Sent 25/3/92
Changes

Rock Mass Movements Across Bedding in Kananaskis Country, Alberta

Hu, Xian-qin
Department of Geology, University of Alberta
Edmonton, Alberta, Canada
T6G 2E3

Cruden, D.M.
Department of Civil Engineering
University of Alberta
Edmonton, Alberta, Canada
T6G 2G7

403 - 492 - 5923

For submission to Canadian Geotechnical Journal

Abstract

Rock mass movements in sedimentary rocks across bedding in Kananaskis Country, Alberta are controlled by discontinuity orientations and topography. When bedding planes dip at less than 50°, small rock masses can slide along strike joints or fall and slope angles remain unchanged. When bedding surfaces dip at 65° to 70°, large rock masses topple and then slide or simply slide along sheeting joints or combinations of bedding surfaces and strike joints to reduce slope gradients.

Block toppling and sliding models of large slope movements in highly jointed rock masses indicate that toppling mode is more critical than the sliding mode. A natural example, the 6×10^6 m^3 Elk Ridge landslide shows toppling from bedding planes followed by sliding can be catastrophic.

Keywords: Topple, slide, landslide, rock, Rockies

INTRODUCTION

All large rockslides described from the Canadian Rockies have slid down bedding planes (Cruden, 1985). So when Cruden and Eaton (1987) reported rock slopes in Kananaskis Country, Alberta (Fig. 1) where movements had taken place across bedding planes, we conducted a more detailed investigation of the mechanisms of these movements. We have now identified 19 such movements on Eaton's (1986) airphoto interpretations. All 19 slope movements are on anaclinal slopes (Cruden, 1988) where bedding planes dip into slopes.

In Kananaskis Country, rock masses on anaclinal slopes have been displaced either parallel or oblique to tectonic discontinuities and along sheeting joints. We report typical geological structures, lithology and characteristics of the displaced rock masses and rupture surfaces from these anaclinal slope movements. We give the first description of a major catastrophic topple on an anaclinal slope in the Canadian Rockies to our knowledge. The major slope movement, the Elk Ridge landslide, is evaluated using the block toppling model of Goodman and Bray (1976) and the models of sliding in highly-jointed rock masses from Hoek and Bray (1977).

The terminology used in describing the slope movements follows Varnes (1978), symbols follow Barsvary et al. (1980) and the legend of the maps and overlays is in accord with Dearman et al. (1972).

THE PHYSICAL ENVIRONMENT

Kananaskis Country is cut by now inactive thrust faults striking northwest-southeast (Bielenstein *et al.*, 1971). Strong old sedimentary rocks uplifted by thrust faults form mountain ranges and somewhat weak and younger rocks floor the valleys. Rock slope movements on anaclinal slopes have occurred in the Devonian Fairholme Group and Palliser Formation, in the Mississippian Exshaw, Banff Formations and the Rundle Group that includes the Livingstone Formation, Mount Head Formation and the Etherington Formation and in the Permo-Pennsylvanian Rocky Mountain Group (Fig. 2). Several anticlines and synclines extend parallel to the strike of the thrust faults (Bielenstein *et al.*, 1971).

The rocks contain at least two joint sets, both perpendicular to bedding surfaces. The strikes of the two joint sets are respectively perpendicular and parallel to the strike of the bedding (Fig. 3). Sheeting joints have formed parallel to slope surfaces. They resemble those in granites (Terzaghi, 1962) in the relationship between their orientations and topography. Their spacing is generally less than 3 metres although they may not closely parallel each other like tectonic joints. Sheeting joints have been found only in units with large discontinuity spacings, such as the Palliser Formation and the Livingstone Formation. Sheeting joints have only been found on anaclinal slopes, where the exposed trace lengths can reach 10 metres.

Four glacier episodes in the Quaternary have reshaped the mountains and tills were deposited on the bottom of the main trunk valleys (Jackson, 1981). Younger neoglacial tills are found on the floors of many higher tributary valleys. During the last glaciation, the valley walls were steepened. Talus now mantles the walls below rock cliffs.

The mean annual temperature varies from 1.4° C to 3.5° C and the highest and lowest temperatures from seven stations around the study area were 34.4° C and -51.1° C (Environment Canada, 1981). The precipitation values range from 471 mm to 657 mm with about 45% falling as snow (Environment Canada, 1981). The area is covered by snow throughout the year except in June, July and August, when there are only some snow patches at higher elevations. Freeze-thaw cycles occur everywhere in the study area during the spring and fall seasons. All the slope movements are above the tree line and there is little vegetation around these slope movements. The wide gapes of joints in both clastic and carbonate rocks have been caused by subaerial physical weathering.

According to Heidebrecht and Tso (1985), the peak horizontal seismic acceleration is 0.04 g in the study area. Seismic activities may have contributed to initiation of some slope movements.

SLOPE MOVEMENTS ON ANACLINAL SLOPES

On anaclinal slopes, bedding planes dip into the slope and the angle between the strikes of the slope and of the penetrative discontinuities is less than 20° (Cruden, 1988). Discontinuities dipping out of slopes in the study area include strike joints and sheeting joints. Kinematic analysis suggests toppling from penetrative discontinuities and sliding along joints where dip angles of joints exceed their friction angles may occur (Cruden, 1988, Fig. 5). The most likely mode of movement is not easily identifiable.

Movements on anaclinal slopes in Kananaskis Country can be divided into large landslides, dominantly rock slides and rock topples and smaller movements, dominantly falls. The accumulation zones of large landslides can be distinguished from those of rockfalls by their extent and form. Generally, displaced materials from large landslides display rock sequences similar to those in their depletion zones. Rock blocks from different units in the displaced rock masses are juxtaposed by rockfalls. Displaced materials at the toes of the slopes from slope movements can be easily identified on air photographs covering the study area.

Rupture surfaces of the 19 slope movements (Table 1) are either parallel to strike joints or parallel to sheeting joints or oblique to all discontinuities. Small slope movements are displaced along strike joints except in one case when the bedding dips at 65°. In contrast, large landslides move along rupture surfaces oblique to bedding planes and strike joints. Large slope movements have occurred only where bedding planes dip at about 65°. Slope movements with less than $0.15 \times 10^6 m^3$ of displaced materials occur where beds dip from 20° to 65°.

The 19 slope movements can then be divided into two groups by the volume of their displaced materials and are discussed separately.

Small slope movements

Sixteen of the nineteen slope movements have volumes less than $0.15 \times 10^6 m^3$. Their displaced material is less than 3 m thick and rock blocks in the displaced materials from different units on the rockwalls are juxtaposed (Fig. 4). Slope angles of anaclinal slopes do not change noticeably because the volumes of displaced materials are small and sliding surfaces are almost parallel to slope surfaces.

In 15 out of these 16 slopes, the bedding dips are less than 50° and the strike joints dip out of the slopes at more than 40°. Rock blocks can slide along these joint surfaces if their roughness angles are small, their basic friction angles are under 42° (Cruden and Hu, 1988, Hu, 1987). The angles of these slopes are generally close to the dips of the strike joints. As the rupture surfaces of the slope movements followed strike joints, these slopes were steepened escarpments before sliding or falling and the strike joints daylighted on the slopes. The small volumes of the displaced material are a consequence of the steep, closely-spaced rupture surfaces, with limited roughness angles and no cohesion at the scale of the mass movements around the slope surfaces.

Since the last glaciation, limited volumes of rock debris accumulated on the slopes to cover the ground as thin layers. The slope movements were not single sliding events but fragmental rockfalls over a period of time. On the rockwalls of all the small slope movements, there are no discontinuities dipping out of the slopes and daylighting on the slope with potential displaced rock masses larger than 0.15×10^6 m^3 on them.

On one of the 16 slopes, the bedding dip is 65° (Table 1). So small slope movements can also develop when the bedding dips at more than 50°. The movements may not only be slides on strike joints but also topples of blocks from bedding or a combination of both of them.

In summary, although slope movements of small magnitude are not restricted to slopes where bedding planes dip into slopes at less than 50°, the events where the bedding dips at less than 50° considerably outnumber those where the bedding dips are larger than 50°. It is reasonable to conclude that the most common type of small anaclinal slope movement is rockfall following sliding along strike joints daylighting on steepened or normal escarpments (Fig. 5). All the small slope movements except one are within 5° of the dips of strike joints, i.e., the slopes are close to normal anaclinal slopes (Fig. 5).

The Elk Ridge Landslide

Three landslides have volumes 0.15×10^6m^3 or larger (Table 1). The bedding around these three slope movements dips at 65°. Both the slope surfaces and the rupture surfaces are oblique to strike joints as well as bedding surfaces. The rupture surfaces underdip the original ground slopes in contrast to the small movements when rupture surfaces are subparallel to original ground slopes (Fig. 5).

The Elk Ridge landslide is analyzed because the displaced material from the east of Elk Ridge is clearly from one big event and looks fresher than at the other two slides. Gardner *et al.* (1983, p.87) first identified the debris east of Elk Ridge and considered it was a large rockfall. The analysis of the Elk Ridge landslide starts with a detailed description and is followed by back analyses using a toppling model and sliding models.

The landslide occurred in rocks from both the Livingstone Formation and the Mount Head Formation in the hanging wall of the Lewis Thrust (Fig. 6). The east side of Elk Ridge has been steepened by glaciation to form slopes at 60°, which are preserved north and south of the landslide. The bedding planes dip at 65°-70° to 240° (represented as 65°-70°/240°) and there are strike joints and dip joints whose orientations are 20°-25°/060° and 90°/150°.

The Livingstone Formation is a strong, fossiliferous, coarse-grained, light-grey limestone. The beds in the Livingstone Formation are 40-60 cm thick. The spacing between the strike joints extending across these beds is 1.5-2 m. Joint spacing is a few centimetres for joints extending less than 5 cm. Sheeting or unloading joints are clearly developed. They are subparallel to the slope surface (Fig. 7). The rock mass quality, $Q = 11.1$, indicates good rock by the classification of Barton *et al.* (1974).

