THE UNIVERSITY OF ALBERTA

Reconnaissance of Rockslide Hazards in Kananaskis Country

by

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The undersigned certify that they have read, and recommend to the Faculty of Graduate Studies and Research, for acceptance, a thesis entitled Reconnaissance of Rockslide Hazards in Kananaskis Country submitted by Timothy M. Eaton in partial fulfilment of the requirements for the degree of MASTER OF SCIENCE.

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Supervisor

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Date..2 April 1986..........

Dedicated To

THE MOUNTAINEERS - 1906

"...to explore, study, preserve and enjoy

the natural beauty of Northwest America..."

Abstract

Kananaskis Country is situated in the Front Ranges of the Rocky Mountains along the Alberta-British Columbia border 50 km southeast of Banff. Sedimentary rock thrust northeastwards forms mountain ridges that trend northwest-southeast parallel to the major thrust faults. About 45% of the 880 km² study area lies above treeline.

Rockslides are larger volume movements that translate initially along a discontinuity. Bedding surfaces are a common form of discontinuity in Kananaskis. The reconnaissance mapped 228 rockslides, 8 km² of rockslide debris and 96 km² of talus. The largest rockslide exceeds 50 x 10⁶ m³.

Older rock from the Permo-Pennsylvanian, Mississippian and Devonian is mainly carbonate. Limestone and dolomite form the ridges and peaks. Younger rocks from the Cretaceous, Jurassic and Triassic are mainly detrital, sandstone, quartzite, siltstone, shale, conglomerate and coal are found. These rocks are easily eroded and occupy mountain passes and valley bottoms.

The greatest relative probability of a rockslide exists 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 rocks.

Slopes were distinguished according to the attitude of the bedding within the slope with respect to the slope. The

greatest relative probability of a rockslide exists 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 useful as a lower bound value for rockslides. It is defined as the friction angle of a sawn rock surface lapped with #80 grit. Basic friction angles of carbonates tested from Kananaskis varied between 23.3°±0.6° and 40.2°±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. The zoning provides a guide for the location of future facilities and the re-evaluation of present ones.

Acknowledgements

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Special thanks is also due my two field assistants, Kevin Lindstrom and Allan Samchek, whose input and many dedicated hours were essential to the thesis.

I am indebted to the staff of the Kananaskis Centre for Environmental Research; Peter Wallis and Trish Harrison for use of the centre's facilities; and Marion Wilson and Julie Zammuto for providing excellent cuisine. The cooperation of staff from Kananaskis Country, Peter Lougheed Provincial Park and the Alberta Forest Service was greatly appreciated.

My advisor, Dave Cruden, with patience and wisdom guided me through the reports and thesis when I could not see the light at the end of the tunnel. Thank you.

Last of all I would like to thank the agents responsible, whoever or whatever they may be, for creating such a scenically and spiritually stimulating environment to perform my fieldwork in.

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ϕ = friction angle of a material

ϕ_b = basic friction of a material

α = inclination of a slide surface

c = cohesion on the base of a block

A = area of the base of a block

W = weight of a block

U = hydrostatic force on the base of a block

V = hydrostatic force in a joint

F = factor of safety

1.0 Introduction

1.1 General

Large slope movements have been the subject of considerable interest for many years. Rockslides are one phenomenon party to this interest. Heim (1882) provided one of the first written accounts in modern times of a rockslide, the Elm rockslide of 1881 in Switzerland. Closer to home in Alberta, several authors were attracted to the Frank Slide which, in 1903, partially destroyed the Town of Frank in southwest Alberta (Cruden and Krahn, 1973).

Shreve (1968), Voight et al. (1979), Whitehouse (1981) and McLellan (1983) investigated the geomorphology of deposits and surrounding terrain to gain insight into the chronology and mechanisms of the movements. Mueller (1964) was fortunate to monitor slope movements and piezometric levels prior to the Vaiont Slide as this site was located above a concrete arch dam in Italy. Whalley (1974), Hsu (1975), Hungr (1981) and Davies (1982) considered different mechanisms of transport. Scheidegger (1973) and Tianchi (1983) took empirical approaches to predict the reach, volume, and velocity of large rockslides. Simmons (1977) observed translational rockslides in the eastern foothills of the Rocky Mountains. Eisbacher (1978) reported on cliff collapse and rock avalanches in the Mackenzie Mountains. Kaiser and Simmons (1980) also made observations of two rock avalanches in the Mackenzie Mountains.

More frequently the question of mobility - how far and how fast would a certain rock mass travel once failure had occurred - has been the object of investigations. This information has obvious practical applications and additional detailed investigations can only increase our understanding and ability to forecast the extent of such slope movements. It is limited however if we are unable to identify which slopes are unstable. Research into hazard mapping is a relatively recent undertaking; Pachoud (1975), Kohl (1976), Porter and Orombelli (1981), Quebec (1981), Carrara (1983, 1984), Whitehouse and Griffiths (1983) and Hansen (1984) provide examples of concerns, hazard models, and hazard reports.

This research undertakes a reconnaissance of rockslide hazards on sedimentary rock slopes. These rocks dominate the Alberta bedrock except in the northeast of the province where Shield rocks are found. The Rocky Mountains situated along the southwest provincial boundary are of sedimentary rock and form the highest, steepest relief and largest rock slopes. The study area for this research is located in the Front Ranges of the Rocky Mountains. Kananaskis Country (Alberta, 1981) is the Alberta Government's region targetted for recreational development and tourism in the Eastern Slopes. Kananaskis Country has seen mining, logging and hydroelectric developments in the last one hundred years.

In addition, the Front Ranges possess a fundamental slope structure which is usually simple and obvious. Primary bedding discontinuities, permitting rockslides, are closely spaced and penetrative in slopes while rockslides may also occur along other discontinuities such as joints and faults.

Further to the west, in British Columbia, mountains are generally more complex. Many have been subjected to high temperatures and pressures, intrusives and some are entirely volcanic. The types of discontinuities are numerous there and their arrangement in a slope can be complex. In contrast, the structure and slope type can be identified with a high degree of certainty in the Rocky Mountains using a simple methodology.

1.2 Purpose and Scope

The purpose of this research is to identify what and where rockslide hazards are in Kananaskis Country. This is the first rockslide hazard mapping scheme performed in the Rocky Mountains of Canada. The findings are presented in the following chapters and appendices.

The study area, environmental conditions and general surficial and bedrock geology are described in Chapter 2. Special attention is given to the Mississippian Rundle Group. Slopes types pertaining to sedimentary rock are also defined. A study area was selected that included terrain with greatest relief, transportation routes and high human use.

Hazards are defined in Chapter 3. An attempt was made to keep the definition of hazards as simple as possible to maintain clarity. The different forms of rock slope movements found in Kananaskis including rockslides, rockfalls, topples, debris flows and creep are reviewed. Mapping by others in Kananaskis is considered.

In Chapter 4 activity or the where, why and magnitude of rockslide hazards is considered. The extent of deposits, and what slopes and what rocks present hazards are discussed.

Rocks collected in Kananaskis were tested using a tilting table. The basic friction angle, ϕ_b', was obtained and considered as a lower bound value for flagging hazardous slopes. Sample preparation and testing procedure are outlined for future reference. This is found in Chapter 5.

A summary and recommendations are presented in Chapter 6. The reconnaissance methodology and interpretation and survey problems are presented in Appendix A. Two large rockslide sites, Mounts Indefatigable and Sparrowhawk are examined in Appendix B. Both possess potential rockslide slopes. A stability analysis is included. The hypothetical rockslide masses are compared to the existing ones and the work of Tianchi (1983).

The hazard mapping is presented on air photograph interpretations in Appendix C. Symbols are explained and a flight line reference map is provided. The mapping was done at a scale that permits consideration of individual sites while using one set of high quality air photographs. The air photographs can be interpreted to provide information such as hazard boundaries, bedrock structure, topography, rock debris and vegetation. Each one covers an area of about 2.9 by 3.6 kilometres. About 10% overlap east-west and 20% overlap north-south occurs on adjacent interpretations.

1.3 Previous Work in the Rocky Mountains

Locat and Cruden (1977) discussed several rockslides in the Rockies. One of these, the Mount Indefatigable slide occurred along the north shore of Upper Kananaskis Lake. Reimchen and Bayrock (1976) mapped surficial geology south of latitude 52° in the mountains and foothills of Alberta. They noted over 900 slides, several of which are rockslides in the present study area. Simmons (1977) observed translational rockslides south of 52° north latitude and cites at least 80 rock slope failures. Mention is made of two rockslides in the Burstall Pass area of Peter Lougheed Provincial Park. Gardner (1980, 1982, 1983) discusses frequency, magnitude and spatial distribution of rockfalls, rockslides and other forms of alpine mass-wasting in the Highwood Pass area of Peter Lougheed Provincial Park.

2.0 Site Features

2.1 The Study Area

Reconnaissance of hazards from rock slope movements has been undertaken in a portion of Kananaskis Country. Kananaskis Country is outlined in the Recreational Development Planning Base Map produced by the Alberta Department of Energy and Natural Resources (Alberta, 1981). The Kananaskis Study Area (Figure 2.1) will refer to the study area encompassing:

1. The whole of Peter Lougheed Provincial Park.
2. The Opal Range to the north of Peter Lougheed Provincial Park including Wedge and Limestone Mountains. The boundary continues north from the park along the divide of the Opal Range, descends into Evan Thomas Creek and follows the creek down to Highway 40.
3. The mountain ranges to the north of Peter Lougheed Provincial Park bounded on the west by Banff National Park and Spray Lakes Reservoir, on the east by Highway 40 but including the Opal Range described above, and to the north by Lorette Creek from Highway 40 up its drainage to latitude 51° 00', west along this latitude to West Wind Creek, up its drainage over the pass and down Spurling Creek to the Spray Lakes Reservoir. Lorette, West Wind and Spurling Creeks are indicated on the Recreational Development Planning Base Map mentioned above.

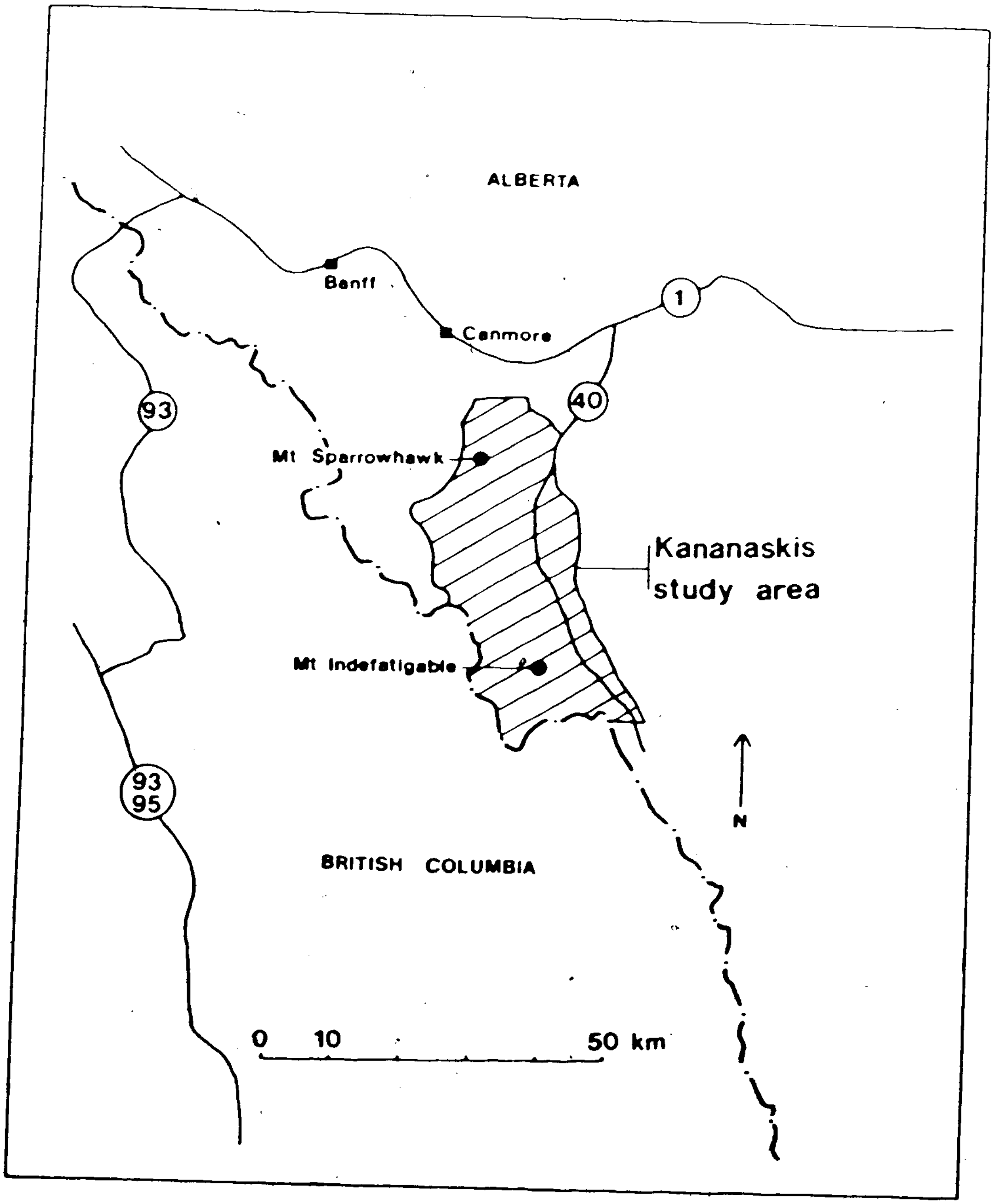


Figure 2.1 Location of the Kananaskis Study Area.

So, the study area covers the majority of the main peaks and ranges of Kananaskis Country and amounts to about 22% of the total Kananaskis Country recreation area. The Three Sisters, the Fisher Range, the Highwood Range and part of the Misty Range fall outside the study area but inside Kananaskis Country and possess mountain topography of high relief and structure similar to that found within the study boundaries. The study area covers approximately 880 km^2. Elevations vary from about 1400 metres in the lower Kananaskis river valley to a peak elevation of about 3420 metres on top of Mount Joffre situated in the extreme southwest tip of Peter Lougheed Provincial Park. About 45% of the terrain lies above treeline.

2.2 Climate

Climatological data within the study area are sparse but seven year-round meteorological recording stations are in close proximity to the east and north. Unfortunately all of these stations are situated at lower elevations in valley bottoms ranging from 1298 metres at Bow Valley Provincial Park, to 1494 metres at the Sheep River Ranger Station. The mean annual temperature of these seven stations varies from 1.4° to 3.5° Celsius, 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. Gardner

(1980) suggested that the mean annual temperature at Highwood Pass in the southwest corner of the study area is probably slightly below freezing. Highwood Pass is at an elevation of 2185 meters which corresponds roughly with treeline although this varies with aspect. Freeze-thaw cycles then can be expected to occur anywhere anytime in Kananaskis, daily during the spring and fall seasons with extended periods at higher elevations. Freeze-thaw conditions were experienced throughout Kananaskis in the first two weeks of June at all elevations in 1984 and 1985. As well freezing and blizzard conditions prevailed during field excursions later in both summers; in mid-July in the vicinity of Aster Lake, 1984, and in late August at all higher elevations in 1984 and 1985. In general snowcover persists until mid-May while snowpatches persist through June, July and even August at higher elevations.

2.3 Surficial Geology

Several glacial episodes in the Quaternary have reshaped the mountains (Jackson, 1981). Tills occupy valley bottoms while steep rock slopes and cliff faces characterize the higher elevations. Reimchen and Bayrock (1976) mapped surficial geology in Kananaskis as part of a larger report. Rockslides, slumps and landslides are included in the 29 surficial units identified. Jackson (1976) mapped surficial geology ~~and a~~ terrain inventory in Kananaskis.

Greenlee (1981) performed a soil survey in designated areas around Kananaskis Lakes with interpretations for recreational use. Although landsliding is not referred to specifically, mention is made of excessive slope and erosion hazard. It is reasonable to assume that similar soil conditions exist elsewhere in the study area's valley bottoms. Soils are poorly developed to non-existant at higher elevations. Therefore slope movements in soils are not considered further.

Wisconsin tills are not well represented in Kananaskis. The Canmore Till (Jackson, 1981) deposited by the Crowfoot Advance (Luckman and Osborne, 1979) is found at lower elevations in the main trunk valleys of the Kananaskis and the Smith-Dorrien-Spray. Younger neo-glacial moraines are found on the floors of many higher tributary valleys abutting against present day glaciers in some cases. Fluvial processes have added to, removed and 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 rock avalanche deposits are found below bedrock slopes and on higher slopes. Bedrock is by far the most abundant material at the ground surface at higher elevations. Additional detail on surficial geology can be found in Appendix C and Cruden and Eaton (1985b).

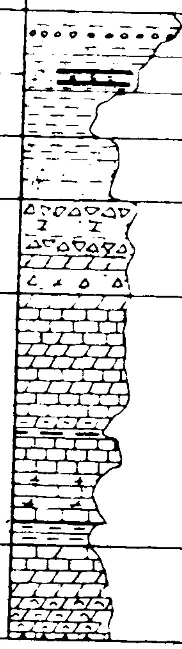
2.4 Bedrock Geology

The Rocky Mountains occupy a strip of land 700 by 60 km inside Alberta's southwestern border with British-Columbia (Banff and Jasper National Parks included). The mountain ranges consist of sedimentary rock formations formed by uplift along listric thrust faults (Dahlstrom, 1970) and erosion. 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.

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

The rock types found in Kananaskis are shown in Table 2.1 (Halladay and Mathewson, 1971). Symbols for lithology are from Dearman (1972). Older rocks from the Permo-Pennsylvanian, Mississippian and Devonian are mainly carbonate. Limestone and dolomite form the ridges and peaks. Younger rock from the Cretaceous, Jurassic and Triassic are mainly detrital where formations of sandstone, quartzite, siltstone, shale, conglomerate and coal are found. These rocks are easily eroded and occupy mountain passes and valley bottoms.

Table 2.1 Stratigraphic column showing the rock 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

The author found that rockslides commonly occur in Permo-Pennsylvanian, Mississippian and Devonian rocks in Kananaskis. Most of the rockslides occur in the Mississippian Rundle Group rocks partly because they dominate the landscape. The two mountain slopes analysed in Appendix C, on Mounts Indefatigable and Sparrowhawk, are contained in this rock group. Descriptions of the Mississippian Formations are provided here. The descriptions are based on stratigraphic work to the south, at Crowsnest Pass and Moose Mountain, and to the north, in Banff and Jasper National Parks. They begin with the oldest and finish with the youngest rocks, the Exshaw, Banff, Pekisko, Shunda, Turner Valley, Mount Head and Etherington Formations, respectively.

The Exshaw Formation (estimated thickness up to 240 m) is found within the lowermost Mississippian. The formation consists of a recessive lower unit of black shale and a resistant calcareous siltstone. The siltstone is medium brown-grey to blue-grey and platy to thin bedded. The siltstone weathers to a conspicuous light-medium yellow to orange brown. The upper boundary lies in argillaceous limestone and is not sharply defined (Ollerenshaw, 1968).

The Banff Formation (estimated thickness over 180 m) is found within the lower Mississipian and overlies the Exshaw Formation. The formation consists of micritic limestones that are argillaceous, dark grey weathering and recessive. They are associated with argillaceous skeletal limestone or argillaceous finely crystalline dolomite and commonly replaced in part by nodular or patchy chert and commonly accompanied by an abundant brachiopod fauna (Middleton, 1963).

The Pekisko Formation (estimated thickness 60 to 150 m) marks the base of the Rundle Group. The formation consists of medium to coarsely crystalline crinoidal limestone in beds as much as 15 m thick, interbedded with finely crystalline dark grey to brown grey argillaceous dolomitic limestone with green chert nodules (Douglas, 1970). The Mount Indefatigable rockslide rupture surface is found within the Pekisko Formation.

The Shunda Formation (estimated thickness 60 to 120 m) consists of mud supported, locally argillaceous, micritic limestones with pelletoid grains, micro to very fine crystalline dolomites, locally silty or argillaceous and local solution breccias, echinoderm limestones and fine to medium crystalline dolomites. The formation is generally medium grey weathering, recessive, low in chert content, generally poor in brachiopod fauna, commonly characterized by pelletoid grains and associated locally with skeletal and oolitic limestones (MacQueen and Bamber, 1967).

The Turner Valley Formation (estimated thickness 0 to 150 m) lies above the Shunda Formation. The formation consists of crinoidal light grey limestone and dolomitic limestone, minor calcarenite and oolite. The sequence also consists of massive bedded, cliff forming echinoderm limestones with variable amounts of fine to medium crystalline dolomite (MacQueen and Bamber, 1967).

The Mount Head Formation (estimated thickness 160 to 200 m) overlies the Turner Valley Formation. The upper member consists of dark grey "birdseye" limestones and very finely grained calcarenite and dolomite, dark grey shales, and a few very coarse poorly sorted encrinites (crinoidal limestone). The middle member consists of coarse grained, grey to light grey, well sorted encrinites, less well sorted grey to dark grey encrinite with chert nodules, fine dolomitic encrinites, oolites or pseudo-oolites. The lower member consists of siltstones, silty or very fine grained sandy dolomites and limestones (calcarenites), calcilutites, oolites, and evaporite solution breccia (Middleton, 1963).

The Etherington Formation (estimated thickness 60 to 160 m) overlies the Mount Head Formation. The formation consists of thin cyclically alternating beds of green and red shale, and dense silty cherty finely crystalline limestones and dolomites that grade westerly into thick coarsely crystalline bioclastic and dark argillaceous limestone (McGugan and Rapson, 1962).

2.5 Slope Types

2.5.1 Introduction

The strength of a rock slope is largely controlled by the orientation of discontinuities within the rock mass

(Selby, 1982). Strength will also be affected by external factors such as climate, seismicity, human intervention and erosion. Unfavorable dip of faults, beds and joints are perhaps the most important causes of rock slope instability while external factors may be the trigger mechanisms for rock slope failures.

It is useful then to classify slopes according to their rock structure. In this way observations can be made regarding the level of activity and hazard for a certain slope type. Bedding is the most common form of discontinuity in Kananaskis. Typical mountain structure in the Kananaskis study area with location of slope type cross sections is shown in Figure 2.2. Symbols are explained in Appendix C.

Five slope types are described in the following sections. Slope types are distinguished according to the attitude of bedding with respect to the slope. Generally southwest aspects contain dip, under-dip and over-dip slopes, and northeast aspects contain reverse-dip slopes. Northwest and southeast aspects contain oblique-dip and strike-dip slopes.

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.

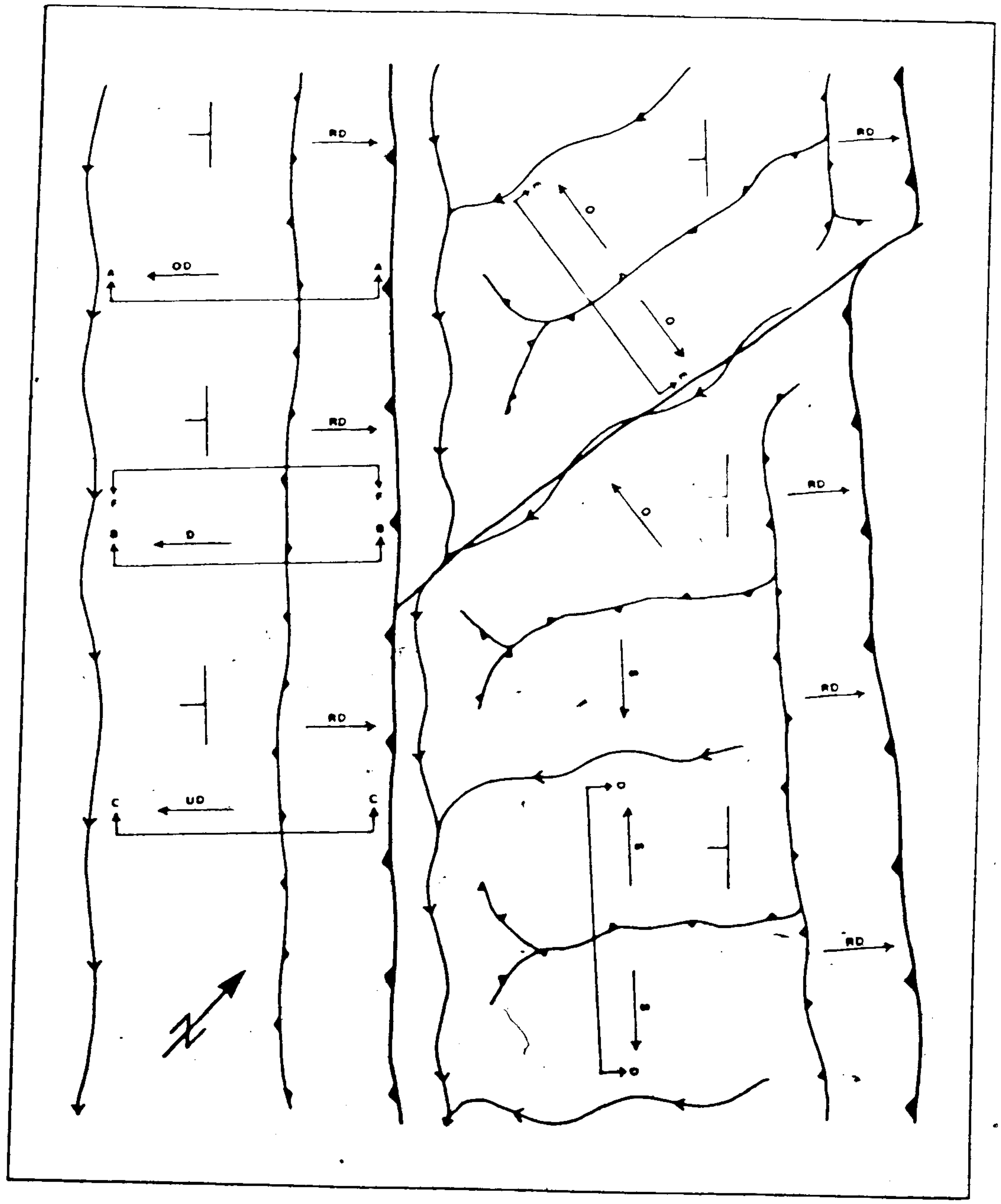


Figure 2.2 Typical mountain structure in Kanannaskis study area showing location of slope type cross sections. Symbols are explained in Appendix C.

2.5.2 Over-Dip Slopes

An over-dip slope has a surface that dips more steeply than the dip of bedrock. The dip directions are the same ±20°. Over-dip slopes (Figure 2.3) although less common than other slope types present a geometry which favours large rock slope movements (Cruden, 1976). Bedding planes are inclined downslope and intersect the surface forming well-defined rupture surfaces on the slope. Any bedding plane can become a sliding surface if the friction and cohesion of the discontinuity are exceeded.

2.5.3 Dip Slopes

A dip slope's surface parallels the dip of bedrock. The dip directions are the same ±20°. Dip slopes (Figure 2.4) may represent the equilibrium phase of an over-dip slope from which over-dipping beds have slid. They do not exhibit as much talus as other slope types because fewer planes of weakness are exposed to processes of weathering. There is a risk of buckling and sliding of weakened surficial beds in steeply inclined dip slopes (Simmons, 1977).

2.5.4 Under-Dip Slopes

An under-dip slope's surface dips less than the dip of bedrock. The dip directions are the same ±20°. Under-dip slopes, because of their geometry (Figure 2.5), are not prone to large rock slope movements. Usually these slopes contain a veneer of talus from surface weathering of bedrock. Downslope transport of material is gradual and dependent upon seasonal climatic fluctuations.

2.5.5 Reverse-Dip Slopes

A reverse-dip slope's surface dips away from the dip of bedrock. The dip directions are opposite ±20°. Reverse-dip slopes (Figure 2.6) are found on the opposite side of ridges or mountains containing over-dip, dip and under-dip slopes. They are generally steep to vertical and possess active talus slopes at their bases. Talus accumulation is from small slope movements but a larger slope movement can occur if a surface of rupture forms across a series of beds perhaps by connecting joints.

2.5.6 Oblique-Dip and Strike-Dip Slopes

On oblique-dip and strike-dip slopes (Figures 2.7, 2.8, 2.9, 2.10) movements can occur in a variety of ways. Rock near bedding planes, faults and joint sets weathers and movements can occur along one or several sets of discontinuities. In oblique-dip slopes the strike of bedding differs with the strike of the slope by more than 20° but less than 70°. In strike-dip slopes the strike of bedding is perpendicular to the strike of the slope ±20°. Observations made during this study indicate that these slopes present the most active hazard areas and heavy talus accumulations are often interstratified with high-magnitude rock slope movement deposits.

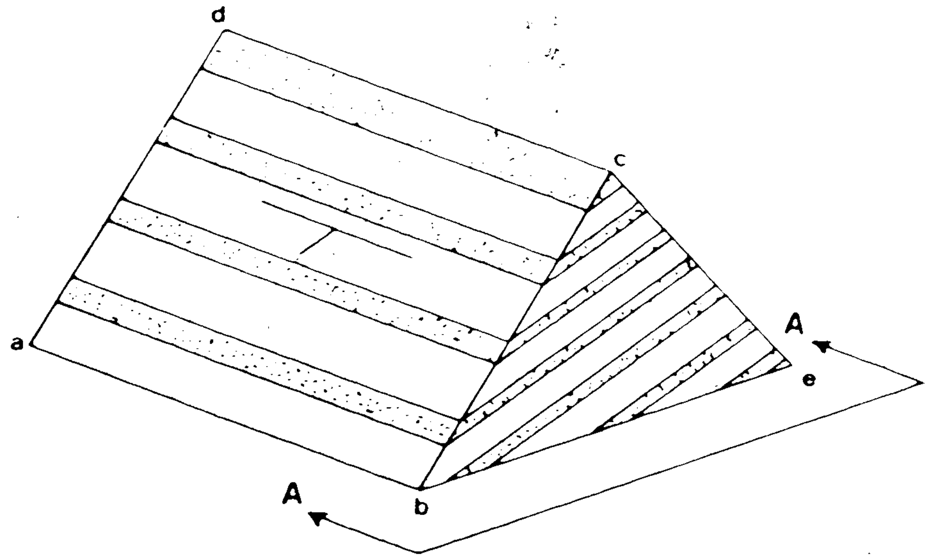


Figure 2.3 A-A, section through an over-dip slope defined by a,b,c,d. Slope dips steeper than bedding. A reverse-dip slope is hidden from view but has corners at c,d,e.

