Reconnaissance of rockslide hazards in Kananaskis Country, Alberta

by

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ABSTRACT

Kananaskis Country is situated in the Front Ranges of the Canadian Rockies in southwestern Alberta. Sedimentary rock thrust northeastwards forms mountain ridges that trend northwest-southeast parallel to the major thrust faults. Older, Palaeoszoic rocks, mainly limestone and dolomite, form the ridges and peaks. Younger Mesozoic rocks, sandstones, quartzites, siltstones, shales, conglomerates and coals, are more easily eroded and form mountain passes and valleys.

The reconnaissance mapped 228 rockslides, 8 km^2 of rockslide debris and 96 km^2 of talus. The largest rockslide exceeds $50x10^6$ m^3. Rockslides are most probable in the Devonian Palliser Formation followed by Permo-Pennsylvanian Rocky Mountain Group, Mississippian Rundle Group, Devonian Fairholme Group, Mississippian Banff Formation and the younger detrital rocks. Rockslides are most probable on dip and over-dip slopes followed by reverse-dip slopes, oblique and strike-dip slopes and under-dip slopes. Large rock masses have not slid on slopes below their basic friction angle, ϕ_b.

The reconnaissance shows that certain facilities in valleys below steep mountain slopes are exposed to rockslide hazards and provides a guide for the location of new facilities. Analyses of two mountain slopes show that there are large, hypothetical hazards in Kananaskis. Rockslides are likely and could be destructive.

Keywords - Front Ranges, Rocky Mountains, Alberta, rockslides, hazards

INTRODUCTION

A reconnaissance of hazards from rock slope movements during the summers of 1984 and 1985 covered about 880 km^2 of the 4000 km^2 recreational development area called Kananaskis Country (Alberta, 1981), most of which lies in the Front Ranges and Foothills of the Rocky Mountains in Alberta (Figure 1). Prior to the recreational development, logging and mining operated in the area. Five hydroelectric reservoirs were also constructed. The City of Calgary, 100 km northeast, will host the 1988 Winter Olympics and alpine and

Figure		Page

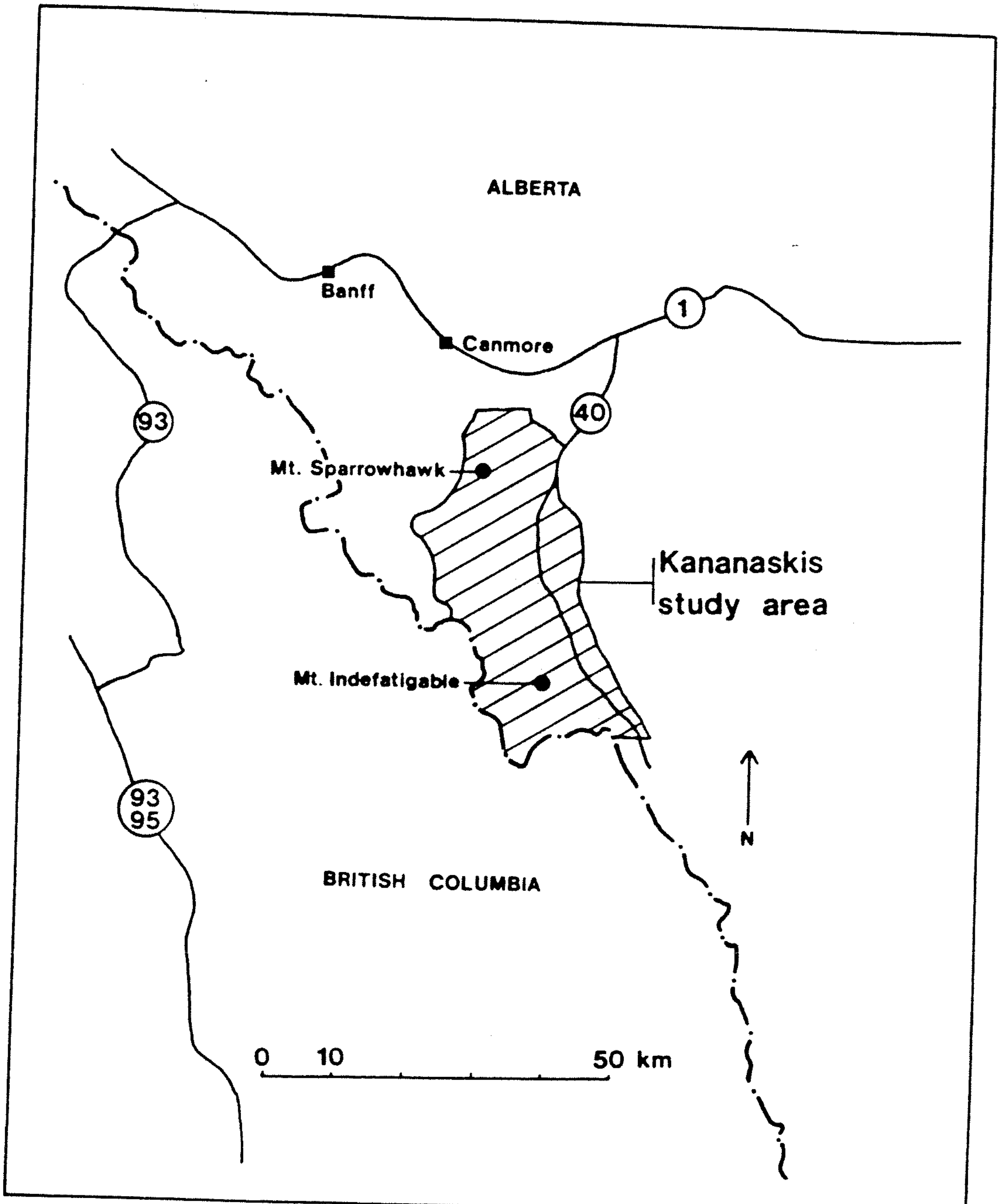


Figure 1. Location of the Kananaskis Study Area. Banff is at 51° 10'N, 115° 34'W

nordic events are planned for Kananaskis Country. The area offers camping, nordic and alpine skiing, hiking, horseback riding, fishing, canoeing and kayaking, off-highway vehicle riding, mountaineering, golfing and sailing.

The object of the study was to map rockslide hazards. These include rockfalls which free fall as the initial movement and rockslides which slide along a discontinuity as the initial movement. Other slope hazards such as topples, debris flows and creep included small movements which form talus and larger movements which leave distinct deposits. Because of scale, only rockslides covering more than 5000 m^2 were mapped as separate deposits on the air photographs. The reconnaissance mapped 228 rockslides, 8 km^2 of rockslide debris and 96 km^2 of talus. This study specifically considered performance of rock types and slope types.

Air photograph interpretations and hazard descriptions for the entire study area are presented by Eaton (1986). A mapping scheme was presented on 100 1:15,840 air photograph interpretations. Only photographs containing hazards were interpreted. The methodology was a two stage process starting with air photograph interpretation and then ground truthing to clarify questionable areas. This process was repeated as necessary.
Hazardous areas from slope movements are defined as:

1. **Active Zone:**Debris of slope movements observed, movements such as rockslides, rockfalls and debris flows are active.

2. **Hypothetical Zone:** Debris of slope movements not observed but natural processes such as solution, and freeze and thaw weathering are active, the topography and attitude of the bedrock suggest a rock slope movement might occur.

The Study Area

The study area, southeast of Banff and southwest of Calgary along the Alberta-British Columbia border, covers the majority of the highest peaks and ranges and amounts to about 22% of the total Kananaskis Country recreation area. Sedimentary rock thrust northeastwards forms mountain ranges that trend northwest-southeast parallel to major thrust faults. Elevations vary from structure is visible in many mountain slopes (Figures 2 and 3).

The mountain ranges trend parallel to northwest- southeast striking thrust faults, anticlines and synclines. Normal, reverse and tear faults occurring at more local scale have orientations either normal or parallel to the strike of bedrock. Dip of the bedrock is generally southwest and moderate to very steep. Exceptions to this bedrock dip can be found on the east limbs of anticlines and the west limbs of synclines.

Rock Types

The rock types found in Kananaskis are shown in Table 1 (Halladay and Mathewson, 1971). Symbols for lithology are from Dearman et al. (1972).

Older rocks from the Permo-Pennsylvanian, Mississippian and Devonian are mainly carbonates. Limestone and dolomite form the ridges and peaks. Younger rocks from the Cretaceous, Jurassic and Triassic are sandstones, quartzites, siltstones, shales, conglomerates and coals. These rocks are more easily eroded and form mountain passes and valley bottoms.

Hence carbonates dominate the landscape (Figure 4). In particular, the Mississippian Rundle Group covers the largest area. While rockslides commonly occur in Permo-Pennsylvanian, Mississippian and Devonian rocks in Kananaskis, most occur in Rundle Group rocks partly because they dominate the landscape. Yet Figure 5 shows rockslides are not distributed among the carbonate formations in the same way as Figure 4. The greatest probability of a rockslide exists in the Palliser Group followed by the Rocky Mountain Group, Rundle Group, Fairholme Group, Banff Formation and the younger detrital rock types (Figure 6). The relative probability of a rockslide in a rock unit is the percentage of all rockslides in that unit divided by the percentage of the surface of the study area occuppied by the unit.

Slope Types

Bedding surfaces are pervasive discontinuities in Kananaskis. They facilitate rockslides because of their continuity and frequency in slopes. Classifying slopes by their bedding structure allows observations of the about 1400 metres in the lower Kananaskis River Valley to 3420 metres on top of Mount Joffre. About 45% of the terrain lies above treeline.