The Mount Head Formation consists of yellowish to gray, fine to coarse-grained, thinly to thickly bedded limestones and dolostones. The bedding thickness in the Mount Head Formation is 40-50 cm and the joint spacing averages 5 cm on the top of the Elk Ridge. Most of the rockwall is not accessible. From the descriptions by MacQueen and Bamber (1968) and Sauchyn (1984) and observations through binoculars, both bedding thicknesses and joint spacings vary from a few centimetres to half a metre. The rock blocks, limestones and dolostones, are not obviously weaker than those in the Livingstone Formation from simple field strength tests using a geological hammer (Herget, 1977, p.88). Strike joints are not throughgoing discontinuities but are offset by bedding planes, particularly in thick beds. Sheeting is not seen in this formation. The rock mass quality, Q = 1.1, indicates poor rock according to Barton *et al.* (1974).

The rupture surface on the east slope of Elk Ridge can be divided into two parts (Figs. 8 and 9). The lower part, in the Livingstone Formation, slopes at 60°, parallel to sheeting joints. Individual sheeting joints may extend over 10 m parallel to the slope surface. The upper part of the rupture surface, in the Mount Head Formation, dips at 45°, oblique to both the bedding surfaces and the strike joints.

The displaced materials (Fig. 8) show the same stratigraphic sequence now exposed on the rupture surface. This suggests the deposit resulted from a single large movement, not from the random accumulation of numerous rock falls from different strata over a period of time. The age of the landslide has not been evaluated by carbon dating or other methods. But the tree cover on the debris is not well developed, suggesting the slide is hundreds rather than thousands of years old. The maximum length, width and thickness of the displaced material are 315 m, 710 m and 55 m respectively. The volume of the debris can then be estimated as $6.4 \times 10^6 m^3$ (WP/WLI, 1990). The volumes of the displaced materials and of the depletion of the landslide (Fig. 9) are the same, so the scarp has not been significantly eroded since landsliding.

The travel angle is 27°, in the middle of the rock avalanches in Hutchinson's (1988, p.15) mobility classification. The rising slope to the east prevented the debris travelling further eastward and may explain the comparatively large travel angle.

Modelling of Elk Ridge Landslide

Toppling model

Goodman and Bray's (1976) kinematic criterion shows it is kinematically possible for toppling from bedding planes to develop on the original slope. Figure 5 also shows that sliding of the displaced materials along the rupture surface of the topple may follow toppling. Here we use the multi-block toppling model of Goodman and Bray (1976, p.209) to back analyze the stability of the original slope.

In the model, the toppled or potential toppled rock mass is divided into blocks (columns) separated by penetrative discontinuities (fig. 10). These columns are separated from the untoppled beds by a stepped rupture surface which is the combination of bedding planes and joints and whose overall orientation can only be assumed. The forces acting on each block in the toppled mass are calculated from the top to the toe of the slope. The failure mode for each block is determined by solving two equations (Goodman and Bray, 1976, Equations (5) and (10)) to calculate the forces exerted by the underlying block to prevent the block from sliding or toppling. The two calculated forces are compared, the solution produces the larger force and gives the failure mode and this force is used for the calculation of the next block below. When the calculations are finished, the support to prevent toppling, PT, or sliding, PS (Fig. 10) of the toe block has been found.. If the support is positive, the slope is not stable. The results of the calculation depend on the friction angles of the discontinuities, ϕ, the dip of the rupture surface, ψ, and the thicknesses of the blocks, DX. The dip of the rupture surface and the slope angle determine the volume of the topple (Fig. 10).

Because the rocks in the Mount Head Formation are limestones and dolostones, their basic friction angles are not likely to exceed 40° (Hu, 1987). In the back analyses, friction angles of 25°, 30°, 35° and 40° are selected for calculation. Friction angles are assumed to be the same for bedding planes and joints following Goodman and Bray (1976). Cohesion is zero considering that weathering and tectonic activity destroyed it along discontinuities. The dip angles of rupture surfaces are assumed to range from 27° to 57° in 3° increments in the model. It is generally not possible to know how many intact blocks were involved in the topple. However, as rock blocks in the displaced materials are up to 5 m across, it is reasonable to consider intact blocks before sliding were more than 5 m thick. In the model, block thicknesses of 10 m, 15 m and 20 m are assumed in the calculations.

The results of the back analyses indicate that the toe block of the original slope needed support to prevent toppling or sliding in most of the combinations of the above parameters (Table 2). The toe block may have been supported by the stronger rock in the Livingstone Formation. After the support of the Livingstone Formation was removed by sliding along sheeting joints or by toppling, the toe block in the Mount Head Formation could move by toppling or by sliding. After the toe block moved, the other blocks can topple or slide and all the rock masses above the rupture surface are displaced along the rupture surface.

The toe block can topple or slide in most of the combinations of rupture surfaces, block thickness and friction angle (Table 2). The support required to prevent either toppling or sliding decreases with an increase in the block thickness. The support required against sliding decreases with an increase of friction angles but there is not a simple relationship between the support against toppling and the friction angle. There are no clear trends in the supporting forces at different dips of the rupture surfaces.

Sliding models

If sliding is the movement mode, the rupture surface might follow the strike joints and bedding surfaces in the Mount Head Formation, with shearing along the strike joints and separation along bedding planes (Fig. 11). In the Livingstone Formation, sliding follows sheeting joints. Assuming the rupture surface is a combination of two surfaces, one in the Mount Head and the other in the Livingstone, the movement may be a compound slide. The rupture surface in the Livingstone Formation is parallel to the slope surface and sheeting joints are close to the slope surface, so the volume of the lower block is considerably smaller than the volume of the upper block in the Mount Head Formation. Sliding of the Livingstone may trigger sliding of the Mount Head. Once the Livingstone has slid, the Mount Head may slide following its own rupture surface.

The rock mass in the Mount Head Formation can be considered as highly fractured because the discontinuity spacings are considerably smaller than the size of the slope and there was possibly some crushing around corners of blocks while sliding. If the rock mass did not slide along any individual discontinuity, then Ladanyi and Archambault's equation as modified by Hoek and Bray (1977, p.104, Equation 28) can be used to back calculate the stability of the slope. The shear strength criterion is

$$\tau = \frac{\sigma(1 - a_s)(\dot{v} + \tan\phi) + a_s \eta \sigma_c \frac{\sqrt{1+n} - 1}{n}\left(1 + n\frac{\sigma}{\eta\sigma_c}\right)^{1/2}}{1 - (1 - a_s)\,\dot{v}\tan\phi} \qquad (1)$$

In the equation, $\dot{v} = (1 - \sigma/\sigma_c)^k \tan i$, is the dilation rate at peak strength; $a_s = 1-(1 - \sigma/\sigma_c)^L$, the proportion of the discontinuity surface which is sheared through intact rock materials; σ_c, the uniaxial compressive strength of the individual blocks within the rock mass; η, the degree of interlocking which defines the freedom of the blocks to translate and to rotate before being sheared or fractured; ϕ, friction angle along discontinuities; i, the roughness angle when sliding down strike joints; n, the ratio of uniaxial compressive to uniaxial tensile strength of the rock material; K and L, constants determined by modes of failure.

Ladanyi and Archambault (1970) proposed three modes of failure of highly fractured rocks and Hoek and Bray (1981, p. 104) illustrated the modes in photographs. (1) Shear along a well defined plane inclined to both discontinuity sets, (2) Formation of a narrow zone in which block rotation has occurred in addition to the sliding and material failure of Mode 1 and (3) Formation of a kink band of rotated and separated columns of 3, 4 or 5 blocks.

We have analysed for all 3 modes of failure. We use the same original slope angles and friction angles as in the toppling model. Hoek and Bray (1977) suggested that for mode (1), $K = 4$, $L = 1.5$ and $\eta = 0.7$; for mode (2), $K = 5$, $L = \tan i$ and $\eta = 0.6$; and for mode (3), $K = 5$, $L = (2/n_r)^3 \tan i$ where n_r is the number of rows of blocks in the kink band, normally 3 to 5 and η is 0.5.

In the stability analysis using equation (1) rupture surfaces were assumed in order to determine along which inclined plane the original slope is weakest. The factor of safety, FS, the ratio of the shear resistance to the driving force was calculated for all these assumed rupture surfaces.

The dip angles of the assumed rupture surfaces ranged from 55° to 25° with an interval of 1°. Because sliding is assumed to occur along the strike joints, the angle between the overall sliding direction and the direction of the dip of the strike joints is the roughness angle i, which ranges from 30° to 0° for the above assumed rupture surfaces

(Fig. 11). The uniaxial compressive strengths of the carbonates are determined by NCB cone indentation tests (Mining Research and Development Establishment, 1977) on fresh rock-sawn surfaces of samples. Uniaxial compressive strengths are between 160 and 230 MPa. Due to weathering and weakening around discontinuities, the actual uniaxial compressive strengths of the rock blocks may be lower. The strengths of rock blocks also decrease with the increase of sizes of blocks due to scale effects. Bandis (1990) reviewed scale effects in the strength and deformability of rocks and discontinuities and gave several empirical criteria for scale effects. However, in this paper, we still use for consistency Goodman and Bray's (1977) suggestion that the uniaxial compressive strength in equation (1) should be a quarter that of unweathered intact rocks. So $\sigma_c = 40$ MPa and 60 MPa are used for the analysis.

The geometry of the slide in the analysis is shown in Fig. 11, here the average driving shearing stress along the rupture surface is

$$\tau_{driving} = W\sin\psi / L = \frac{1}{2}\gamma L\sin\left(\beta - \psi\right)\sin\psi$$

and the average normal stress along the assumed rupture surface is

$$\sigma_n = W\cos\psi / L = \frac{1}{2}\gamma L\sin\left(\beta - \psi\right)\cos\psi$$

where γ is the unit weight of the rock mass, 25 KN/m^3. W is the weight of the sliding rock mass of unit width and $\beta - \psi$ ranges from 5° to 35°. The length of the rupture surface in the Mount Head Formation in the sliding direction is assumed to be equal to the length, L, of the slope surface in the Mount Head Formation in the sliding direction before sliding.