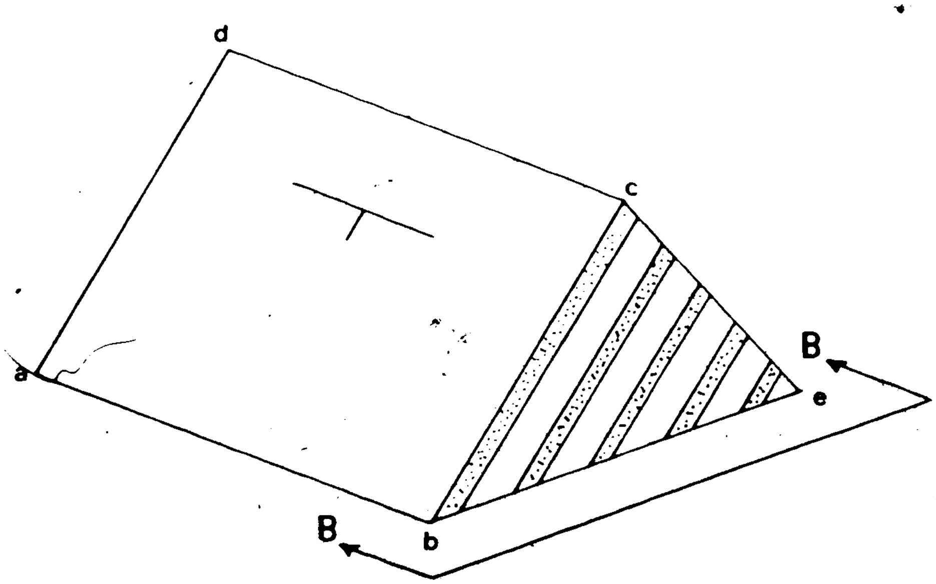


Figure 2.4 B-B, section through a dip slope defined by a,b,c,d. Bedding dips parallel to slope. A reverse-dip slope is hidden from view but has corners at c,d,e.

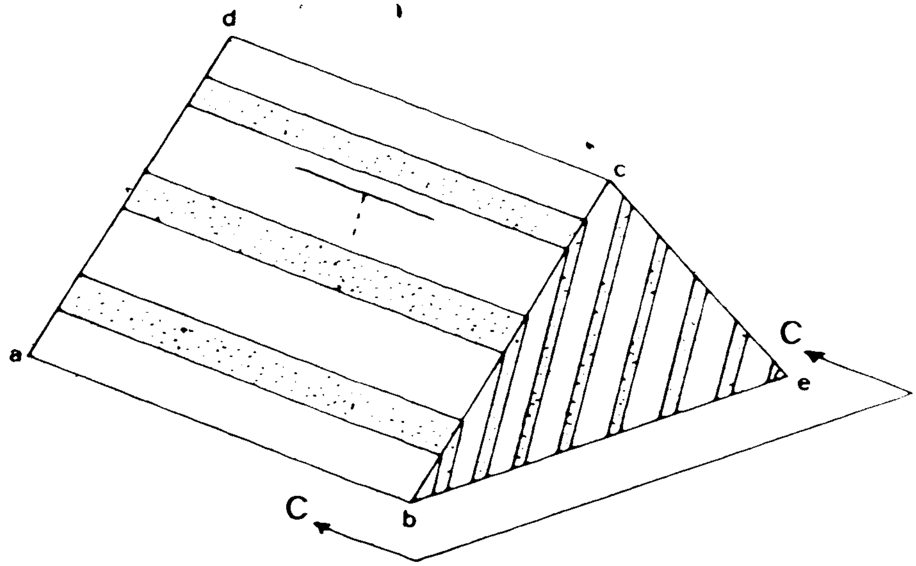


Figure 2.5 C-C, section through an under-dip slope defined by a,b,c,d. Bedding dips steeper than slope. A reverse-dip slope is hidden from view but has corners at c,d,e.

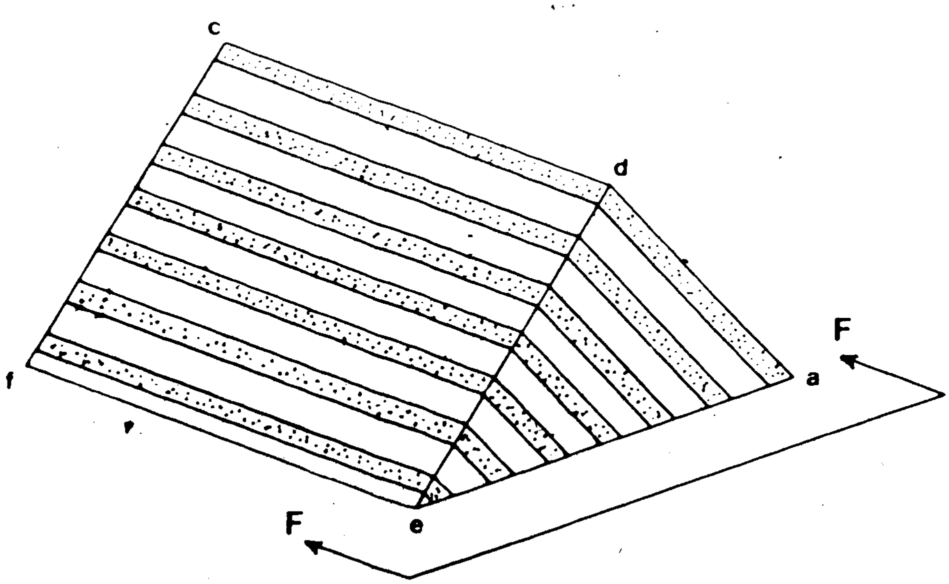


Figure 2.6 F-F a reverse-dip slope defined by c,d,e,f found opposite to the over-dip, dip and under-dip slopes in sections A-A, B-B and C-C. Bedding dips into slope.

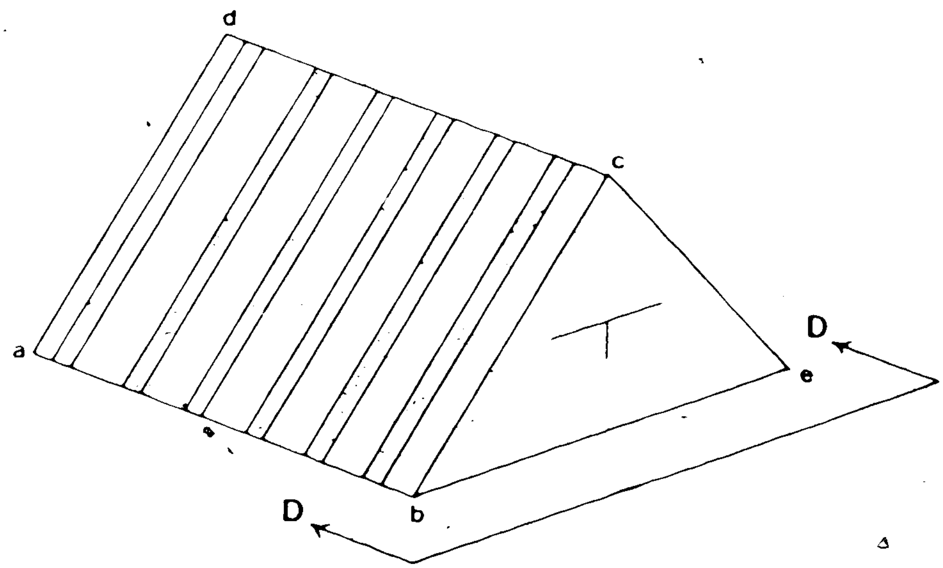


Figure 2.7 D-D, section through a strike-dip slope defined by a,b,c,d. Strike of bedding is perpendicular to strike of slope. Another strike-dip slope is hidden from view but has corners at c,d,e. Bedding is vertical.

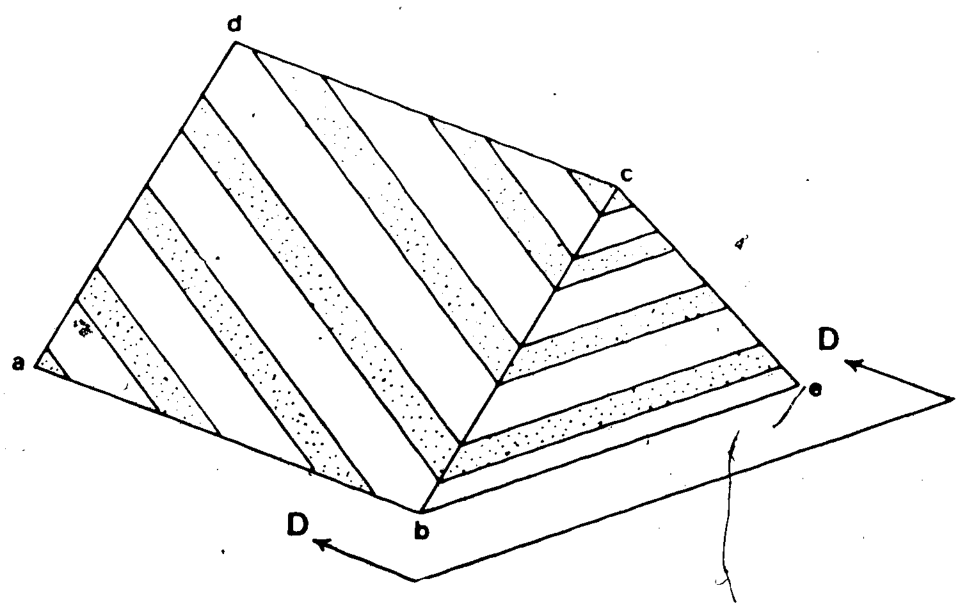


Figure 2.8 D-D, same as above except bedding is inclined.

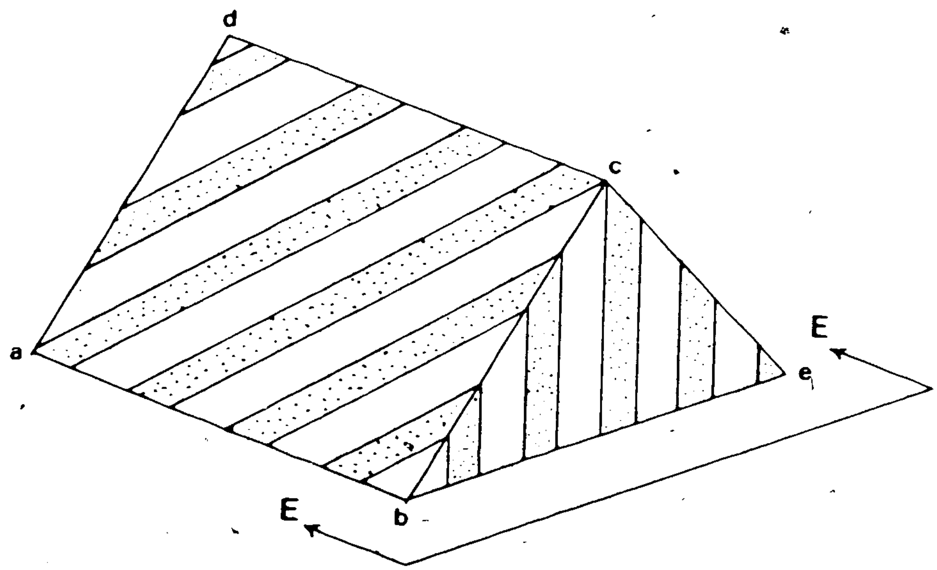


Figure 2.9 E-E, section through an oblique-dip slope defined by a,b,c,d. Strike of bedding is oblique by more than 20° to the strike of slope. Another oblique-dip slope is hidden, corners at c,d,e. Bedding is vertical.

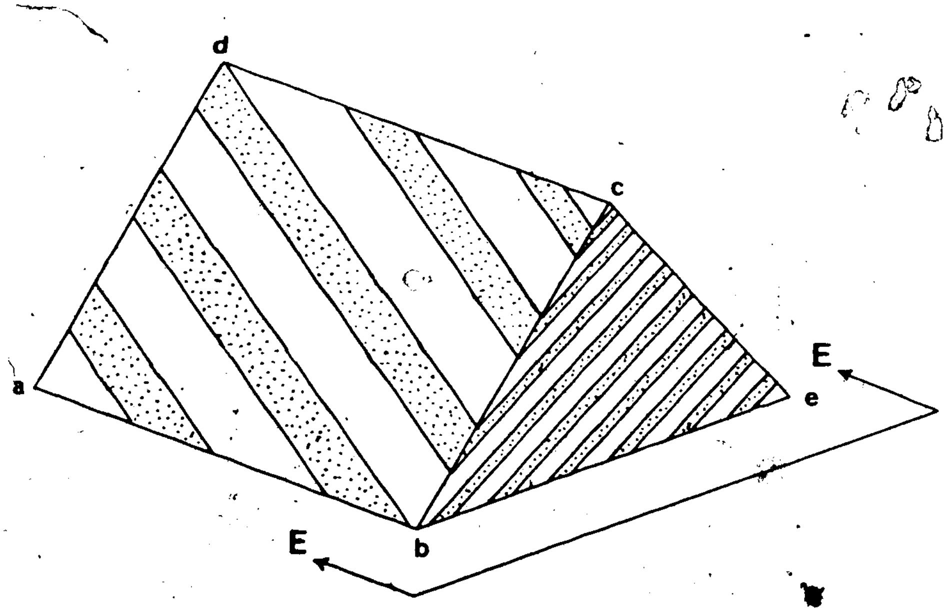


Figure 2.10 E-E, same as above except bedding is inclined.

3.0 Hazards

3.1 Introduction

The aim of the Kananaskis hazard mapping is to provide a reconnaissance of rock slope conditions. This flags those sites requiring more detailed investigation to delineate hazards to developments on these sites in Kananaskis. Hazards from rock slope movements are classified as active or hypothetical and are based upon observations of present activity and conditions. Generally, hypothetical hazards flag areas where larger rock slope movements may occur but smaller movements may already be active.

All deposits which are mapped post-date the last Wisconsin glaciation (about 10000 years B.P.) even though rock slope movements can be associated with the orogeny which began about 100 million years ago in western Alberta (Beaty, 1975). Hazards from rockslides show themselves in several types of movement. Rockslides, rockfalls and topples are the specific types of movement considered here in creating 'rockslide hazards'. Debris flows are discussed by Cruden and Eaton (1985a, b) when evaluating rockslide hazard in specific sites and are included here for completeness. Debris flows can incorporate rock fragments of various sizes in a fluvial process. Although kinematically not a rockslide or rockfall phenomenon they pose a hazard to facilities in King Creek and other areas. Creep or the slow downslope movement of soil and rock debris is considered. The definition of creep is complicated by the fact that it can grade into one of the above modes of movement.

Gardner (1980) discussed rockfall in terms of low-magnitude and high-magnitude occurrences. Low-magnitude events include rock fragments, boulders and blocks less than 10^3 m^3. High-magnitude events were larger than 10^3 m^3. Generally a rockfall or rockslide event greater than 10^3 m^3 leaves a deposit that is recognizable as a different landform apart from talus. High-magnitude deposits mapped on the air photographs used are generally larger than this because of scale. Minimum surface area coverage distinguishable on the photographs exceeded 5 x 10^3 m^2. Many smaller high-magnitude deposits have likely been covered by subsequent accumulation of low-magnitude debris during the Holocene. Large rockslide deposits should be clearly visible. Features do become subdued with age and reworking of some by neo-glacial episodes, snow avalanches and fluvial processes alters features further.

The following sections consider rockslides, rockfalls, topples and debris flows. This, the first mapping of rockslide hazards in the Canadian Cordillera looks at the mapping by others (Gardner, 1980; Reimchen and Bayrock, 1976; and Jackson, 1976) that mapped some rockfall and rockslide deposits, without specifically considering hazards from rockslides. A literature review served to select and define terms suitable and practical for use in the report. A simplified approach avoided the confusion resulting from the multiple application ~~of te~~rms by different authors in past publications. Varnes (1978) has made a useful contribution towards a working synthesis in this area. The selected terms, hazard, rockslide, rockfall, topple, debris flow and creep are described in the following headings.

3.2 Definition of Hazards

Therefore to establish a working framework for mapping rockslide hazards, 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.

3.3 Rockslides

Movement by sliding consists of shear displacement along a relatively narrow zone. More than one surface may be involved. There are two types of slides, rotational or planar. Rotational slides occuring on circular concave surfaces are more common in soils. The slide mass rotates down and out along the slide surface. Planar or translational slides are common in hard bedrock. Sliding usually occurs along a well-defined discontinuity in the rock mass. Sedimentary rock possesses many planar discontinuities at bedding contacts. Other planar discontinuities are formed by thrust and tear faults or by the linking of series of joint sets in the rock. The material may slide as an intact block or may be greatly deformed after the initial sliding has occurred.

Sliding occurs when the driving forces, or those forces that act to move the rock, exceed the resisting forces, or those forces that act to keep the rock in a stable and stationary position. The strength of the plane of weakness is given by cohesion and friction components. Bedding planes and other discontinuities can be much weaker than the intact rock itself. Frequently it is reasonable to assume that some pre-shearing has already occurred along the discontinuities under consideration. Pre-shearing occurs as a result of folding processes and is commonly referred to as flexural-slip. The pre-sheared surface then relies solely on friction to maintain stability as cohesion is destroyed or reduced to a negligible value. A rockslide will occur when the discontinuity is inclined at an angle greater than the friction angle of the discontinuity, the slope is inclined at an angle steeper than the discontinuity, the slope and discontinuity possess similar dip directions, and when there are no other forms of restraint present such as lateral or toe restraint provided by adjacent rock (Matheson, 1983).

Over-dip slopes provide a favourable geometry permitting rockslides to occur, especially when cohesion is destroyed. There are no toe restraints as the slope dips more steeply than bedding. Glacial or fluvial erosion can create such slopes. They may also be created by engineering works such as road cuts or open pit excavations. A mountain slope truncated by valleys at either end has all lateral restraint removed. If the slope is not truncated at either end, tear faults, gullies or series of joint sets in the slope may provide the necessary lateral margins with little or no resistance. Driving forces may be great enough to overcome some lateral resistance. An over-dip slope with steeply inclined bedding may be stable if it possesses cohesion or other forms of resistance to the driving forces. On the other hand an over-dip slope with pre-sheared beds dipping at less than the friction angle may fail because:

1. Pore pressures reduce the frictional resistance of the slide mass.
2. The slide surface is filled with a gouge material of low shear strength.
3. An earthquake provides a horizontal thrust to the potential slide mass sufficient to release it.

Pore pressures result from the presence of groundwater in open cracks, bedding planes, faults and joints. Gouge material results from extensive pre-shearing and grinding of the rock surfaces and weathering along the discontinuity.

Rockslides are the largest, single-event form of mass-wasting of rock slopes observed in Kananaskis. Large rockslides with well-defined bedding plane rupture surfaces exist in the study area. Other large rockslides appear to be failures on rupture surfaces other than bedding. Connecting joint sets or a minor fault displacement form the plane(s) of weakness on which these large rockslides occurred.

Rock slope movements are distinguished according to the characteristics of initial movement as either rockslides or rockfalls. Rockslides initially slide along one or more discontinuities and rockfalls free fall or topple in the initial phase of motion. Sliding may continue but more commonly the moving mass acquires other characteristics of motion. The topography of the slide route may induce free-fall, bounce or roll components to motion. The moving mass may disintegrate and if conditions are favourable, move according to one or more combinations of several physical hypothesis. These theories of motion include (Hungr, 1981):

- lubrication by mud
- air layer lubrication
- air fluidization
- pore pressure
- rock dust liquefaction
- mechanical fluidization
- acoustic fluidization
- thermal disassociation of carbonate rock

Rockslides are sudden and rapid when they occur. The Frank Slide, in 1903, is a dramatic example of such an event. Studies by Tianchi (1983), Davies (1982), Hsu (1975), and Scheidegger (1973) show that rockfalls and rockslides usually greater than 0.5×10^6 m^3 can travel long distances. Hsu adopted the term "sturzstrom" for these mobile deposits, a term first introduced by Heim in describing the famous Elm rockfall of 1881. The term large rockslide is used in this report to describe the high-magnitude deposit greater than 0.5×10^6 m^3, but excessive mobility is not implied. Sixteen large rockslides are listed in Table 3.1. All are active hazard zones. Mount Indefatigable and Mount Sparrowhawk possess hypothetical slide masses in over-dip slopes that can slide (Appendix B). If a rockslide should occur at either of these sites it may travel a long distance. It is not possible to identify hypothetical masses on reverse-dip, oblique-dip or strike-dip slopes even though many high-magnitude deposits and several large rockslides are found at the bases of these slope types. Most of these areas still possess high steep scarps and are very active low-magnitude rockfall areas which limits access. Close inspection is necessary to locate plane(s) of weakness favourable for a high-magnitude rockslide to occur. In general, the topography and attitude of the bedrock on reverse-dip, strike-dip and oblique-dip slopes suggest that large slope movements are not likely.

Table 3.1 Location of large rockslide deposits in the Kananaskis study area. Refer to Appendix C for air photograph interpretations.

LARGE ROCKSLIDE	AIR PHOTOGRAPH	U.T.M. location (m)	
name	number	northing(N)	easting(E)
Mt Tyrwhitt	AS 749 5025 223	5605700 N	640400 E
unnamed	AS 748 5027 80	5609300 N	639200 E
Mt Indefatigable	AS 748 5027 74	5610200 N	629200 E
unnamed	AS 748 5029 164	5614300 N	622900 E
unnamed	AS 748 5029 167	5615300 N	625700 E
unnamed	AS 748 5030 212	5616100 N	623200 E
unnamed	AS 748 5030 212	5616800 N	623000 E
unnamed	AS 748 5030 213	5616800 N	625300 E
Burstall Pass	AS 747 5033 101	5624700 N	615500 E
Mt Birdwood	AS 747 5033 101	5625900 N	615600 E
Mt Shark	AS 746 5036 5	5632600 N	612800 E
Mt Buller	AS 746 5039 155	5640000 N	619000 E
Quartzite Ridge	AS 746 5040 204	5641800 N	619800 E
Sparrowhawk Rge	AS 746 5040 204	5642300 N	621000 E
unnamed	AS 746 5041 12	5642900 N	623100 E
unnamed	AS745 5042/43 95	5648800 N	625300 E

U.T.M.=Universal transverse mercator grid on National Topographic System 1:50,000 maps 82J/10, 11 and 14.

Moreover, low-magnitude events are predominantly rockfalls and high-magnitude events seem to be initiated as rockslides although rapid comminution of the slide mass may occur. Further discussion of rockslides is provided in Chapter 4 on Activity.

3.4 Rockfalls

Movement in a rockfall involves little or no shear displacement. The mass descends by free fall, bouncing and or rolling. Falls of newly detached rock are primary falls, and those involving earlier transported loose debris are called secondary falls (Rapp, 1960). Rockfall is widespread in Kananaskis. Most steep rock slopes and scarps are abundant sources of rockfall. The most active slopes appear to be oblique and strike-dip slopes (Section 4.3). Generally, talus accretes from low-magnitude, high-frequency rockfall consisting of rock fragments, boulders and blocks. Whereas rockslides are the largest single form of mass wasting in Kananaskis, rockfall appears to contribute greater quantities to lower slopes and valley floors over longer periods of time (Section 4.2). Deposits are subsequently modified by other processes which include weathering, snow avalanches, fluvial processes, consolidation and talus shift (Gardner et al., 1983). High-magnitude rockfalls are mapped using the same symbol as for high-magnitude rockslide deposits, but none approaches the magnitude of the large rockslides previously mentioned

(Table 3.1).

Climate and weathering processes affect the outermost few metres of rock faces. There is no general agreement but in addition residual stress, joint water pressure, valley geometry, aspect and characteristics of the rock all seem to play a role in the frequency, magnitude and spatial distribution of rockfall. Gardner (1980) observed frequencies of 0.83 and 0.70 events per hour of observation from the Highwood Pass and Lake Louise areas, respectively. Luckman (1976) obtained a value of 0.66 from the Surprise Valley area of Jasper National Park. Both had most of their events clustered in particular hours so that no events were recorded in a majority of the observation periods. No observations were possible during nocturnal hours. The rockfall frequency was at its highest throughout the midday and early afternoon hours. Gardner (1980) found that the highest frequencies and largest talus are associated with major free faces. In his Highwood Pass study area these are generally northwest to northeast facing. They retain more snow and ice during the summer and exhibit more freeze-thaw cycles, contributing factors in low-magnitude rockfall occurrence. Gardner qualified his findings that frequency decreases as magnitude increases:

1. That debris from small, frequent rockfall exceeds the volumes transported by high-magnitude rockfall and rockslide.
2. Present rates of rockfall do not account for debris

accumulation during postglacial time.

3. Other agents such as snow avalanches, debris flows and surface runoff also contribute material to talus.
4. Low-magnitude rockfall, like high-magnitude rockfall and rockslide, may have been more frequent in the past.
5. Talus may include moraines, hidden underneath, which predate deglaciation.

Frequencies were not observed but rather, slope type, bedrock structure, lithology and rockslide and rockfall deposits were mapped in this reconnaissance of rockslide hazards. Debris from rockfall and rockslide is extensive in Kananaskis with talus from low-magnitude rockfall exceeding debris from high-magnitude events (Section 4.2). Low-magnitude rockfall was seen or heard on a daily, if not hourly, basis when in the field near steep slopes and scarps. Snow avalanches were observed transporting rock debris to lower slopes and evidence of mass transport by debris flows was found (Section 3.6). These findings are in general agreement with Gardner's view on frequency and magnitude.

More importantly active rockfall and rockslide slope types and rock types are identified (Sections 4.3 and 4.4). Hazardous zones are mapped on the air photograph interpretations in conjunction with slope types. Topographic conditions can vary frequently over short distances on some slopes. A slope type symbol indicates the conditions prevailing only at the arrowhead but often reflects the dominant slope type on that particular aspect. Further discussion of rockfalls is provided in Chapter 4 on Activity.

3.5 Topples

Topples, mapped as a form of rockfall on the interpretations, involve rotation of columns or blocks of rock about an axis below their centres of gravity. The topple may be preceded by creep followed by a sudden and rapid failure, or continue by creep until the kinematically possible rotation is complete at which point the slope may stabilize or creep movements may continue by some other mode of movement.

Toppling by creep is providing a continuous supply of debris to the Rock Glacier (Peter Lougheed Provincial Park Interpretive Trail) and other adjacent talus immediately east of Highway 40 in the Highwood Pass area. These movements appear to be widespread in the Triassic Sulphur Mountain Formation in Highwood Pass. The Sulphur Mountain Formation is found in the Spray River Group which is a predominantly red sequence of thin to medium bedded carbonates and shales occurring on the lower southwest slopes of the Misty Range (Allan and Carr, 1947). The Spray River Group is not mapped in the study area (Bielenstein et al., 1971). It appears to contribute material to other forms of rock slope movement as well (Section 3.6). Here the beds, almost vertical, dip southwest and are rotating southwestwards out of the slope.

A large rockfall deposit mapped on the southwest slopes of Mount Elpoca, also in the Highwood Pass area, appears to be the result of a rapid toppling failure. The deposit contains about 100 x 10^3 m^3 of debris. The topple is likely in the Tunnel Mountain Formation of the Permo-Pennsylvanian Rocky Mountain Group. The Tunnel Mountain Formation consists of cliff forming, brown weathering dolomitic siltstones and sandstones, some bedded and nodular chert and less resistant siltstones and thin shales (McGugan and Rapson, 1962). The Tunnel Mountain Formation is not mapped in the study area (Bielenstein et al., 1971). Beds, almost vertical, dip southwest. The failure could have occurred as relief weathered (mainly by freeze-thaw cycles) recessive beds or bedding contacts behind the scarp face (also upslope) were kept open and enlarged by rock fragments falling into them from above. Rock wedging continued, forcing the beds away from the slope, until overturning forces caused a rapid topple in the column of rock.

Similar bedrock structure and slope aspect exist along the west slopes of the east ridge of the Opal Range for most of its length and along portions of the west ridge. Similar structure and slopes are found in the ranges of the Spray Mountains along the west boundary of Peter Lougheed Provincial Park between Burstall Pass and Aster Lake. Talus slopes are extensive in this area. Topples are possible.

3.6 Debris Flows

Debris flows, although not a kinematic form of rockslide or rockfall, presented hazards that could not be overlooked when reconnaissance of two special sites was done by Cruden and Eaton (1985b). Debris flows were only mapped in specific sites by them. Much more field reconnaissance would have been required to consider this hazard throughout the whole study area.

Debris flows are considered here as rockslide hazards. They are most common in high mountains and in semi-arid areas which have little or no vegetation (Selby, 1982). They occur in regolith, initiating on steep slopes, in gullies and ephemeral stream channels. They can be initiated by intense precipitation, snow-cover melt, glacial melt or wet snow avalanches. Wet snow and ice can be incorporated in the debris so a fluvial process becomes a mass wasting process. They can travel at high velocities and great distances (Plafker and Erikson, 1979). An abundant supply of water permits motion of the debris mass. The initial characteristics of motion may begin as a landslide or slurry (Johnson and Rodine, 1984). Gardner (1982) has documented debris flows in the vicinity of Elpoca Mountain which obstructed Highway 40 in 1975 and again in 1979. These resulted from intense rainfall.

A small debris flow was encountered high above the valley floor on a steep southeast facing slope of Mount Bogart. Snow and ice were still mixed in the mud and rock debris when found in early June, 1985. The debris flow must have occurred earlier in the spring. Debris flowed around several trees in its path, scarring the tree trunks. Although located on a treed slope in a small gully, the debris was probably incorporated into a wet snow avalanche initiating on open upper slopes. Small flows such as this one are not mappable on air photographs and are only encountered by chance during field reconnaissance. Their frequency and distribution throughout the study area are not known.

Debris flows are more extensive and active in two of the specific sites. It appears that certain rocks, in particular the Triassic Sulphur Mountain Formation, the Jurassic Fernie Group and the Permo-Pennsylvanian Rocky Mountain Group, are susceptible to debris flows. Some of the shales and sandstones are readily eroded and provide the small particle sizes along with larger fragments, boulders and water necessary for a debris flow to occur. Debris flow deposits were found in King Creek and the site east of the Smith-Dorrien-Spray Trail (Cruden and Eaton, 1985b). In King Creek debris flows have been deposited in the canyon section and further down on the active floodplain of the alluvial fan. East of the Smith-Dorrien-Spray Trail, debris flow deposits lie in South Sparrowhawk Creek on the active floodplain down to the Spray Reservoir. The debris flow hazard is active in those areas.

Another source of debris flows in mountainous glaciated terrain is from dam bursts, breaches of moraine dams, and jokulhlaups, catastrophic glacial outburst floods. The debris flow forms as a result of the sudden release of the large volume of water which scours its runout channel of all loose soil and rock and may then flow for many kilometres downstream from its source.

At present, a small moraine lake one kilometre south southeast of Maude Lake could pose such a hazard. This lake covers about 20,000 m^2 and has cut a channel through the moraine, so it has been higher in the past. The lake is fed by glacial melt from the Beatty Glacier. A period of abnormally high recharge, from glacial melt and precipitation, could precipitate a dam burst. In the same area, evidence of a dam burst lies one kilometre south of Lawson Lake. This former moraine lake was also fed by the Beatty Glacier.