Climate

Climatological data within the study area is sparse. Along the eastern edge of the study area the mean annual temperature varies from 1.4° to 3.5° Celsius and precipitation values range from 471 mm to 657 mm with about 45% falling in the form of snow (Environment Canada, 1980). Higher precipitation values and colder temperatures can be expected along the continental divide ranges. Freeze-thaw cycles can be expected year round in Kananaskis, daily during the spring and fall. Snowcover persists until mid-May while snowpatches persist through June, July and August at higher elevations.

Surficial Geology

Several glacial episodes in the Quaternary have reshaped the mountains (Jackson, 1981) but glacial deposits are not widespread in Kananaskis. Tills occupy some valleys while bedrock slopes and cliff faces characterize the higher elevations. Soils are thin to absent at higher elevations.

Wisconsin tills are represented in Kananaskis by the Canmore Till (Jackson, 1981) deposited by the Crowfoot Advance (Luckman and Osborn, 1979) which is found at lower elevations in the main trunk valleys. Younger, neo-glacial moraines on the floors of higher tributary valleys abut against glaciers in some cases. Fluvial processes have reworked tills in the main trunk valleys. Alluvial deposits are found at the mouths of most tributary valleys and along major streams and rivers. Colluvium covers many slopes. Talus and rockslide deposits are found below and on bedrock slopes.

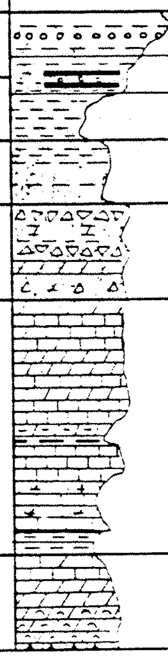
Bedrock Geology

The mountain ranges consist of sedimentary rock formations pushed to the surface along listric thrust faults (Dahlstrom, 1970). Drainage is controlled by structural weaknesses in the rock. Bedrock contains at least three joint sets; two are orthogonal to bedding, and one is parallel to bedding. Bedrock

Figure 2. Mountain ranges in Kananaskis Country west of Upper Kananaskis Lake show bedrock structure and relief.

Figure 3. Highway 40 through Highwood Pass in Kananaskis Country carries industrial and recreational traffic.

Table 1 Stratigraphic column showing the rock units and types found in Kananaskis.

PERIOD	LITHOLOGY	FORMATION	GROUP	SYMBOL
Cretaceous Jurassic		Kootenay	Blairmore Fernie	Kbl JK Jf
Triassic		Sulphur Mntn		Trs
Permian, Pennsylvanian			Rocky Mntn	Prm
Mississippian		Etherington Mount Head Turner Valley Shunda Pekisko Banff (with Exshaw)	Rundle	Mr Mb
Devonian		Palliser	Fairholme	Dp Df

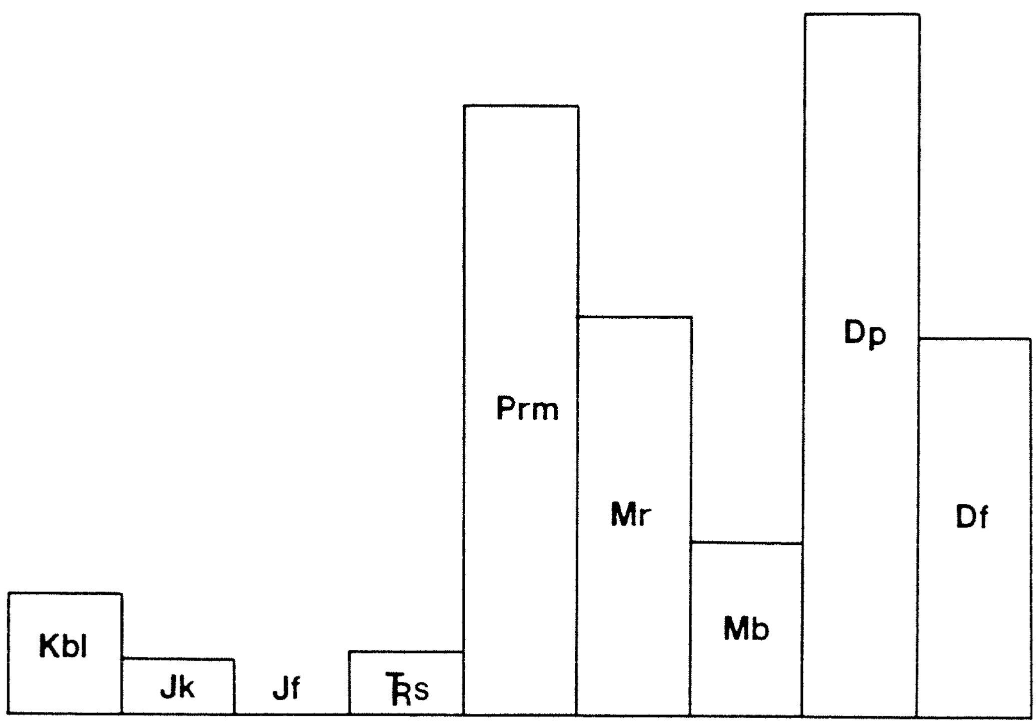


Figure 6. Relative probability of a rockslide according to rock unit. Symbols are explained in Table 1.

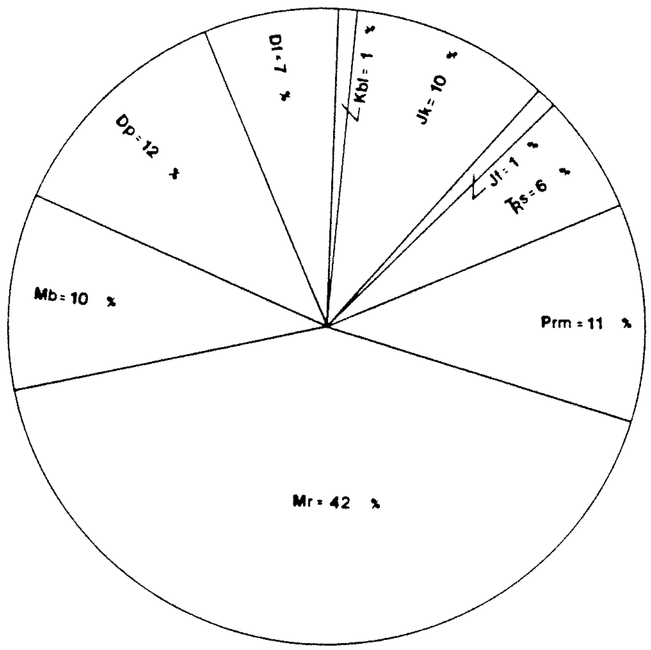


Figure 4. Percentage of each rock unit near the surface in Kananaskis. Symbols are explained in Table 1.

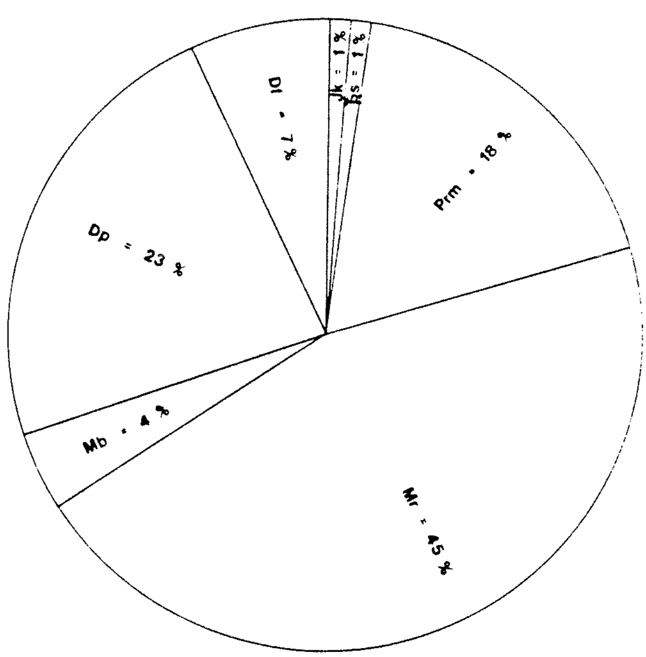


Figure 5. Percentage of rockslides according to rock unit. Symbols are explained in Table 1.