In the calculations, shear stresses and normal stresses are assumed constant along the rupture surfaces and equal to the average values. Then, factors of safety are calculated for the different rupture surfaces. With all the variations of the uniaxial compressive strengths and the friction angles, the factor of safety reaches a minimum between 40° and 50° for failure mode 1 when the friction angles are 35° and 40° and the factor of safety reaches a minimum at 55°, the steepest rupture surface when the friction angles are 25° and 30° (Fig. 12). When the dip of the assumed rupture surface is between 35° and 45°, the factor of safety reaches a minimum for failure mode 2 (Fig. 13). The minimum factors of safety for mode 3 fall between 38° and 43° and the number of rows in the kink bands has little influence on the factors of safety (Fig. 14). Except when the friction angle is 25° in mode 2 and in mode 3, the factors of safety are larger than one. So the sliding may have been assisted by some forces other than gravity such as seismic forces and pore pressures at the beginning of the event. Pore pressures in cracks, mainly from melting snow, are not likely to be maintained when the rock masses move a short distance (Henkel, 1967).

If the displaced rock mass in the Mount Head Formation slid along the rupture surface at 45° under gravity alone, the friction angle of the rupture surface would have been 25 degrees or less for failure modes 1 and 2 and 28 degrees or less for failure mode 3. Figure 15 shows the good correlation between the factor of safety and the friction angle for all 3 modes of failure.

There is no direct evidence to show whether the sliding was in mode 1 or mode 2 or mode 3. The back analyses only give simplified results for the sliding models. Unlike slides along penetrative discontinuities, sliding surfaces on anaclinal slopes are determined by several factors, such as discontinuity orientations, friction angles, topography and probably external forces.

Because the factors of safety for most of the combinations of the friction angles, the dips of rupture surfaces and the uniaxial compressive strengths are larger than one and the friction angles required for factors of safety of one in sliding models are 28° or less, sliding is not as critical as toppling. As the friction angles of carbonates are generally larger than 28° (Cruden and Hu, 1988), sliding is unlikely to have been the first movement of the landslide. The landslide is probably a complex rock topple rockslide, toppling then sliding as Figure 5 indicates. Both the toppling model and sliding models are two-dimensional, factors of safety are probably conservative compared to those in three-dimensional models. Our modelling is mainly aimed at comparing the different failure modes and explaining the processes.

CONCLUSIONS

The stability of anaclinal slopes in stratified rocks in the Canadian Rockies and the magnitude of landslides from them are controlled by their geological structures as well as the lithologies which determine the strength of the rocks. In the Paleozoic carbonate rocks and clastic rocks in the study area, the orientations of the discontinuities control the magnitude of slope movements.

Large landslides are found where the bedding planes dip into the slope at about 65°, the strike joints dip out of the slope at about 25° and the slopes are 60° (Fig. 5). Sheetings form rupture surfaces where the rocks are strong and have large tectonic joint spacings. Depending on discontinuity orientations and spacings, it is kinematically possible for large slope movements from a steep slope to either topple or slide along a combination of bedding surfaces and strike joints. Analysis of the Elk Ridge landslide indicates that this catastrophic movement probably occurred along the rupture surfaces of a topple rather than a slide. Toppling can be analyzed by Goodman and Bray's (1976) model and sliding along combinations of discontinuities can be modelled by Hoek and Bray's (1977) modification of Ladanyi and Archambault's (1970) criterion. With the all the assumptions of the geometry of rupture surfaces and mechanical properties of rock blocks, toppling is found to be more critical than sliding models. Sliding after toppling can be catastrophic on steepened anaclinal slopes.

Most of the small events occur where bedding is gentler than 40° while the strike joints are steeper than 50° (Fig. 5). Small rock falls initiated by sliding are the main type of small slope movement.

ACKNOWLEDGEMENTS

Hu's Ph.D. thesis was supported by the Killam pre-doctoral fellowship at University of Alberta. Cruden's work in Kananaskis Country has been assisted by grants from NSERC and the Alberta Research Council and a contract from Alberta Transportation. We are both grateful for useful discussions with colleagues at University of Alberta and for the hospitality of Kananaskis Environmental Research Centre, University of Calgary.

References

Bandis, S.C., 1990, Scale effects in the strength and deformability of rocks and rock joints, Proceedings of the First Workshop on Scale Effects in the Rock Masses, Loen, Norway, 59-76.

Barsvary, A.K., Klym, T.W., Franklin, J.A., 1980, List of terms, symbols and recommended SI units and multiples for geotechnical engineering, Canadian Geotechnical Journal, 17: 89-96.

Barton, N., Lien, R. and Lunde J., 1974, Engineering classification of rock masses for the design of tunnel support, Rock Mechanics, 6: 189-236.

Beach, H.H., 1943, Moose Mountain and Morley map area, Alberta, Canada Geological Survey, Memoir 236, 74p.

Bielenstein, H.U., Price, R.A. and Jones, P.B., 1971, Geology of the Seebe-Kananaskis area, Map in Halladay, I.A.R. and Mathewson, D.H., A guide to the geology of the Eastern Cordillera along the Trans Canada Highway between Calgary, Alberta and Revelstoke, British Columbia, Alberta Society of Petroleum Geologists, Calgary, 94p.

Charlesworth, H.A.K., Cruden, D.M., Ramsden, J., Huang, Q., 1989, Orient: An interactive Fortran 77 Program for processing orientations on a microcomputer, Computers and Geosciences, 15: 275-293.

Cruden, D.M., 1985, Rockslope movements in the Canadian Cordillera. Canadian Geotechnical Journal, 22: 528-540.

Cruden, D.M., 1988, Thresholds for catastrophic instabilities in sedimentary rock slopes, some examples from the Canadian Rockies, Zeitschrift fur Geomorphologie, supplementband 67: 67-76.

Cruden, D.M. and Eaton, T.M., 1987, Reconnaissance of rockslide hazards in Kananaskis Country, Alberta, Canadian Geotechnical Journal, 24: 414-429.

Cruden, D.M. and Hu, Xian-qin, 1988, Basic friction angles of carbonate rocks from Kananaskis Country, Canada. Bulletin of the International Association of Engineering Geology, 38: 1147-1152.

Dearman, W.R., et al., 1972, The preparation of maps and plans in terms of engineering geology, Quarterly Journal of Engineering Geology, 5: 293-382.

Douglas, R.J.W., 1958, Mount Head map area, Alberta, Geological Survey of Canada, Memoir 291.

Eaton, T.M., 1986, Reconnaissance of rockslide hazards in Kananskis Country. M.Sc. Thesis, University of Alberta, Edmonton, 291p.

Environment Canada, 1981, Canadian climate normals, temperature and precipitation, prairie provinces, 1951-1980, Environment Canada, pp. 12, 21, 66, 91, 103, 104 and 161.

Gardner, J.S., Smith, D.J. and Deslodge, J.R., 1983, The dynamic geomorphology of the Mount Rae area: A high mountain region in southwestern Alberta, Department of Geography, University of Waterloo, 237p.

Goodman, R.E. and Bray, J.W., 1976, Toppling of rock slopes, Proceedings, Specialty Conference on Rock Engineering for Foundations and Slopes, Boulder, Colorado, American Society for Civil Engineers, Vol. 2, 201-234.

Henkel, D.J. 1967, Local geology and stability of natural slopes, Proceedings, American Society of Civil Engineers, 93, SM4, 437-446.

Herget, G., 1977, Pit Slope Manual Chapter 2 - Structural Geology. Canadian Centre for Mineral and Energy Technology report 77-41, 123p.

Heidebrecht, A.C. and Tso, W.K., 1985, Seismic loading provision changes in National Building Code of Canada 1985, Canadian Journal of Civil Engineering, 12, 653-660.

Hoek, E. and Bray, J.W., 1977, Rock slope engineering. the Institute of Mining and Metallurgy, London, 402p.

Hoek, E. and Bray, J.W., 1981, Rock slope engineering, the Institute of Mining and Metallurgy, London, 358p.

Hu, X.Q., 1987, Potential rocksliding along bedding surfaces in Kananaskis Country, M.Sc. thesis. University of Alberta, Edmonton, 212p.

Hutchinson, J.N., 1988, General report: Morphological and geotechnical parameters of landslides in relation to geology and hydrogeology, Proceedings of the Fifth International Symposium on Landslides, Balkema, Rotterdam, Vol. 1, 3-35.

Jackson, L.E. Jr., 1981, Quaternary stratigraphy of the region between Calgary and the Porcupine Hills, *in* Field Guide to Geology and Mineral Deposits, edited by R.I. Thompson and D.G. Cook, Geological Association of Canada annual meeting, 79-99.

Ladanyi, B. and Archambault, G., 1970, Simulation of shear behaviour of a jointed rock mass. Proceedings 11th Symposium on Rock Mechanics, AIME, New York, 105-125.

MacQueen, R.W. and Bamber, E.W., 1967, Stratigraphy of Banff Formation and Lower Rundle Group (Mississippian), Southwestern Alberta, Geological Survey of Canada, Paper 67-47, 37p.

MacQueen, R.W., Bamber, E.W. and Mamet, B.L., 1972, Lower Carboniferous stratigraphy and sedimentology of the southern Canadian Rocky Mountains, 24th International Geological Congress, Montreal, Canada, 62p.

Mining Research and Development Establishment, 1977, NCB Cone Indenter, MRDE Handbook, No. 5, 12p.

Ollerenshaw, N.C., 1968, Preliminary account of the geology of Limestone Mountain map area, southern Foothills, Alberta, Geological Survey of Canada, Paper 68-24, 37p.

Raymond, P.E., 1930, The Paleozoic formations in Jasper Park, Alberta, American Journal of Science, 20, 289-300.

Sauchyn, D.J., 1984, Open rock basins and debris fans in the Kananaskis area, southern Canadian Rocky Mountains, Ph.D thesis, University of Waterloo, Waterloo, 348p.