There are no lakes impounded by bodies of glacier ice in Kananaskis. So the possibility of a dam burst seems remote and that of a jokulhlaup does not exist. There are no significant hanging or tumbling glaciers in Kananaskis so the possibility of an avalanche of glacier ice does not exist either other than the release of individual blocks from some of the small remaining pockets of ice on northern aspects.

3.7 Creep

Creep or the slow downslope movement of soil and rock debris is also included in the hazards considered here. The definition of creep is complicated by the fact that creep grades into or can be combined with other types of slope movement (Radbruch-Hall, 1979) such as slides, falls, topples, lateral spreads, flows and slumps. Usually there are three types of creep (Hansen, 1984):

First is seasonal creep, or movement within the depth of regolith affected by seasonal changes in temperature and moisture. This form of creep although widespread in Kananaskis is not a hazard due to the slow and incremental nature of the movement. Smith (1985) discusses this in detail. On exposed talus slopes or in cold climates where freeze-thaw processes are common rates up to 0.5 metres per year have been recorded (Selby, 1982).

Second is continuous creep, where shear stresses exceed the strength of the material. Most of the conditions necessary for continuous creep occur in Kananaskis. Generally, poorly indurated rocks, interbedded soft and hard rocks, active tectonism, or steep-sided ridges are necessary for continuous creep in rock. Steep sided ridges are found in Kananaskis but these are active rockfall and rockslide hazard zones. Undercutting of slopes by glacial or fluvial processes can contribute to creep but these conditions are again identified by active and hypothetical rockslide hazards. Deep seated movements are a bedrock phenomenon not mappable by the methods of this study.

Third is progressive creep, which is associated with slopes reaching the point of failure by other mass movements. This may be deep seated or superficial and can precede large or small rock slope movements. Deep seated progressive rock mass creep has been measured at rates up to 20 centimetres/day (Muller, 1964). There is evidence that progressive creep is occuring along bedding planes at sites in the Opal Range and Burstall Pass.

A rockslide occurred from an over-dip slope in the west ridge of the Opal Range just north of Grizzly Creek. Closer examination of the rupture surface, a bedding plane, reveals that buckling of the surface has continued since the rockslide failure. The rock involved is a highly fractured argillaceous limestone. The Lewis Thrust Fault is nearby. Was progressive creep a mechanism preceding the rockslide and is it occurring further north along the slope which possesses similar structure? The present slide has a volume of about 100 x 10^3 m^3, while another 700 x 10^3 m^3 of over-dip slope dissected by several gullies repose above Highway 40, a Trans-Alta transmission line, a private residence and a service centre. Further investigation could provide some interesting results at this site although exposure to natural hazards might be a hindrance.

The Burstall Pass site involves a hypothetical over-dip rockslide mass. The volume of rock is about 600 x 10^3 m^3. Beds dip at 40° at the base and steepen upslope. The upper area was not accessible but the author estimates the dip does not exceed 50°. A volume of fractured rock in a dip slope below the hypothetical mass is creeping downslope under its own self weight or by that of the hypothetical mass as well. The potential rupture surface is already dilated at the point of inspection, note this is in the dip slope portion. The dip slope and over-dip slope masses are separated by a two metre fissure, following strike, filled with rock debris. Again an interesting site but access and natural hazards may prove to be a hindrance to further investigation.

3.8 Mapping by Others

Mapping of rockfall and rockslide deposits in the Kananaskis study area has been carried out by Reimchen and Bayrock (1976), Gardner (1983, 1982) and Jackson (1976). Smith (1985) reported on solifluction and gelifluction, Sauchyn (1984) on open rock basins and debris flows in Kananaskis and Gardner et al. (1983) on dynamic geomorphology in Highwood Pass.

Reimchen and Bayrock's mapping is part of a larger surficial geology map report covering the foothills of Alberta south of 52° latitude. This includes the Kananaskis study area. Within the area they indicate twelve rockslide deposits and one slump and landslide deposit. The slump and landslide deposit was found to be an area of high low-magnitude rockfall activity from strike-dip slopes.

Their mapping of the Mount Indefatigable rockslide deposit has a different outline from that seen on the air photographs or in the field reconnaissance of this study. Of the remaining eleven deposits, six are mapped by this study while the other five could not be confirmed by the methods of this study. It must be kept in mind that Reimchen and Bayrock mapped at a scale of 1:50,000. Only deposits in the large rockslide range can be mapped effectively at this scale and these should be recognizable. Yet, two obvious large rockslides have been overlooked and five others appear to be erroneously indicated. Some of the sixteen large rockslide deposits mapped in the present study fall at the bottom end of the scale and could be too small in area to map at 1:50,000.

Gardner's work is restricted to Highwood Pass and considers the frequency, magnitude and spatial distribution of rockfalls and rockslides. Within the boundaries of his and this study area Gardner maps six high-magnitude rockfall deposits in a size range from 10^3 m^3 to greater than 10^4 m^3. The present study maps the same six deposits although two of the deposits are considered as being two or more deposits. Garder used 1:50,000 scale maps but was able to carry out extensive field reconnaissance in his study area (only 100 km^2) which is relatively small compared to the study area of Reimchen and Bayrock.

Jackson reported using two sets of maps, one each on surficial geology and terrain inventory respectively. At a scale of 1:250,000 only two "landslides" were indicated on the terrain inventory in the present study area. The scale is too large to map rockfall and rockslide deposits effectively.

The reports by Smith (1985), Sauchyn (1984) and Gardner et al. (1983) present useful information on other forms and processes of slope movements in Kananaskis. The studies performed by Gardner and Smith are presented in a modified form in the text authored by Gardner et al. (1983). It appears that presentation of low-magnitude and high-magnitude rockfall and rockslide activity at scales of 1:50,000 or larger can be misleading.

4.0 Activity

4.1 Introduction

Rockslide and rockfall occur on steep terrain in Kananaskis. The terrain or slope has a bedrock structure, aspect, relief, rock type and groundwater regime determined by its history. History includes external past and present stresses on the slope from depositional environment, diagenesis, orogeny (including seismicity), climate (including glacial episodes and microclimate fluctuations), and more recently, human-induced stresses (mainly engineering works, but war and pollution as extremes). The depositional environment and diagenesis are locked into the rock structure and type. Orogeny produces aspect and relief and may alter the rock structure and type. Climate alters the rock composition, aspect, relief and groundwater regime through the influence of temperature, precipitation and wind on denudation rates of weathering, transportation and erosion.

Human works can increase or decrease the stability of a slope. Maintenance of vegetation on slopes in King Creek will aid in promoting stability (Cruden and Eaton, 1985b). Supporting or increasing the vegetation cover stabilizes the slope cover and decreases the hazard from debris flows. Cuts or fills in slopes for various engineering structures can, in some cases, stabilize a slope but more often it increases the risk of slope movements. A rock cut necessary for the construction of Highway 40 created an over-dip slope that had to be stabilized by post-tensioned cables. A retaining structure was necessary to control debris flows in a creek crossed by the Smith-Dorrien-Spray Trail. It is important then to recognize which slopes are naturally susceptible to movements and why.

Bedrock structure, aspect and relief combine to produce a certain slope type, and rock type is divided according to age, composition and depositional environment into groups, formations and beds. Observations of slope type and rock type type are made in this study. Some references are made to different stresses and processes that have influenced the study area's slopes, but the main objective is to flag hazardous slopes and areas. This chapter will consider the different slope types defined in Section 2.5 and the rock types already mapped in the area, Section 2.4, to discuss hazards and activity.

In order to present information and compare slope and rock types, low and high-magnitude rockfall and rockslide was mapped and areas were classed according to their slope and rock type. Emphasis is placed on high-magnitude events as they are the most destructive. The activity of slope and rock types is compared separately and then together.

The activity index is obtained by taking the percentage of high-magnitude rockslide and rockfall, or percentage of cluster areas (of high-magnitude rockslide and rockfall) in the target area (for example over-dip slopes; Rundle Group etc.) and dividing by the target area as a percentage of the total area (for example Rundle Group as a percentage of all rock types).

$$\text{Activity} = \frac{\text{\% of all events or clusters in target area}}{\text{target area as \% of total area}}$$

The activity index provides a relative probability of a rockslide according to slope and rock type in Kananaskis. This information is useful for purposes of the study. The findings are presented in the following three sections.

4.2 Extent of deposits

The Kananaskis study area covers about 880 km². Of that about 45% or 400 km² are exposed bedrock slopes, usually above treeline. Of the total area 10.9% or 96 km² is covered by talus, 0.9% or 8 km² is covered by high-magnitude rockslide and rockfall, 2% or 18 km² is covered by glaciers, and there are 228 high-magnitude rockslides.

When estimating quantities from air photos, several problems arise. The further an object lies from the centre of a photograph, the greater its dimensions are distorted. This is amplified in mountainous terrain because of the steep slopes and great relief. If a slope dips towards the centre of the photograph, everything on that slope will appear larger than its projection on a horizontal plane. Conversely, if a slope dips away from the centre of the photograph, everything on that slope will appear smaller than its projection on a horizontal plane. If the slope dips at some other orientation with respect to the centre of the photograph, distortions are introduced as well. The author has assumed that the combined effect of the distortions cancel each other out and that the estimates of talus and rockslide deposits are representative of those projected to a horizontal plane. The comparisons of slope and rock types were done on topographic maps so that quantities are estimated from a horizontal plane.

Only areas where accumulation of talus is active are considered by the mapping scheme. The active talus areas include steep slopes with talus on ledges or in gullies. The accummulation zone at the bottom is usually visible but it is not always possible to map on the air photographs the talus on ledges, in gullies or in shadows beneath northeast scarps. Those slopes with gentler grades covered by a thin veneer of loose rock are not included in the active talus zone. These rock fragments do not bounce or roll into place but rather accummulate from in situ weathering and displace by creep. These deposits are regarded as belonging to the broader grouping of colluvium. Talus zones that are being strongly reclaimed by vegetation are considered no longer active. Other areas possessing active talus zones less than the grid size of 80 x 80 m (6400 m^2) are not mapped.

So, high-magnitude events are all those that were mappable using the 80 x 80 m grid. Large rockslides are those which exceed 0.5×10^6 m^3. This volume distinction is made to give an idea of how many rockslides and rockfalls are in the volume class which Hsu (1975) observed could exhibit an excessive travel distance and features of 'flowing'.

Rockslide and rockfall deposits are subject to greater discussion. Those deposits that initially come to rest on Little Ice Age or Neo-glacial glaciers are hopefully included in the estimates. Older deposits emplaced on glacier ice from the last major glaciation (over 10,000 years B.P.) may exhibit mature glacial and weathering features and thus are not included. The characteristics of a rockslide or rockfall phenomenum eventually fade as the deposit is incorporated and reworked by the glacier. This is not an attempt to suggest that all moraines are of rockslide origin.

What is suggested is that we have 228 deposits in Kananaskis whose features are characteristic of a rockslide or rockfall or whose features are predominantly those of a rockslide or rockfall even though glacier ice may have participated in final transport and deposition of the debris. Secondly, these events have arrived in the last few thousand years since major glaciation, a relatively short time. If we consider the greatest period of time acceptable with current estimates of the last major glacier retreat or 10,000 years (Jackson, 1976), then a high-magnitude rockslide or rockfall has occurred once every 44 years. Thirdly, minor fluctuations in climate in the last few thousand has been sufficient enough to initiate glacier advances (Luckman, 1976). The advance and retreat of these glaciers may influence the occurrence of rockslide and rockfall by creating over-dip slopes and weakening rock structure. Some rockslide deposits appear to be glacially reworked. A period of glaciation, even a short one of only a hundred years or so, is an important agent in reducing the resisting strength of a potential rockslide or rockfall slope.

4.3 Slope Type Activity

Slope types were defined in Section 2.5. Figure 4.1 shows typical dip and strike directions and the range of slope types in Kananaskis. The slope type is dependent upon the strike and dip of the bedrock and the strike and dip of the mountain slope. In general, strike of bedrock is 150° or 330° and dip direction is 240° or 60°, respectively. Dips are usually between 20° and 90°. The trend of thrust faults, folds and bedrock varies about ±20° from the typical strike across the study area. Dip directions can be reversed on slopes found in the west limb of a syncline or the east limb of an anticline. Note how this changes the aspect of certain slope types in Figure 4.2 from those in Figure 4.1.

The range, in degrees, over which a simple sliding failure can occur on a discontinuity must satisfy the following requirement: the dip direction of the slip surface lies within 20° of the dip direction of the slope (Matheson,

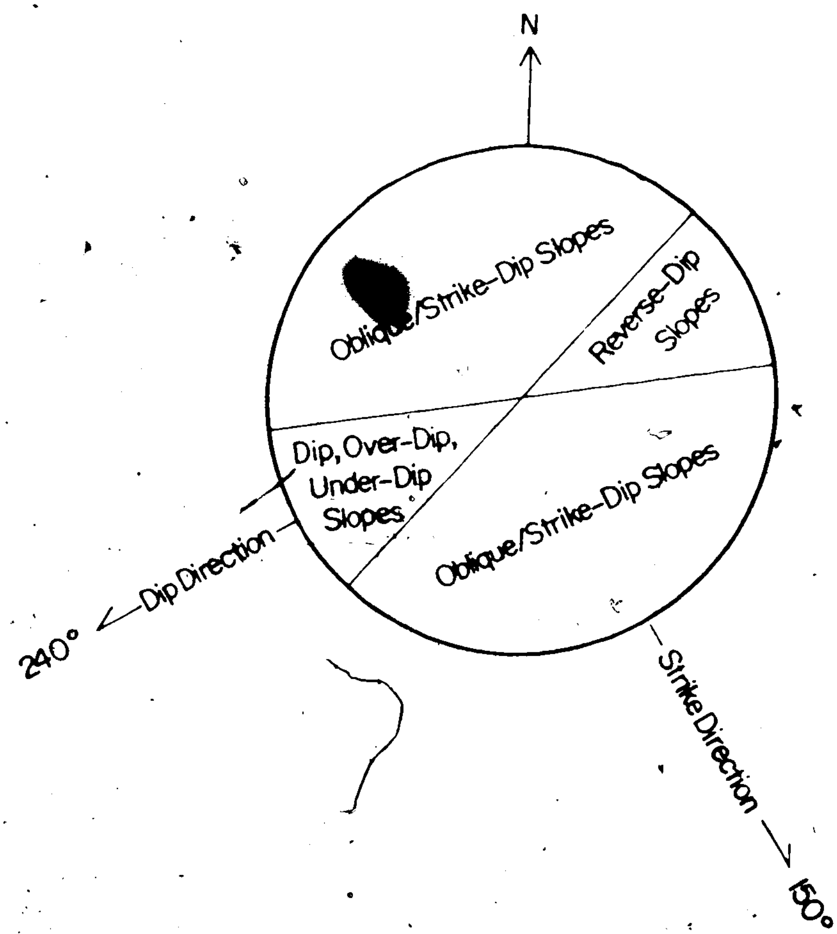


Figure 4.1 Range of slope types when the dip direction of bedrock = 240°. The variation in dip and strike directions and therefore slope types = ±20°.

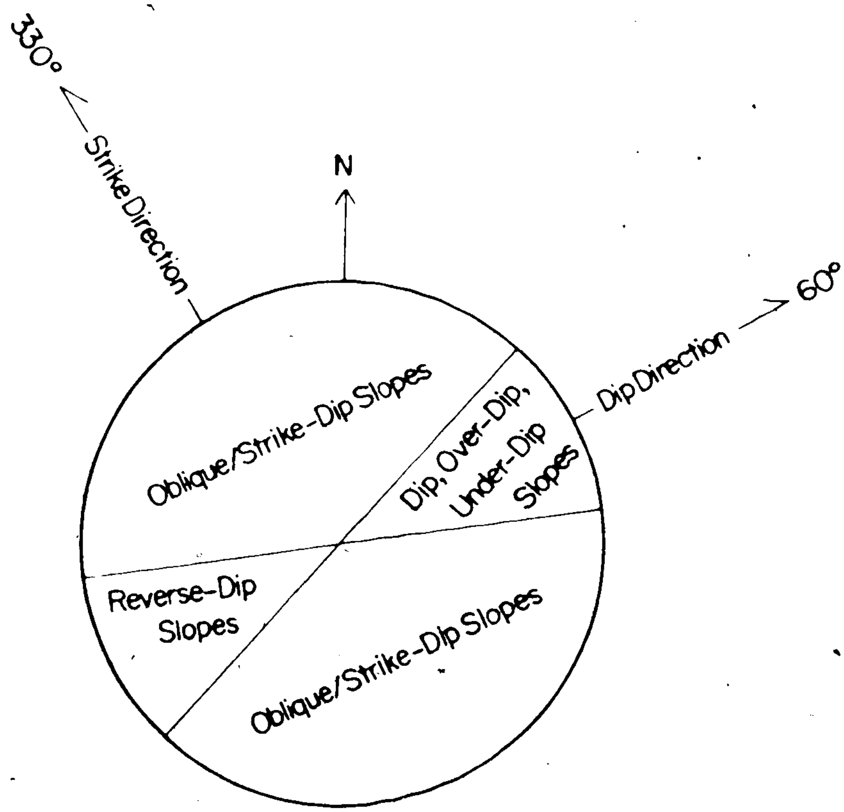


Figure 4.2 Range of slope types when the dip direction of bedrock = 60°. The variation in dip and strike directions and therefore slope types= ±20°.

1983). The typical dip direction of bedding is 240°, therefore over-dip slopes with dip directions, or aspects, between 220° and 260° can fail in simple sliding. Beyond this range the failure mechanism no longer occurs by simple sliding. The inclination of the slip surface must exceed the friction angle of the slip surface as well, other considerations such as pore pressures and earthquake loading etc. excluded. This requirement applies equally to:

1. Over-dip slopes, as mentioned above.
2. Dip slopes, being the resulting slope type after an over-dip slope failure.
3. Simple toppling from under-dip slopes (Matheson, 1983).
4. Reverse-dip slopes since they are found on the opposite slope from dip, over-dip and under-dip slopes and providing the reverse-dip slope possesses a discontinuity that satisfies the simple sliding requirement.

Considering all aspects, slope types have the following ranges for typical strike and dip (i.e. dip direction = 240°):

1. Dip, over-dip and under-dip slopes 220° to 260° = 40° = 11% of all aspects.
2. Reverse-dip slopes 40° to 80° = 40° = 11% of all aspects.
3. Oblique and strike-dip slopes 80° to 220° and 260° to 40° = 280° = 78% of all aspects.

Non-typical strike and dip (i.e. dip direction = 60°)have the same ranges but the aspects are reversed for 1 and 2 above. Oblique and strike-dip slopes have a much wider range than other slope types, 78% of possible aspects, though they do not occur with that frequency in the study area. The majority of valleys follow structurally weak zones in the bedrock. These are found along thrust zones and axes of folds which normally are parallel to the typical strike of 330°. Most of the valley slopes fall into the aspect ranges for dip, over-dip, under-dip and reverse-dip slopes. Some valleys, particularly in the Kananaskis Range, follow other structural weaknesses like tear faults. These valleys have a majority of oblique and strike-dip slopes.

Some slope types are considered separately and others are grouped together. Oblique and strike-dip slopes are considered collectively as a mountain slope can alternate over very short distances between the two; they are difficult to separate on air photographs and they release rock by similar mechanisms usually involving two or more joint sets and bedding surfaces. Reverse-dip and under-dip slopes are considered separately. Dip and over-dip slopes are considered collectively as they are both associated with rockslide sites.

Gardner (1980) offered that mountain slopes have been oversteepened by glacial erosion and that low and high-magnitude rockfall and rockslide may have been more frequent in the past. Oversteepened slopes in valleys parallel to bedrock strike should favour the formation of over-dip slopes on both sides of a syncline valley and one side of a thrust fault valley (Figures 4.3 and 4.4, respectively). Anticline valleys cannot have over-dip slopes and tear fault valleys do not exhibit over-dip slopes in Kananaskis.

Present over-dip and dip slopes are the most active high-magnitude slope types in Kananaskis (Table 4.3 and Figure 4.7). If their extent was greater during and immediately after the last deglaciation, then high-magnitude rockslides were also more frequent during and immediately after deglaciation. Gardner has made the same conjecture regarding high and steep scarps (oblique-dip, strike-dip and reverse-dip slopes). Over-dip slopes appear to be unstable slope types that geomorphic processess change, when thresholds are exceeded, to dip slopes and then to under-dip and eventually stable vegetated slopes. Glacial or fluvial erosion can cause the cycle to repeat.

Tables 4.1 and 4.2 present the study area in 26 sub-areas with respect to slope type and low-magnitude and high-magnitude rockfall and rockslide activity. Low-magnitude rockfall activity is based on the extent of talus cover visible in the air photographs. High-magnitude rockfall and rockslide activity is based on the number and size of deposits in a given area. Activity is classed as high, low to moderate or non-active. High activity implies that there are extensive talus deposits, several

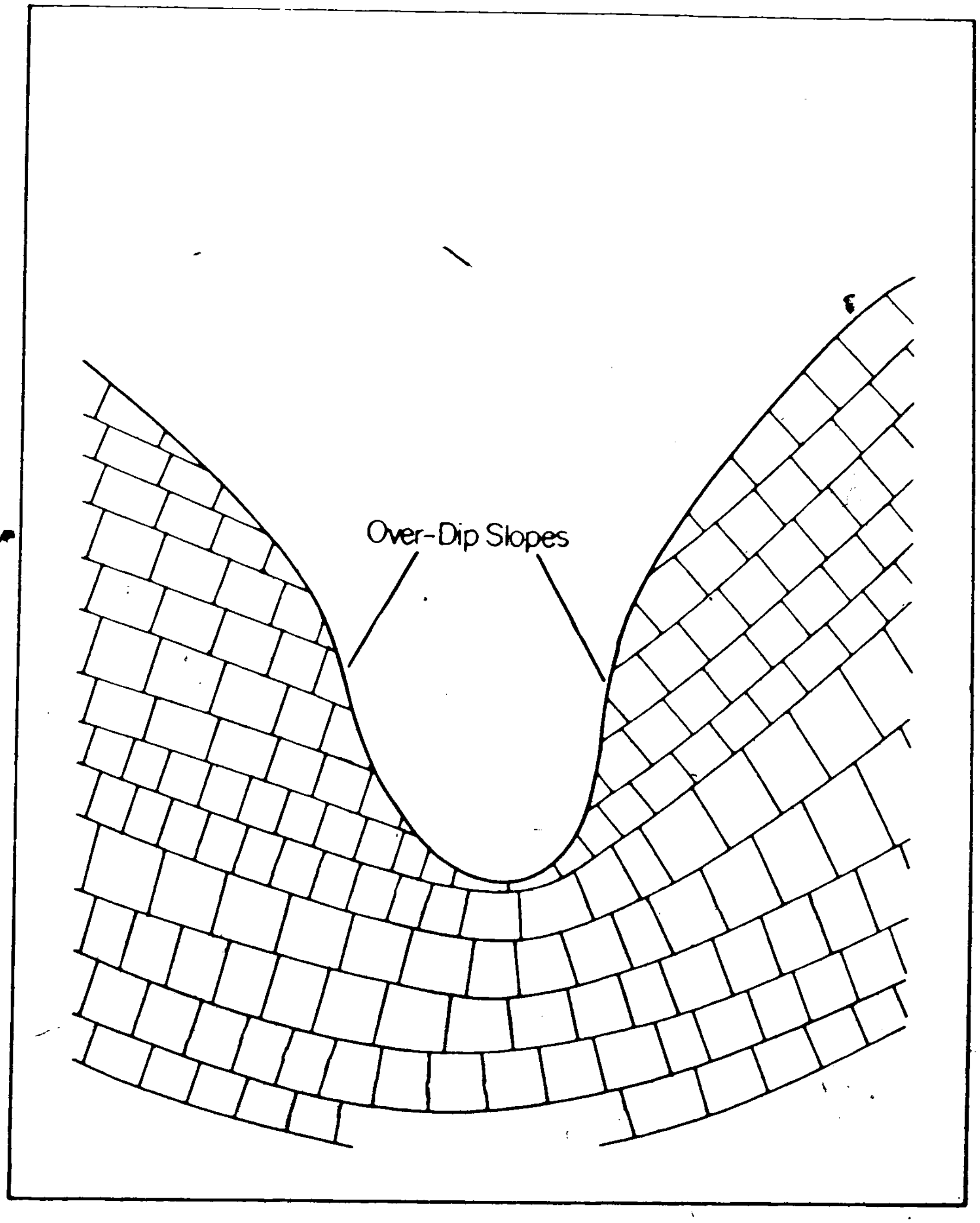


Figure 4.3 A syncline valley can create over-dip slopes on both sides from glacial or fluvial erosion.

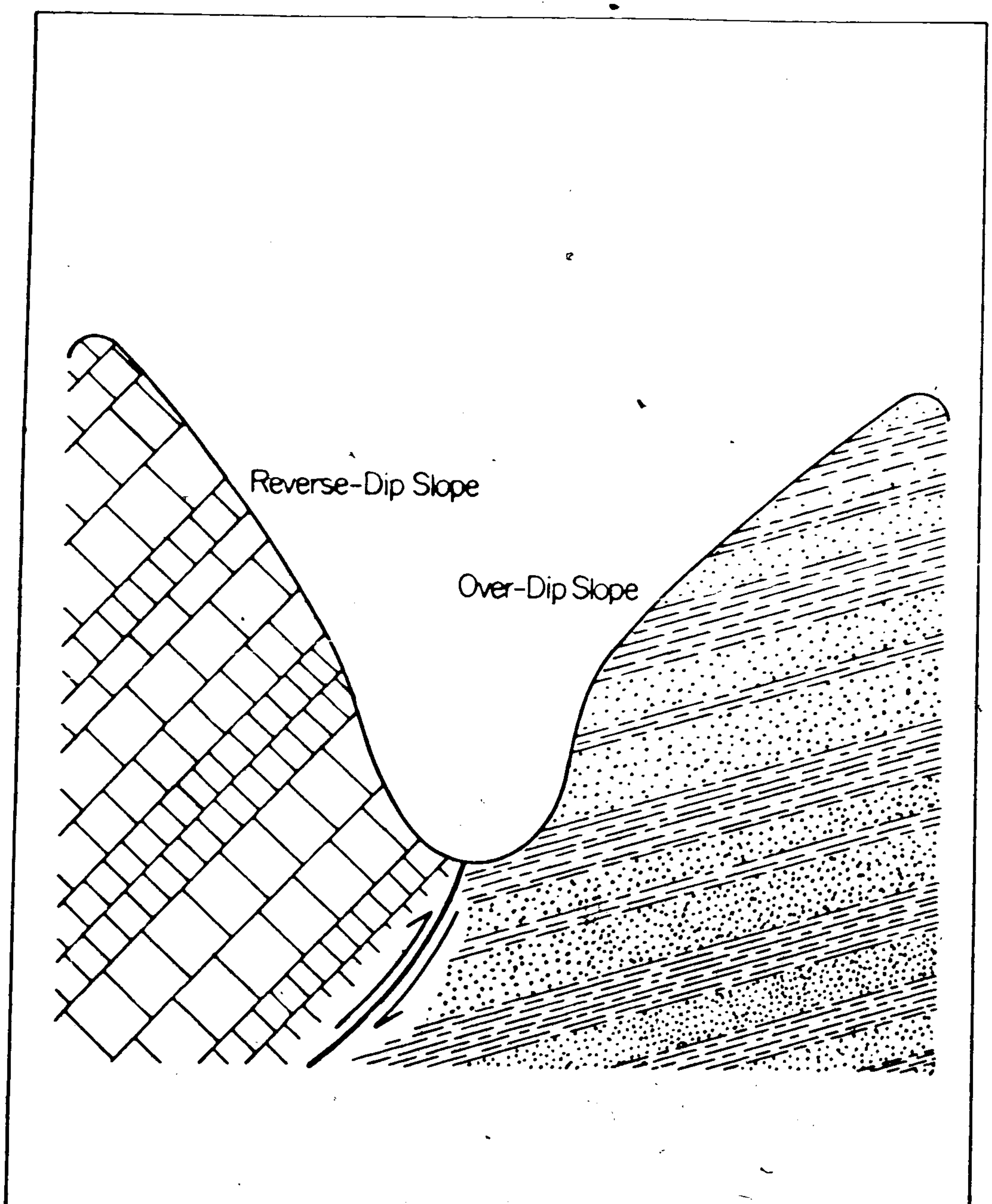


Figure 4.4 A thrust fault valley can create an over-dip slope on one side (the footwall side) from glacial or fluvial erosion.

high-magnitude rockslides and rockfalls or at least one large rockslide in the area under consideration. Low activity describes limited talus deposits, few high-magnitude rockfalls and rockslides and no large rockslides in the area under consideration. Non-active means that talus deposits are too small to be mapped, rockfall and rockslide is infrequent and insignificant.

The study area is arbitrarily divided into 26 sub-areas. Some homogeneity is implied within each sub-area; either a dominant slope type(s), slopes are all part of the same massif, or a conspicuous level of activity within the sub-area. The boundaries between the different sub-areas are not precisely defined but usually follow valley bottom, ridge crest or mountain pass. The Kananaskis study area is dissected in three main mountain ranges by the Kananaskis River Valley and the valley formed by Smith-Dorrien and Smuts Creeks. They are from east to west:

1. The Misty, Opal and Elk Ranges, sub-areas 1-5.
2. The Kananaskis Range, sub-areas 6-14.
3. The Spray Mountains, sub-areas 15-26.

Tables 4.1 and 4.2 reveal the following behaviour, and percentages are of sub-areas showing activity on the air photograph interpretations initially:

1. Low-magnitude and high-magnitude rockfall and rockslide activity is high throughout the study area, 85% and 65%,

Table 4.1 Rockfall and rockslide activity throughout the Kananaskis study area by considering 26 sub-areas.

sub-area	rockfall/slide activity						active slope			
	low-mag.			high-mag.						
Misty, Opal & Elk Ranges:	non	low	hi	non	low	hi	osd	rd	ud	dod
1. Limestone Mtn		x		x			x	x	x	
2. West Opal Ridge site		x				x			x	x
3. Opal Range			x		x		x	x	x	
4. Elk Range			x			x	x	x	x	
5. Misty Range			x			x	x	x	x	x
percentages % :	0	40	60	20	20	60	80	80	100	40
The Kananaskis Ranges:										
6. Mt Allan massif		x			x?		x	x	x	
7. Mt Lougheed massif			x		x		x	x	x	x
8. Mt Sparrowhawk massif			x			x		x		x
9. Quartzite Ridge			x			x				x
10. Mt Kidd massif			x		x		x	x		x
11. Mt Bogart massif			x		x		x	x		x
12. Ribbon Lake			x			x	x	x		x
13. Mts Buller-Inflexible			x			x	x	x		x
14 Mt Lawson-Kent syncline			x			x	x	x	x	x
percentages % :	0	11	89	0	44	56	78	89	33	89

continued on next page...