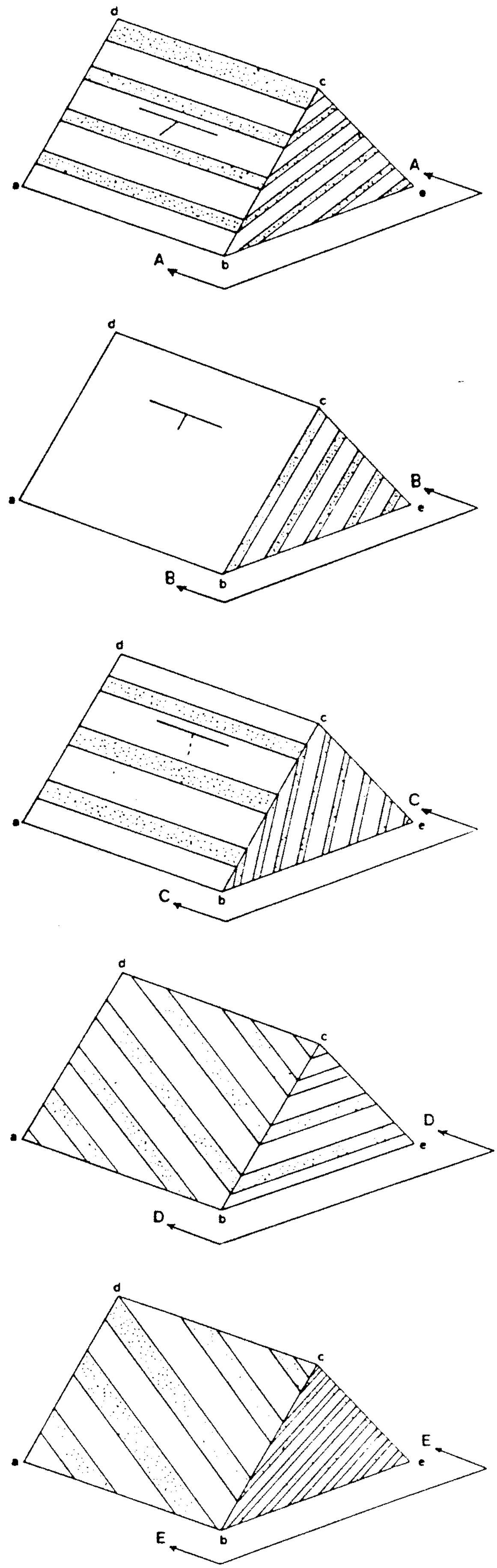


Figure 7. Slope types

activity and hazard of certain slope types.

Bedding surfaces are not perfectly planar on any scale so there is some judgement used in the classification of a slope. Slopes have been classified by their predominant form at a scale of 100 m and larger.

In over-dip, dip and under-dip slopes the bedrock possesses a dip direction similar to the surface of the slope. Bedrock dips less than the surface in over-dip slopes, parallel to the surface in dip slopes and more steeply than the surface in under-dip slopes. Bedrock dips into the slope with a dip direction opposite to the surface in reverse-dip slopes. Oblique and strike-dip slopes have bedrock dip directions that differ by more than 20° from the slope surface (Figure 7).

In Figure 7, A-A is a section perpendicular to an overdip slope with corners at a, b, c and d. The slope is steeper than the dip of the bedding. A reverse dip slope with corners at c, d and e is hidden from view. B-B is a section perpendicular to a dip slope with corners at a, b, c and d. Bedding and the slope are parallel. A reverse dip slope with corners at c, d and e is hidden from view. C-C is a section perpendicular to an underdip slope with corners at a, b, c and d. The slope is gentler than the dip of the bedding. A reverse dip slope with corners at c, d and e is hidden from view. D-D is a section perpendicular to a strike-dip slope with corners at a, b, c and d. The strike of bedding is parallel to D-D. Another strike-dip slope with corners at c, d and e is hidden from view. E-E is a section perpendicular to an oblique-dip slope with corners at a, b, c and d. The strike of bedding is between 20 and 70 degrees from the line of section. Another oblique-dip slope with corners at c, d and e is hidden from view.

While oblique and strike-dip slopes are the most common in the study area, had the azimuths of slopes been distributed at random with respect to bedding 78% of the slopes might have been expected in this category (Figure 8). The relative abundance of reverse-dip and underdip slopes shown in Figure 6 demonstrates the control of topography by rock fabric. Over-dip and dip slopes are not common.

Rockslides are not distributed uniformly among the slope types. Most of the rockslides occur on over-dip and dip slopes where movement is along bedding surfaces (Figure 9). A typical over-dip slope is shown in Figure 10. The relative probability of a rockslide on a particular slope type is the percentage of all rockslides on that slope type divided by the percentage of the study area occuppied by the slope type.

The greatest relative probability of a rockslide is on dip and over-dip slopes followed by reverse-dip slopes, oblique and strike-dip slopes and under-dip slopes (Figure 11). Over-dip and dip slopes although less common than other slope types present a geometry which favours large rock slope movements. Bedrock is inclined downslope and intersects the slope surface forming well-defined rupture planes on the slope. Any bedding plane can become a sliding surface if the friction and cohesion on the discontinuity are exceeded by disturbing forces.

Analysis of Two Mountain Slopes

Hazard mapping was presented on photograph interpretations which flag active and hypothetical hazards. The interpretations provide a quick evaluation of a site to see if it lies inside a hazard zone. The nature of the surficial debris, either talus or rockslide deposits, the slope type and the hazard either active or hypothetical can be obtained from the interpretations. Sites as small as 100 x 100 m can be evaluated at the scale of the interpretations to aid in determining if detailed investigations are necessary.

A review of two specific sites from the study area will illustrate the magnitude and nature of large rockslide and hypothetical hazards in Kananaskis. The sites, Mounts Indefatigable and Sparrowhawk, are described in the sequence: bedrock geology, surficial geology, active hazards, hypothetical hazards and analysis.

Mount Indefatigable

Mount Indefatigable is situated north of Upper Kananaskis Lake and is indicated on the National Topograhic System 1:50,000 map 82J/11. The rockslide from Mount Indefatigable is locally referred to as the Palliser Rockslide after the Palliser Expedition which traversed the debris while seeking routes

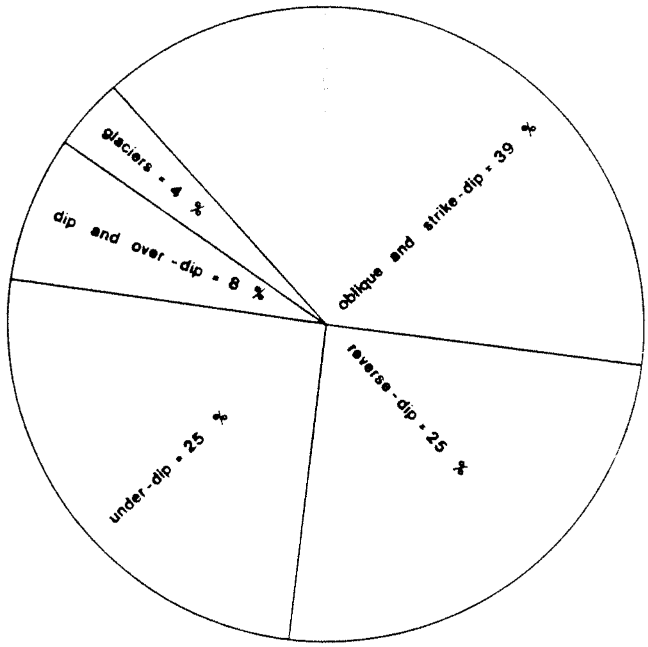


Figure 8. Percentage of each slope type in Kananaskis.

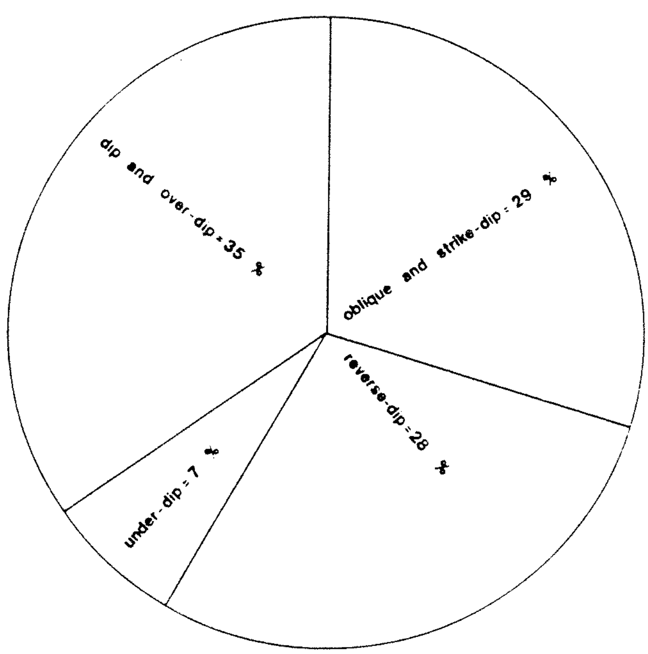


Figure 9. Percentage of rockslides according to slope type.

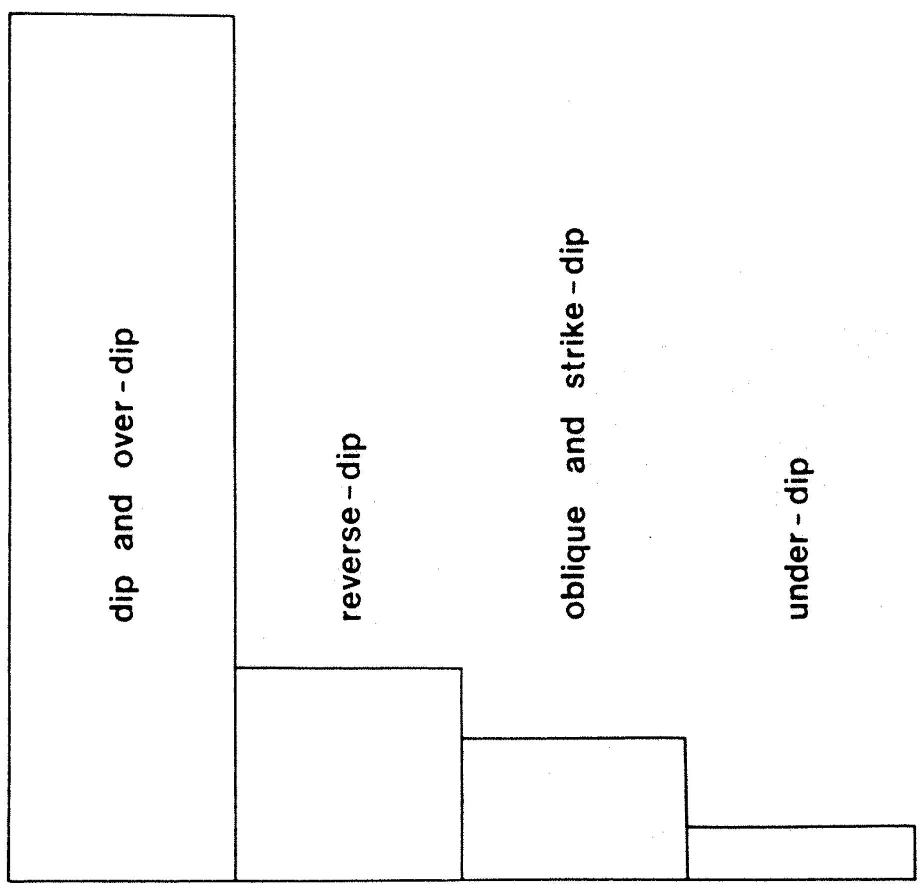


Figure 11. Relative probability of a rockslide according to slope type.