Terzaghi, K., 1962, Dam foundation on sheeted granite. Geotechnique, 12: 199-208.

Varnes, D.J., 1978, Slope movement types and processes, in Landslides: Analysis and Control, edited by R.L. Schuster and R.J. Krizek, Transportation Research Board, special report 176, National Research Council, Washington, D.C., 234p.

WP/WLI (International Geotechnical Societies' UNESCO Working Party on World Landslide Inventory), 1990, A suggested method for reporting a landslide, Bulletin of the International Association of Engineering Geology, 41: 5-12.

Table 1 Location, geology and volume of 19 landslides on anaclinal slopes

	U.T.M. location Northing	Easting	Geological Formation	Slope angle	Bedding dip	Volume ($10^6 m^3$)
1	5648500	621000	Dp-Me-Mb-Mr	50-70	20-40	0.01
2	5645000	621700	Mr	60	30	0.02
3	5644600	623000	Mr	60-70	20-30	0.02
4	564300	622900	Mr	65-75	20-30	0.10
5	5640800	624600	Mr	60-70	20-30	0.01
6	5639800	619600	Df	60	20-30	0.03
7	5637500	619600	Dp	60	30	0.01
8	5636000	620700	Dp	60	30	0.01
9	5637700	622000	Mr	60	30	0.02
10	5633500	622000	Dp	50	35	0.01
11	5633600	623200	Df	55	30-35	0.04
12	5631400	624700	Mr	60-70	20-30	0.03
13	5624500	626300	Prm	60	30	0.03
14	5622700	616800	Dp	50	40	0.04
15	5609500	621000	Df	60	35	0.03
16	5618600	623700	Dp-Me-Mb-Mr	60	65	0.01
17	5632500	611500	Df-Dp	45	65	0.15
18	5617000	624500	Mb-Mr	50	65	1.10
19	5609500	638500	Mr	45-60	65	6.09

The U.T.M. locations are from the topographic maps 82J/11 and 82/14. The slope angles are current slope angles. The Elk Ridge landslide is Site 19.

Table 2 The results of back calculations using a toppling model.

Dx is the block thickness in metres; ϕ, the friction angle; ψ, the dip of the rupture surface in degrees; PT, PS, forces to prevent toppling or sliding of the toe block in MN, unit width assumed; X, indicates PT, PS cannot be calculated because all the individual blocks slide.

DX	ϕ \ ψ	27	30	33	36	39	42	45	48	51	54	57	
10	25	−2344	−744	−325	−122	55	377	224	604	628	5888	10	PT
		414	466	495	612	859	1601	5245	1343	1206	10686	17	PS
	30	−594	−97	35	103	167	279	149	229	180	627	41	PT
		241	254	249	274	325	465	223	321	239	805	51	PS
	35	143	129	111	103	93	75	82	48	36	149	237	PT
		127	122	107	100	91	74	81	47	36	145	235	PS
	40	391	184	117	87	65	42	191	26	15	−8	−7	PT
		74	68	55	48	40	27	136	18	11	−7	−6	PS
15	25	−1794	−523	−247	−79	40	242	122	318	251	641	11	PT
		321	320	383	415	590	1021	337	705	480	1109	17	PS
	30	−470	−63	34	79	127	196	92	134	78	7	X	PT
		199	188	206	202	243	322	135	186	102	8	X	PS
	35	147	112	105	87	80	60	87	37	33	5	X	PT
		112	98	96	81	75	57	84	35	32	4	X	PS
	40	361	152	104	67	50	27	138	6	−11	−13	X	PT
		61	50	45	33	27	14	97	2	−11	−13	X	PS
20	25	−1244	−440	−170	−49	32	162	74	123	39	10	11	PT
		229	277	275	285	411	668	197	268	72	16	17	PS
	30	−318	−46	33	63	96	133	58	47	21	14	X	PT
		149	169	156	145	176	214	81	62	26	16	X	PS
	35	150	116	91	72	66	46	106	23	31	0.2	X	PT
		87	90	75	60	57	40	101	19	29	−2	X	PS
	40	304	148	86	51	34	11	102	−14	−29	−20	X	PT
		42	42	30	19	12	−0.5	68	−15	−27	−18	X	PS

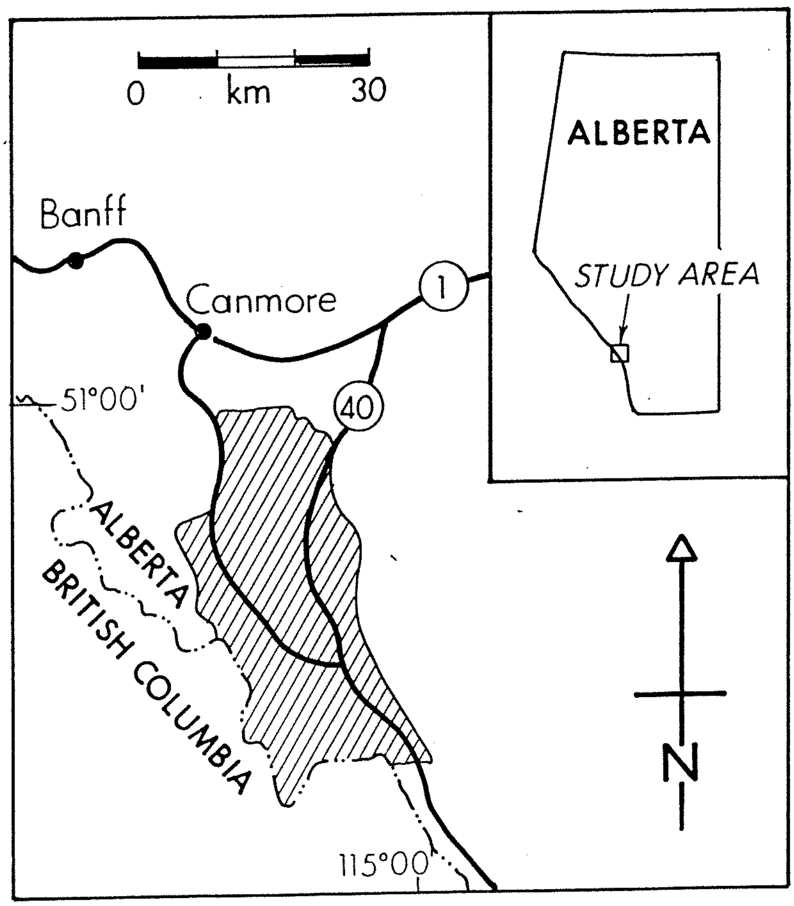
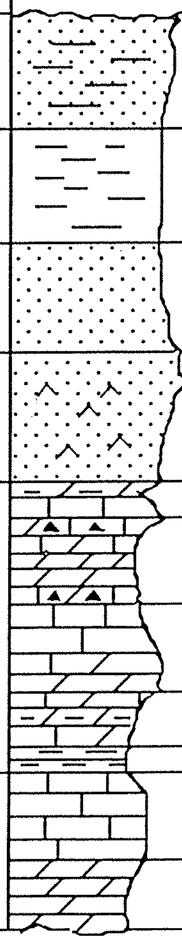


Figure 1. Study area with provincial highways and boundary.



PERIOD	LITHOLOGY	GROUP	FORMATION	SYMBOL	
Cretaceous-Jurassic			Kootenay	Jk	
Jurassic		Fernie		Jf	
Triassic		Spray River		Trs	
Permian, Pennsylvanian		Rocky Mountain		Prm	
Mississippian		Rundle	Etherington	Mr	Mth
			Mount Head		Mh
			Livingstone		Ml
			Banff	Mb	
			Exshaw	Me	
Devonian			Palliser	Dp	
		Fairholme		Df	

LEGEND

- Limestone
- Dolostone
- Quartzite
- Sandstone
- ▲ Chert
- — — — Shale

Figure 2. Stratigraphical column, lithologies of Mth and Ml are from Douglas (1958), Mh, Mb and Mc are based on Macqueen et al. (1972), Dp is based on Beach (1943), Df is based on Raymond (1930) and Ollerenshaw (1968), Trs, Jf and Jk are based on Bielenstein et al. (1972).