Table 4.2 Continued from previous page...

sub-area	rockfall/slide activity						active slope			
	low-mag.			high-mag.						
The Spray Mountains:	non	low	hi	non	low	hi	osd	rd	ud	dod
15. Mts Shark-Birdwood			x			x	x	x	x	
16. Burstall Pass			x			x				x
17. Mts Burstall-Putnik			x		x		x	x	x	
18. Black Prince W. slopes		x				x			x	x
19 Murray-Inde. E. cirques			x			x	x	x		x
20. Grassi Lake			x			x	x	x	x	x
21. Mt Inde. West slopes			x			x	x	x		x
22. Three Isle lake			x			x	x	x	x	
23. Mt Lyautey			x		x		x	x	x	
24. Mt Sarrail-Foch massif			x			x	x	x		x
25 Mt Marlborough syncline			x			x	x			x
26. Mangin Glacier			x	x			x	x	x	x
percentages % :	0	25	92	8	17	75	83	75	58	67
total percentages % :	0	15	85	8	27	65	81	81	58	69

? Deposit may be a moraine.

osd = oblique/strike-dip slopes
rd = reverse-dip slopes
ud = under-dip slopes
dod = dip and over-dip slopes
Inde. = Indefatigable

respectively.

2. All slope types are active throughout the study area, 58 to 8'%.
3. Under-dip slopes are not very active in the Kananaskis Range; they are not common.
4. Dip and over-dip slopes, although active in the Misty, Opal and Elk Ranges, are not common.
5. All slope types are active in the Spray Range.

Table 4.3 and Figure 4.5 distribute high-magnitude rockfall and rockslide according to slope type. Figure 4.6 shows the percentage of each slope type in the study area. The relative probability of a rockslide or rockfall according to slope type is shown in Figure 4.7. They reveal the following behaviour:

1. Dip and over-dip slopes have the highest occurrence of high-magnitude rockfall and rockslide, with 35% of all events.
2. Oblique/strike-dip slopes and reverse-dip slopes are active with 29% and 29% of all events, respectively.
3. Under-dip slopes are not very active with 7% and glaciers provide no rockfall or rockslide.
4. 44% of large rockslides occurred from dip and over-dip slopes. Three large rockslides, 19%, appear to be from under-dip slopes. The pre-slide slope profile may actually have been a dip or over-dip slope eroded by glacier ice. Simmons (1977) commented that dip slopes over 50° may fail by rupture across discontinuities. In

Table 4.3 High-magnitude rockfall and rockslide activity according to slope type. Slope types are defined in Section 2.5.

	osd	rd	ud	dod	gla	total
large rockslides #	1	5	3	7	0	16
>.5x10⁶ m³ %	6	31	19	44	0	100
other high-magni #	66	60	13	73	0	212
-tude events %	31	28	6	35	0	100
total #	67	65	16	80	0	228
total %	29	29	7	35	0	100
area km	156	100	102	31	15	404
area %	39	25	25	8	4	100
activity =	0.7	1.2	0.3	4.4	0	1.0

osd = oblique/strike-dip slopes
rd = reverse-dip slopes
ud = under-dip slopes
dod = dip and over-dip slopes
gla = glaciers

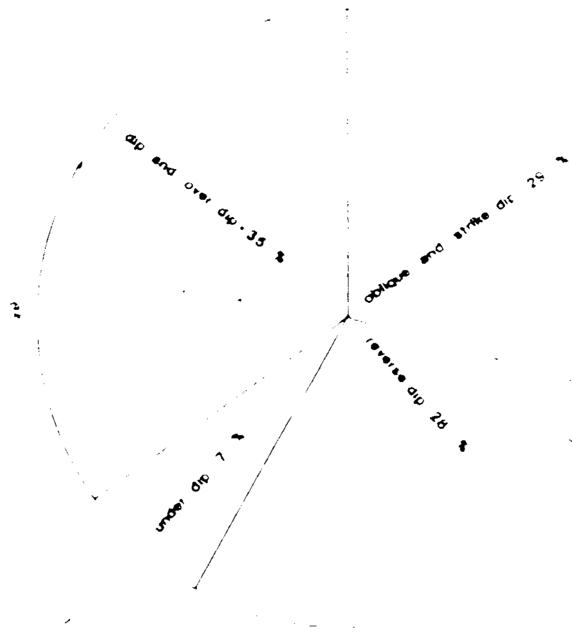


Figure 4.5 Percentage of all high-magnitude rockslide and rockfall according to slope type. Slope types are defined in Section 2.5.

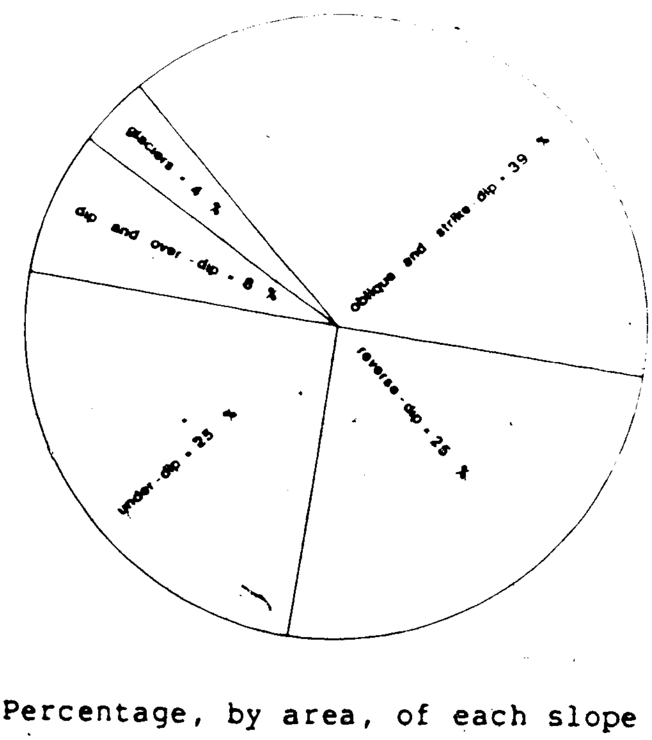


Figure 4.6 Percentage, by area, of each slope type in the study area. Slope types are defined in Section 2.5.

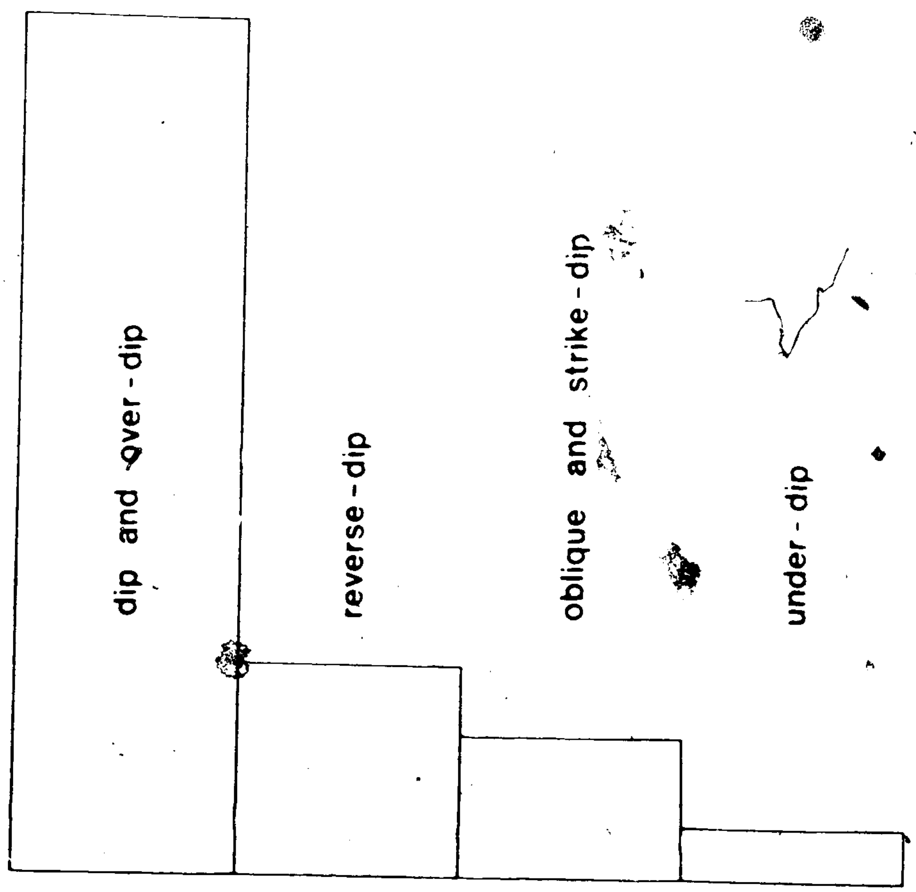


Figure 4.7 Relative probability of a high-magnitude rockslide or rockfall according to slope type in Kananaskis.

that case, 63% of large rockslides may originate on dip and over-dip slopes.

5. Dip and over-dip slopes are not frequent, covering only 8% of the study area.

6. Dip and over-dip slopes exhibit br far the highest relative probability of a rockslide.

In addition the bedrock structural control of valley or slope orientation is reflected in Table 4.3 when considered together with Figures 4.1 and 4.2:

1. Oblique and strike-dip slopes cover 39% of the area yet they occupy 78% (280°) of the aspect range.
2. Reverse-dip slopes cover 25% of the area, yet they occupy only 11% (40°) of the aspect range.
3. Under-dip, dip and over-dip slopes together occupy only 11% (40°) of the aspect range. Yet, under-dip slopes cover 25% of the area and dip and over-dip slopes cover only 8% of the area.
4. This suggests that present and recent geomorphic processes favour under-dip and reverse-dip slopes rather than oblique and strike-dip slopes, or the dip and over-dip slope forms.

In summary all slope types are active in Kananaskis. Low-magnitude and high-magnitude rockfall and rockslide occur throughout the Kananaskis study area. Most high-magnitude rockslides and rockfalls occur on dip and over-dip slopes (rockslides only) followed closely by oblique and strike-dip slopes then reverse-dip slopes (rockslides and rockfalls). Dip and over-dip slopes are not widespread, suggesting that they are unstable because of their geometry. Dip and over-dip slopes exhibit the highest relative probability for rockslides suggesting that thresholds are exceeded as episodic events interspersed with periods of relative stability. The threshold stress is exceeded by: introduction of an external stress; reduction of internal strength; or a gradual change in slope conditions (Selby, 1982).

4.4 Rock Type Activity

Rock types are taken from the map compiled by Bielenstein et al. (1971). There is no detailed stratigraphy available for Kananaskis; further subdivision into formations is beyond the scope of this report and would necessitate additional field reconnaissance. The oldest rock type found in the area, the Devonian Fairholme Group is about 365 million years old. There are two basic rock types, clastic rocks and carbonate rocks. The older or Paleozoic rocks are mainly carbonates (limestone and dolomite). The younger or Mesozoic rocks are mainly clastic rocks (shale, sandstone, siltstone, conglomerate, quartzite and coal). The division is not exclusive and beds of one rock type can be found in the other, especially in the boundary rocks, the Triassic Sulphur Mountain Formation and the Permo-Pennsylvanian Rocky Mountain Group. The rock types are closely-jointed with the exception of conglomerates observed in the Cretaceous Blairmore Group. The carbonate groups are very closely jointed. The carbonate groups are also a more resistant rock as they dominate the mountain peaks, ridges and scarps. The younger detrital rocks are less resistant to weathering as they occupy the mountain passes and gentler slopes. On the whole their features are more subdued.

Locat and Cruden (1977) found that major bedding plane slides occur in carbonates of the Mississippian Rundle Group. They went on to suggest that the base of the lower Rundle Group appears to be the location of major rockslides in the Paleozoic rocks of the southern Canadian Rockies, and that debris flows will occur in shale or thinly bedded sandstone and shale.

Debris flows and rock glaciers are noted in the Kananaskis study area. Rock glaciers occur in the Triassic Sulphur Mountain Formation, shales and carbonates, in the Highwood Pass area on slopes adjacent to Highway 40 and in the unnamed valley due south of Quartzite Ridge (northing = 5640000 metres, easting = 620000 metres). Gardner (1982) documented debris flows in the vicinity of Mount Elpoca. Debris flow activity is noted in King Creek and South Sparrowhawk Creek and occurs in Jurassic Fernie Group, Triassic Sulphur Mountain Formation and Permo-Pennsylvanian Rocky Mountain Group rocks. They may occur in these rock types elsewhere in the study area for they were only considered where they occur in specific or other appropriate sites discussed by Cruden and Eaton (1985b).

From Tables 4.1 and 4.2 we saw that low-magnitude rockfall and rockslide is widespread in Kananaskis, 85% of 26 sub-areas exhibit high activity. It is reasonable to infer that Tables 4.1 and 4.2 suggest all rock types are active with respect to low-magnitude rockfall and rockslide. The Mount Allan massif and portions of the Misty, Opal and Elk Ranges are exceptions and exhibit low activity amongst the Mesozoic rocks.

Table 4.4 and Figure 4.8 distribute high-magnitude rockfall and rockslide according to rock type. Figure 4.9 shows the percentage of each rock type in the study area. Figure 4.10 shows the relative probability of a high-magnitude rockslide or rockfall according to rock type. They reveal the following behaviour:

1. Almost all of the high-magnitude events, including large rockslides, occur in Paleozoic carbonates, 97% and 94% respectively. (The one large rockslide mapped in the Cretaceous Blairmore Group has subdued features, developed surface drainage and would receive an 'inactive-mature' age classification according to McCalpin (1984). It may actually be a moraine).
2. Large rockslides and other high-magnitude events are most frequent in the Mississippian Rundle Group, 56% and 44% respectively.
3. The Devonian Palliser Formation has the highest activity level, 1.9, followed by the Permo-Pennsylvanian Rocky Mountain Group, with 1.6. The Mississippian Rundle Group

Table 4.4 High-magnitude rockfall and rockslide activity according to rock type. Rock type symbols are explained in Table 2.1.

	MESOZOIC				PALEOZOIC					
	Kbl	Jk	Jf	TRs	Prm	Mr	Mb	Dp	Df	tot
large rockslides #	1	0	0	0	1	9	0	4	1	16
>.5x10⁶ m³ %	6	0	0	0	6	56	0	25	6	100
other high-magni- #	0	3	0	2	39	93	10	49	16	212
-tude events %	0	1	0	1	18	44	5	23	8	100
total #	1	3	0	2	40	102	10	53	17	228
%	0	1	0	1	18	45	4	23	8	100
area km	5	36	5	21	40	158	37	47	28	377
%	1	10	1	6	11	42	10	12	7	100
activity =	0	0.1	0	0.2	1.6	1.1	0.4	1.9	1	1.0

94% of large rockslides are Paleozoic.
98% of other high-magnitude events are Paleozoic.
Rock type abbreviations are explained in Table 2.1.
tot = total

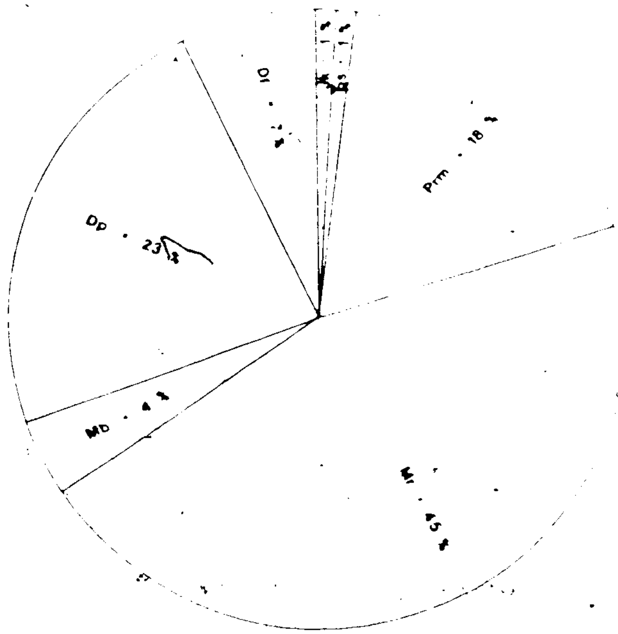


Figure 4.8 Percentage of all high-magnitude rockslide and rockfall according to rock type. Symbols are explained in Table 2.1

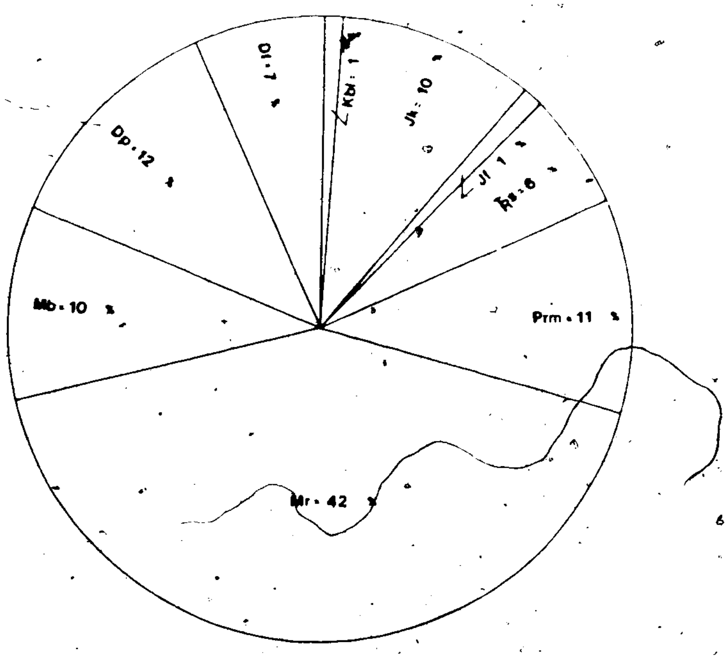


Figure 4.9 Percentage, by area, of each rock type in the study area. Symbols are explained in Table 2.1.

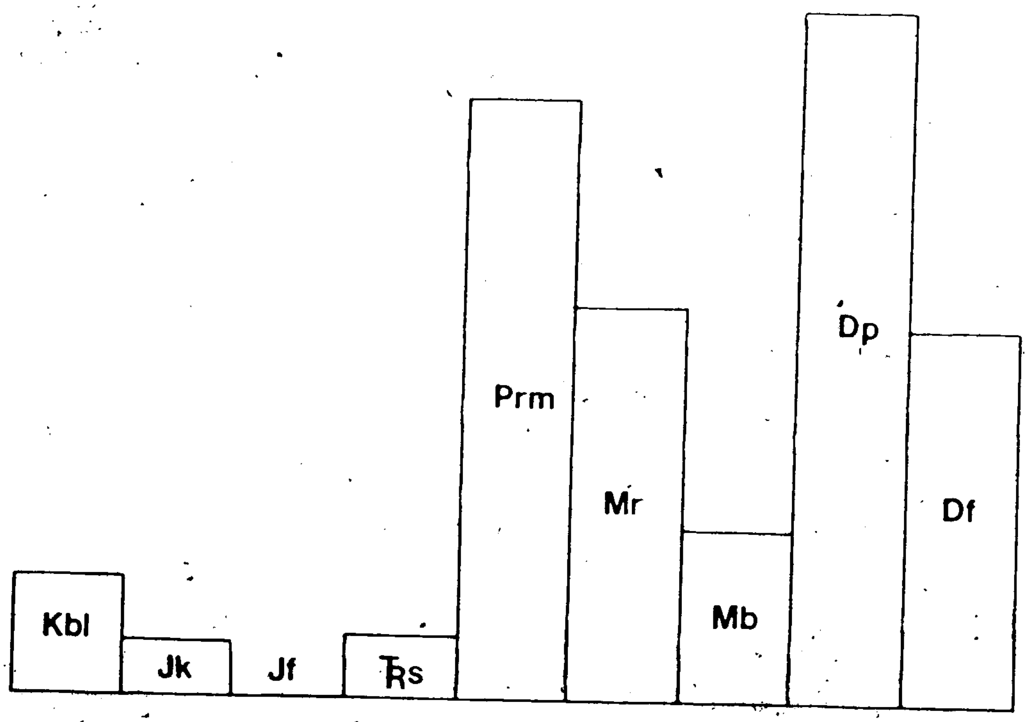


Figure 4.10 Relative probability of a high-magnitude rockslide or rockfall according to rock type.

is third with an activity level of only 1.1.

This should be qualified by adding that high-magnitude rockfall and rockslide occur in clusters in several of the sub-areas used in Tables 4.1 and 4.2. Table 4.5 lists the cluster areas, air photograph locations, active slope types, active rock types, number of high-magnitude events and dips of the rupture surfaces. Table 4.5 reveals the following behaviour:

1. All the carbonate rock types, with the exception of the Mississippian Banff Formation exhibit cluster activity.
2. More of the activity, 89%, has occurred from dip and over-dip slopes.
3. None of the cluster areas have dips below 25°.

In Table 4.6 a distribution of high-magnitude rockslide and rockfall is given with respect to all the combinations of slope type and rock type. The activity is given for each combination. The Mesozoic rock types are not included in this breakdown since they exhibit a low activity (Table 4.4) which is attributable to their being highly weathered with subdued features and gentler slopes. In addition the Cretaceous Blairmore Group, Jurassic Fernie Group and Triassic Sulphur Mountain Formation have small sample areas, 1%, 1% and 6%, respectively. The Jurassic Fernie Group lacks high-magnitude rockfall and rockslide deposits and the four deposits found in the Cretaceous Blairmore Group and Jurassic/Cretaceous Kootenay Formation are highly weathered, possibly of late Pleistocene age (over 10,000 years B.P.).

Table 4.5 High-magnitude rockfall and rockslide cluster area activity.

cluster areas	air photograph line & photo #	active slope type	active rock	# falls /slides	rupture surface
Sparrowhawk R.	5040 204, 206	over-dip	Mr	5*	25-30
Quartzite R.	5040 204	over-dip	Prm	7	25-30
Ribbon Lake	5037 157	over-dip	Prm	6	25-30
Mt Lawson-Kent syncline	5033 109	over-dip	Prm	11	>40
Mt Shark	5035 199 5036 5	reverse-d.	Dp Df	9	>60
Burstall Pass	5032 53 5033 101	over-dip	Dp	13	>40
Mt BlackPrince west slopes	5031 8	over-dip	Mr	6	>45
Mt Sarrail	5025 215	over-dip	Mr	11	25-30
Mt Marlborough syncline	5024 162	over-dip	Mr	8?	>40

* The large rockslide may represent 4 high-magnitude rockslides.
? The large rockslide contains at least 2 large events.

Note: Although a large rockslide may actually contain more than one single event, when they are defined by a contiguous boundary they have been counted as one event only.

Note: Rock type abbreviations are explained in Table 2.1.

Therefore with the Mesozoic rocks removed activity levels in Table 4.6 will not be identical to those in Tables 4.3 and 4.4 although similar. Table 4.6 reveals the following behaviour:

1. All of the rock types possess at least two of the slope types; oblique/strike-dip, reverse-dip or dip and over-dip slopes, which are favourable to high magnitude rockfall and rockslide.
2. Dip and over-dip slopes exhibit the highest activities with the exception of the Devonian Fairholme Group which possesses no dip or over-dip slopes for activity to occur on.
3. The Mississippian Banff Formation has the lowest activity at 0.4.
4. The Devonian Palliser Formation and the Permo-Pennsylvanian Rocky Mountain Group exhibit the highest activities (as in Table 6.4) at 1.7 and 1.4, respectively.

Dip and over-dip slopes are preferred locations for high-magnitude rockslides. Many of these slopes exhibit cluster activity. Dip and over-dip slopes appear to be unstable slope forms that adjust episodically by high-magnitude events. The structural features of over-dip slopes are favourable for the release of rock along bedding plane discontinuities. All the over-dip slopes that exhibit cluster activity have beds that dip at or exceed 25° and half of those (4) have beds that exceed 45°. The cluster

Table 4.6 High-magnitude rockfall and rockslide activity given with reference to slope and rock type.

rock type		slope type				
		osd	rd	ud	dod	total
Prm	% slides/falls	3.2	4.5	1.8	8.6	18
	% area	3.8	1.6	6.0	1.6	13
	activity	0.8	2.8	0.3	5.7	1.4
Mr	% slides/falls	18	9.0	3.2	16	46
	% area	21	10	13	5.4	49
	activity	0.9	0.9	0.2	3.0	0.9
Mb	% slides/falls	3.2	0.5	0.0	0.9	4.6
	% area	4.9	4.4	0.7	0.6	11
	activity	0.6	0.1	0.0	1.5	0.4
Dp	% slides/falls	5.4	9.0	2.3	7.2	24
	% area	3.8	5.5	2.8	1.9	14
	activity	1.4	1.6	0.8	3.8	1.7
Df	% slides/falls	2.3	5.4	0.0	0.0	7.7
	% area	4.6	2.9	1.3	0.0	8.8
	activity	0.5	1.9	0.0	0.0	0.9
total	% slides/falls	32	28	7.0	33	/
	% area	38	25	24	9.0	/
	activity	0.8	1.1	0.3	3.7	/

Glaciers cover 4% of the area, and have 0.0 activity.
Slope type abbreviations are explained in Table 4.3.
Rock type abbreviations are explained in Table 2.1.

activity exhibited on Mount Shark reverse-dip slopes is attributable to tear faults and local drag folds producing a weakened structure in the slopes. One or more of either thrust faults, synclines, anticlines, tear faults and drag folds are present at all of the sites examined. Activity is apparently increased by these features.

In summary, low-magnitude rockfall and rockslide occurs in all rock types but Paleozoic carbonates are the most active. High-magnitude rockfall and rockslide occurs almost exclusively in Paleozoic carbonate rock types. This is, in part, due to highly weathered, subdued features and gentler slopes in Mesozoic clastic rocks. Although high-magnitude rockslides have occurred in the Mississippian Rundle Group elsewhere in the Canadian Rockies, the inference that it is the locus of such activity or 'a bad actor' may be misleading. Findings of this study suggest that the Permo-Pennsylvanian Rocky Mountain Group and the Devonian Palliser Formation are the most active rock types in Kananaskis. A greater number of low and high-magnitude rockfalls and rockslides occur in the Mississippian Rundle Group only because it covers a larger land area and possesses the greatest relief. Where other Paleozoic carbonate rock types occupy scarp slopes and over-dip slopes low and high-magnitude rockfall and rockslide occurs. The Mississippian Banff Formation is the quiet exception to this behaviour. It seems then that rock structure or slope type has a greater influence on the level of activity. When cluster areas of high-magnitude rockfall and rockslide were considered, over-dip slopes were by far the dominant factor while rock types participated with nearly equal frequency. Other important factors are features which contort and weaken the structure on a local scale such as faults and folds. Flexural-slip along bedding contacts is pervasive at these sites butit was not always possible to document it in the field.

5.0 Friction Angles of Rock Samples

5.1 Introduction

This testing program investigates the basic friction angle, ϕ_b, of limestones from Kananaskis Country using a tilting table constructed at the University of Alberta. ϕ_b is defined as the friction angle of a sawn rock surface lapped with #80 grit (Coulson, 1972). The preparation of samples and testing procedure is outlined for future reference. Previous descriptions of tilting tables (Bruce 1978, Cawsey and Farrar 1976) have provided only results of tests and little information about the sample preparation and testing procedure.

5.2 Tilting Table Test History

Hoek and Bray (1974, p. 149) suggested that the angle of friction could be obtained by a simple tilt test [illegible] clearly defined failure surface existed. Hoek and Bray (1981, p. 100) recommended that tilting tests for the basic friction angle were unreliable because of the influence of very small scale surface roughness.

Cawsey and Farrar (1976) used a tilting table to measure the statical friction angle of naturally rough surfaces of soft Upper Chalk. They argued that the direct shear box created uneven stress distributions and the confinement of the sample prevented any rotations in the failure plane. As well, their apparatus could accommodate large size specimens. Hencher (1976), in a discussion of their paper summarized some advantages:

1. Observation of the mode of failure is easier than it is in an enclosed shear box.
2. Failure is due to gravity as it is in the field.
3. Sliding may be repeated several times to give much greater displacements than are generally practicable using a simple shear test.
4. The effect of block geometry and distribution of load may be analyzed and tests designed towards this field of research.
5. Testing procedure is simple.

Limitations of the test are as follows:

1. The applied loads are due to the weight of the upper block which puts practical restriction on the range of loads possible.
2. The test involves sudden sliding of the block; displacement cannot be controlled with the apparatus in its present form.
3. The stress distribution along the contact between the slider and plate is uneven, once the plane of contact is other than horizontal. The steeper the inclination of this plane the greater the stresses in the leading edge contact area. When the slider is about to topple the stresses along the leading edge are high.

Barton and Choubey (1977) used a tilting table to estimate the residual friction angle, ϕ_r, on flat, sawn rock surfaces. They suggested that this test yielded the residual friction angle of the sample because for all practical purposes, the surfaces were non-dilatant. They found that tests on rough, natural discontinuities caused toppling of the upper block from the lower block because of the interlocking of asperities.

Bruce (1978) used a tilting table to evaluate the mineralogic and basic friction angles of a quartzite and a dolomite. Sawn surfaces lapped with #80 grit best represented the basic friction angle, ϕ_b, and surfaces lapped with #600 grit and polished with tin oxide on a vibrating table approached the mineralogic friction angle, ϕ_m. He measured the asperities, i, of unpolished surfaces and found that $\phi_b = \phi_m + i$.

So, the tilting test is accepted as a means of determining the basic friction angle of hard rocks. But, as with the direct shear box, there are problems associated with stress distribution and mode of failure. It is however a quick and easy test to perform. Naturally rough surfaces are not suitable for tilting tests because of the natural asperities interlocking, resulting in toppling rather than sliding.

5.3 Sample Collection and Preparation

Samples were obtained in Kananaskis Country during the summers of 1984 and 1985 at sites of rockslides of interest during a reconnaissance of rockslide hazards. Samples were taken from talus, rockslide debris and bedrock itself, where removal of suitable samples was safe and possible. Samples were tested from the following sites in Kananaskis:

Mount Indefatigable

Mount Sparrowhawk

Burstall Pass

Quartzite Ridge

Field samples had to be large enough so that prepared samples of 5 x 5 x 2 cm could be cut from them. Substantially larger samples, at least 15 x 15 x10 cm, were collected as field samples sometimes broke unexpectedly during transportation or preparation because of discontinuities through the rock that were not visible on exposed surfaces. The maximum size collected was limited by what could be carried in a backpack while hiking over steep and irregular terrain. Access was more often than not along sometimes indistinct game trails more suited to those with locomotion on four limbs rather than two.

