

Between the concave slopes, the narrow ridge contains weathered outcrops of mudstones and sandstones. At the summit, sandstones are moderately weathered, relatively soft, loose, and blocky, whereas in deeper portion, they are fresh and stiff, and are distributed continuously. The weathered beds in the summit show reddish brown colours, which gradually change below to yellow colour. Hence, the weathering profile seems to be parallel to the natural slope, but two concave slopes disrupt it.

Surface deposits

The older debris flow deposits cover a large portion of the NCS and the gully on the left flank of the WCS (Fig. 5). They contain boulders, sand, silt, and clay in variable proportions with a few erratic blocks. They are predominantly sandy to muddy in nature. Sediments are subangular to angular, poorly sorted, and form loose masses.

The younger debris flow deposits are distributed at various places on the NCS and along the gullies of the WCS (Fig. 5). They comprise mainly mud and gravel mixtures with abundant rock rubbles and erratic blocks composed of sandstones, calcrete, siltstone, and mudstone. They are loose, poorly sorted and contain angular to sub-angular clasts. Occasionally, trees and grasses are buried in them.

Colluvial deposits occur adjacent to cliffs of the NCS and on gentler portion of the WCS (Fig. 5). On the WCS, the colluvial debris is represented by muddy gravel with erratic blocks, whereas the downhill side of the Highway is covered by fill material.

Alluvial deposits are distributed on the channel and banks of the Chor Khola and the Surai Khola, and are grouped as the riverbed, lower terrace, and older terrace deposits (Fig. 5).