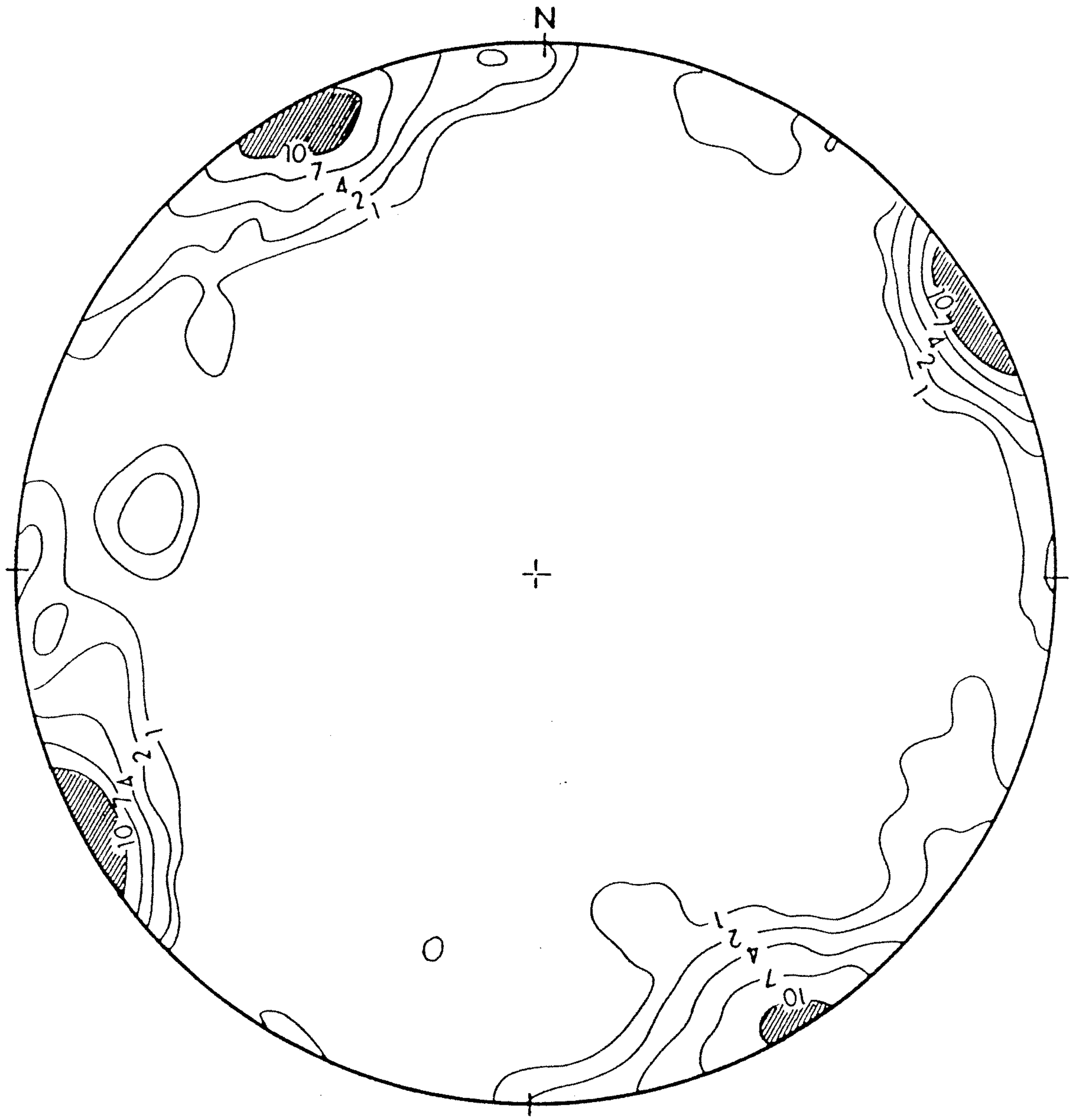


Figure 3. Polar diagram of joints from Kananaskis Country. The probability diagram with K = 100 on an equal angle projection (Charlesworth et al., 1989) used 446 joints from all the units in Figure 2. Sheeting joints were excluded. All the joints have been rotated by the local bedding dip about the strike of the bedding (about 150°).

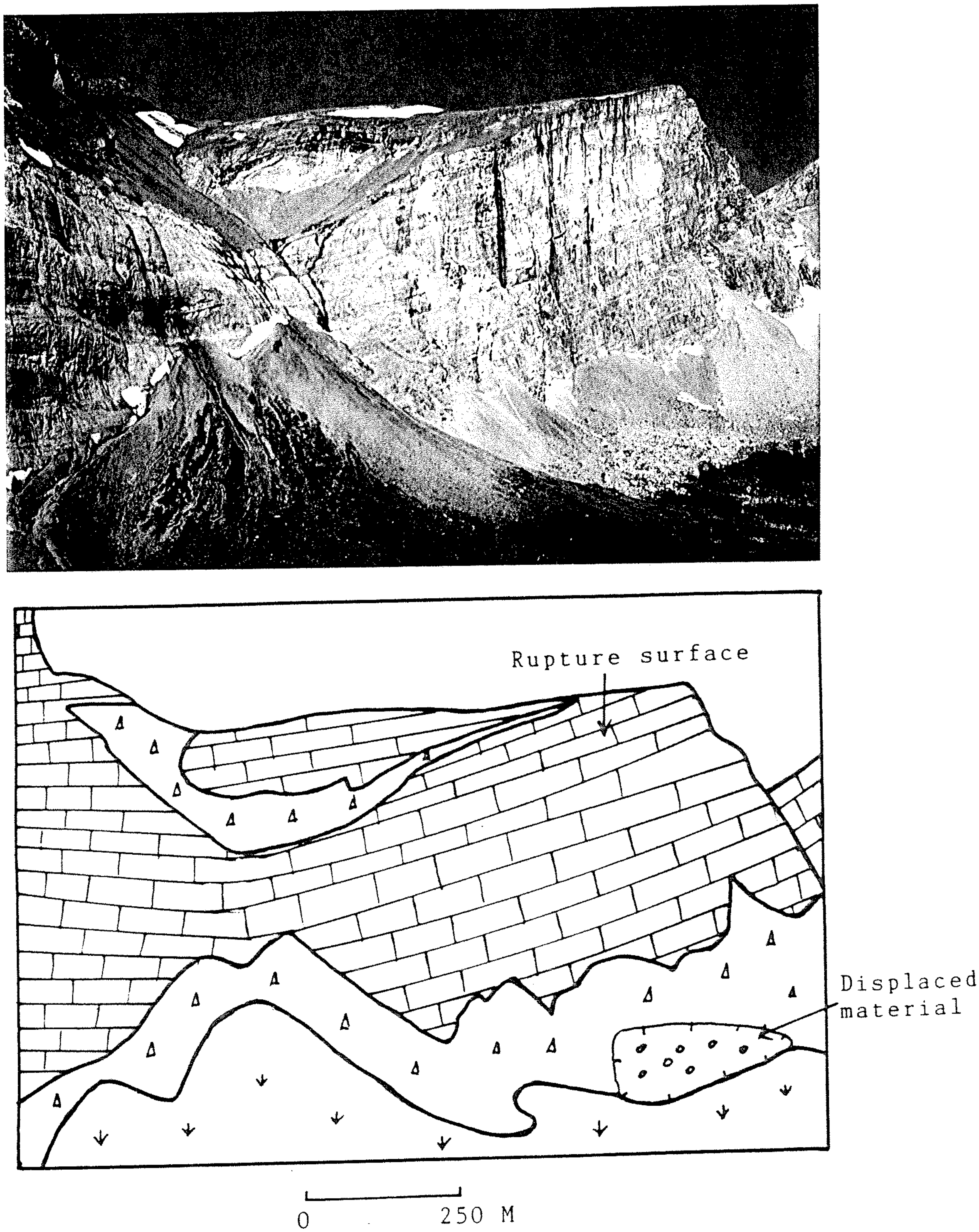


Figure 4. A typical example of a small slope movement in limestones of the Rundle Group (Site 12, Table 1).

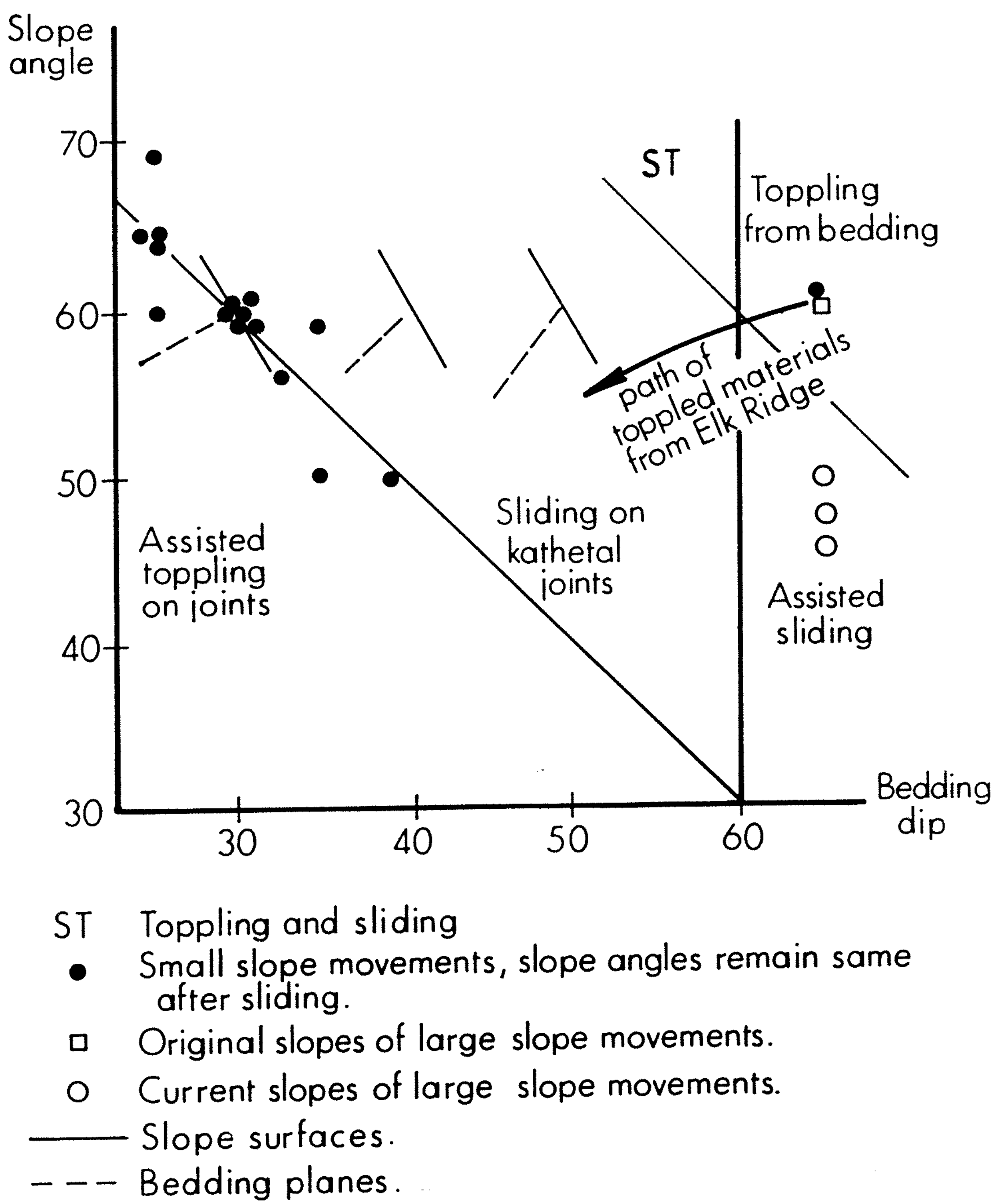


Figure 5. A process diagram for the anaclinal rock slopes, ϕ is assumed to be 30°, cohesion and pore pressures are absent.