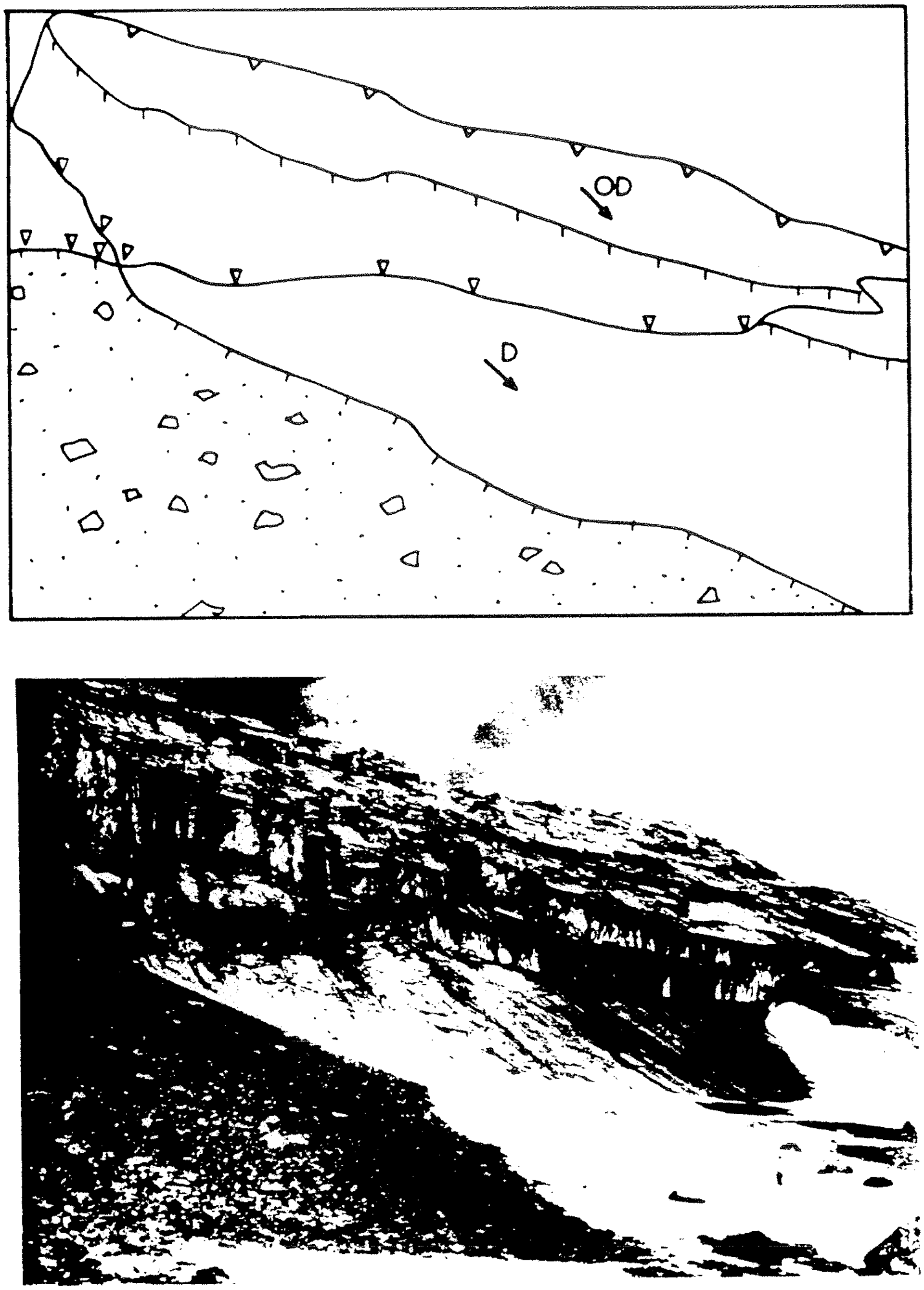


Figure 10. Over-dip slope on a ridge. Note person in foreground on snow slope and rockslide debris in left of photo.Symbols in the overlay above follow those in the Appendix


UD
Grass Ck
Mt. Indefatigable
RD
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through the Rockies in 1858 (Spry 1963, p. 135). A sample air photograph interpretation from Eaton (1986) shows the Palliser Rockslide deposit and rupture surfaces (Figure 12).

Bedrock Geology

The main structural features are indicated in Figure 12. The Bourgeau Thrust Fault cuts along the base of the northeast slopes of Mount Indefatigable trending northwest. The trace of the synclinal axis passes northwestwards down Grassi Creek just behind the scarp face in the toe of the southwest slopes of Mount Indefatigable. Limestones and dolomites of Mississippian and Devonian age are thrust over Jurassic shales and sandstones (Halladay and Mathewson, 1971).

East of the thrust fault, beds dip moderately to steeply southwest. Immediately west of the fault, some variation is created by drag folds but generally beds dip steeply southwest flattening as they near the synclinal axis. West of the synclinal axis, beds dip northeast and are visible in the west canyon walls of Grassi Creek and in the reverse-dip scarp in the toe of the southwest slopes of Mount Indefatigable. A tear fault cuts across the southeastern end of Mount Indefatigable below 1830 metres trending northeast from Upper Kananaskis Lake to Lower Kananaskis Lake.

The large rockslide from the south end of Indefatigable Ridge has exposed extensive bedding surfaces which create steep dip slopes. The northwest lateral slide margin is an oblique-dip scarp. Further northwest, along the ridge the southwest aspects are under-dip slopes. At the base of these slopes, the beds reverse their dip direction across the syncline axis to form a reverse-dip scarp immediately to the west. The northeast slopes of Mount Indefatigable are all reverse-dip. The main rupture surface is located in the Pekisko Formation within the Rundle Group (Table 1).

Surficial Geology

The Palliser Rockslide slid southwest from the south end of Mount Indefatigable and deposited 90 x $10^6 m^3$ of angular debris in and along the north shore of Upper Kananaskis Lake. West and northwest of the rockslide, till covers the valley floor. Farther west, the Upper Kananaskis River has deposited an alluvial fan. Talus lines the base of the synclinal buttress, the north slide margin and the rupture surfaces of Mount Indefatigable. Talus covers the upper portions of the rockslide deposit. Bedrock is exposed on rupture surfaces, the slide margin, the synclinal buttress, the ridge top and on reverse-dip slopes on the northeast slopes of Mount Indefatigable. The large under-dip slope on the southwest aspect is covered by thin colluvium; higher up, just beneath the ridge is talus.

Active Hazard Zones

Below the slide margin and rupture surfaces many metres of talus have accumulated. In one location talus extends over two hundred metres up the dip slope. Rock fragments and boulders fall from the oblique-dip scarp and bounce or roll downslope. Higher up, rock fragments fall and bounce from the ridge onto talus just below. On the northeast reverse-dip slopes, talus receives fragments and boulders that fall, bounce and roll downslope. These are mapped as active hazard zones. The rest of the site including the valley bottom and the lower three quarters of the under-dip slope do not appear to have any active hazards.

Hypothetical Hazard Zones

The volume of rock that slid into the valley and lake is difficult to estimate as the pre-slide topography of the valley, lake floor and mountain is not known.

The movement was a slide along bedding so the rupture surface is curvilinear in section. Beds are horizontal at the syncline axis and dip at 50° at the top of the rupture surface. Evidence of flexural-slip was found in the sidescarp where a zone of deformed rock sheared between two beds indicates that the upper bed slid upslope relative to the lower bed. Calcite is visible on recently exposed beds on the main rupture surface, though calcite is not evident on older rupture surfaces, possibly having been removed by erosion and solution.

Figure 12. A sample air photograph interpretation showing Mount Indefatigable, the rupture surfaces and rockslide deposit. Symbols on the overlay of Alberta Government photo AS 748-121 follow the Appendix, scale and directions may be locally distorted.