It was hoped that samples could be collected from rupture surfaces. This proved difficult to do. In most cases, sampling of the upper surface was not possible because of talus cover and hazard from rockfall. At the Opal Range site, samples of sufficient size could not be obtained because the rock was a soft and heavily fractured argillaceous limestone in drag folds adjacent to a fault zone. It was difficult to extract a sample with hand tools from some rupture surfaces. Most samples were acquired from the stepped surfaces of over-dip and dip slopes or the loose rock fragments on or below them.

Samples were cut in the laboratory with a 60 cm diameter, self-advancing, diamond tipped, water lubricated saw. With practice, samples were cut to orthogonal dimensions of 5 x 5 x 2 cm. Samples weighed between 170 and 200 gm. A smaller saw, hand controlled, was used for delicate final cuts. Examination of fresh cut surfaces showed no distinctions between cuts parallel to bedding and cuts orthogonal or oblique to it in most of the limestone and dolomite. If a change in lithology was noted, the sample was discarded or cut in a new direction. Some variation in grain size was visible in one quartzite sample but this horizon was irregular. Coulson (1972) made no reference to orientation of the artificial surface with respect to bedding so this was not considered further.

A lapping table was used to finish the saw-cut surfaces. The table was levelled before use. The rotating circular table with raised sides has three rings(3 cm lengths of 20 cm diameter steel pipe) on it held in place by overhead guides. One sample is placed inside each ring. The table rotates and the samples spin around within the rings. The rings distribute the grit evenly over the table, spin and contain the samples. There are grooves in the base of each ring which distribute the grit. With usage, the base of the ring will wear and the grooves disappear. If so, they can be renewed with a grinding tool or file. Dry or wet lapping can be performed.

Too little grit does not cover the table and too much piles up against the outside wall when dry lapping. The grit has to be changed when rock dust reduces the effectiveness of the grit. The table was vacuumed clean and new grit used after every three hours of dry lapping. Samples were lapped 45 to 90 minutes depending on the flatness and hardness of the sawn surfaces.

When wet lapping, the quantity of grit is not so critical as the water aids grit distribution. Lapping times could also be increased before a grit change. The same grit was not used for periods exceeding six hours as water holds the rock dust in suspension. Water evaporates during lapping and if water content drops too low a thick mud can develop. Low water content also creates excessive resistance for the electric motor drive.

Because of discontinuities in the rock samples, the hardness of the rock and agitation during lapping, all samples were wrapped with fiberglass tape to prevent them from breaking apart or chipping corners while spinning on the lapping table.

Lapping samples were examined for flatness. Each sample was held up to a strong light source and a straight edge placed diagonally across the surface from corner to corner. High and low spots were found in this way and the sample relapped if necessary.

Lapping with #80 grit did not produce the same surface roughness in all samples. Six different samples were examined using a Talysurf roughness measuring device before testing. Twelve profiles were obtained from each sample; 3 pairs in the X (sliding) direction and 3 pairs in the Y direction. There did not appear to be any difference between X and Y, which is reassuring with respect to the lapping table, so the twelve profiles were averaged together.

Dry lapped samples all possessed a film of rock dust that clung to the surface despite cleaning with compressed air. Wet lapped samples were washed with tap water and then blown dry. No rock dust could be seen on their surfaces with a 10X hand lens after cleaning. The collection site, rock type, mode of preparation (wet or dry lapping), sliding direction and use as slider or plate were recorded for each sample.

5.4 The Tilting Table

A tilting table designed by the author and built by the Department of Civil Engineering Workshop at the University of Alberta was used for testing rock specimens. The tilting table is illustrated in Figure 5.1.

A rigid frame supports a hinged table and electric motor drive assembly. The drive assembly rotates a drum which has a wire cable attached to the hinged tilting table. A second wire cable is attached to the drum in the opposite direction, connected to a counterweight at the other end,

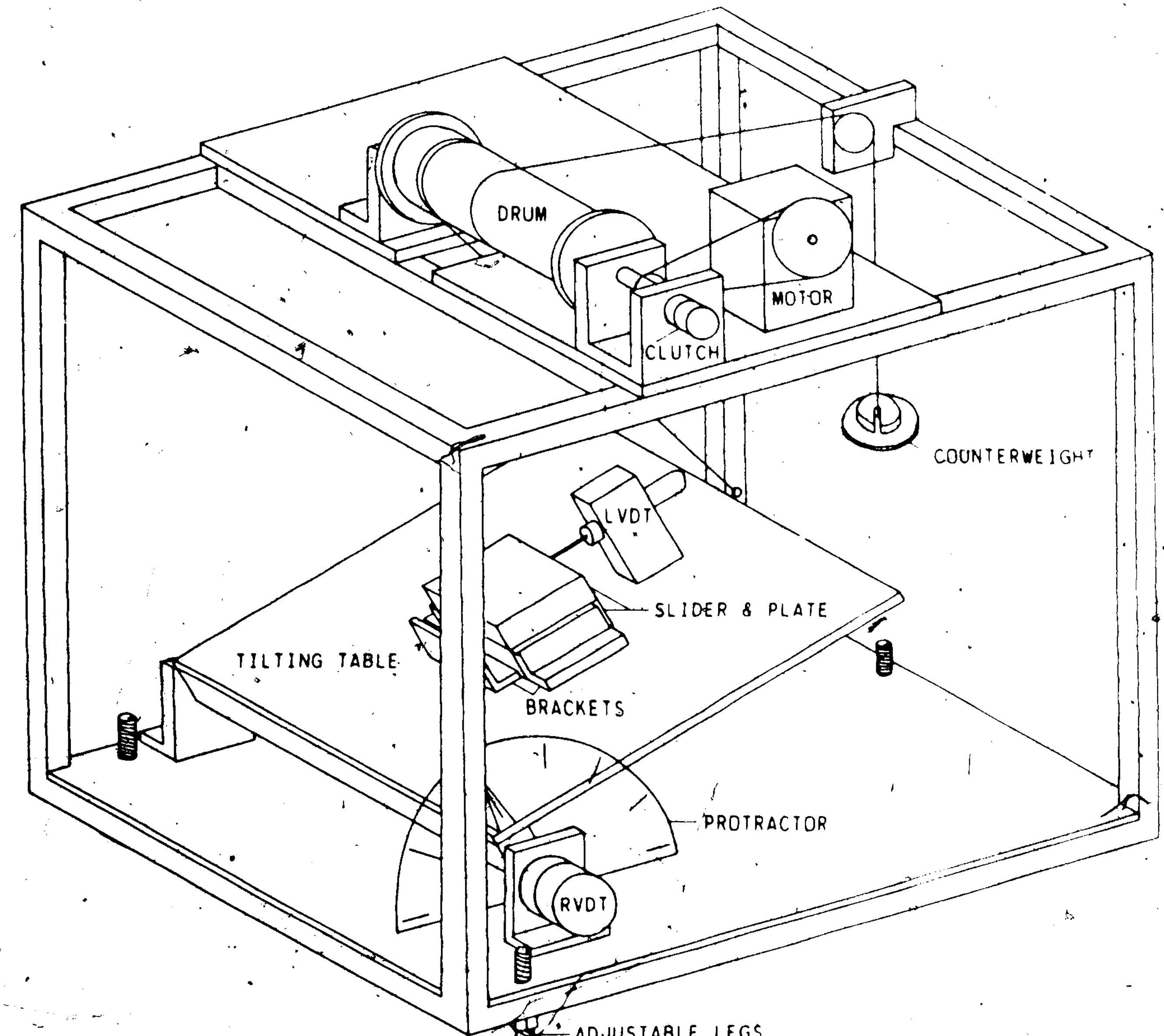


Figure 5.1 Isometric view of the tilting table.

and assists the electric motor drive in tilting the table. The electric motor without the counterweight cannot raise the table when the 5:1 gear ratio or large samples are used. The counterweight can be changed depending on the size of sample being tested. The hinged table is equipped with brackets to hold samples from 5 x 5 cm to 15 x 15 cm. Sample thickness from 15 to 35 mm is accepted unless sliding displacements are not desired then a thicker sample can be used. Geometry of the sample and strength of the drive-tilt assembly will place practical restrictions on the thickness allowed. The plate sample is mounted in the brackets and the slider sample placed on top of it. The lower bracket stops the slider after 2 cm of movement. A linear voltage displacement transducer (LVDT) is mounted on the table behind the samples. A teflon pad on the LVDT shaft is glued to the slider to monitor displacements. The LVDT can be raised or lowered and moved ahead or back to accommodate the size of the sample.

Without samples in place on the table, the rod and teflon pad of the LVDT slides between 25° to 27°. The shaft and pad weighed 4.61 gm and was glued to the slider specimen when used to monitor displacement. The plate specimen was positioned and the slider placed on top. A drop of glue was placed on the back of the slider where the teflon pad would come to rest. The teflon pad and rod were then brought up against the slider. Testing could begin in a few minutes once the glue had set. There is enough free play between the rod and LVDT shaft so as not to bind during sliding.

A rotary voltage displacement transducer (RVDT) and a protractor are mounted on the end of the hinge of the tilting table. The protractor, with divisions to 0.5°, provides quick visual reference while the RVDT transmits changes in rotation potential to the X-Y recorder or datalogger. Two condensors are soldered to the terminals of the RVDT. The solders could be broken altering the output from the RVDT. The LVDT and RVDT were calibrated. Both are linear. The LVDT's calibration is 4.206 mm per volt and the RVDT's calibration is 6.329 degrees per volt.

The table rotates from 0° to 52° with the present mounting of the drive and drum assembly. This range could be altered if desired. The present setting should be suitable for testing all #80 grit prepared surfaces. The rotation rate is adjustable by changing the gear ratio of the drive system. A clutch mounted on the drum shaft allows the electric drive to be disengaged and the drum raised by hand rotation, or with the motor still running the table can be lowered and a another test begun. Wing nuts on the threaded studs of the electric motor enabled the drive chain to be removed quickly to change gear ratios.

The tilting table rests on three adjustable threaded legs. These are used to level the top of the plate specimen when 0° is indicated on the protractor. A fish-eye level mounted on the rigid frame indicates the adjustment required to level the apparatus but a small line level must be placed on the top of the plate specimen to level it.

5.5 Test Procedure

When the samples are clean and the sliding direction of the slider and plate are indicated the plate is mounted on the tilting table by either clamping with the side brackets or resting the leading edge against the bottom or lower bracket. The author found it convenient to allow samples to rest against the lower bracket. If the sawn surfaces are not flat, or cut parallel, the slide surface of the plate may not be parallel to its base. If the plate then rocks on an uneven base surface, it can be clamped with the side brackets. Alternatively, the plate can be rested against the lower bracket and shims of paper placed under the corners until rocking is eliminated.

Once the plate no longer rocks, the top of the plate (slide surface) is levelled by adjusting the three threaded legs. The line level is used to level the slide surface in the slide direction and 90° to it. This levelling is repeated for each new slider and plate. Tension in the drive system and the cable eliminates slack when levelling the slide surface.

When using the X-Y plotter it may be necessary to recalibrate the plotter or rotate the RVDT about its axis to bring the voltage into range. Scales of 1 cm = 0.5° on the X axis and 1 cm = 0.1 mm on the Y axis gave up to 10 plots on one graph, or a full set of repeated tests. The plotter was not started until 5° before expected acceleration of the slider down the plate. Displacement occurs before this but the slope of the line is indiscernible so this quantity is considered negligible.

A datalogger recorded rotation and pre-slide displacement in the form of digital output in millivolts on a paper roll. A logging interval of 30 seconds was used. When the expected failure range was approached the interval was increased to five seconds or continuous output. The digital output from the datalogger is not as easy to visualize as is the output from the plotter.

Tests were performed at two rates. A 5:4 gear ratio provided rotation at 2.5° per minute. A 5:1 gear ratio provided rotation at 8° per minute. Hand rotation was also used with a rate of about 8° per minute. A test using the 5:4 gear ratio and monitoring equipment took about 12 minutes including resetting the apparatus and instrumentation. Quick tests using the 5:1 gear ratio or hand rotation without monitoring took less than two minutes.

Repeated tests were performed with slider and plate specimens always oriented in the same way. Air pressure was provided by a regulator set at 965 kPa. Air was expelled through a wide rimmed orifice which could be brought about 1 mm from the rock surface until air pressure held the nozzle away when using gentle hand pressure. The rock surface was then blown clean with steady, short strokes.

The tilting table was located in a room without any vibrating equipment or atmospheric control. The effect of vibrations from the electric motor drive and the driving effect of the teflon pad and rod of the LVDT remained to be evaluated.

Each test is an average of 8 or 7 tilts of the specimens. Eight tilts were run for repeated cleaned samples and 10 tilts were run for repeated uncleaned samples. More tilts were performed with the uncleaned samples as the first three tilts reflected some influence of the previous cleaning. Uncleaned tests were performed right after cleaned tests with the same specimens.

5.6 Test Results

The frictional resistance of rocks collected from Kananaskis Country has been investigated using a tilting table. The test procedure involves tilting two rock specimens until the top one, the slider, slides off of the bottom one, the plate. The angle of rotation is recorded at the point of sliding.

Fourteen of the samples are limestone but two quartzite and one dolomite were tested as well. The limestones vary in lithology from calcite crystals to coarse grained fossiliferous limestone and fine-grained limestone. Descriptions are from visual examination using simple aids such as a hand lens, a penknife and 10% HCl. The grains referred to are various fossil remains, limestone and lime-mud particles. When the adjective fossiliferous is added, it implies that distinct fossil structures can be discerned, such as crinoid segments, or other shell and coral fragments. Classification is based on textural features and particle size. Geologists have several different approaches to classification of carbonate rock. Classification can be based on (Ham, 1962):

-particle size

-particle origin

-textural features

-mineralogy

-energy levels (hydraulic, biologic and biochemical conditions)

-depositional fabric

-sorting

-pore space

-major role played by organisms

-skeletal vs. nonskeletal elements

All of the samples tested are from the Mississipian Rundle Group and Devonian Palliser Formation with the exception of the quartzite which is from the Permo-Pennsylvanian Rocky Mountain Group.

Table 5.1 shows a comparison of tests run by motor at two rates of 2.5° and 8° per minute, and tests by hand at a rate of about 8° per minute, respectively. All data is from repeated uncleaned tests. In the first six rows samples tested by motor at 2.5° and 8° per minute displayed little

Table 5.1 Comparison of tests run by motor at two different rates and by hand.

SITE	ROCK TYPE	ROTATION BY MOTOR		BY HAND	DIF.
		2.5/min.	8/min.	8/min.	
B.P.	f-mg lst	31.0+0.9	29.2+1.1	30.2+0.7	+1.0
B.P.	f-mg lst	35.6+1.2	32.8+1.5	34.0+1.3	+1.2
B.P.	f-mg lst	30.7+1.1	29.2+1.1	30.4+0.8	+1.2
Q.R.	mg quartzite	16.4+0.8	19.6+0.4	22.2+1.1	+2.6
Spar.	f-mg lst	29.2+0.7	28.9+0.8	28.8+1.2	-0.1
Spar.	fg dol	25.6+1.0	26.9+0.4	26.6+0.9	-0.3
				aver. dif.	+0.9
B.P.	f-mg lst	32.5+1.0		33.7+1.3	+1.2
B.P.	f-mg lst	38.4+0.8		39.4+1.7	+1.0
B.P.	cg fos lst	37.0+0.6		36.8+1.0	-0.2
Inde.	fg dolc lst	22.3+0.5		24.5+0.7	+2.2
Q.R.	mg quartzite	22.6+0.5		24.4+0.7	+1.8
				aver. dif.	+1.2

All tests are repeated uncleaned.
DIF. = Difference between sliding angles.
B.P. = Burstall Pass, Inde. = Mount Indefatigable
Q.R. = Quartzite Ridge, Spar. = Mount Sparrowhawk
fg = fine grained, mg = medium grained, cg = coarse grained
fos = fossiliferous, dolc = dolomitic, lst = limestone

difference. Samples tested at 2.5° per minute have an average increase of 0.3° over the results at 8° per minute. Four showed decreases while two showed increases from the 2.5° to the 8° rates. It appears that there is little difference achieved by the two rates used. The samples tested at 8° per minute by hand and by motor displayed an average increase of 0.9° from motor to hand tilts. In the bottom 5 rows, samples tested at 2.5° per minute by motor and 8° per minute by hand also displayed an average increase of 1.2° from motor to hand tilts. It appears that vibrations from the electric motor depress the sliding angle by about 1°.

The amount of displacement before acceleration of the slider down the plate is greater with dry lapped samples (Table 5.2). Powder on the slide surface distributes the shear forces across a wider shear zone. More powder accumulates on the slide surface from repeated slides and decreases the friction angle to a lower value. This additional quantity has the same effect on wet lapped, washed samples with no visible film as they also decrease in friction angle with repeated uncleaned slides although they do not displace as much as the dry lapped samples before acceleration. The film of powder on the lapped surfaces behaves as a plastic soil that will creep before sliding.

Repeated tests comparing cleaned and uncleaned slider and plate specimens were made. In 14 out of 16 comparisons of pairs of test sets, the cleaned surfaces displayed the

Table 5.2 Comparison of preslide displacements for wet and dry lapped samples.

ROCK TYPE	TEST TYPE	PRESLIDE DSPL.
cg fos lst	wet, uncleaned	0.077 (mm)
mg quarzite	wet, uncleaned	0.005
f-mg lst	wet, uncleaned	0.063
f-mg lst	wet, uncleaned	0.045
f-mg lst	wet, cleaned	0.074
f-mg lst	dry, uncleaned	0.150
f-mg lst	dry, uncleaned	0.123
f-mg lst	dry, cleaned	0.342

DSPL. = displacement
fg = fine grained, mg = medium grained, cg = coarse grained
fos = fossiliferous, dolc = dolomitic, lst = limestone

higher sliding angle (Table 5.3). The two pairs of test sets that displayed the opposite behaviour were from the same sample but a retest of one pair fell in the majority group. The average standard deviation of all test sets was ±1.0° with an individual high of ±1.9° and a low of ±0.4°. The first three slides in the sets of repeated uncleaned slides were not included in any calculated averages of sliding angle as they appeared to display some influence of previous cleaning (ie. the angle was still decreasing). This was arbitrarily selected from visual inspection of the data. The average decrease is 2.8°.

The decrease in friction angle from cleaned tests to uncleaned tests is attributed to powder lubricating the slide surfaces and filling in low points to provide a smoother surface. Grouping the data in sites suggests that Devonian carbonates from Burstall Pass may have a higher friction angle than Mississipian carbonates from Mounts Indefatigable and Sparrowhawk. Permo-Pennsylvanian quartzite from Quartzite Ridge is not considered here, being of different mineralogic composition. The author noted in the field that samples were much harder to extract from bedrock at Burstall Pass. Striking the rock with a geologist's hammer resulted in a resounding ring and little damage to the rock. The older Devonian samples may have a higher friction angle because they are harder than the younger Mississipian samples.

Table 5.3 Comparison of results for cleaned and uncleaned samples tested by hand rotation.

SITE	ROCK TYPE	CLEAN	UNCLEAN	DIF.
B.P.	f-mg lst	38.0+1.0	33.7+1.3 32.5+1.0*	-4.3
B.P.	f-mg lst	42.9+0.7	39.4+1.7	-3.5
B.P.	f-mg lst	35.6+0.9	37.9+0.7	+2.3
B.P.	cg fos lst	39.0+1.1	36.8+1.0 37.0+0.6*	-2.2
B.P.	f-mg lst	37.2+0.6*	38.4+0.8*	+1.2
Inde.	fg dolc lst	27.2+1.6	24.5+0.7 22.3+0.5*	-2.7
Inde.	cal / lst	41.9+1.4	40.2+0.7	-1.7
Inde.	calcite	41.5+0.8	39.9+1.0	-1.6
Inde.	fg lst	29.9+1.9	25.3+1.2*	-4.6
Q.R.	mg quartzite	29.0+1.5	27.9+0.8	-1.1
Q.R.	mg quartzite	26.7+1.7	24.4+0.7 22.6+0.5*	-2.3
Spar.	cg fos lst	33.6+1.6	30.5+0.6	-3.1
Spar.	fg dol	28.5+1.1	23.3+0.6	-5.2
Spar.	f-mg lst	34.9+0.6	34.2+0.4	-0.7
Spar.	f-cg lst	37.7+1.0	35.5+1.3	-2.2
Spar.	f-mg lst	36.5+1.3*	30.8+1.1*	-5.7
All Sites				-2.8

All tests by hand rotation except where indicated.
DIF. = Difference between sliding angles.
* = Tested by motor rotation.
B.P. = Burstall Pass, Inde. = Indefatigable
Spar. = Sparrowhawk, Q.R. = Quarzite Ridge
fg = fine grained, mg = medium grained, cg = coarse grained
fos = fossiliferous, dolc = dolomitic, lst = limestone

Calcite sliding on limestone gave sliding angles of 41.9°±1.4° for cleaned repeated slides and 40.2°±0.7° for uncleaned, repeated slides. Similarly calcite sliding on calcite gave 41.5°±0.8° and 39.9°±1.0° respectively. One can argue that the softness and crystal structure of calcite creates higher sliding resistances because asperities from the mating surface (harder limestone) are not crushed or broken but rather gouge into the softer calcite. Conversely, the asperities on the calcite surface, being softer, are crushed or worn down when sliding on the harder limestone. Gouging into the surface or breaking of asperities on calcite occurs by large angular fragments that also maintain a high frictional resistance.

The overall effect in these tests appears to be a greater sliding resistance for calcite on limestone or calcite on calcite as opposed to limestone on limestone. If a roughened limestone were slid on a polished calcite, one would expect a higher sliding resistance than with a roughened calcite on a polished limestone since the roughened limestone will gouge into the polished calcite but the roughened calcite should not gouge into the polished limestone but rather break off and wear down asperities. Solutioning and weathering may reduce the frictional resistance of calcite considerably as it is less resistant than limestone. This has not been examined.

Sliding calcite on limestone provided a colour contrast that enabled the transfer of powder and crushing of asperities to be observed visually with a magnifying lens. This was not possible with limestone on limestone. Although powder could be seen, it provided a poor contrast and some powder was probably present as a result of lapping.

Comparisons indicate that the sliding angle decreases as the CLA decreases (Table 5.4, Figure 5.2). The trend although not strong, is apparent. One would expect roughness to decrease with friction angle, at least up to a certain smoothness (Bruce, 1978) where contaminants and adhesion cause the angle to increase again. This smoothness cannot be achieved by the sample preparation or repeated testing used in this program. Talysurf CLA's may reflect the grain size and type and matrix of the sample.

Hencher (1976) referred to high stresses on the leading edge of the plate specimen. The same six specimens used for obtaining CLAs were matched once again with their slider or plate pair, washed and run through another set of repeated cleaned tests. CLAs were measured again after the tests with the intent of examining the effect of higher stresses on the CLA on the leading edge. With about 2 cm of displacement occurring with each slide, specimens had undergone between 26 and 36 slides for total displacements between 52 and 72 cm. CLAs were measured on the bottom third and then the top third of the slide surface (Table 5.5).

Limestone samples showed a decrease in roughness from the top third of the slide surface to the bottom third. In addition, the cleaned sliding angle decreased for all rock

Table 5.4 Comparison of surface roughness and sliding angle.

ROCK TYPE	CLA	SLIDING ANGLE	
	(10^{-3} mm)	cleaned	unclean
calcite on lst	5.59	41.9	40.2
cg fos lst	4.32	39.0	36.8
f-mg lst	4.06	34.9	34.2
cg fos lst	3.68	37.7	35.5
mg quartzite	3.56	26.7	24.4
fg dolomite	3.17	28.0	23.3

CLA = centre line average roughness profile
fg = fine grained, mg = medium grained, cg = coarse grained
fos = fossiliferous, lst = limestone

Table 5.5 Comparison of surface roughness before and after cleaned tests.

ROCK TYPE	CLA*	CLA ($\times 10^{-3}$ mm)		SLIDING ANGLE, CLEANED		
	(10 mm)	bot1/3	top1/3	1st set	2nd set	change
calcite	5.59	4.64	6.10	41.9	40.0	-1.9
cg fos lst	4.32	3.47	3.85	39.0	35.1	-3.9
f-mg lst	4.06	3.51	4.23	34.9	32.2	-2.7
cg fos lst	3.68	3.62	4.00	37.7	28.4	-9.3
mg quarzite	3.56	3.64	3.49	26.7	20.4	-6.3
fg dolomite	3.17	3.22	3.00	28.0	20.2	-7.8

* = First average of CLA in X and Y directions, before testing.
= Average of CLA in X, sliding direction only, after testing.
bot1/3 = Roughness measured on the bottom third of the slide surface.
top1/3 = Roughness measured on the top third of slide surface.
fg = fine grained, mg = medium grained, cg coarse grained
fos = fossiliferous, lst = limestone

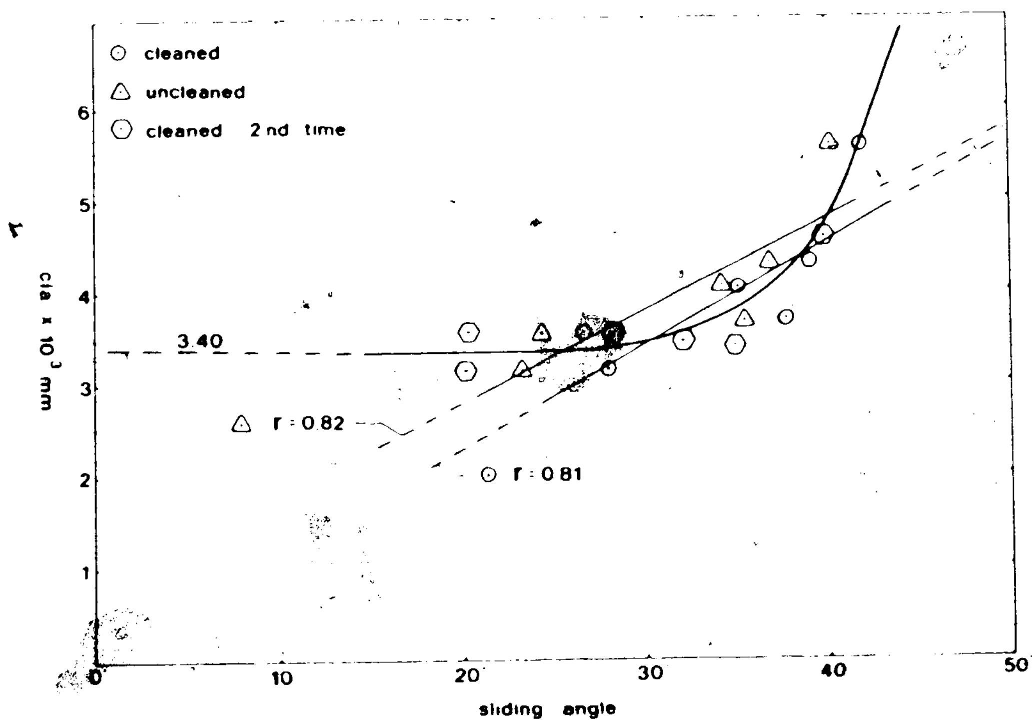


Figure 5.2 Comparison of surface roughness and sliding angle. Repeated sliding appears to reduce roughness to a lower value near 3.40 x 10^{-3} mm.

types. It appears that 52-72 cm displacements with the tilting table reduces the frictional resistance by wearing down the highest asperities. On the other hand, powder generated during earlier sliding tests might still be present during the second set of cleaned tests and filling in some of the depressions on the slide surface. This seems to indicate that surface roughness is approaching an ultimate value around 3.40 x 10^{3} mm (Figure 5.2) from repeated tilt tests.

In Figure 5.3 surface profiles before and after displacement show the reduction in peaks of the highest asperities for the two roughest samples, calcite and a coarse grained fossiliferous limestone.

The author had limited success in duplicating test results. Two sample pairs from the same field rock did not provide the same friction angle in all four cases (Table 5.6). Similar angles were obtained though. The motor derived values have been increased by 1° to compensate for vibrations and are indicated inside brackets. Retesting of samples usually produced a decrease in friction angle.

Samples from the same rock should produce the same friction angle. Differences may be due to sample preparation. The samples may possess a different surface roughness, especially if one was not lapped long enough to remove anomalous asperities. This could not be examined prior to testing. The Talysurf measuring device is unable to detect large scale curvature of the slide surface. This may

Table 5.6 Comparison of friction angles of samples from the same field rock.

SITE	SAMPLE NO.	ROCK TYPE	AVG. ANGLE
B.P. B.P.	Jy31-4 A/B Jy31-4 C/D	f-mg lst f-mg lst	(38.8) 36.8
Q.R. Q.R.	Ag13-1 A/B Ag13-1 C/D	mg quartzite mg quartzite	28.4 25.6
Spar. Spar.	Jn22-4 A/B Jn22-4 C/D	f-mg lst f-mg lst	(34.6) 34.6
Spar. Spar.	Jy5-1 A/B Jy5-1 C/D	fg dolomite fg dolomite	25.9 26.7

The sliding angle is an average of the first two sets of tests, a cleaned and an uncleaned test.
The values in brackets were obtained from motor tilts and are increased by 1°.
B.P. = Burstall Pass, Inde. = Mount Indefatigable
Q.R. = Quartzite Ridge, Spar. = Mount Sparrowhawk
fg = fine grained, mg = medium grained, cg = coarse grained
fos = fossiliferous, dolc = dolomitic, lst = limestone
r = correlation, b = slope of straight line, $y = a + bx$.

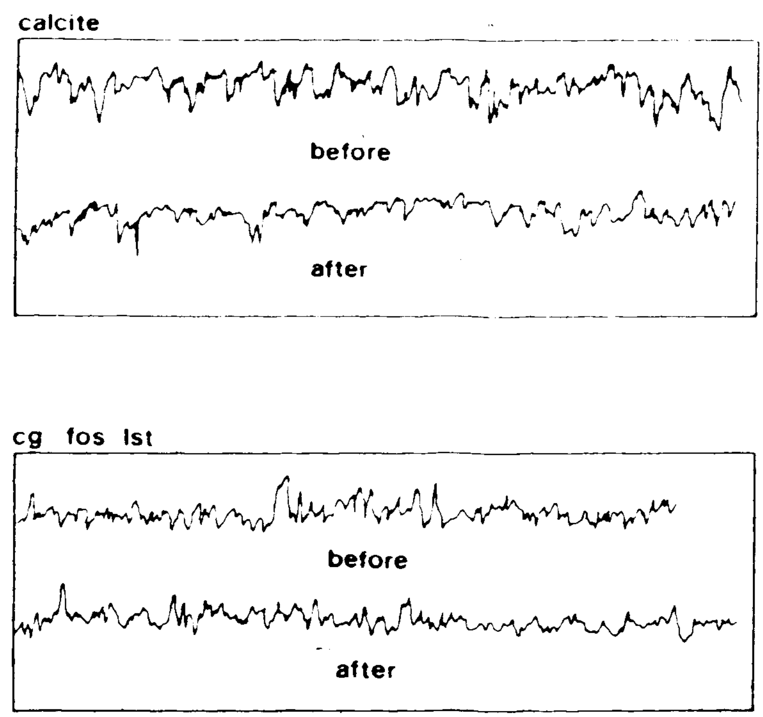


Figure 5.3 Surface roughness profiles before and after testing.

occur from lapping as well but could not be confirmed. There may be a difference in lithology between the sample pairs even though they were cut from the same field rock. Cutting orientations were the same. Variations in environmental conditions or contaminants on the slide surfaces may have weakened reproducibility. Tilt tests were performed over a 5 month period.