Figure 6. Geology around the Elk Ridge rockslide overlain on airphoto AS748-5027 80. A is 5 km N of the Highwood Pass, B-B' is the line of Figure 9.

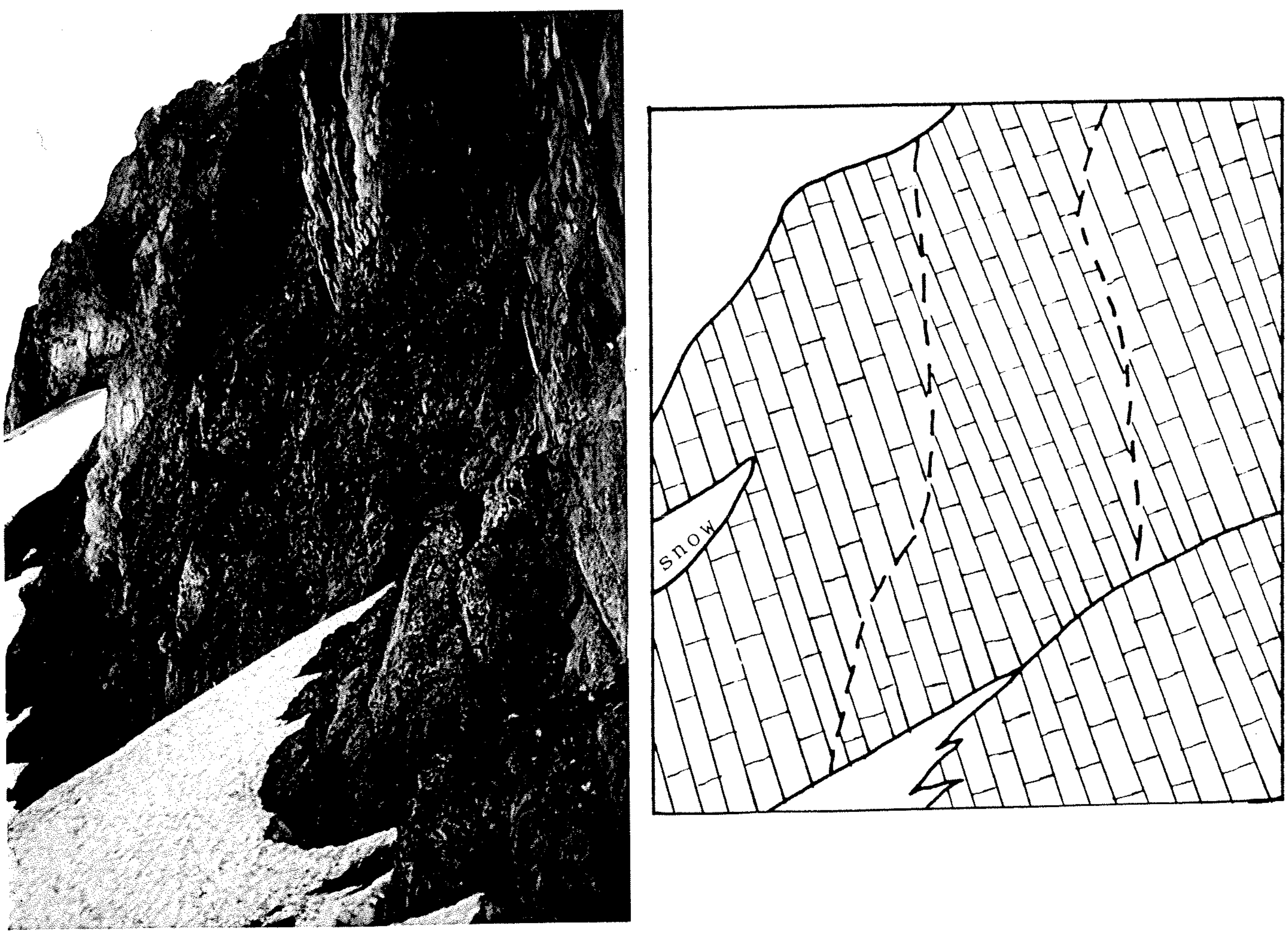


Figure 7. Sheeting joints from the Livingstone Formation below Elk Ridge are represented by dashed lines on the overlay.

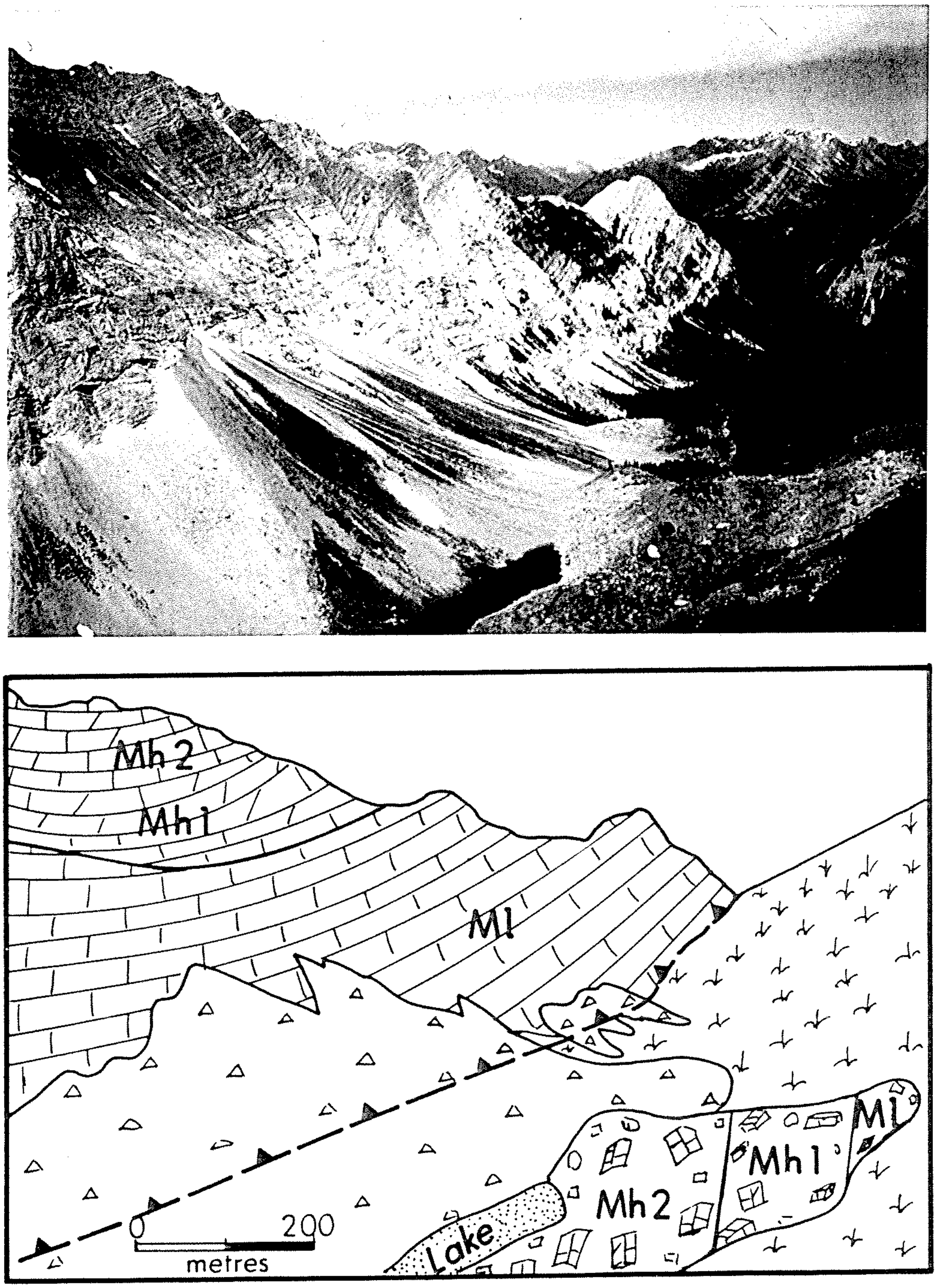


Figure 8. The slide from Elk Ridge, with both the debris and the rupture surface. Displaced materials, Mh2, Mh1, are from the Mount Head Formation; Ml1 is from the Livingstone Formation.