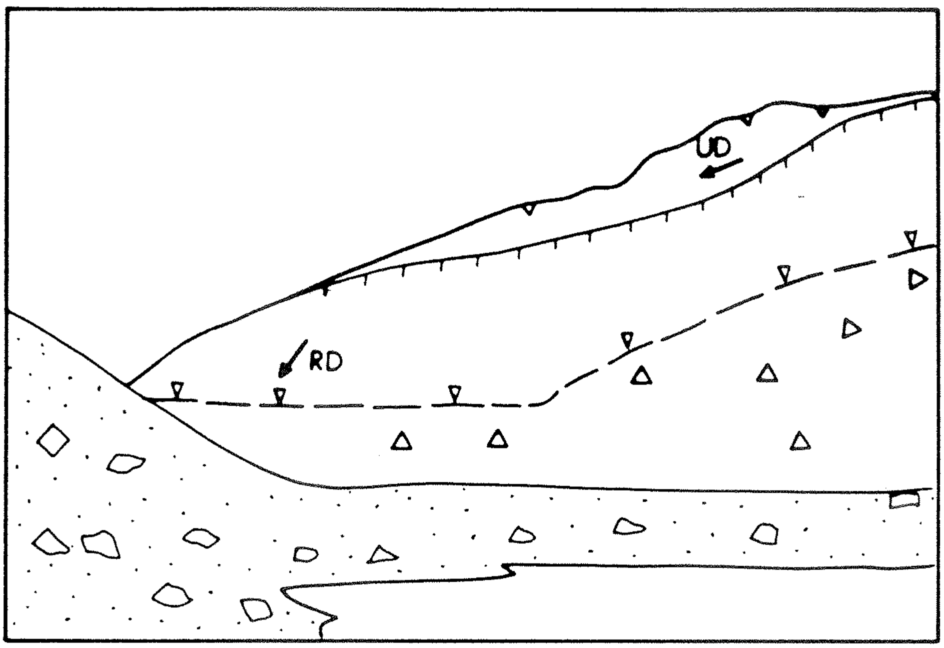

Figure 13. The hypothetical rockslide slope on Mount Indefatigable seen from near the tip of the debris, volume exceeds 300 x 10^6 m^3.Symbols in the overlay above follow those in the Appendix.

The rock on the rupture surface is a well jointed limestone of the Pekisko Formation. The Rundle is reported as having slid elsewhere in the Canadian Cordillera (Locat and Cruden, 1977). Basic friction angles of limestones from Mount Indefatigable varied between 23.3°±0.5° and 25.3°±1.2° (Eaton, 1986).

The southwest slopes of Mt. Indefatigable, north of the slide area, are similar in structure to the pre-slide mass. But additional resistance to sliding is still provided by a buttress of rock dipping northeast into the mountain formed by the syncline in the toe of the slope. The buttress is an active rockfall source. Solution caves are visible in the sidescarp near the syncline axis suggesting water enters the rock mass through under-dip slopes above, flows downslope and then along the syncline axis. Rockfall, seepage and solution processes are active. Over 300 x 10^6 m^3 of the slope possess the topography and attitude of the slid mass (Figure 13). So this area is mapped as a hypothetical hazard zone.

Based on the empirical study by Li (1983), the travel distance of a slide from the slope could exceed 5 kilometres. Comparison with the Palliser Rockslide indicates the debris would slide up to the base of Lyautey Ridge 4 kilometres across the valley from the top of Mount Indefatigable and this Ridge would redirect the slide. So, the hypothetical zone extends across the valley to the base of Lyautey Ridge. Debris sliding into Upper Kananaskis Lake and the consequent wave generation may impact dam structures and hydroelectric facilities downstream.

Stability Analysis of Mt. Indefatigable

A stability analysis of the Palliser Rockslide and the hypothetical hazard section was performed using the method proposed by Sarma (1979) and a program written by Wong (1985). With the Sarma method, an external horizontal load can be introduced and pore pressures can be varied. The method considers rigorously the kinematics of sliding blocks on general slip surfaces and large slices can be used (Morgenstern and Sangrey, 1978; Sarma, 1979).

The slip surfaces for both sections are defined by the existing main rupture surface (Figure 15). The first section, A-A, Figure 16, is the

Palliser Rockslide sidescarp near the south end of the Mount Indefatigable ridge, and the second is the hypothetical slide, section B-B, Figure 17, 500 metres north of the sidescarp.

Four cases are considered for each section:

1. No pore pressure and no earthquake loading.

2. Pore pressure and no earthquake loading.

3. Pore pressure and earthquake loading.

4. No pore pressure and earthquake loading.

The water table is arbitrarily selected, no data is available on groundwater conditions at Mount Indefatigable. It is conjectured that the water table is at considerable depth except during Spring runoff or after an intense rainstorm when it may rise substantially for a short time.

A horizontal earthquake loading of 0.04g is taken from Heidebrecht and Tso (1985). Cohesion is considered to be destroyed by flexural-slip for all cases. The interslice value is assumed to be 100 kPa for cohesion and 30° for the friction angle in all cases.

The value for the friction angle is varied in each case between 40°, 30° and 25°. The 40° and 25° are approximated ϕ_b values from calcite and limestone taken from the site. The basic friction angle, ϕ_b, was measured, following Coulson (1972), on sawn surfaces of the rocks lapped with #80 grit using a tilting table. The basic friction angle is a useful estimate of the lower bound of friction angles likely to exist during rockslides (Cruden, 1985). The lower value for limestone is used here although values up to 35.5°±1.3° were obtained from Rundle limestones elsewhere in the study area (Eaton, 1986). The value of 30° has been suggested for rockslides in Rundle limestone elsewhere (Cruden, 1985).

The sidescarp section is shown in Figure 16 and the results in Table 2. The following are apparent:

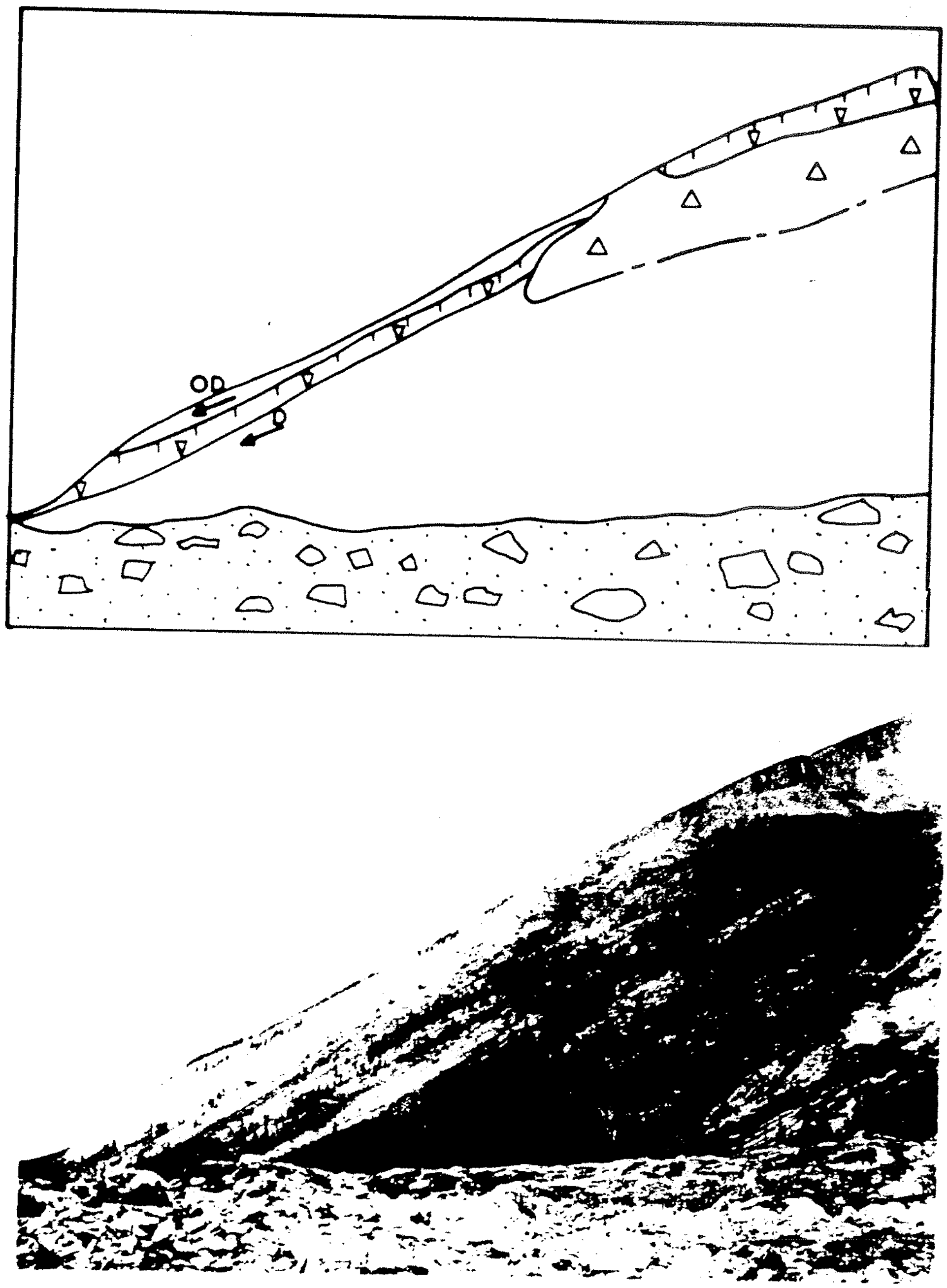

Figure 14. The hypothetical rockslide slope on the sub-peak of Mount Sparrowhawk seen from rockslide debris 1 km up valley, volume exceeds 30×10^6 m^3. Symbols in the overlay above follow those in the Appendix.