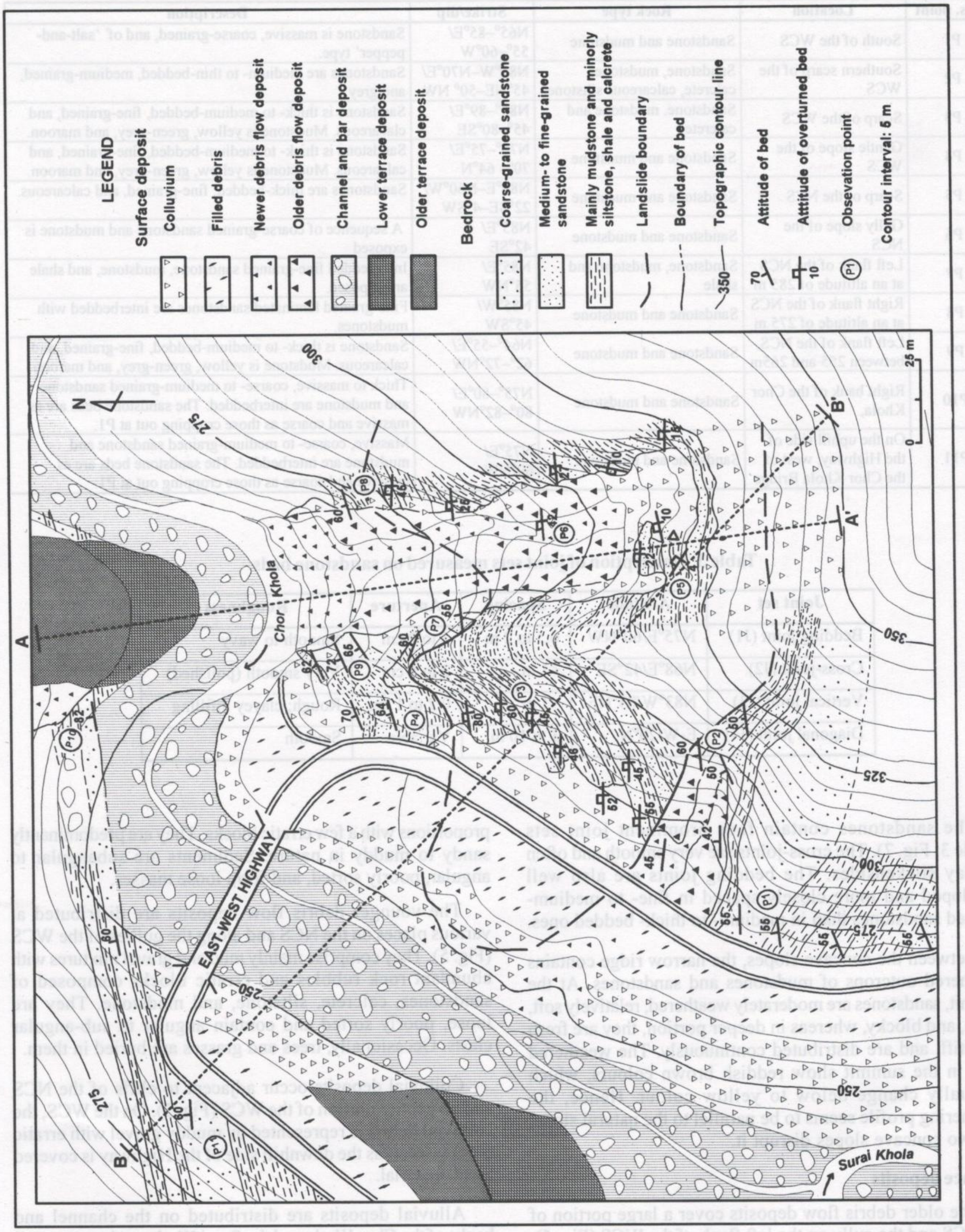


Fig. 5: Geological map of the Chor Khola Landslide area

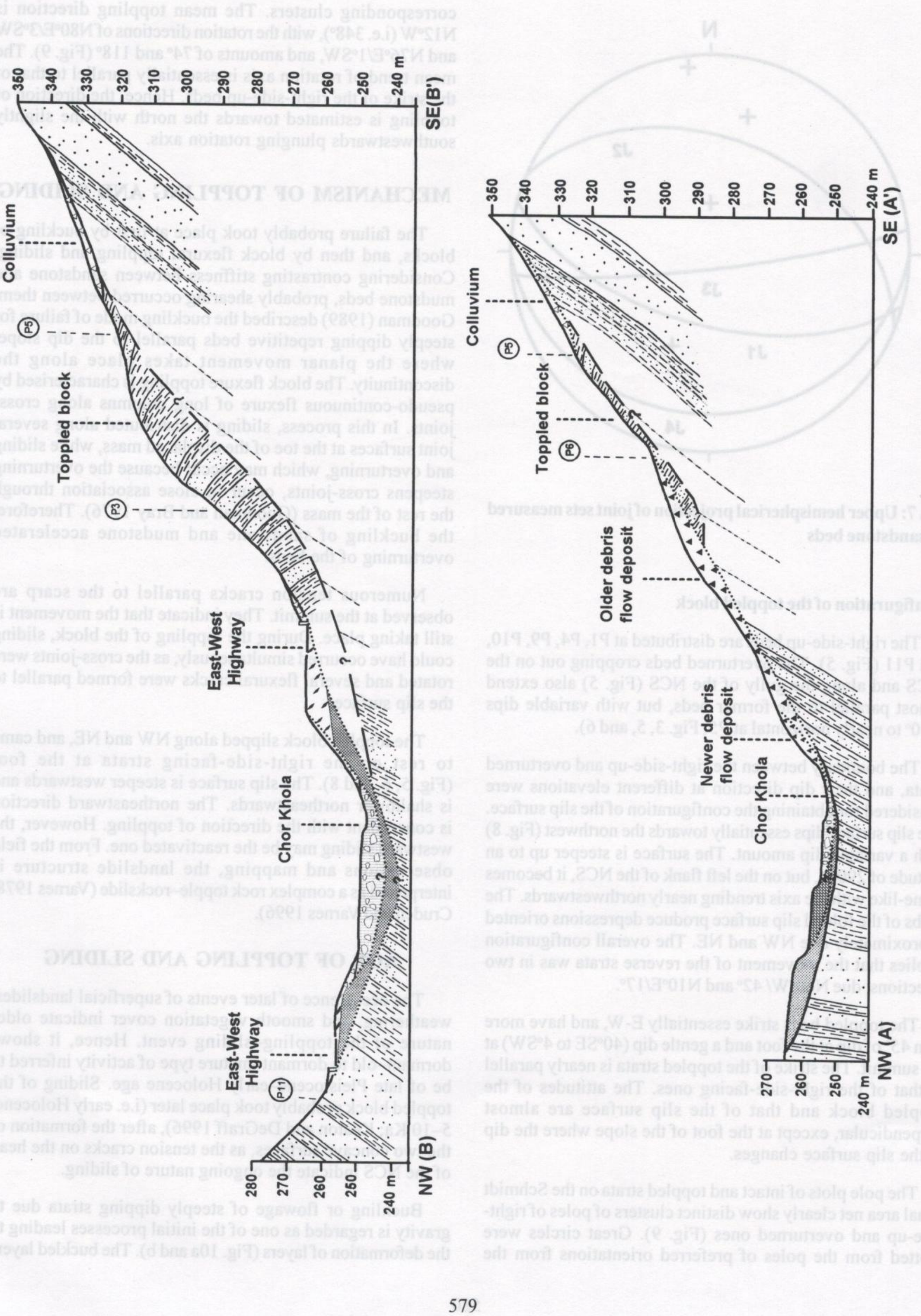


Fig. 6: Cross-sections along B-B' and AA' (the lines are shown in Fig. 5.)

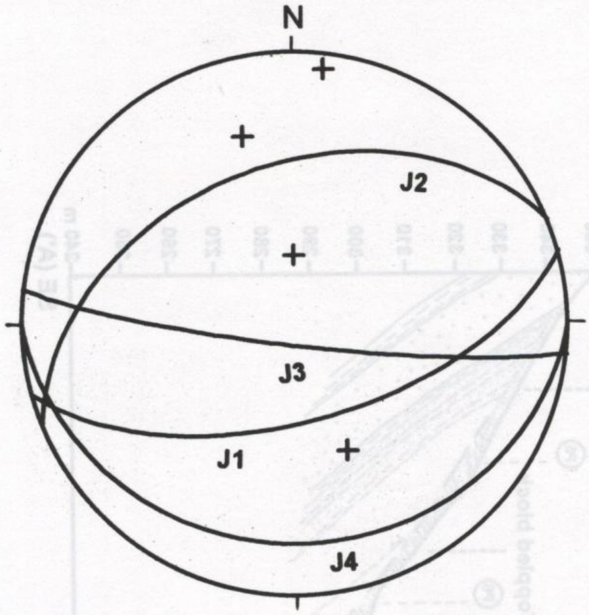


Fig. 7: Upper hemispherical projection of joint sets measured on sandstone beds

Configuration of the toppled block

The right-side-up beds are distributed at P1, P4, P9, P10, and P11 (Fig. 5). The overturned beds cropping out on the WCS and along the gully of the NCS (Fig. 5) also extend almost parallel to the former beds, but with variable dips (>40° to nearly horizontal at P5; Fig. 3, 5, and 6).

The boundary between the right-side-up and overturned strata, and their dip direction at different elevations were considered for obtaining the configuration of the slip surface. The slip surface dips essentially towards the northwest (Fig. 8) with a variable dip amount. The surface is steeper up to an altitude of 290 m, but on the left flank of the NCS, it becomes dome-like with the axis trending nearly northwestwards. The limbs of the folded slip surface produce depressions oriented approximately due NW and NE. The overall configuration implies that the movement of the reverse strata was in two directions: due N60°W/ 42° and N10°E/17°.

The toppled beds strike essentially E-W, and have more than 45° of dip at the foot and a gentle dip (40°SE to 4°SW) at the summit. The strike of the toppled strata is nearly parallel to that of the right-side-facing ones. The attitudes of the toppled block and that of the slip surface are almost perpendicular, except at the foot of the slope where the dip of the slip surface changes.