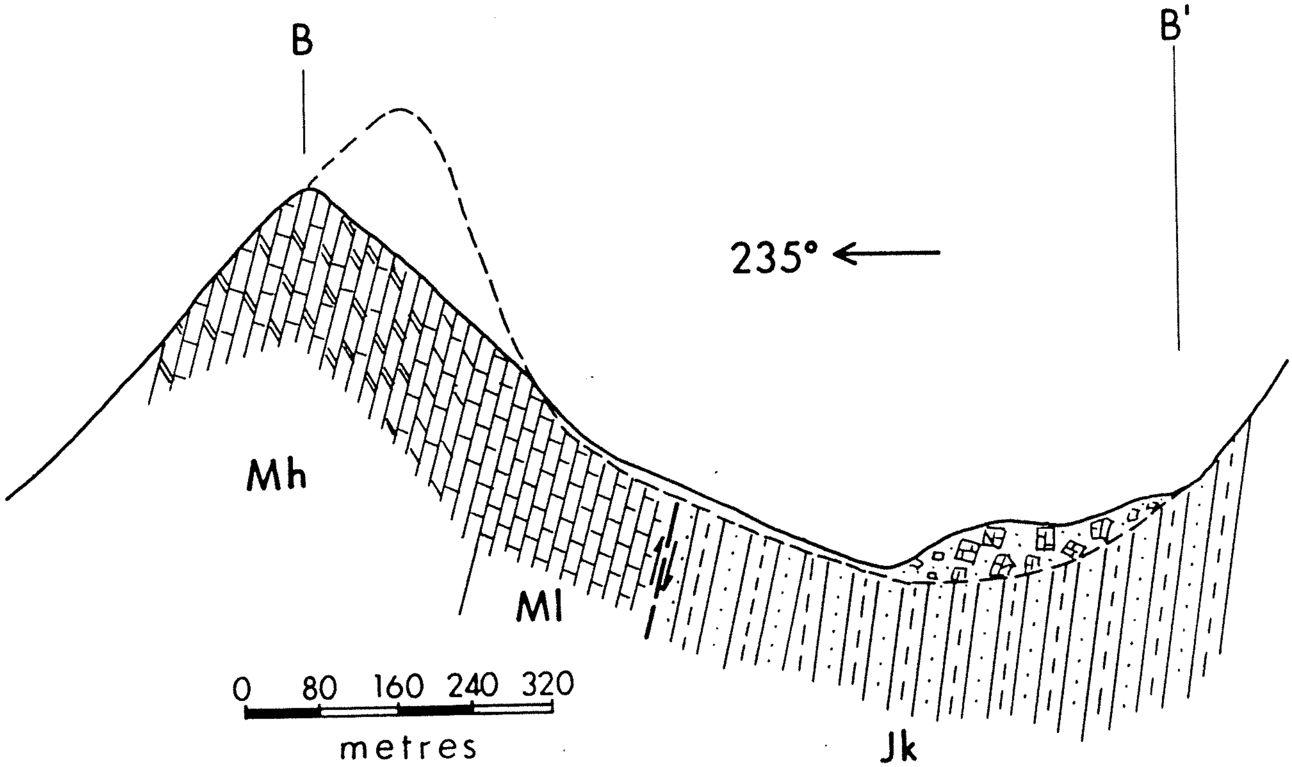


Figure 9. Cross-section of the Elk Ridge slide along the sliding direction. Symbols follow Fig. 2 and Dearman et al. (1972). B-B' is from Fig. 6.

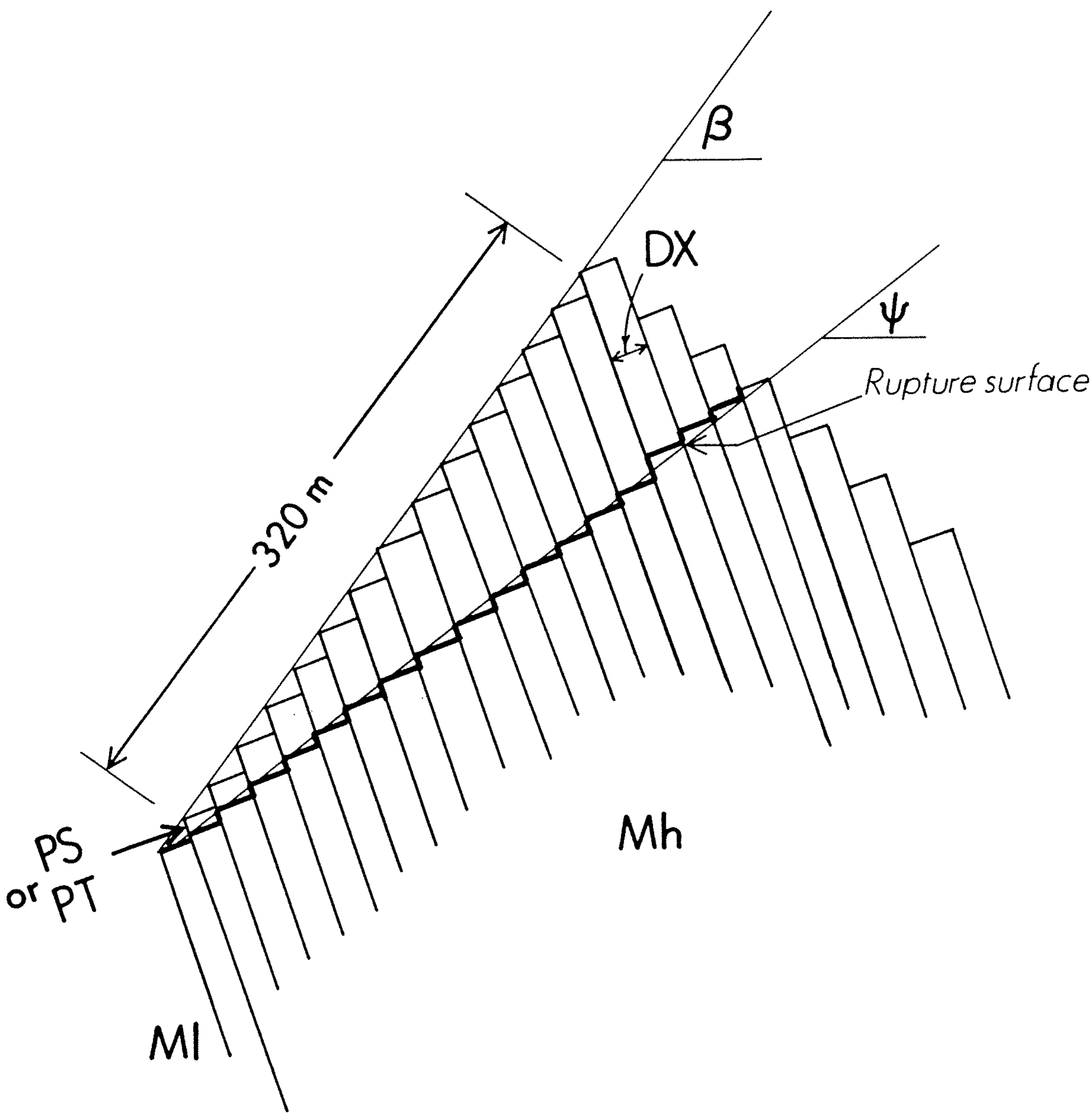


Figure 10. Assumed geometry of the slope for toppling analysis. PS, PT are forces which prevent sliding or toppling of the toe block.

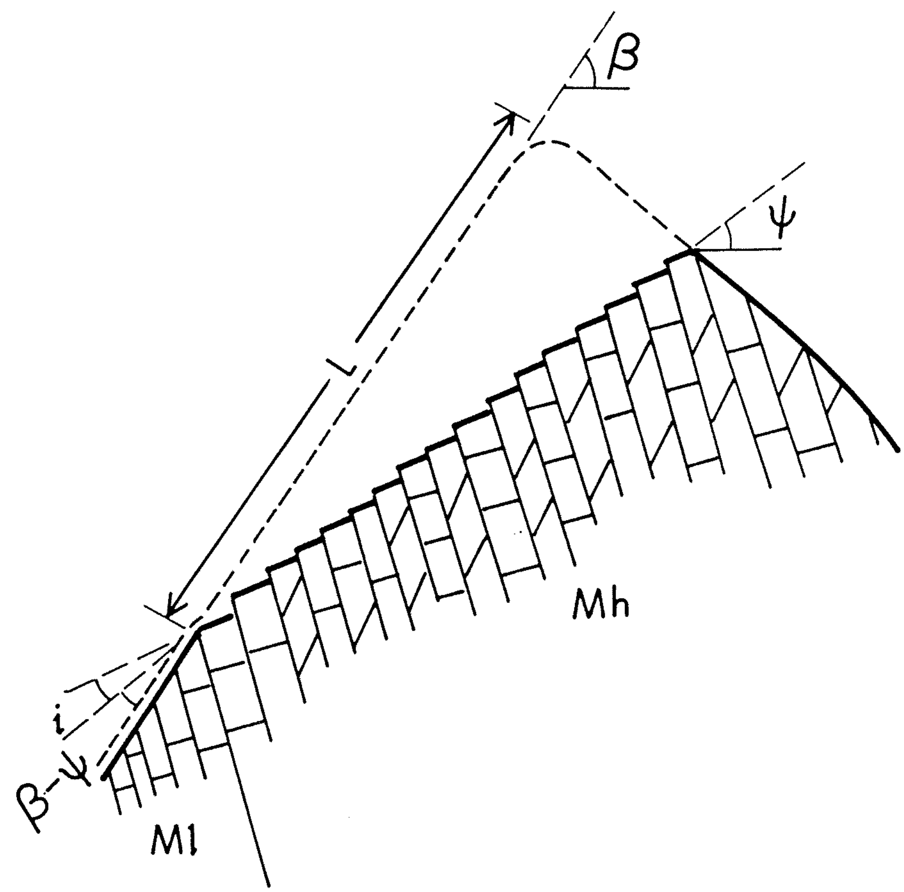


Figure 11. Assumed geometry of the slope for sliding models; i is the roughness angle, ψ is the dip of the rupture surface.

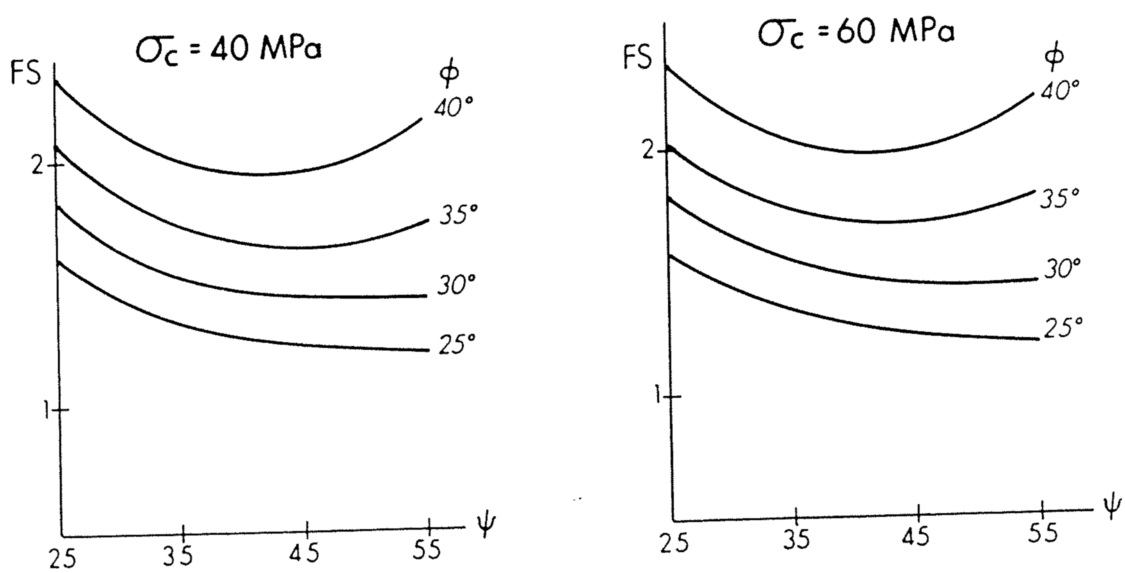


Figure 12. Relationship between factor of safety, friction angles and the dips of the rupture surfaces for mode 1 of the sliding model, σ_c is the uniaxial compressive strength of the rock blocks, ϕ is the friction angle, ψ is the dip of the rupture surface.