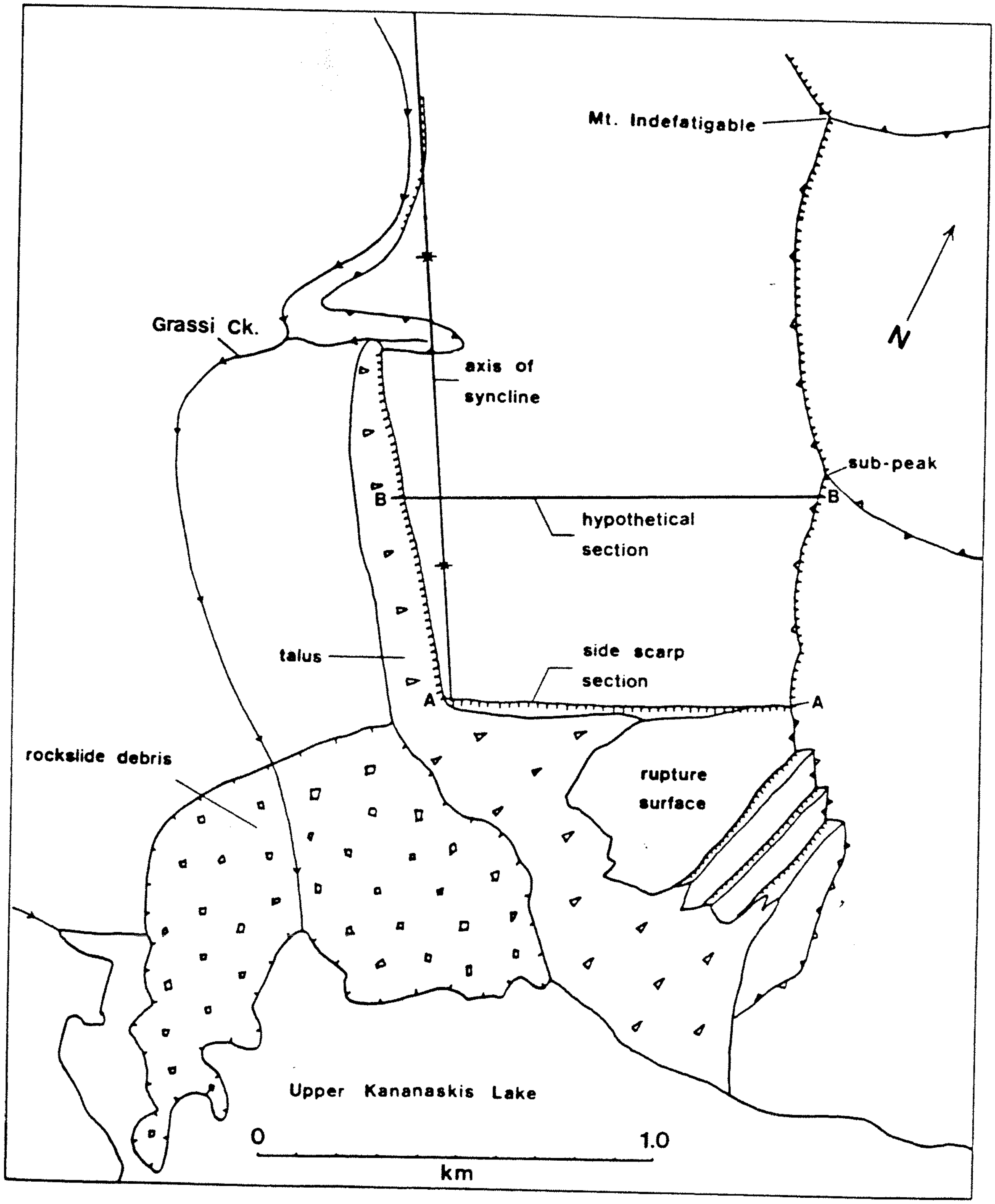

Figure 15. Physical features of Mount Indefatigable showing the location of sections A (Figure 16) and B (Figure 17). Symbols follow the Appendix.

Table 2 Sidescarp Section, Mount Indefatigable: results of analysis using Sarma Method.

Rupture Surface			
Pore Pressure	Friction Angle	Earthquake Load, Horizontal	Factor of Safety
0	40	0	1.7
0	30	0	1.3
0	25	0	1.1
X	40	0	1.5
X	30	0	1.2
X	25	0	1.0
X	40	0.04 g	1.5
X	30	0.04 g	1.2
X	25	0.04 g	1.0
0	40	0.04 g	1.6
0	30	0.04 g	1.3
0	25	0.04 g	1.1

g = acceleration of gravity
X = water table as indicated in Figure 17
Rupture surface cohesion = 0 for all cases
Interslice cohesion = 100 kPa for all cases
Interslice friction angle = 30° for all cases
Unit weight = 20 kN/m^3

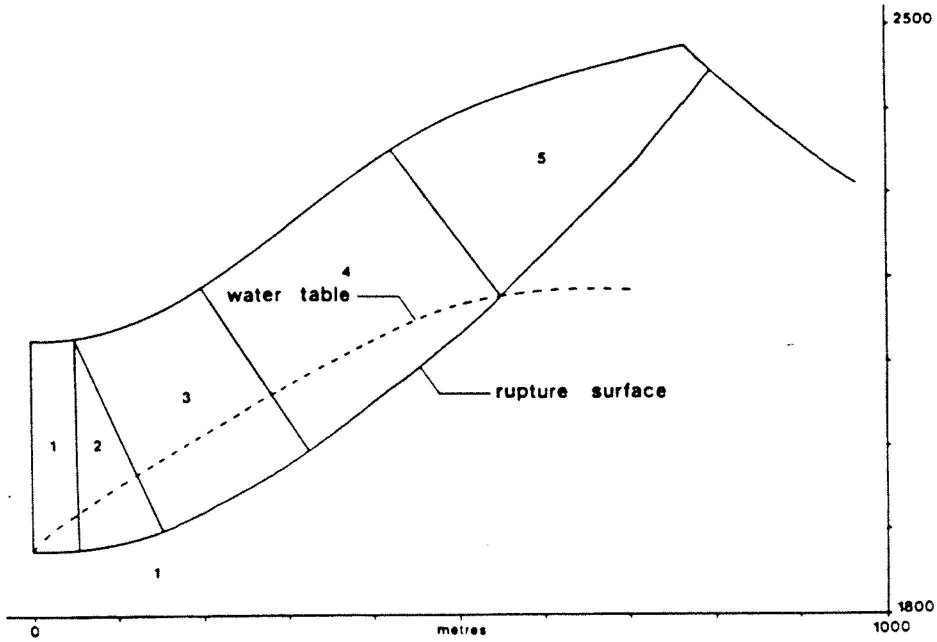

Figure 16. North sidescarp section of Palliser Rockslide showing slices and water table used in analysis.

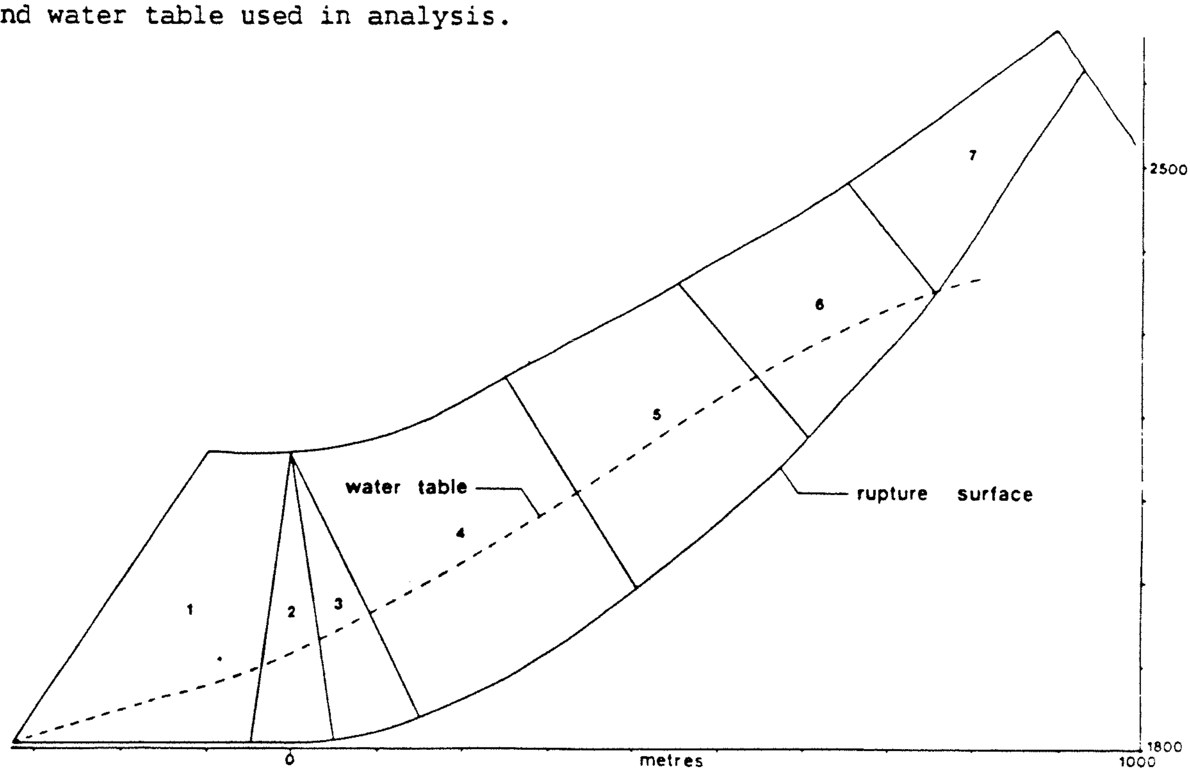

Figure 17. Hypothetical section through Mount Indefatigable showing slices and water table used in analysis.