The pole plots of intact and toppled strata on the Schmidt equal area net clearly show distinct clusters of poles of right-side-up and overturned ones (Fig. 9). Great circles were plotted from the poles of preferred orientations from the corresponding clusters. The mean toppling direction is N12°W (i.e. 348°), with the rotation directions of N80°E/3°SW and N76°E/1°SW, and amounts of 74° and 118° (Fig. 9). The mean trend of rotation axis is essentially parallel to that of the strike of the right-side-up beds. Hence, the direction of toppling is estimated towards the north with the slightly southwestwards plunging rotation axis.

MECHANISM OF TOPPLING AND SLIDING

The failure probably took place at first by buckling of blocks, and then by block flexural toppling and sliding. Considering contrasting stiffness between sandstone and mudstone beds, probably shearing occurred between them. Goodman (1989) described the buckling mode of failure for steeply dipping repetitive beds parallel to the dip slope, where the planar movement takes place along the discontinuity. The block flexure toppling is characterised by pseudo-continuous flexure of long columns along cross-joints. In this process, sliding is distributed along several joint surfaces at the toe of the displaced mass, while sliding and overturning, which may occur because the overturning steepens cross-joints, occur in close association through the rest of the mass (Goodman and Bray 1976). Therefore, the buckling of sandstone and mudstone accelerated overturning of the beds.

Numerous tension cracks parallel to the scarp are observed at the summit. They indicate that the movement is still taking place. During the toppling of the block, sliding could have occurred simultaneously, as the cross-joints were rotated and several flexural cracks were formed parallel to the slip surface.

The toppled block slipped along NW and NE, and came to rest on the right-side-facing strata at the foot (Fig. 5, 6, and 8). The slip surface is steeper westwards and is shallower northeastwards. The northeastward direction is concordant with the direction of toppling. However, the westward sliding may be the reactivated one. From the field observations and mapping, the landslide structure is interpreted as a complex rock topple–rockslide (Varnes 1978; Cruden and Varnes 1996).

AGE OF TOPPLING AND SLIDING

The occurrence of later events of superficial landslides, weathering, and smooth vegetation cover indicate older nature of the toppling–sliding event. Hence, it shows dormant–old to dormant–mature type of activity inferred to be of late Pleistocene–early Holocene age. Sliding of the toppled block probably took place later (i.e. early Holocene: 5–10 Ka; Keaton and DeGraff 1996), after the formation of the two concave surfaces, as the tension cracks on the head of the NCS indicate the ongoing nature of sliding.

Buckling or flowage of steeply dipping strata due to gravity is regarded as one of the initial processes leading to the deformation of layers (Fig. 10a and b). The buckled layers