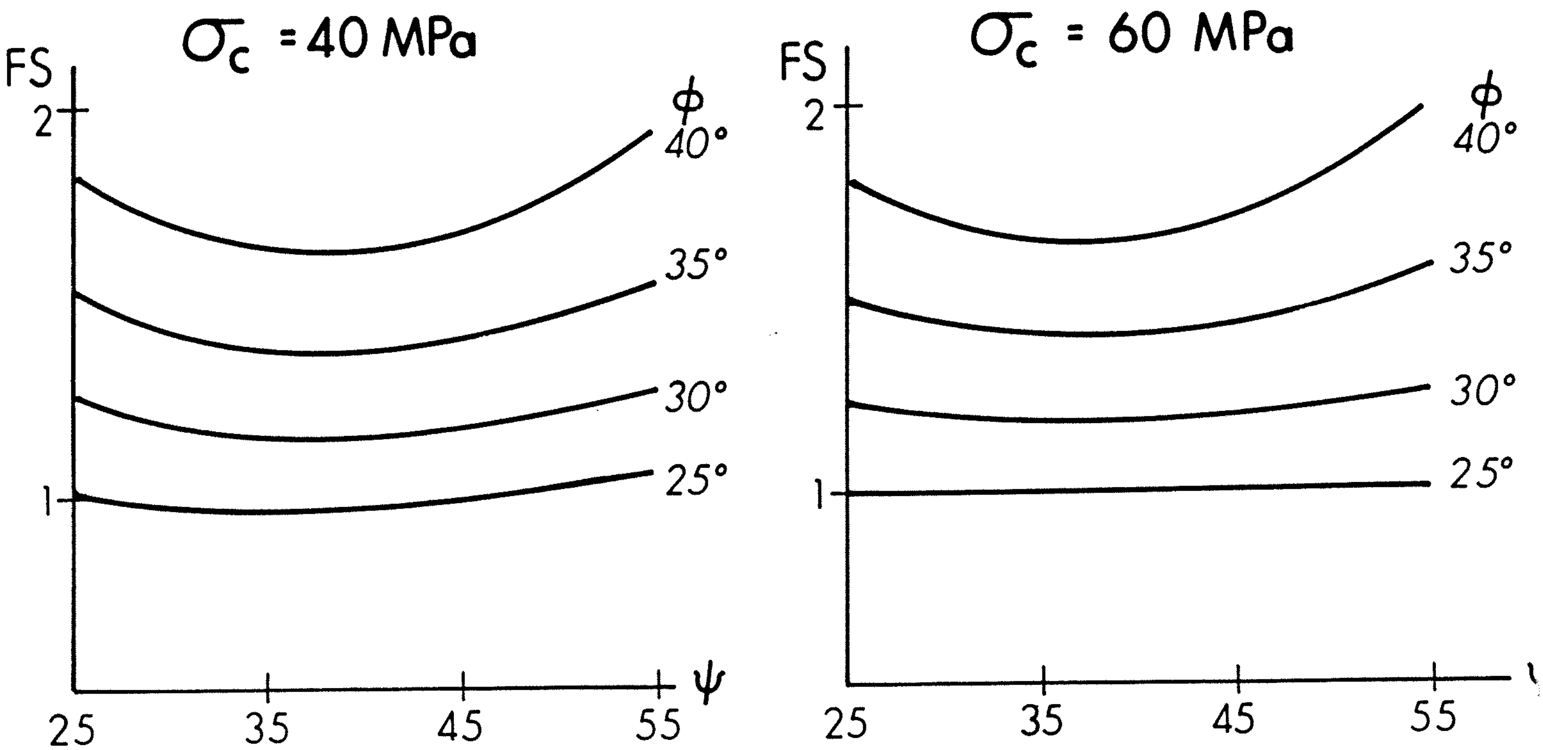


Figure 13. Relationship between factor of safety, friction angles and the dips of rupture surfaces for mode 2 of the sliding model. Legend as Figure 12.

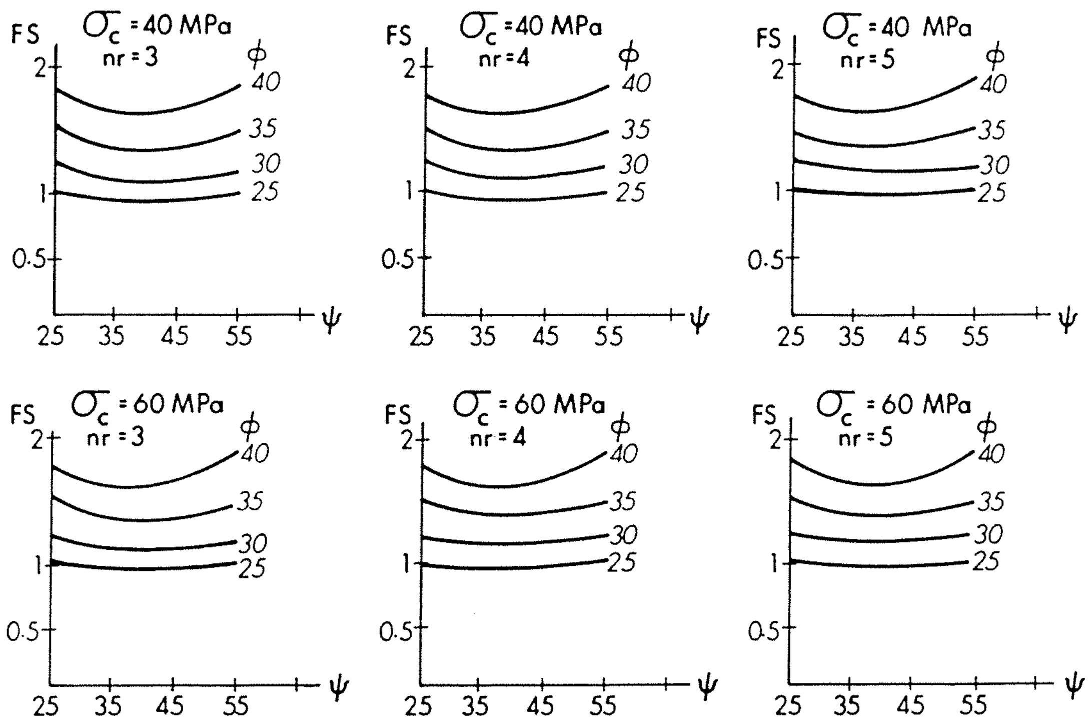


Figure 14. Relationship between factor of safety, friction angles and the dips of rupture surfaces for mode 3 of the sliding model. Legend as Figure 12.

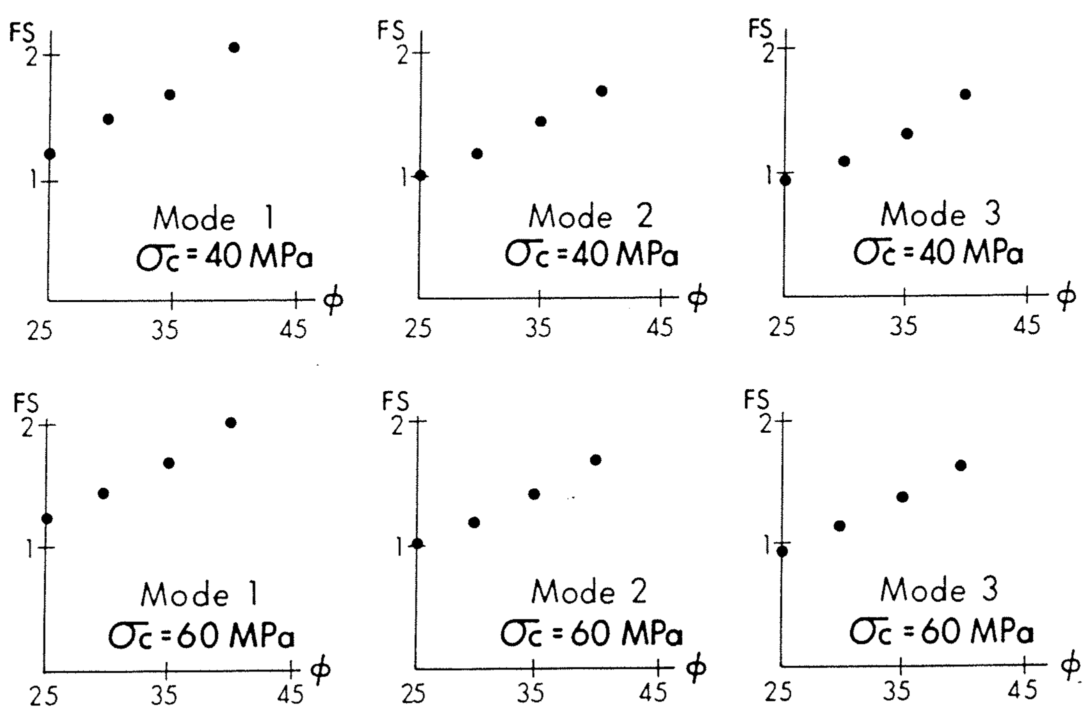


Figure 15. Relationship between factor of safety and friction angles assuming a sliding surface at 45°.