Retesting the same sample usually produced a reduced friction angle but as can be seen in Table 5.7 the correlation is weak. The last two rows have data sets of only two each. The motor derived values have been increased by 1° to compensate for vibrations and are indicated inside brackets.

Friction angles decrease because repeated sliding wears down asperities and powder accumulates on the slide surface. Again, variations in environmental conditions or contaminants on the slide surfaces may have weakened this trend. A moistened sample slid at successively higher angles until it did not slide at all because of increased surface tension. An oven warmed sample also slid well above its' expected friction angle, until it cooled to room temperature. Environmental data are not available for the testing location. At least one curious onlooker handled a sample by the slide surface before the author noticed this. This may have occurred in the author's absence as well.

Table 5.7 Comparison of sliding angle with testing sequence

SITE	ROCK TYPE	TESTING SEQUENCE					LINEARITY	
		1	2	3	4	5	r	b
Spar	f-mg lst	(31.8)	(29.9)	28.8	(30.2)		+0.23	+0.57
B.P.	f-mg lst	37.9	(33.8)	34.0	(36.6)		-0.24	-0.37
B.P.	f-mg lst	(33.5)	33.7	(30.2)	30.4	(31.7)	-0.66	-0.69
B.P.	f-mg lst	(39.4)	39.4	(30.2)	30.2	(32.0)	-0.80	-2.40
Q.R.	mgquartzite	(23.6)	24.4	(20.6)	22.2	(17.4)	-0.83	-1.46
Spar	fg dol	(27.9)	26.6	(26.6)			-0.87	-0.65
B.P.	cg fos lst	(38.0)	36.8				-1.00	-1.20
Inde	fg dolc lst	(23.3)	24.5				+1.00	+1.20

B.P. = Burstall Pass, Inde. = Mount Indefatigable
Q.R. = Quartzite Ridge, Spar. = Mount Sparrowhawk
fg = fine grained, mg = medium grained, cg = coarse grained
fos = fossiliferous, dolc = dolomitic, lst = limestone
r = correlation, b = slope of straight line, y = a + bx.

5.7 Testing by Others

Bruce (1978) examined the basic friction angle, ϕ_b, of quartzite from Jonas Ridge and dolomite from Whitehorse Creek using a tilting table. The testing was done at the University of Alberta. Unfortunately the samples and tilting table could not be located for examination. Descriptions of the samples were not provided. The tilting table used by Bruce was lifted by a hand-turned threaded crank and was not as refined as the testing apparatus described here. Test rates are not known. Samples were 5 x 5 cm but thicknesses must have been greater as some specimens with natural surfaces toppled at about 40°. Results are believed to be first time cleaned tests after wet lapping.

The results are presented in Table 5.8. The CLA's and friction values are similar to those in Table 5.4. The sliders had natural or sandblasted surfaces which are rougher than samples prepared by lapping with #80 grit. So, more resistance would be provided by the interlocking of asperities. The plates were lapped with #80 grit or sandblasted. Surface preparation of dolomite and quartzite in the present testing program produced flatter CLA's and lower friction angles.

Coulson (1972) examined the frictional resistance of smooth and irregular surfaces of 10 rock types using a direct shear apparatus. The initial friction values for the lowest and highest normal stresses are presented in Table 5.9 for 3 rock types. The values are similar to those in

Table 5.8 Results of tilting table tests by Bruce.

PLATE	#80 GRIT	SANDBLASTED
SLIDER CLA x 10'mm	3.81*	5.08*
Quartzite		
-natural	31.3 + 1.5	30.8 + 2.4
-sandblasted	31.0 + 2.2	30.2 + 2.2
Dolomite		
-natural	34.3 + 1.2	34.2 + 1.3
-sandblasted	34.1 + 0.3	34.2 + 2.6

* An average value for plate specimens.

Table 5.9 Results of direct shear tests by Coulson.

ROCK TYPE	N (kPa)	Ø initial
Oneota Dolomite	84 7000	36 32
Bedford Limestone	84 7000	34 39
Solenhofen Limestone	84 9000	36 33

Table 5.3. Coulson offered that ϕ_b does not change significantly over the normal loads commonly investigated in surface workings. Bruce's results of ϕ_b shear tests conducted over the stress range expected at either Jonas or Whitehorse Creeks indicate that ϕ_b is stress independent for this stress range.

5.8 Discussion

The test results reveal that carbonates in Kananaskis possess a wide range of basic friction angles. Asperities influence the resistance of artificial discontinuities under the very low normal stresses that prevail in tilting table tests. Unless quite smooth, it is not recommended that natural discontinuities be tested using the tilting table. Sawn surfaces lapped with #80 grit are believed to represent the basic friction angle of hard rocks.

Wet lapping and repeated uncleaned testing is recommended. Wet lapping prevents an electrostatic film from adhering to the sample. Repeated uncleaned tests allow powder to accumulate from shearing of asperities, similar to a flexural-slip bedding surface. Hand or motor rotation are both acceptable as vibrations from the motor can be accounted for. The lower bound values for various rock types are: limestone 25.3°±1.2°, dolomite 23.3°±0.6°, dolomitic limestone (23.3°)±0.5°, calcite 39.9°±1.0° and quartzite (23.6°)±0.5°. The values in brackets are adjusted for vibrations.

Different limestones have different sliding angles when lapped with #80 grit (Table 5.3). This testing demonstrates that limestones possess a range of basic friction angles that range between 23.3°±0.6° and 40.2°±0.7° for wet lapped uncleaned tests. These angles may also reflect the variations in lithology of limestones in the Kananaskis study area and beyond. A single limestone bed can vary in lithology over short distances such that its friction angle may also fluctuate by several degrees across a slope. This assumes that lapping with #80 grit represents the basic friction angle, ϕ_b, the lower bound for rockslides (Cruden, 1984).

This complicates the problem of flagging hazardous slopes. With variable structure, slope type, dip of bedding and friction angles, controlling the behaviour of slopes, how do we evaluate the rockslide hazard of an area? How do we estimate cohesion? A conservative approach is necessary. From Table 5.3 we see that a bottom end value for cleaned and uncleaned tests is around 23°. It appears that dolomite and dolomitic limestone possess the lowest basic friction angles. The values obtained by motor rotation, of course, are depressed by 1° and quartzite values are not being considered at this time.

In any carbonate bedrock slope in Kananaskis, one can expect to encounter a variation in lithology from bed to bed. Beds with low frictional resistance may exist in the slope. Recognition of this possibility is paramount when considering over-dip slopes because of their high activity and the widespread structural evidence of flexural slip and thrust zones. In this regard, any over-dip slope with beds steeper than 20° should be considered as a potential hazard and rockslide source even in light of some evidence of previous movements. Further geotechnical investigation should be undertaken if human activities are to occur below, on or in such a slope. The investigation will, of course, examine the geology and frictional properties of the bedrock in greater detail and consider pore pressures and groundwater flow, the fabric of the discontinuities, their orientation and other engineering properties of the bedrock.

Other types of rock like the younger Mesozoics which are mainly detrital, such as the quartzite tested, may have different ranges of basic friction values again because of grain size, shape, type and matrix as in mudstone, siltstone, sandstone, shale, coal and conglomerate, etc.

Is there a classification system for carbonate rocks that would facilitate estimation of the basic friction angle, ϕ_b? This special-purpose classification would be useful for further hazard evaluation and mapping in the Canadian Rocky Mountains. The system should consider present classifications previously mentioned such as age, texture and particle composition, size, shape and percent Samples from different regions representing the different classes could be collected and quickly tested with the tilting table.

Other test results show rougher samples displayed more creep displacement than smoother ones before sliding occurred. Dry lapped samples possessed a film of powder that adhered probably electrostatically to the surface and behaved like a plastic soil which permitted the greatest amount of pre-slide creep. Continued displacement by sliding wears down the highest asperities, or fills in troughs with powder, reducing the apparent roughness of the surface even at stresses below 0.6 kPa. Total displacements are in the order of 50-75 cm. This wearing down of the surface roughness occurs mainly on the leading one third of the slide surface of the plate and slider specimens.

Rock surfaces lapped with #80 grit may approach ultimate frictional roughness after 50 cm of displacement at lower normal stresses below 0.6 kPa. The difference in frictional resistance of different samples possessing this characteristic roughness is probably attributable to their mineralogic friction properties.

6.0 Conclusions

6.1 Summary

The Kananaskis study area is situated in the Front Ranges of the Rocky Mountains 100 km southwest of Calgary, Alberta. The study area receives between 450 to over 650 mm of precipitation per year and is subject to freeze thaw conditions any time of the year. Gardner (1982) made observations on the frequency and magnitude of rockfall in the southeast corner of the Kananaskis study area. This study identifies the nature of rockslide hazards in Kananaskis and the slopes and rocks prone to these movements.

Tills are poorly developed in the area. The Canmore Drift is most common in the main valley bottoms. Neo-glacial and Little Ice Age moraines are found in tributary and hanging valleys, but deposits are not extensive. Alluvial deposits are found where the higher valleys discharge into main valleys and in the lower Kananaskis River Valley. Colluvium covers the weathered bedrock slopes which are not too steep in a thin veneer. About 45% of the Kananaskis, or 400 km^2, is above treeline. This is generally where steep slopes and the origin of rockslide hazards are found. Rockslide debris and talus are found at the bases of and on these slopes.

The bedrock consists of younger Mesozoic detrital rocks and older Paleozoic carbonates. The detrital rocks from the

Cretaceous, Jurassic and Triassic Groups are more readily weathered and occupy mountain passes and valley bottoms. The carbonate rocks from the Permo-Pennsylvanian, Mississippian and Devonian Formations and Groups are more resistant to weathering and form the peaks and ridges.

The sedimentary strata were uplifted along listric thrust faults that trend in a general northwest southeast direction. Major mountain ranges and valleys follow the same trend. Bed dips are moderate to vertical. The general dip direction is southwest except on the east limb of an anticline or the west limb of a syncline, where it is reversed.

Bedding is the most common large scale discontinuity in Kananaskis, therefore slopes are considered according to the orientation of the bedding in the slope with respect to the slope. This system is useful for classifying slopes in sedimentary strata and identifying the hazardous ones. Bedding and slopes with similar dip are either dip, over-dip or under-dip slopes. Bedding and slopes with opposite dip are reverse-dip slopes. Bedding and slopes with a dip that is not parallel are either oblique-dip or strike dip slopes.

Hazard areas are defined as active or hypothetical, and other areas have no hazards. Processes of rockslide or rockfall and their deposits are observed in the active zone. Processes of rockslide or rockfall are not observed in the hypothetical zone but the attitude of the bedrock and slope suggest that this could occur. Other processes such as solution and freeze and thaw cycles are active in the hypothetical zone. None of the above processes or deposits are observed in the zones with no hazards.

Slope hazards are related to several processes: Rockslides, simple sliding in the initial movement, rockfall, free fall in the initial movement, topples, an overturning about the base in the initial movement, debris flows, a combination of flowing rock debris, regolith, vegetation, snow, ice and water, creep, slow movement under a constant load. Rockslides, rockfall and topples involve only rock initially whereas debris flows and creep incorporate rock debris with other materials.

Low-magnitude and high-magnitude rockfall and rockslide and their deposits are widespread in Kananaskis. The reconnaissance mapped 8 km^2 of rockslide debris containing 228 high-magnitude rockslides and 96 km^2 of talus. Oblique-dip, strike-dip and reverse-dip slopes are the most active low-magnitude rockfall and rockslide slopes, especially where they form scarps. Dip and over-dip slopes, considered together because of their close association with rockslides are the most active high-magnitude slopes and often display cluster activity. Oblique-dip, strike-dip and reverse-dip slopes exhibit high-magnitude activity as well. Large rockslides (greater than 0.5×10^6 m^3) have occurred from over-dip and reverse-dip slopes only. Connecting joints in the set normal to bedding but with the same strike as bedding form the discontinuity which becomes the rupture surface in a reverse-dip slope.

Glaciers appear to be an important recent agent in weakening rock structure. Flexural-slip as a result of thrusting, folding and unloading has destroyed cohesion between many beds. Structural weaknesses in the rock appear to be greater in areas of high activity. The Mesozoic rocks are relatively inactive because of subdued topography, compared to the Paleozoic carbonate rocks. The Mississippian Rundle Group is not be the sole locus of large rock slope failures in the Canadian Rockies. The Devonian Palliser and Permo-Pennsylvanian Rocky Mountain Groups exhibit higher activity levels although more rockfalls and rockslides occur in Mississippian Rundle rock because it dominates the Kananaskis landscape.

A tilting table was used to evaluate the basic friction angle, ϕ_b, of rock samples from Kananaskis. The basic friction angle is useful as a lower bound limit for rockslides. One can observe the failure directly in a test. Wet lapping and repeated uncleaned testing is recommended. Wet lapping prevents an electrostatic film from adhering to the sample. Repeated uncleaned tests allow powder to accumulate from shearing of asperities, similar to a flexural-slip bedding surface. Hand or motor rotation are both acceptable as vibrations from the motor can be accounted for.

The lower bound values for various rock types are: limestone 25.3°±1.2°, dolomite 23.3°±0.6°, dolomitic limestone (23.3°)±0.5°, calcite 39.9°±1.0° and quartzite (23.6° ±0.5°. The values in brackets are adjusted for vibrations. Repeated slides even under the low normal stresses prevalent with the tilting table reduces the surface roughness and consequently the friction angle. The lower bound surface roughness from repeated sliding is about 3.40×10^{-3} mm.

The basic friction angle of carbonates tested varies from 23.3°±0.6° to 40.2°±0.7°. The variation is attributed to differences in lithology. A quartzite tested at (23.6°)±0.5° to 27.9°±0.8° but detrital rocks were not investigated in detail because there is little activity in these rocks in Kananaskis.

The tilting table appears useful for evaluating the basic friction angle of rocks. The test is simple, easy to interpret and fast. Values obtained from shear and tilt testing are similar over the normal stress range encountered in surface mining.

6.2 Recommendations

A reconnaissance of rockslide hazards was reported by Cruden and Eaton (1985a,b). The air photograph interpretations are provided in Appendix C. Rockslide hazards were mapped over an area of 880 km². The mapping scheme flags active and hypothetical hazards.

The interpretations provide a tool which is available to others working in the Kananaskis study area. A quick evaluation can be made of a site to see if it lies inside a hazard zone. The surficial debris (talus or rockslide deposits), slope type and nature of the hazard (active or hypothetical) provide an indication of the magnitude of future movements. Sites as small as 100 x 100 m can be evaluated at the scale of the interpretations. This will aid in determining if a detailed investigation is necessary.

Some recreational, private, industrial and transportation facilities are located below steep mountain slopes in hazard zones. Some are close to the hazard zones. Immediate relocation of a storage facility and the working face of a borrow pit were recommended by Cruden and Eaton (1985b) and several specific sites were evaluated for the client.

This study only considered one fifth of the district known as Kananaskis Country. Most of Kananaskis Country is located in mountainous terrain with similar geology, structure, facilities and activities as in the study area. The hazard mapping should be extended into the rest of Kananaskis Country, particularly along the Bow Corridor and around man-made lakes such as the Spray Lakes Reservoir where the consequences of a large rockslide could be disastrous.

Over-dip slopes are identified as the locus of rockslides and the basic friction angle as a convenient lower bound value for the occurrence of rockslides. A set of average basic friction angles correlated with a stratigraphic column representing the strata of the Rocky Mountains would be useful in identifying hypothetically hazardous over-dip slopes. Detailed surveys of over-dip slopes identified in this study used with the basic friction angle in analysis might provide insight into the amount of cohesion existing along a bedding surface. Comparison of the tilting table and direct shear devices should be continued to quantify their compatibility. Tilting tests should be expanded to other rock types.

The author found that one high-magnitude rockslide could have taken place every 44 years since the retreat of the last major glaciation. Determining the chronology of the rockslide deposits in the study area would indicate how closely these events are linked with periods of glacier activity and when these occurred.

The author feels that mapping of rockslides alone is not as useful as a multidisciplinary effort. A more comprehensive mapping scheme considering all slope hazards would provide a once only tool for the evaluation of land and the location of facilities. This should consider soils, rocks, vegetation, water, snow and ice; small incremental movements and large rapid ones, natural and man made. At present in Kananaskis several forms of slope movement have been studied. Some mapping has been undertaken in all the projects but the site size and location varies greatly. The rockslide reconnaissance covers the largest area and encompasses the other study boundaries.

The projects of Gardner (1980, 1982), Greenlee (1981), Niemann et al. (1984), Sauchyn (1984), Cruden and Eaton (1985a, b), Johnson et al. (1984), Smith (1985) and Tang (1986) could be applied to a designated test area in Kananaskis Country. If this project proved successful then it could be expanded to cover a larger area. This rockslide reconnaissance boundary might be appropriate because it includes a large provincial park in the south and two alpine ski resorts, a golf course, future hotels are located in the north. Two highways knife through the area and expansion to the north and northwest would include the Bow Valley Corridor and Spray Lakes Hydroelectric Reservoir. Many hikers and skiers travel in the backcountry. The area is very active.

This study would include mapping of solifluction, gelifluction, soil erosion susceptibility, debris flows and torrents, rockslide, rockfall, topples and snow avalanches. The list is no doubt incomplete but a lot of the groundwork methodology has been worked out and needs only to be streamlined. The information could be presented in a digitized form on overlays for aerial photographs at 1:12,000 or larger, or on overlays for large scale maps created from the aerial photographs (1:5,000 or larger). The use of satelite imagery enables large areas to be mapped at one time but at the sacrifice of detail. This may simply be a matter of economics but the author suggests that the additional detail afforded by large scale maps or photographs is necessary for adequate evaluation of any site.

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Appendix A

Methodology

A.1 Introduction

Rockslides rupture along weaknesses in rock structure. In Kananaskis, discontinuities formed during deposition, orogeny and weathering. The strongest agent of weathering appears to be glacier activity which is in turn a response to climatic conditions and fluctuations. It is beyond the scope of this report to take a closer look at deposition, orogeny and weathering other than to recognize the importance of their respective influences.

The evaluation of hazards from rock slope movements in Kananaskis involved two stages; first an office research, mapping and interpretation stage, and second a field reconnaissance mapping stage. The sequence was repeated when necessary.

Physical surveys in mountainous terrain pose special problems. Different surveying techniques were considered. Weather, relief, manpower and resources are factors to be considered.

A.2 Mapping

The evaluation of hazards from rock slope movements in Kananaskis involved two stages; first an office research, mapping and interpretation stage, and second a field reconnaissance mapping stage. In the first stage available geologic and topographic maps and a set of high quality aerial photographs were obtained for the study area. The best available geologic map (Bielenstein et al., 1971) is at a scale of 1:126,720. Topographic maps were from the National Topographic System 1:50,000 scale series and include parts of 82J/10, 82J/11 and 82J/14. A set of 1:15,840 scale black and white photographs were obtained from the Aerial Photo Data Service, Alberta Energy and Natural Resources. Refer to Appendix D for the air photograph interpretations. This single series was photographed in 1957 and 1958, covers the whole study area and has good resolution.

Air photo interpretation was undertaken with the above to identify rock avalanche deposits, talus, structure of rock slopes and large scale features of weathering and erosion related to rock slope instability. Subsequent to the initial air photo interpretation, areas of uncertainty and special interest were selected for ground truthing and further examination in the field. The field data was collected on foot using basic geological surveying instruments and recorded in a field notebook. The field information served to clarify areas of complexity, confirm air photo interpretation in areas of special interest, confirm the structural geology and aided in the selection of sites desirable for detailed investigations. When stage two field work was completed stage one interpretations were reviewed and changes made. The procedure was repeated as necessary.

A.3 Areas of Uncertainty

The distinction of talus and avalanche deposits from rock slope movements is facilitated in Kananaskis where the vegetation cover is sparse and the structure of the surrounding bedrock is readily discernible. So recent rock slope movements can generally be identified by their deposits. However the possibility of a moraine being classified as rock slope movement debris exists. The reverse is also possible.

During the Holocene, two minor glacial episodes may have occurred (Gardner, 1982). The first, an early Holocene episode (8,000-10,000 years B.P.) referred to as the Crowfoot Advance (Luckman and Osborne, 1979) and the second, neoglacial advance (last 2500 years), culminated in the Little Ice Age (250-150 years B.P.). Glaciers have been receding since that time. So debris of some rock slope movements may actually be interstratified with young Holocene moraines. Glaciers and rockslides often move down the same valleys. Usually glaciers leave concentric curved ridges of morainal debris and rockslides come to rest as lobate deposits with transverse ridges. As features become subdued with weathering the distinction between the two is increasingly difficult. The gross external characteristics of the resulting deposits may become broadly similar.

Very detailed physical surveys, lichenometric and radio-carbon dating and extensive sampling possibly by excavation or drilling would probably be necessary to elucidate these dubious deposits. Although no single criterion permits unequivocal identification of either type of unit, in combination they may allow the origin of deposits to be deduced (Porter amd Orombelli, 1981).

A.4 Mountain Surveys and Mountain Weather

Mountain weather is varied and unpredictable. Here the particular weather patterns of the Kananaskis study area are discussed as they affect surveying techniques.

Topographic information can be obtained in three ways: from aerial photography, from topographic maps or from physical surveys in the field by measuring vertical and horizontal angles and elevations or by measuring vertical and horizotal angles and slope distances. Vertical and horizontal angles are measured with a Brunton compass. The Brunton compass is also used for obtaining data on geological structures. Elevations are obtained with an altimeter, watch and thermometer. Slope distances are obtained with an optical distance tape measure.

The use of conventional surveying techniques; theodolite, level, Distomat, rods and reflectors are too cumbersome and sensitive for human portability in mountainous terrain by a light small party. Considerable expense, manpower and machinery (a helicopter) is necessary to mobilize this equipment which was beyond the budget of the current research.

Typically, weather systems move in from the Pacific west of the Rockies. These systems are often series of warm and cold fronts, variable skies and precipitation. Occasionally, an arctic high descends from northern latitudes bringing clear skies and in the winter, a very cold, dense air mass which other systems have difficulty in displacing. Less common is a weather system from the south bringing milder temperatures but usually accommpanied by cloud and some precipitation. Least frequent are systems from the east.

High and low pressure systems come in from the Pacific. They can bring clear skies or moisture laden cloud. All systems must cross several mountain ranges starting with those on Vancouver Island and the Queen Charlotte Islands before reaching the Rockies. As an air mass meets a mountain range, the air is forced upward, condensing and cooling on the way up. This releases moisture in the air mass in the form of rain or snow or variations thereof. When the air mass passes east of the Rockies, little moisture is retained and that is why Alberta and Saskatchewan are in a rain shadow zone where little moisture falls. Agriculture, industry and hundreds of communitites rely on the annual spring and summer runoff from the Rockies for their water supply. That is also one reason why almost all glaciers in the Rockies are currently retreating; they are not receiving enough precipitation in the form of snow to accummulate firn snow which eventually turns to glacier ice after sufficient consolidation, metamorphosis and pressure.

It should be noted that retreat of current glaciers may trigger rockslides in the future, but as the glaciers continue to retreat and decrease in area, rockslides will occur further up valleys in locations more removed from man and his activities.

Glaciers still exert an influence on the weather patterns in Kananaskis, in particular the Mangin Glacier, Haig Glacier and the glaciers surrounding Mount Assiniboine. The glaciers aid in cooling the air mass and accelerating it down the eastern slopes of the range. Adiabatic winds from the Mangin and Haig Glaciers funnel down Aster Creek and the Upper Kananaskis River onto Upper Kananaskis Lake. Winds exceeding 50 kilometres per hour are common. A large obstacle stands in the way of these winds before they can continue their journey down the main Kananaskis River Valley. The winds must funnel around the southern end of Mount Indefatigable.

Similarly, adiabatic winds descending from the lofty regions and glaciers of Mount Assiniboine follow the path of least resistance down the Spray Reservoir which offers a smooth surface compared to a treed and rolling valley bottom. The west flanks of several mountains protude into this channel of which Mount Sparrowhawk is one.

With weather patterns such as these, barometric surveys become quite difficult, if not impossible to perform in a satisfactory manner. High pressure air forms on the southwest facing slopes. Turbulent air passes by the ends of the ridges creating moving alternating high and low pressure zones. Negative (relative to a static atmospheric condition) or low air pressure develops on the northeast facing slopes with the greatest negative pressure just below the ridge. At an even smaller scale, gullies and small scarps may possess their own wind patterns and pressure regimes.

Barometric surveys were performed in Kananaskis. American Paulin System survey equipment; a micro-barograph and altimeter, and precision altimeter survey procedures were used. A choice of several procedures was available (Hodgson, undated):

1. The single altimeter method assumes that the change in pressure is constant while a survey is performed away from a known point. This method is not suitable in Kananaskis because vertical control is required in a number of locations. One cannot assume constant barometric variations, and mountainous terrain does not permit one to travel any significant distance in a short time span.

2. The single base method uses two altimeters. One altimeter remains at a base station taking readings while a second altimeter performs the survey. The roving altimeter(s) return to base for a final reading to finish the survey. This method assumes that the barometric changes

recorded by the base station altimeter, during the time of the survey, can be used to correct the readings taken by the roving altimeter(s). This places limitations on the distance and time that roving altimeters can operate away from the base station.

3. The moving base method is an adaptation of the single base method where altimeters alternate at prearranged time intervals to act as the base station; one altimeter is always recording barometric changes for the other(s). Frequent checks with known vertical control are necessary with this method, as well as an experienced survey team.

4. The skip-stop or leapfrog method takes the moving base method one step further. Two altimeters take turns alternating between the base altimeter and the roving altimeter every altimeter reading. This method is very time consuming.

5. Two other methods; the hi-lo method and the multi-base method were not feasible because of the requirements of aircraft or additional personel and altimeters. Their underlying assumptions are also not applicable in Kananaskis (Hodgson, undated).

The single base method appeared to be the preeminent method that held any promise for success in Kananaskis. All other methods were dismissed because of equipment and manpower limitations, local terrain and climate regimes, lack of existing vertical control and the time available to perform surveys.

The American Paulin System surveying micro-barograph was substituted for the base altimeter. This device provides a continuous record of pressure changes on a drum chart for a maximum duration of 15 hours. This enabled two operators, each equipped with an American Paulin System altimeter to perform surveys away from the base station. Ideal climatic surveying conditions would be those with either a high or low pressure system stationary over the study area and winds less than 25 kilometres per hour. The nearest Environment Canada weather offices in Banff and Calgary do not attempt to forecast the weather in specific mountain localities such as the Kananaskis study area. There is one rule in weather forecasting especially relevant to mountainous terrain. It is: There are no rules (Twomey, 1985).

Since accurate weather forecasts are not available for Kananaskis, one could only hope for ideal conditions and be prepared to redo any day's survey. In retrospect, only a handful of days occurred in each of the last two summers that were favourable for barometric surveys, hardly enough time to profile a mountain slope or rockslide deposit.

Other problems arose with the single base method. The micro-barograph is a sensitive instrument. It is rather heavy and bulky for transporting in a packsack up mountain slopes on a daily basis. Placing the instrument at the base of a southwest slope for surveys on that same slope did not always provide barometric information reflective of the barometric changes that occur in the area of the survey, as unacceptable basis often resulted. Weather patterns still vary somewhat on the windward exposure, typically the dip and over dip slopes, be it attributable to tree cover_lower down around the base station, surface roughness of gullies and scarps further up, layered winds, the radius of concavity and convexity of the slope, its dip and aspect or other unrecognized reasons. The only way to overcome these problems would have necessitated limiting the distance and time that the operators are away from the base station to such an extent that surveys become too time consuming and unfeasible.

The method of obtaining digital topograhic data from analytical stereoplotter analysis of aerial photographs was considered initially but decided against. Analysis of each pair of photographs is expensive. The selected site(s) must lie at or near the center of the photographs for best resolution. At least relative vertical and horizontal control must be established within the site by conventional theodolite triangulation and accuracy. A minimum of three points are required. The points must also be easily identified and pinpointed on the photographs. Even with this information, distortions occur in the peripheral margins of the photographs and where any near vertical or vertical terrain exists. Because of the cost and the labour and equipment intensive preparaton required, this method was not considered any further. Initially, the author was anticipating collecting data from as many as six sites, same of which were quite large (exceeding 10 km²) and some were remote. In the end, limited data was obtained only from Mt. Indefatigable and Mt. Sparrowhawk because of time constraints and problems with surveying technique. In retrospect, stereoplotter analysis, may have been the proper route to follow had one been able to establish at the outset only one or two sites of interest.

The survey method affording the best results, greatest ease and level of flexibility involved the use of an optical distance tape measure in conjunction with a Brunton compass. A Rangefinder with ranging power from 45 to over 1000 metres was selected. This method removes the dependency on ideal altimeter surveying conditions. As well, horizontal or gently sloping altimeter surveys can introduce large errors particularly in horizontal control where calculated horizontal distances are so dependent on accurate barometric readings. The biggest limitation of the Rangefiner is ranging on targets. Terrain above treeline in Kananaskis lacks good contrasting colours and well defined shapes. Poor light magnifies the difficulties in ranging. The easiest objects to range on are a tree or a rock prominent against a clear sky or a sharply defined vertical crack in a cliff face. Fluorescent orange survey ribbon was tied to stations to provide a colour contrast which helped, but often the ribbon would flap in the wind and make the focusing difficult. In accordance with proper surveying practice, foresight and backsight azimuths and vertical angles and averages of a minimum of three range distances were taken between every pair of survey stations to reduce errors. The Rangefinder was always used in its most accurate range, between 46 and 100 metres. A plastic measuring tape was used for distances less than 46 metres. Occasionally distances beyond 100 metres were ranged but the accuracy decreases from 1% error at 100 metres to about 5% error at 200 metres. Closures of traverses were better than 1:100 vertically, 1:300 horizontally and often exceeded 1:1000.

So, mountain weather is variable and adversely affects the accuracy of barometric surveys in Kananaskis. Obtaining data from steroplotter analysis requires suitable photographs encompassing accurate horizontal and vertical ground control within the stereo pair. Plotting is costly, especially for large areas. The best compromise of accuracy, lightness, mobility and cost appears to be the use of the optical distance measuring tape in conjunction with a Brunton compass. The use of the altimeter is recommended as a quick indicator for location in the field. It is important to carefully evaluate the budget, manpower and equipment constraints, try to find out as much about the weather conditions of the area beforehand and know how much time is likely available to perform the survey.