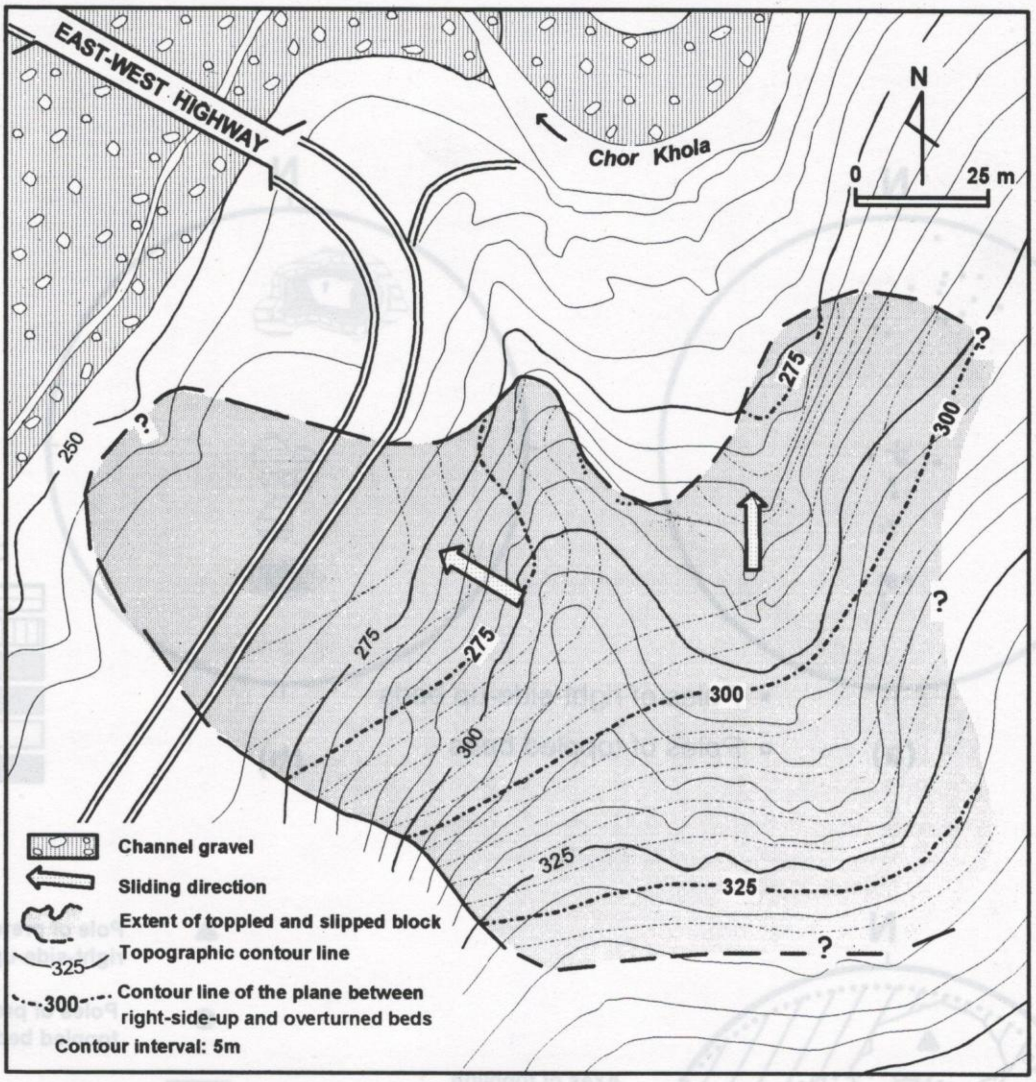


Fig. 8: Configuration and extent of toppled and slipped block. Contours show the plane between right-side-up and overturned strata.

experienced flexural slip along the mass discontinuities probably in late Pleistocene. As there are also prominent cross-joints and gentle diagonal joints with their strikes nearly parallel to the bedding plane, the block flexural toppling of layers (Fig. 10c) also took place.

Weathering proceeded in the toppled block before burial of the Chor Khola Valley by the riverbed deposits, and the geomorphic surfaces formed over the toppled block (Fig. 10d) probably in Holocene. The Chor Khola re-incised into the valley due to rapid uplift.

The toppled mass slid as a result of (a) formation of a slip surface parallel to cross joints or flexural cracks and (b) unloading of rock mass of the valley slope by erosion of the toe of the slope, thus, increasing instability and loading the head by colluvial debris. These events could have occurred in late Holocene (Fig. 10e).

The old toppled block slid down slope as the dissection of the valley progressed. Numerous tension cracks might have existed on the head of the slope, as they are still forming at that place (Fig. 10e).

Terrace deposits buried the landslide toe and increased its stability (Fig. 10f). Newer slip surfaces developed on the crest of the toppled mass, giving rise to the debris slide–debris flow deposit (Fig. 6b). These deposits have widely covered the rock topple–rockslide on the NCS.