1. ϕ_b exerts the greatest influence on stability.

2. 40° seems too high to represent the friction angle, 25° may be too low.

3. ϕ_b = 30° gives factors of safety near 1.0.

4. Both pore pressure and earthquake loading reduce the factor of safety, together they are more than sufficient to lower the factor of safety below 1.0 when ϕ_b = 30°.

It is reasonable to assume that the pre-slide configuration south of the sidescarp possessed a similar or less stable geometry. The effect of buttress support is examined in the hypothetical section (Figure 17). It possesses a longer slip surface and additional rock buttress in the toe of the slope. The slip surface in the toe was assumed horizontal as there is no evidence at the site to support the idea that the present rockslide debris slid up northeast dipping beds when the slope failed. Rupture could have occurred across bedding in the toe, or the buttress weathered back to horizontal bedding before failure.

The new geometry increases the overall factor of safety (Table 3). The worst case, that of pore pressures, earthquake loading and ϕ = 25° gives a factor of safety of 1.0 although pore pressures and an earthquake acting simultaneously are unlikely.

The water tables for both cross-sections are over 150 metres below the surface. Water levels in the secondary porosity, bedding, joints and faults could rise higher than this in adverse conditions. Their influence would lower the factor of safety further.

So, the analysis gives a post-mortem on the north slide margin, section A-A, and the present state of health for the hypothetical slope, section B-B. The Palliser Rockslide occurred when retreat of the synclinal buttress, pore pressures and seismic loading acting independently or in combination triggered the rockslide. The hypothetical slope has a higher factor of safety at present. Severe conditions, exceeding those used in the analysis, would be necessary to trigger a rockslide in the immediate future.

Table 3 Hypothetical Section, Mount Indefatigable: results of analysis using Sarma Method.

Rupture Surface			
Pore Pressure	Friction Angle	Earthquake Load, Horizontal	Factor of Safety
0	40	0	1.3
0	30	0	1.0
0	25	0	0.9
X	40	0	1.3
X	30	0	1.0
X	25	0	0.9
X	40	0.04 g	1.2
X	30	0.04 g	0.9
X	25	0.04 g	0.8
0	40	0.04 g	1.3
0	30	0.04 g	1.0
0	25	0.04 g	0.9

g = acceleration of gravity

X = water table as indicated in Figure 16

Rupture surface cohesion = 0 for all cases

Interslice cohesion = 100 kPa for all cases

Interslice friction angle = 30° for all cases

Unit weight = 20 kN/m^3

Mount Sparrowhawk

Mount Sparrowhawk is situated east of the Spray Lakes Reservoir and is indicated on the National Topographic System 1:50,000 map 82J/14.

Bedrock Geology

Mount Sparrowhawk is part of a thrust sheet bound by the Rundle Thrust Fault to the northeast and by the Sulphur Mountain Thrust Fault to the southwest (Halladay and Mathewson, 1971). Rundle Group rock is exposed throughout the site. The Turner Valley and Shunda Formations form the lower southwest slopes. They are overlain by the Mount Head and Etherington Formations which form the skyline of Sparrowhawk (Table 1).

Bedrock dips between 25° and 30° southwest over the entire site. Erosion by glaciers has created over-dip slopes on the lower southwest aspects. Where not oversteepened by erosion, slopes are planar dip slopes. Field reconnaissance revealed several minor reverse, normal and tear fault systems within the site. Two tear faults, one reverse and one normal fault likely provided margins for the rockslide. Several tear faults were also noted in the sub-peak over-dip slopes and in the reverse-dip slopes southwest across the valley.

Surficial Geology

The Canmore Drift covers lower slopes near the Spray Lakes Reservoir but ice scoured bedrock floors the upper valley with the exception of the large rockslide deposit 3.5 kilometres up the valley. Talus covers steep slopes around the valley floor. Bedrock is exposed on steeper slopes. A thin veneer of colluvium covers the upper dip slopes which are not steeply inclined. Rockslide debris and talus is found below the ridge crest between Mount Sparrowhawk and Mount Bogart and in places these deposits extend to the valley floor.

Hazardous Zones

The active hazardous zone is extensive. Rockfall and small rockslides occur from slopes around the upper valley of Middle Creek, Sparrowhawk Peak and in North Creek. These are from over-dip slopes on Mount Sparrowhawk and Ridge, oblique-dip slopes at the valley head and from reverse-dip slopes along the southwest ridge of the valley and in North Creek. Material moves by falling, sliding, bouncing and rolling downslope. The main dip slopes on Mount Sparrowhawk do not pose any active hazards, and neither do the forested slopes adjacent to the lake.

Hypothetical Hazardous Zones

The hypothetical hazards cover large portions of the Sparrowhawk site. A large rockslide exceeding 10 x 10^6 m^3 occurred from Sparrowhawk Ridge (Figure 18). Over-dip slopes line Sparrowhawk Ridge, the toe of the sub-peak and the main peak's slopes. The bedrock dips into the valley at 25° to 30°.

The present configuration of the sub-peak and most of the main peak is similar to that of the pre-slide mass. Evidence of flexural-slip was not found on the Sparrowhawk site and cohesion may persist along beds. Bedding surfaces are poorly exposed because of talus or colluvium.

Vertical tear faults define both the left and right margins of the slide following joint sets normal to bedding which strike in the dip direction of bedrock. A reverse fault and a normal fault through the pre-slide mass follow joint sets normal to bedding but strike parallel to the strike of bedding. So, this over-dip slope was actually dissected into large blocks by these faults.

Tear faults were also noted in the over-dip slope at the base of the sub-peak. Over 30 x 10^6 m^3 of rock dip into the valley at 25° to 30° (Figure 18). This attitude is repeated again in the main peak, where the portion of the main peak northwest of a line joining the sub-peak and main peak exceeds 100 x 10^6 m^3. Here a lateral margin is well defined by the northwest end of the mountain in a prominent scarp. A tear fault or even connecting joint sets down dip enlarged by gully erosion could provide the other lateral margin.

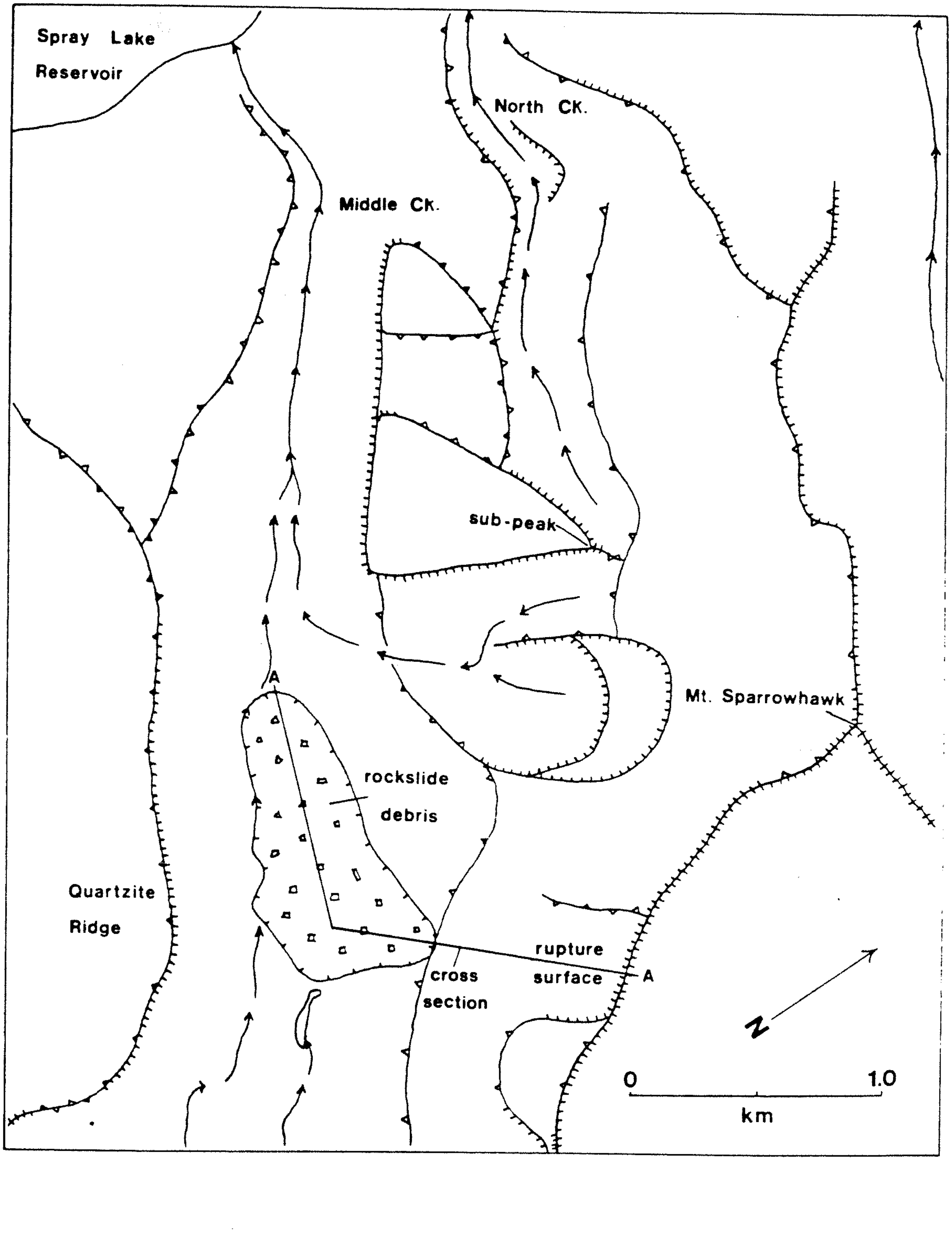

Figure 18. Physical features of Mount Sparrowhawk showing the location of section A (Figure 19). Symbols follow the Appendix.