Appendix B

Analysis of Two Mountain Slopes

B.1 Introduction

The ensuing discussion of Mount Indefatigable and Mount Sparrowhawk is presented under the follwing headings for each site: access and margins of site, bedrock geology, surficial geology, active hazards, hypothetical hazards and analysis.

The morphology of the rockslide deposits is considered as far as it is a distinct surficial landform. No attempt has been made to order the chronology of the deposits. The reader is referred to Voight (1979) which provides discussion of several well known examples or to Muller (1964), Shreve (1968), Hungr (1981) and Mclellan (1983). All contain additional references.

The emphasis herein is placed on the hazards from rockslides, active and hypothetical, found within each site.

The rockslide at Mount Indefatigable is locally referred to as the 'Palliser Rockslide'. The name does not originate from a confusion in the geology of the mountain (the Devonian Palliser Formation underlies the Mississipian Banff Formation) but rather it recognizes the first white man to travel over and note the slide debris. Captain John Palliser (1807-1887) led the British North America Expedition of 1857-60. In August 1858 he led a party up the

Kananaskis River and over North Kananaskis Pass. Spry (1963, p.135) quoted Palliser's account of his passage beyond Upper Kananaskis Lake:

> "The broken, rocky country beyond the lake, with great blocks of limestone heaped up in artificial looking masses, was difficult for horses,...."

The findings of the Palliser Expedition established the feasibility of settling immense tracts of land in what are now the prairie provinces and practicable passes had been found through the Rockies (Fraser, 1969). The name 'Palliser Rockslide' should be retained as a tribute to those early explorers who opened the west for others to follow.

B.2 Mount Indefatigable

B.2.1 Access and Margins of Site

The margins and topography of the site are shown in Figure B.1. Access is from the end of the Kananaskis Lakes Trail at Interlakes day parking area.

Follow the Three Isle Creek trail to gain the deposit zone, lower rupture surface, syncline buttress and Grassi Creek Canyon. Follow the Mount Indefatigable Trail to gain the upper rupture surface, southwest and northeast slopes, ridge crest and peak. The sub-peak is two to three hours from the trail head and the main peak another hour. The

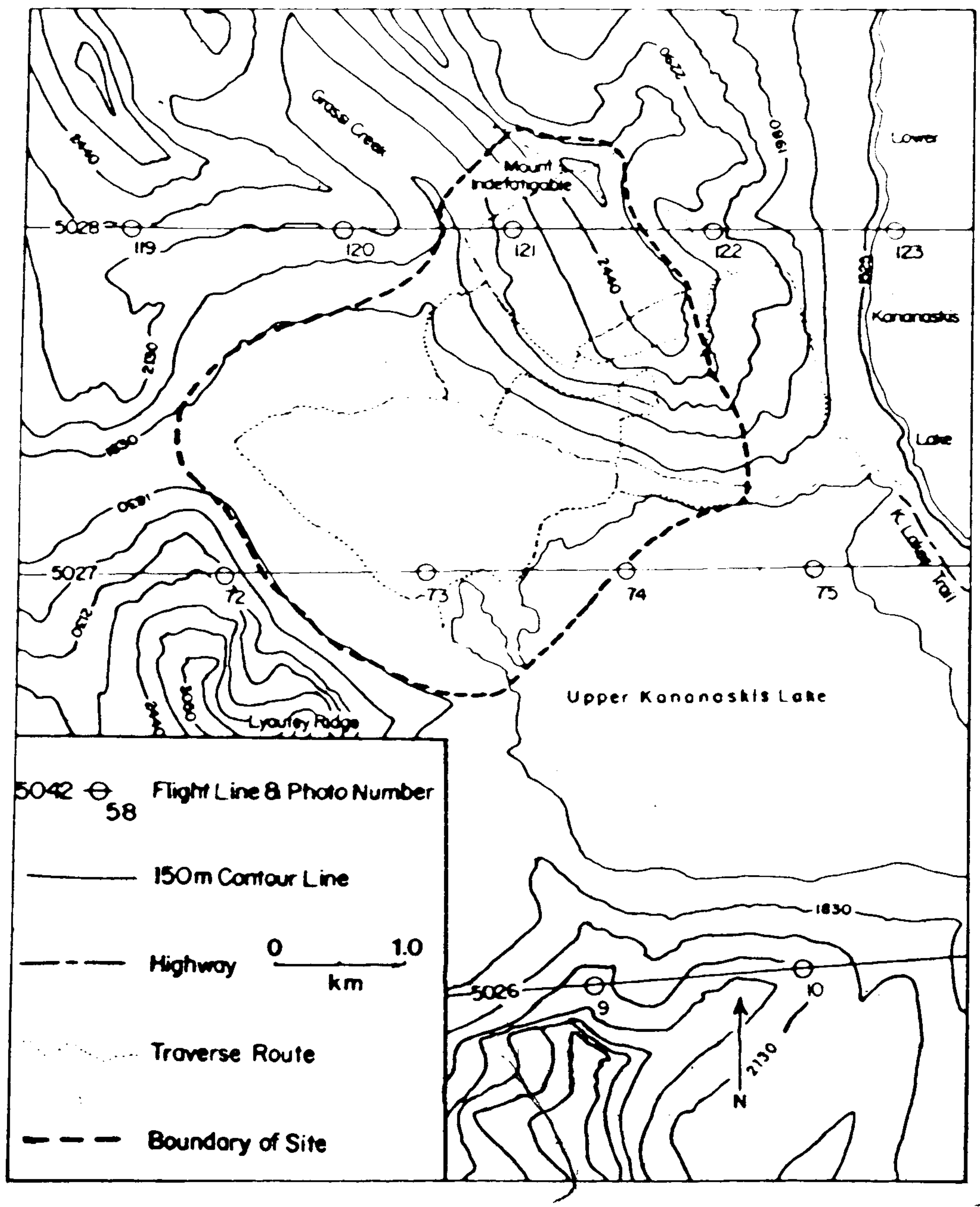


Figure B.1 Margins and topography of Mount Indefatigable.

ridge crest between the sub-peak and main peak is narrow and exposed.

Margins assigned to this site should include the area within these boundaries: The northwest margin follows the ridge of Mt. Indefatigable one hundred metres below on the northeast reverse-dip slope, parallel to the ridge. This margin runs southeast from the peak down to the lake. The southeast margin extends from where the Indefatigable Ridge meets Upper Kananaskis Lake, southwest across the lake to where the northeast end of Lyautey Ridge meets Upper Kananaskis Lake. The southwest margin follows the northeast base of Lyautey Ridge. The northwest margin cuts across the valley from the northeast shoulder of Lyautey Ridge, up the canyon section of Grassi Creek and then up a gully system to the Indefatigable Ridge.

The site is covered by the following air photograph interpretations:

AS 748 5027 72 and 74

AS 748 5028 121

B.2.2 Bedrock Geology

The main structural features are indicated on the air photographs. The Bourgeau Thrust Fault cuts along the base of the northeast slopes of Mount Indefatigable trending northwest. A syncline also trending northwestwards passes 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 (Bielenstein et al., 1971).

East of the fault zone beds dip moderately to steeply southwest. West of the fault zone some variation is created by drag folds immediately to the west but generally beds dip steeply southwest flattening as they near the syncline axis. West of the syncline axis, beds dip steeply 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 slope in the scarp immediately west. The northeast aspects of Mount Indefatigable are all reverse-dip slopes.

The rupture surface is located in the Pekisko Formation. It overlies the Banff which overlies the Exshaw Formation. The last two formations are found in the northeast reverse-dip slopes of Mount Indefatigable. A conspicuous recessive lower unit of black shale identifies the Exshaw Formation on the lower portion of the northeast slopes. The Mississippian Shunda and Turner Valley Formations overly the Pekisko respectively and are found in the southeast under-dip slopes. These Formations are described in Section 2.4.

B.2.3 Surficial Geology

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

B.2.4 Active Hazard Zones

The talus below the scarp faces and dip slopes on the south and southwest aspects of the mountain have accumulated many metres of talus; in one location talus extends over two hundred metres up the dip slope. The talus is loose and moves downslope underfoot; it is receiving new material from the scarps above. Rock fragments and boulders fall from the oblique-dip scarp and bounce or roll downslope. Rockfall was heard whenever in this vicinity. The process of rockfall is active and the area is mapped as a hazardous zone. Higher up, rock fragments fall and bounce from the ridge onto talus just below. This is an active hazard zone. On the northeast reverse-dip slopes (partially inside the site) talus (outside the site) receives fragments and boulders that fall, bounce and roll downslope. This is mapped as an active hazard zone. The rest of the site including the valley bottom and the lower three quarters of the under-dip slope does not appear to have any active hazards. See hazardous zones mapped on Air Photo Interpretations AS 748 5027 72 and 74, and 5028 121.

B.2.5 Hypothetical Hazard Zones

The Palliser Slide removed the south shoulder of Mount Indefatigble. Locat and Cruden (1977) gave 130×10^{6} m^{3} as the volume of rock that slid into the valley and lake. The author feels that this estimate may be on the high side although it is difficult to make an accurate estimate of the volume of rock involved. The pre-slide topography of the valley, lake floor and mountain are not known. It is not possible to prepare estimates from the rockslide deposit because a considerable volume of debris entered the lake.

The present north margin of the rupture surface is formed by a side scarp illustrated in Figure B.2. The side scarp has an area of 180,000 m^2. Depending what pre-slide configuration is assumed for the south end of Mount Indefatigable determines the pre-slide volume estimate. Since the side scarp is smaller in area than a cross-section through the sub-peak, and the ridge slopes into the lake, the original south margin was certainly smaller than the north margin of the slide. The width of the mass is about 500 metres, so the pre-slide volume should fall within the range of 50 to 90 x 10^6 m^3.

The movement was a slide along bedding. The rupture surface is curvilinear in section. Beds are horizontal at the syncline axis and 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.

Several thin calcite beds, 1 to 10 cm thick, were traced along the reverse-dip slope (northeast aspect) over a kilometre. The beds appear to occupy the same plane as the main rupture surface. Calcite is visible on recently exposed beds on the main rupture surface. Traces of calcite are not

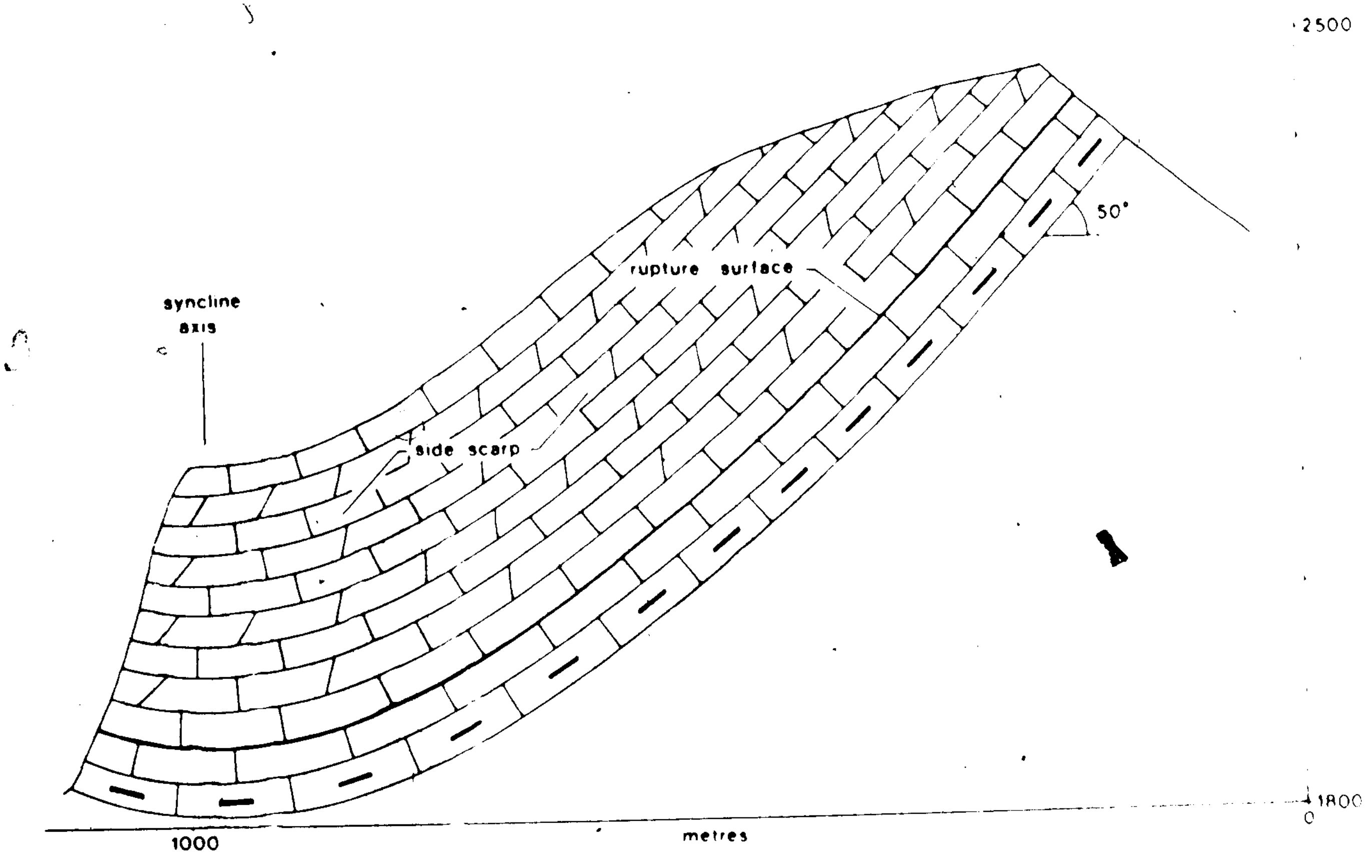


Figure B.2 Rock structure and rupture surface in the north lateral scarp of the Palliser Rockslide.

evident on the older main rupture surface. Calcite could have been comminuted during the slide movement and subsequently removed by erosion and solution. So, the slide may have occurred in this calcite zone and solution may have served to lessen the resistance along this contact. Other movements also occurred. Shearing normal to bedding along the dip direction of bedrock on the rupture surface is indicated where calcite veins are dislocated by several centimetres.

The rock in the slide surface is a well jointed limestone of the Pekisko Formation (Section 2.4). The Rundle is reported as having slid elsewhere in the Canadian Cordillera (Locat and Cruden, 1977). Pre-sheared limestone beds have a reduced strength perhaps best estimated by their basic friction angle, ϕ_b, of about 30° (Cruden, 1984). Basic friction angles of limestones from Mount Indefatigable varied between 23.3°±0.5° and 25.3°±1.2° (Table B.3, repeated uncleaned tests). Those of calcite and calcite on limestone were 39.9°±1.0° and 40.2°±0.7°, respectively. Solution may reduce the friction angle of calcite but this has not been confirmed.

With no cohesion between beds and dips exceeding their basic friction angle over much of the rupture surface the Palliser Slide could have occured when support was reduced in the synclinal buttress, high pore and seepage pressures developed, or a seismic acceleration occurred.

The southwest slopes of Mt. Indefatigable, north of the slide area, are similar in structure to the pre-slide mass. Additional resistance to sliding is still provided by a buttress of rock dipping northeast into the mountain because of 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 diverts along the syncline axis. Rockfall, seepage and solution processes are active. Over 300 x 10^6 m^3 of slope possess the topography and attitude of the slid mass.

This area is mapped as a hypothetical hazard zone. See hypothetical zones mapped on Air Photograph Interpretations AS 748 5027 72 and 74, and 5028 121. Based on the empirical study by Tianchi (1983), the travel distance of the slide could exceed 5 kilometres (Figure B.3). The base of Lyautey Ridge is 4 kilometres across the valley from the top of Mount Indefatigable and would redirect the slide. Debris could flow up the Upper Kananaskis River Valley, up the slopes of Lyautey Ridge and fall back upon itself and debris would flow into Upper Kananaskis Lake. It is not the scope of this study to consider the mechanics and route of such a rockslide. Comparison with the Palliser Rockslide indicates the debris would slide up to the base of Lyautey Ridge. The extent of the hypothetical zone has been based on this comparison and not on the greatest travel distance that Figure B.3 suggests for such a volume. No analysis has been

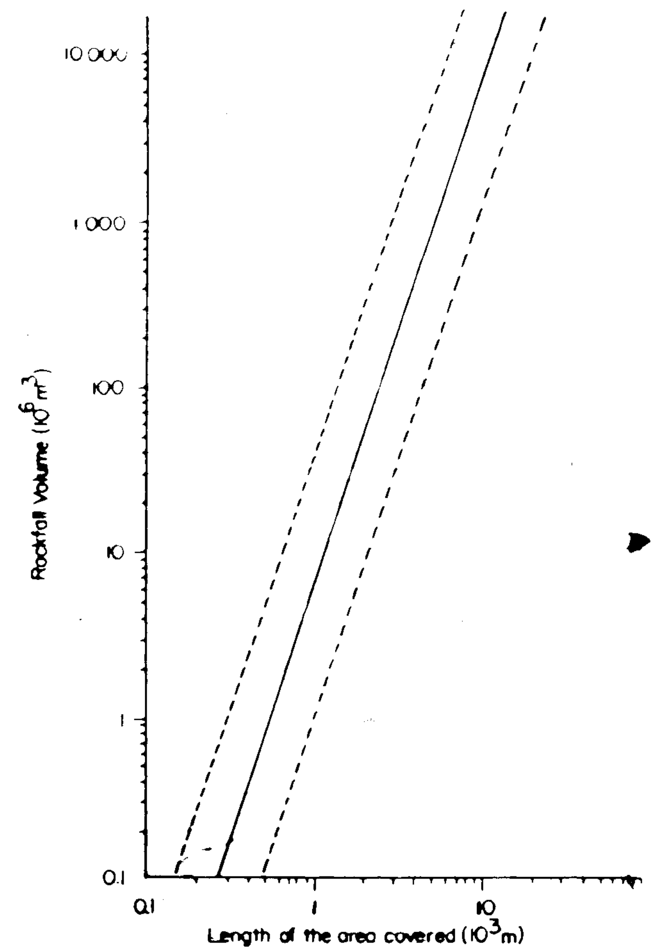


Figure B.3 The length of the deposit area in relation to the volume of rockfall. Broken lines represent the standard deviation of the full correlation.

carried out of the effects of such a volume of debris sliding into Upper Kananaskis Lake and the subsequent wave generation and hazards to dam structures and facilities downstream.

B.2.6 Analysis of Mt. Indefatigable

Analysis of the Palliser Rockslide and hypothetical section was performed using the method of stability analysis proposed by Sarma (1979). The analysis was done at the University of Alberta using a program written by Wong (1985) for the Department of Civil Engineering.

The Sarma method was selected over others because of the availability of a computer program, an outside horizontal load can be introduced, pore pressures can be varied, it considers rigorously the kinematics of sliding blocks on general slip surfaces and large slices can be used (Morgenstern and Price, 1965; Morgenstern and Sangrey, 1978; Sarma, 1979).

The slip surface for both sections is defined by the existing rupture surface. It is projected into the slope based on field measurements and observations for the hypothetical section.

Inclusion of seismic loading seems appropriate to complete the analysis. Seismic activity is considered a trigger mechanism in the Nevados Huascaran (1970), Sherman Glacier, Hope, Madison Canyon and Lower Gros Ventre landslides (Voight, 1979) as examples.

Two sections are considered (Figure B.4). The first is the Palliser Rockslide sidescarp, section A-A, near the south end of the Mount Indefatigable ridge, and the second is the hypothetical slide, section B-B, 500 metres north of the sidescarp.

Four sets of 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 most of the year except during spring runoff or after an intense rainstorm when it may rise substantially for a short time. Recharge is enhanced by the large under-dip slope on the southwest aspect and the reverse-dip slope on the northeast aspect.

A horizontal earthquake loading of 0.04g is taken from the 1985 Canadian seismic loading map (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 set between 40°, 30° and 25°. The 40° and 25° are rounded ϕ_b values obtained from tilt tests on calcite and limestone

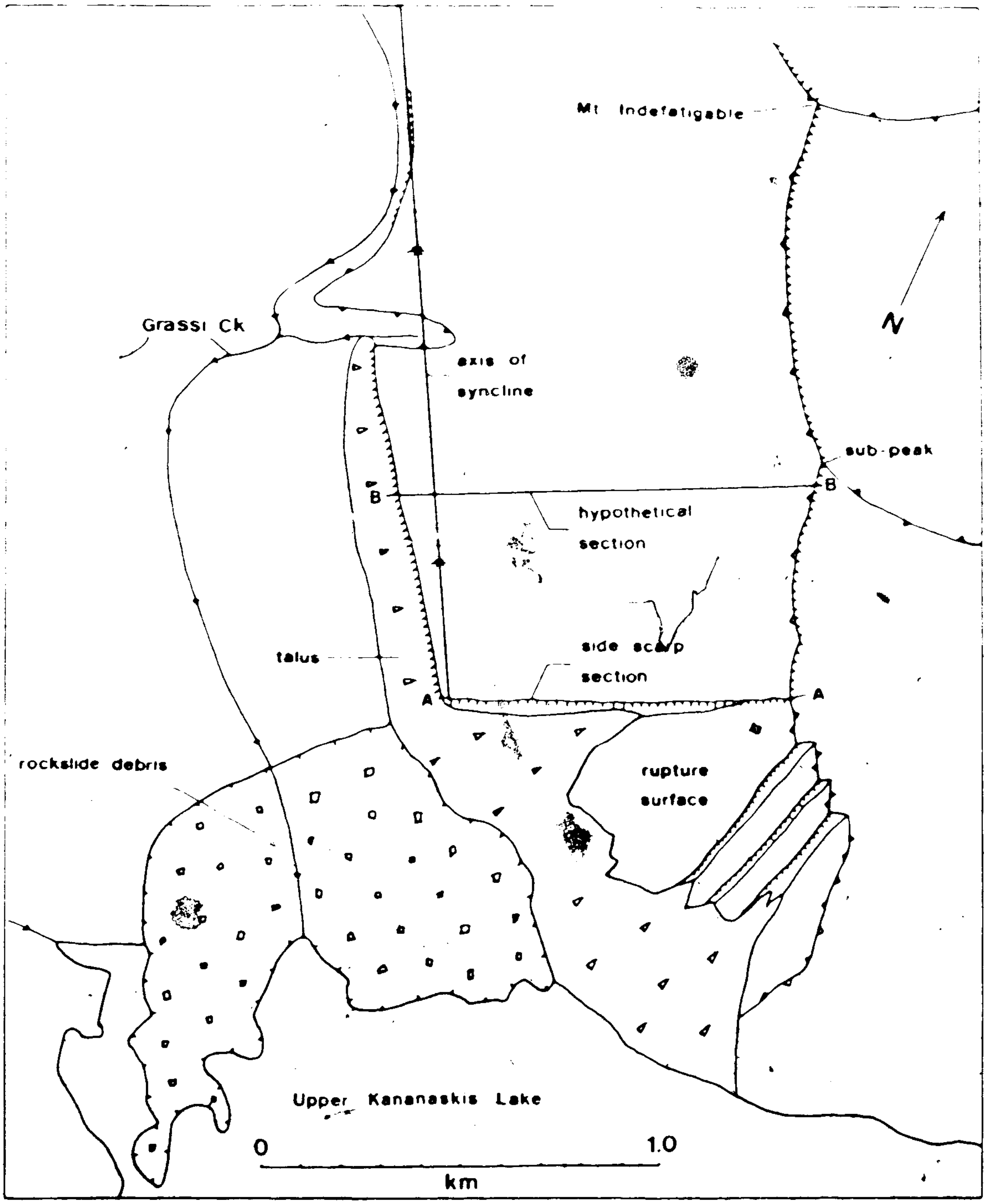


Figure B.4 Physical features of Mount Indefatigable showing the location of sections. Symbols are explained in Appendix C.

taken from the site, respectively. The lower value for limestone is used here although values up to 35.5°±1.3° (repeated uncleaned tests) were obtained from Rundle limestones in the study area. The value of 30° has been suggested for rockslides in Mississippian Rundle limestone elsewhere (Cruden, 1984).

The sidescarp section is shown in Figure B.5 and the results in Table B.1. The following are apparent:

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. Seperately, pore pressure and earthquake loading reduce the factor of safety in a similar amount. Either one is sufficient to lower the factor of safety below 1.0.

It is reasonable to assume that the pre-slide configuration south of the sidescarp possessed a similar or less stable geometry.

Effect of buttress support is examined in the hypothetical section (Figure B.6). It possesses a longer slip surface and additional rock buttress in the toe of the slope. The slip surface in the toe was made horizontal. Following the bedding surfaces in the toe west of the syncline axis (Figure B.2) produced tension in the base of the first slice. There is no evidence visible at the site to support the idea that the present rockslide debris slid up northeast dipping beds when the slope failed. Rupture could

Table B.1 Sidescarp Section results of analysis using Sarma Method.

RUPTURE SURFACE		EARTHQUAKE LOAD, HORIZONTAL	FACTOR of SAFETY
PORE PRESSURE	FRICTION ANGLE		
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	0.04g	1.2
X	30	0.04g	0.9
X	25	0.04g	0,8
0	40	0.04g	1.3
0	30	0.04g	1.0
0	25	0.04g	0.9

g = acceleration of gravity
X = water table as indicated in Figure 9.5.
Rupture surface cohesion = 0 for all cases.
Interslice cohesion = 100 kPa for all cases.
Interslice friction angle = 30° for all cases.

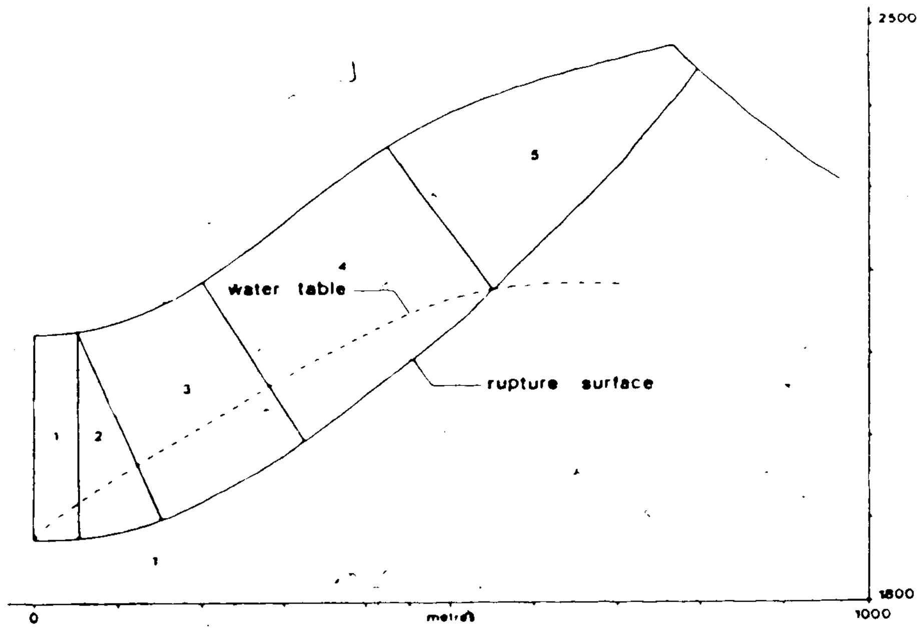


Figure B.5 North sidescarp section of Palliser Rockslide showing slices and water table used in analysis.

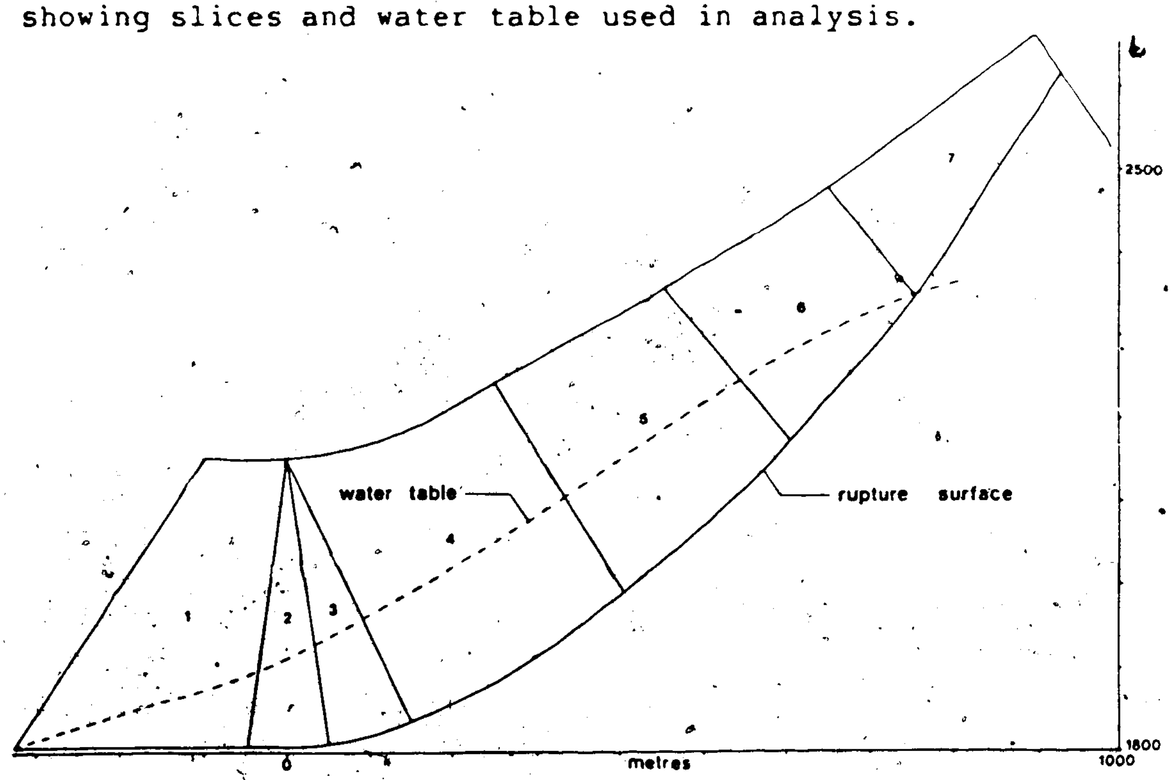


Figure B.6 Hypothetical section through Mount Indefatigable showing slices and water table used in analysis.

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 B.2). The worst case, that of pore pressures, earthquake loading and ϕ = 25° gives a factor of safety of 1.005 although pore pressures and an earthquake acting simultaneously is unlikely.