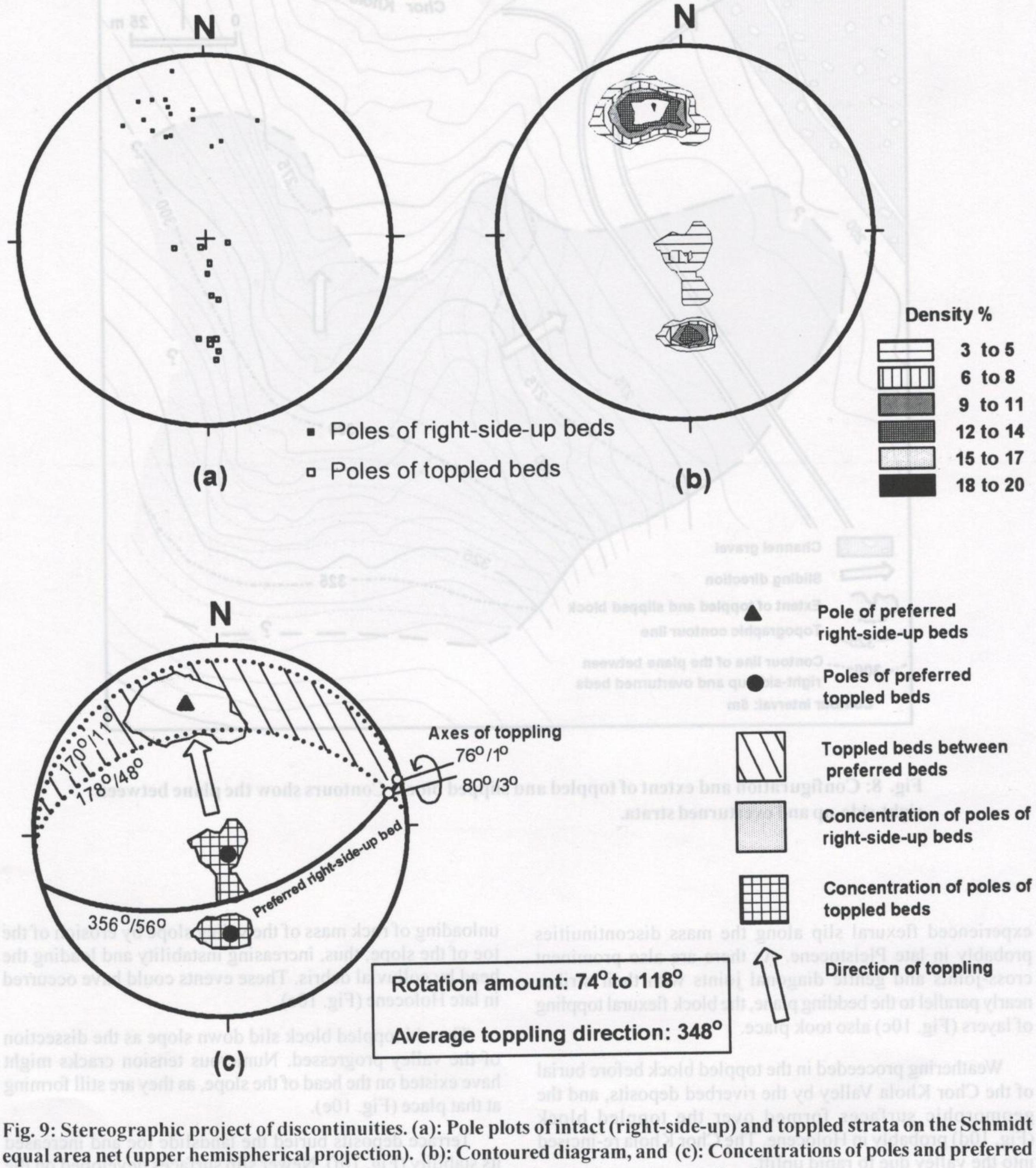


Fig. 9: Stereographic project of discontinuities. (a): Pole plots of intact (right-side-up) and toppled strata on the Schmidt equal area net (upper hemispherical projection). (b): Contoured diagram, and (c): Concentrations of poles and preferred planes of toppled and intact strata, the mean directions of toppling and rotation are also shown.