Therefore the hypothetical hazards zone includes the sub-peak and adjacent slopes, Mount Sparrowhawk and all slopes west and northwest, Middle and North Creeks, and the forested slopes between and adjacent to Middle and North Creeks down to and into the Spray Lakes Reservoir. The Sparrowhawk area is considered a hypothetical site because the volumes are large and the attitude of the slopes are similar to those from which limestones have slid in the same valley. Again stratigraphy falls in the Mississipian Rundle Group which exhibits a high probability of rockslide occurence in Kananaskis.

A rockslide from the main peak could exceed 100 x 10^6 m^3. According to Li (1983) such a rockslide may come to rest in the Spray Lakes Reservoir.

Stability Analysis of Mount Sparrowhawk

The Mount Sparrowhawk site can be analyzed as a simple slide down an inclined plane. The limit equilibrium equation for simple frictional sliding complete with cohesion, a water filled joint and a horizontal earthquake load is:

$$F = \frac{cA + (W\cos\psi - U - E\sin\psi)\tan\phi}{W\sin\psi + V + E\cos\psi} \qquad (1)$$

Where:

ϕ = friction angle on the slide surface

ψ = inclination of the slide surface

c = cohesion on the base of the block

A = area of the base of the block

W = weight of the block

E = earthquake loading

U = hydrostatic force on the base of the block

V = hydrostatic force in the joint

F = factor of safety

Without cohesion, a water filled joint and earthquake loading, Equation 1 reduces to:

$$F = \frac{\tan\phi}{\tan\alpha} \tag{2}$$

A cross section (Figure 19) shows bedding inclined at 25° to 30° on an over-dip slope. The range of basic friction angles from Sparrowhawk are 23.3° to 35.5° so the dip of bedrock and the basic friction angles are similar.

Portions of Mount Sparrowhawk could presently be at a limiting state of equilibrium. If bedding is inclined at its friction angle, cohesion is destroyed and lateral margins are available then a water filled crack or seismic acceleration could provide the driving force to trigger a rockslide.

Summary

The reconnaissance has shown that there are substantial differences in rockslide hazards from one Formation or Group to another.

The probability of a rockslide is highest in Devonian Palliser Formation rocks followed by Permo-Pennsylvanian Rocky Mountain Group, Mississippian Rundle Group, Devonian Fairholme Group, Mississippian Banff Formation and the younger detrital rock types.

Slopes were classified by the attitude of the bedrock with respect to the slope and, again, substantial differences in rock-slide hazard occur. The relative probability of a rockslide is highest on dip and over-dip slopes followed by reverse-dip slopes, oblique and strike-dip slopes and under-dip slopes.

The basic friction angle, ϕ_b, appears to be a lower bound value for rockslides on dip slopes. Basic friction angles of carbonates from Kananaskis varied between 23.3°±0.6° and 42.9°±0.7°.

Some transportation, recreation and industrial facilities located in valley bottoms below steep mountain slopes are exposed to rockslide hazards. The hazard mapping has flagged these areas in Kananaskis and provided a guide

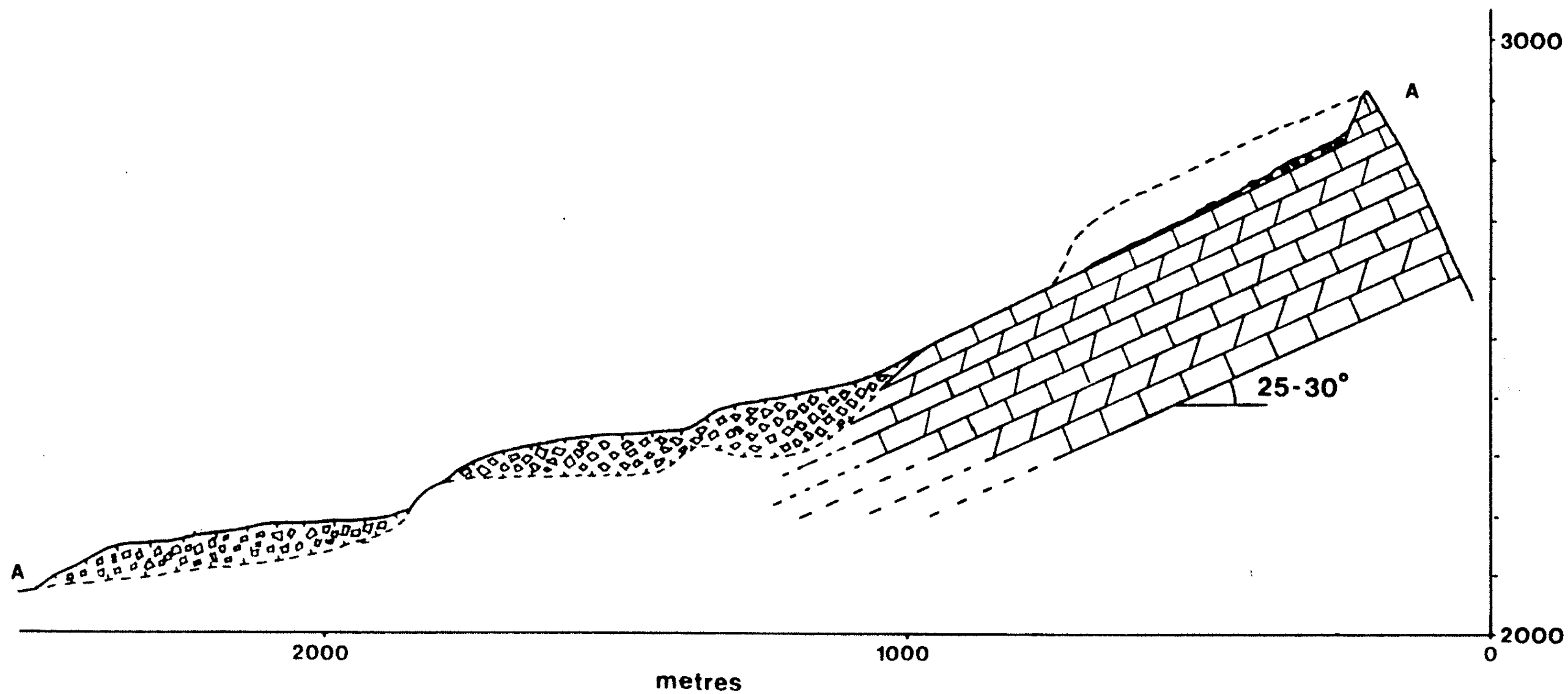

Figure 19. Section A through the rupture surface and rockslide deposit at Mount Sparrowhawk.

for the location of future facilities and the re-evaluation of present ones. The hazard mapping can now be extended into the rest of Kananaskis Country, particularly along the Bow Corridor and around man-made lakes such as the Spray Lakes Reservoir.

Two more detailed reconnaissances show the potential for large rockslides exists at Mount Indefatigable and Mount Sparrowhawk. Hypothetical hazards occur on over-dip slopes (which exhibit the highest probability for large rockslides in Kananaskis) in the Rundle Group which also exhibits a high probability of rockslides. Either pore pressures or earthquake loading may act as the critical trigger mechanism.

Mapping demonstrates that since the last major glaciation (about 10,000 yrs B.P.), rockslides have modified Mounts Indefatigable and Sparrowhawk. Future rockslides may send debris into either the Upper Kananaskis Lake or the Spray Lakes Reservoir, and waves and floods may result.

Acknowledgements

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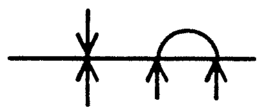
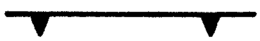
List of Symbols used on Figures

• • • • • • • • • • Boundary of 'specific site' or 'other relevant area'.

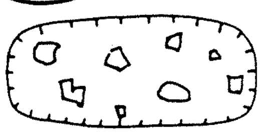
Boundary of hypothetical hazard.

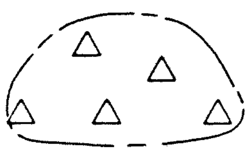
Boundary of active hazard.

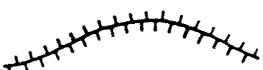

Axial trace of syncline.


Thrust fault, teeth on up thrust side.


Debris flow channel.


Rockslide or rockfall deposit.


Talus deposit, triangles point-up slope.


Ridge crest, sharp, free faces on either side.


Ridge crest, rounded.

Dip slope, strike of slope and bedding are parallel within 20°. Beds dip parallel to slope, arrows point downslope.

Over-dip slope, as above except slope steeper than bedding.

Under-dip slope, as above except bedding steeper than slope.

Reverse-dip slope, as above except bedding dips into slope.