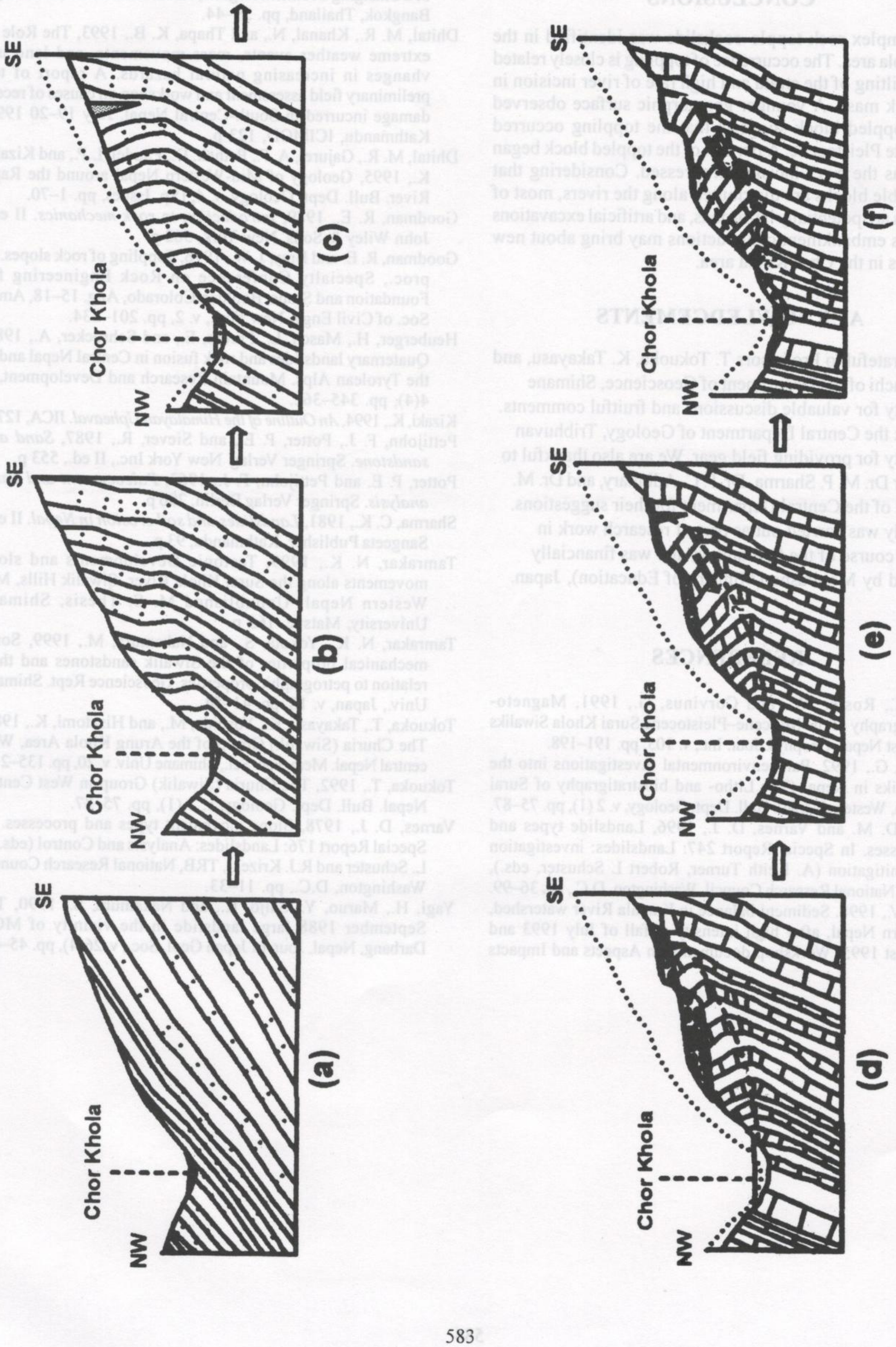


Fig. 10: Schematic diagrams showing the kinematics of toppling and sliding

CONCLUSIONS

A complex rock topple–rockslide was identified in the Chor Khola area. The occurrence of toppling is closely related to rapid tilting of the strata and high rate of river incision in weak rock mass. A younger geomorphic surface observed on the toppled block suggests that the toppling occurred during late Pleistocene. A portion of the toppled block began to slide as the river incision progressed. Considering that the unstable blocks are distributed along the rivers, most of the slopes are potentially hazardous, and artificial excavations as well as embankment constructions may bring about new landslides in the Chor Khola area.

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