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

So, the analysis gives us a post-mortem for the north slide margin, section A-A, and the present state of health for the hypothetical slope, section B-B. The Palliser Rockslide occurred with a friction angle of about 30° along the rupture surface. Retreat of the synclinal buttress, pore pressures and seismic loading acting independently or in combination may have 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 foreseeable future. This is unlikely considering present environmental conditions.

Table B.2 Hypothetical Section results of analysis using Sarma Method.

RUPTURE SURFACE		EARTHQUAKE LOAD, HORIZONTAL	FACTOR of SAFETY
PORE PRESSURE	FRICTION ANGLE		
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	0.04g	1.5
X	30	0.04g	1.2
X	25	0.04g	1.0
0	40	0.04g	1.6
0	30	0.04g	1.3
0	25	0.04g	1.1

g = acceleration of gravity
X = water table as indicated in Figure 9.6.
Rupture surface cohesion = 0 for all cases.
Interslice cohesion = 100 kPa for all cases.
Interslice friction angle = 30° for all cases.

B.3 Mount Sparrowhawk

B.3.1 Access and Margins of Site

The margins and topography of the site are shown in Figure B.7. Access to the site is from the Smith-Dorrien-Spray Trail. Park at the first creek (North Creek) which crosses the road north of Goat Range Viewpoint. Strike off up the true right bank, the true left and right banks are those when looking downstream, to gain access to the upper main slopes, ridge and peak of Mount Sparrowhawk. There is no district trail but stay well above the creek and leave it completely after a short distance when steep slopes appear through the trees on your left. Switchback up these until above treeline where the route becomes obvious.

Park at the Goat Range Viewpoint to gain access to the sub-peak, rockslide deposit, rupture surface and the upper reaches of Sparrowhawk Valley. Strike off up the true right bank of the creek (Middle Creek), stay well above the creek and follow distinct game trails up the valley. After 25 minutes you will enter the valley proper and catch glimpses of over-dip slopes on the sub-peak to your left. Continue valley another hour to gain the rockslide deposit.

Margins assigned to this site should include the area within these boundaries: The west margin lies in the waters of Spray Lakes Reservoir from South Creek to North Creek. The north margin follows east along the north bank of North Creek up the ridge crest to Mount Sparrowhawk. The east

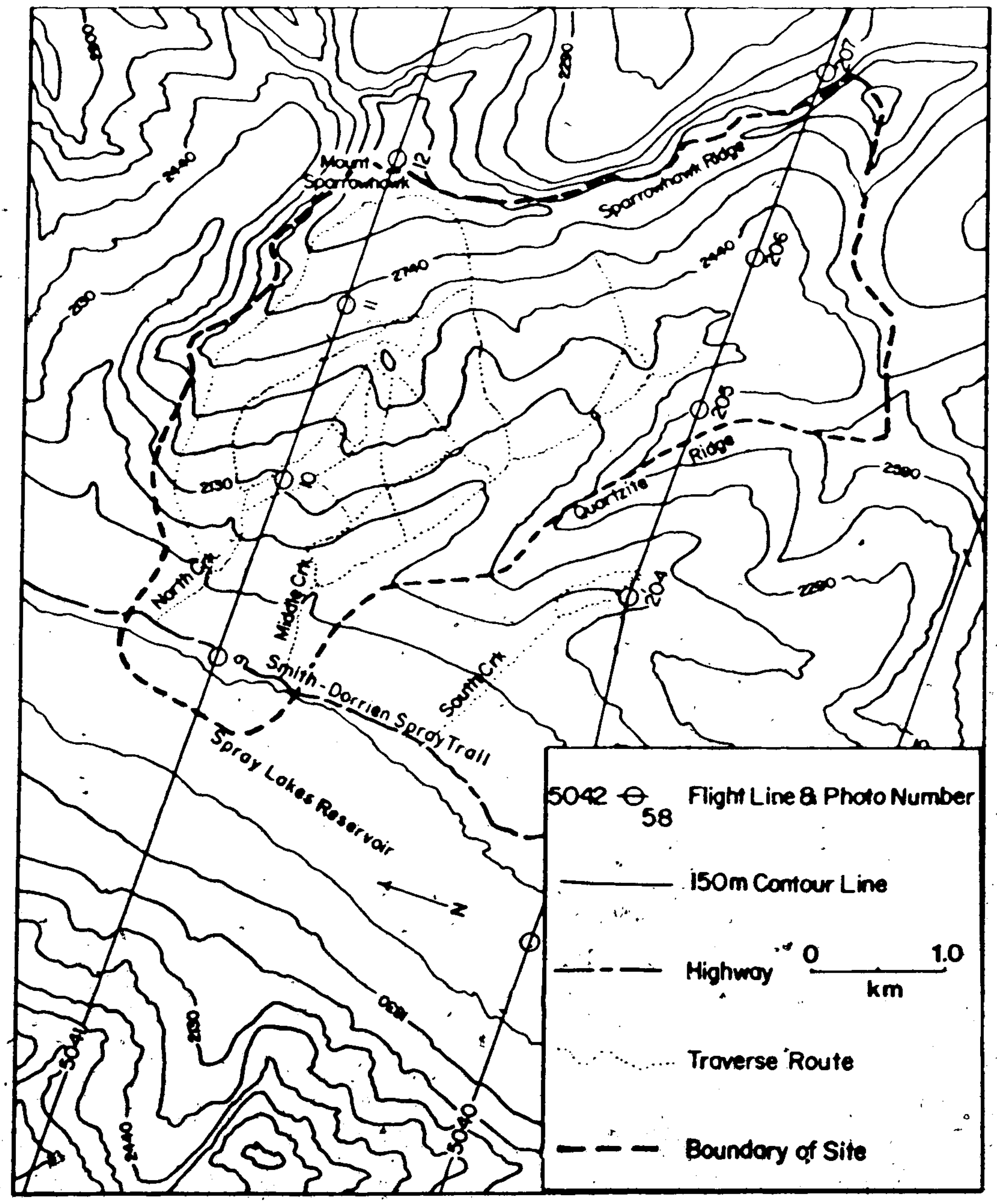


Figure B.7 Margins and topography of Mount Sparrowhawk.

margin follows the ridge crest south from Mount Sparrowhawk to Mount Bogart. Incorrectly indicated on National Topographic System map 82J/14, Mount Bogart is 1.5 kilometres southwest of the peak so named (Kananaskis Country Ranger, Pat Harrison, personal communication). The south and southwest margin of the site follows the ridge crest west from Mount Bogart and then northwest along another ridge crest back to the lake down Middle Creek staying on the true left bank of the creek.

The site is covered by the following air photograph interpretations:

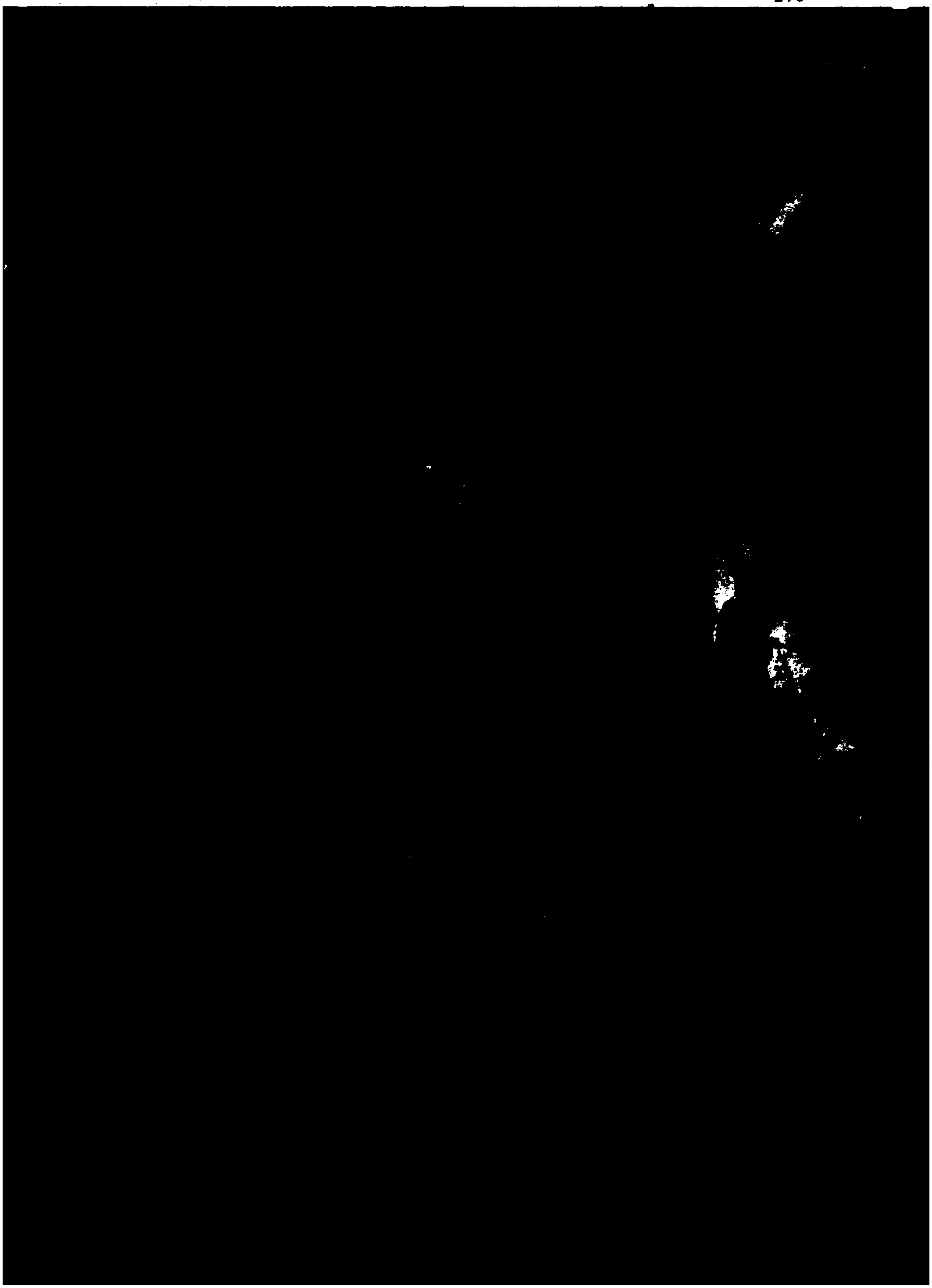
AS 746 5040 204 and 206

AS 745 5041 9, 10 and 12

B.3.2 Bedrock Geology

The main structural features are indicated on the air photographs. 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 (Bielenstein et al., 1971). Mississipian Rundle Group rock is exposed throughout the site. The Turner Valley and Shunda Formations are contained in the lower southwest slopes. They are overlain by the Mount Head and Etherington Formations which form the skyline of Sparrowhawk. Refer to Section 2.4 for geological descriptions of these formations.

Beds dip 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 were located in the vicinity of the rupture surface and likely provided slide 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.

B.3.3 Surficial Geology

The Canmore Drift covers lower slopes near the Spray Lakes Reservoir (Jackson, 1976). In the valley proper ice scoured bedrock floors most of the 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 [illegible]aces these deposits extend to the valley floor.

B.3.4 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 Sparrowhawk Peak 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.

See hazardous zones mapped on Air Photograph Interpretations AS 745 5041 9, 10 and 12. The main dip slopes on Mount Sparrowhawk do not pose any active hazards, and neither do the forested slopes adjacent to the lake.

B.3.5 Hypothetical Hazardous Zones

The hypothetical hazards cover large portions of the Sparrowhawk site. A large rockslide exceeding 10×10^6 m^3 occurred from Sparrowhawk Ridge (Figure B.8). Over-dip slopes line Sparrowhawk Ridge, the toe of the sub-peak and main peak's slopes. The beds dip linearly 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. Bedding surfaces are poorly exposed because of weathering, talus, colluvium or inaccessibility. Folding is not evident and cohesion may persist along beds.

Other evidence indicates a weakened rock structure and indirectly supports the possibility that flexural-slip has occurred. Tear faults define both the left and right margins of the slide. These tear faults follow joint sets normal to bedding and strike in the dip direction. A reverse fault and

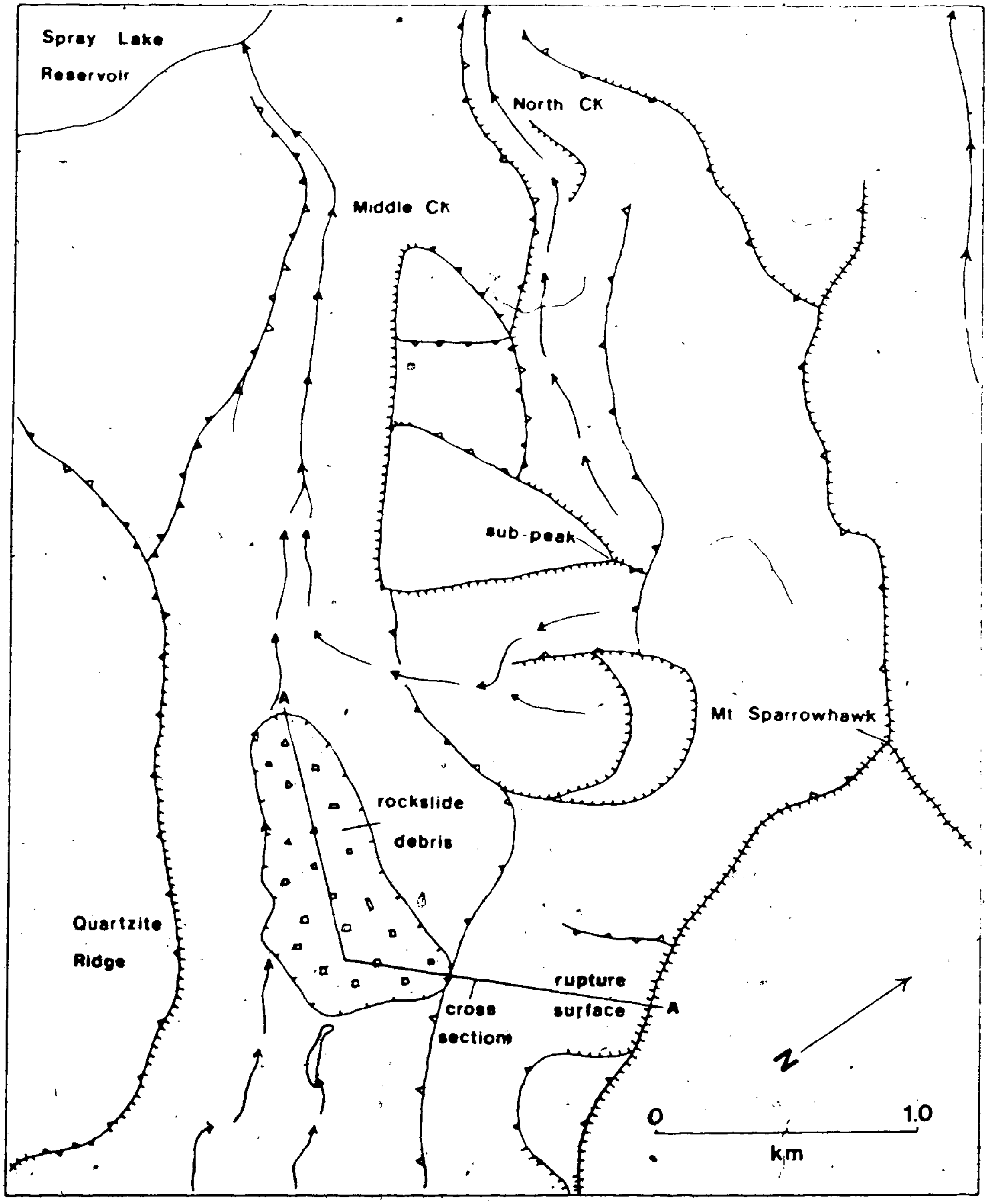


Figure B.8 Physical features of Mount Sparrowhawk showing the section location. Symbols are explained in Apppendix C.

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 fault systems. Flexural-slip was probably induced along some beds in conjunction with these fault displacements.

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°. This attitude is repeated again in the main peak, in particular that portion of the main peak which is situated 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 connecting joint sets down dip aggavated by gully erosion could provide the other lateral margin.

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.

See hypothetical zones mapped on Air Photograph Interpretations AS 745 5041 9, 10 and 12. 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. Stratigraphy falls in the Mississipian Rundle Group which has been unstable elsewhere in the Canadian Cordillera (Locat and Cruden, 1977) and exhibit a high probability of rockslide occurence in Kananaskis.

A rockslide from the main peak could exceed 100 x 10^6 m^3. According to Tianchi (1983) such a rockslide may come to rest in the Spray Lakes Reservoir (Fig. B.3). No analysis has been carried out on the effects of such a volume of debris 'flowing' into Spray Lakes Reservoir and the subsequent wave generation.

B.3.6 Analysis of Mount Sparrowhawk

The Mount Sparrowhawk site can be regarded by simple sliding down an inclined plane. Pore pressure and earthquake loading can be considered. The limit equilibrium equation for simple frictional sliding complete with cohesion, a water filled joint and a horizontal earthquake load is:

$$F = \frac{cA + (W\cos\alpha - U - E\sin\alpha)\tan\phi}{W\sin\alpha + V + E\cos\alpha} \qquad \text{Eqn. B.1}$$

Where:

ϕ = friction angle on the slide surface

α = 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

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 B.1 reduces to:

$$F = \frac{\tan\phi}{\tan\alpha} \qquad \text{Eqn. B.2}$$

A cross section (Figure B.9) shows bedding inclined at 25° to 30° on an over-dip slope. The lowest value for the basic friction angle from Sparrowhawk was obtained from a dolomite which slid at 23.3°±0.6° on the tilting table. The highest value was from a limestone which slid at 35.5°±1.3° (repeated uncleaned tests). The dip of bedding and the basic friction angle are in the same range.

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 lower the factor of safety below 1.0 and trigger a rockslide.

Rockslides from Mount Sparrowhawk are evidence that this condition has occurred in the past. Resistance to sliding may be enhanced by cohesion, but weathering eventually destroys this. Rockslides can be expected from Mount Sparrowhawk when these conditions repeat in the future. It is not possible to predict the scale and frequency of such events. We know that one or more large rockslides (depending on the chronology of the contiguous rockslide deposit) took place since the last major glaciation.

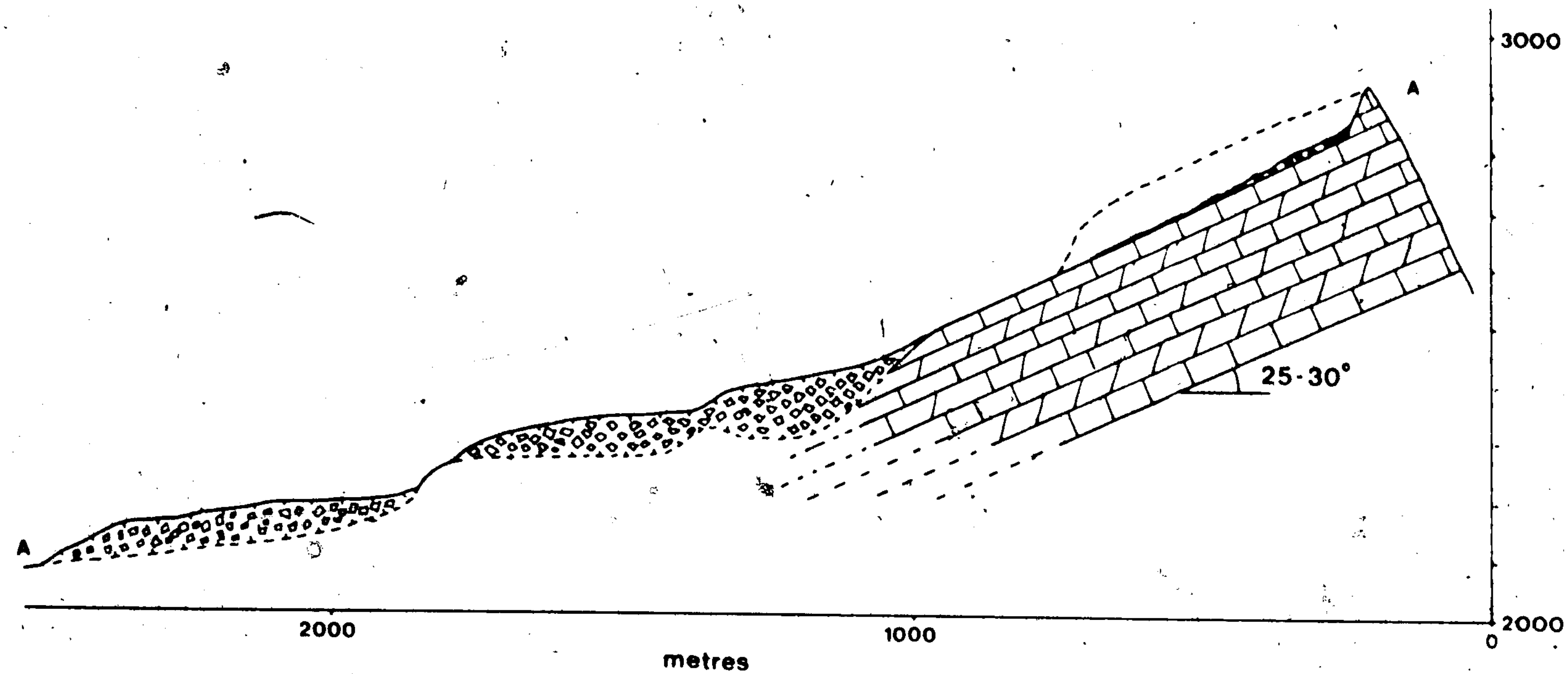


Figure B.9 Section through rupture surface and rockslide deposit at Mount Sparrowhawk.

So, at Sparrowhawk we have a minimum frequency of 1 large event in 10,000 years. The frequency may be higher than this. Inspection of the rockslide deposit suggests there may be 5 separate events based on geometry and 2 distinct ages based on weathering of surface debris in the deposit. The 5 lobes are indicated in Figure B.10, and the 2 ages in Figure B.11. A higher frequency of 1 large event every 2,000 years is possible.

If 5 smaller rockslide deposits located along the ridge between Mount Sparrowhawk and Mount Bogart are included, a frequency of 1 event every 1000 years is possible. Cruden (1984) suggested 1 event every 500 years is possible in the Canadian Cordillera.

B.4 Summary

The potential for large rockslides exists at Mount Indefatigable and Mount Sparrowhawk. Both sites contain over-dip slopes which exhibit the highest probability of large rockslides in Kananaskis. The slopes are in Mississippian Rundle Rock which also exhibits a high probability for rockslides.

A hypothetical slide mass surpasses 300 x 10^6 m^3 at Indefatigable and 100 x 10^6 m^3 at Sparrowhawk. The basic friction angle, ϕ_b, used as a lower bound suggests that the hypothetical masses may not possess factors of safety significantly above 1.0, especially during seasonal rises in the water table. Pore pressures and earthquake loading may

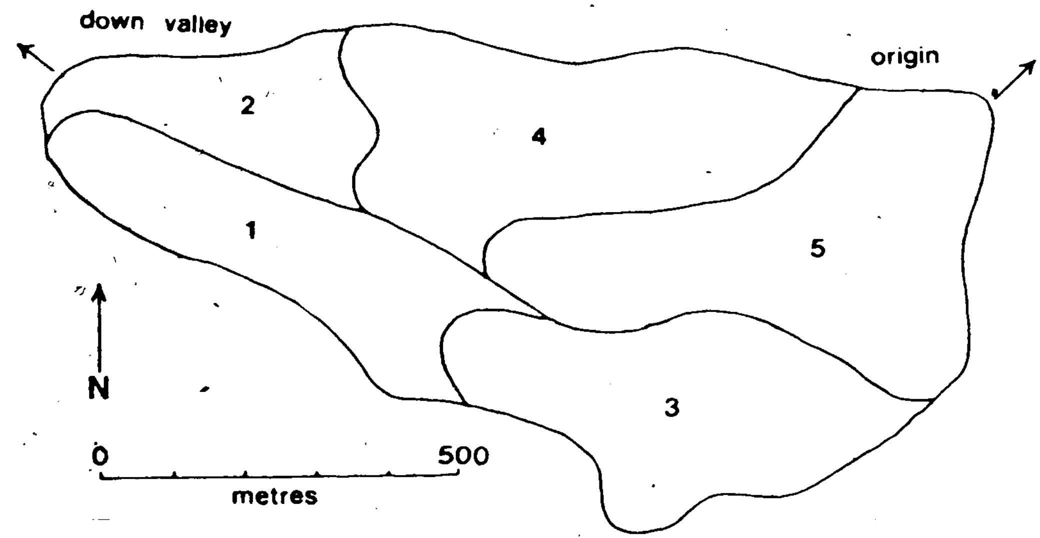


Figure B.10 Five lobes in the Mount Sparrowhawk rockslide deposit.

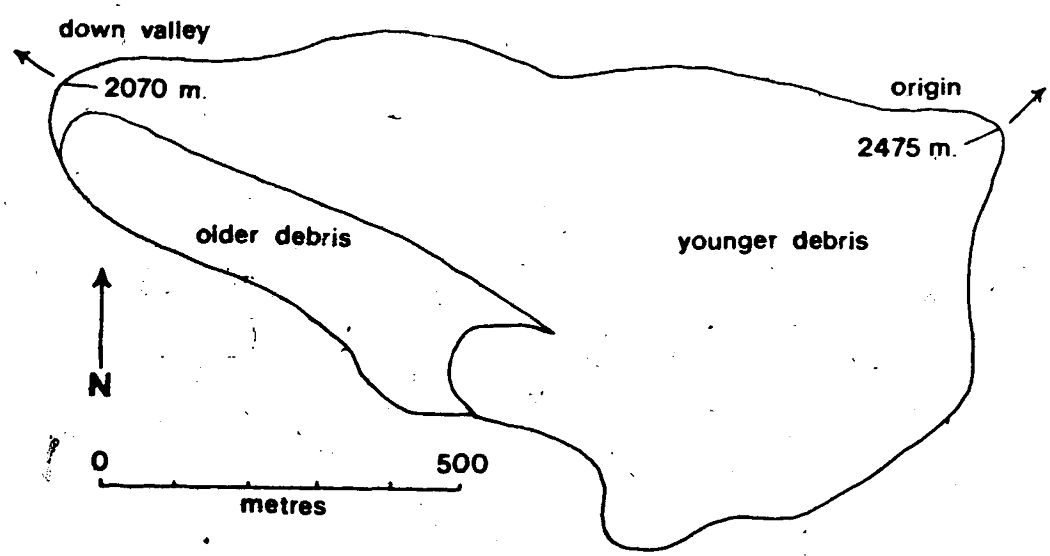


Figure B.11 Two distinct ages in the Mount Sparrowhawk rockslide deposit.

act as the critical trigger mechanism(s).

Processes of weathering are active. Freeze and thaw cycles can occur any time of the year, daily during the spring and fall. Rockfall frequency exhibits diurnal cycles dependent on freeze and thaw (Gardner 1983, and Luckman, 1976). Water was noted seeping from bedding, joints and solution caves. Karren are common on exposed bedrock.

In the short time scale since the last major glaciation (about 10,000 yrs B.P.) extreme events such as rockslides have modified the landscape of Mounts Indefatigable and Sparrowhawk. The exceeding of a threshold stress causes a step-like change in landforms, but the nature of the threshold may be one of three kinds (Selby, 1982):

1. An increase in external stress produces a sudden change - as pore pressures rise after a storm or the loading from an earthquake.
2. A reduction in internal resistance by progressive weathering - as cohesion and friction are lowered.
3. A gradual landform change until a condition of potential instability is reached - as rockfall reduces the buttress support in the toe of Mount Indefatigable.

Future rockslides are inevitable at both sites and could send debris into either the Upper Kananaskis Lake or the Spray Lakes Reservoir, respectively. Flood waves could be generated.

Appendix C

Air Photograph Rockslide Hazard Interpretations

C.1 Introduction

All the symbols used in air photograph interpretations are explained in the following list. A brief explanation is provided to the right of each symbol. Topographic conditions can vary frequently over short distances on some slopes. A slope type symbol indicates the conditions prevailing only at the arrowhead but often reflects the dominant slope type on that particular aspect. The geomorphilogical and mass movement symbols are from Dearman (1972).

A flight line map provides a reference for locating the air photograph interpretations which flag rockslide hazards in Kananaskis. The clear rectangular areas indicate areas interpreted along each flight line, and the circles are the centres of individual air photographs interpreted. The shaded areas are not interpreted and generally represent valley bottoms and forested terrain.

A list of air photograph interpretations is included. Photographs are ordered from left to right along flight lines, and flight lines increase from 5023 in the south to 5043 in the north. The air photographs can be interpreted to provide visual information such as hazard boundaries, bedrock structure, topography, rock debris and vegetation. Each one covers an area of about 2.9 by 3.6 kilometres.

About 10% overlap east-west and 20% overlap north-south occurs on adjacent interpretations.

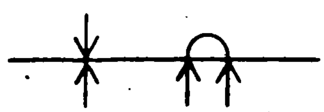
Air photograph interpretation symbols:

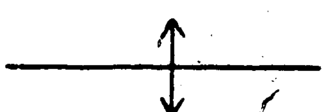
Boundary of Kananaskis study area and 'specific site' or 'other relevant area' when appropriate.

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

Boundary of hypothetical hazard.

Boundary of active hazard.

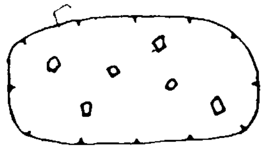

Axial trace of syncline, arrows point in.


Axial trace of anticline, arrows point out.

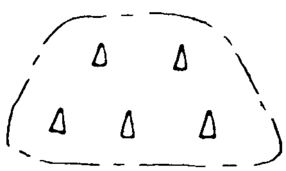

Thrust fault, points on up-thrust side.

Tear fault,

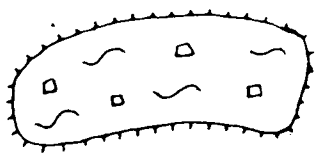
Debris flow channel.



Rockslide or rockfall deposit, high magnitude low frequency, process active.



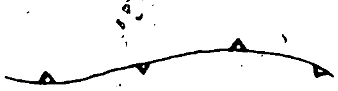
Talus deposit, triangles point up-slope, low magnitude high frequency, process active.



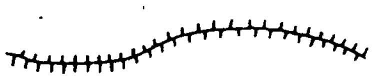
Rock glacier, a form of seasonal creep but not a rockslide or rockfall deposit.

Cross-section illustrated in figures.

Geomorphological symbols found in Figures 2.1, B.4, B.8:



Ridge crest, rounded.



Ridge crest, sharp, free faces on either side.

Ridge crest, free face on one side only.

Slope type symbols: Used on air photograph interpretations, these symbols describe conditions at arrowhead only. Arrows point down-slope.

D → Dip slope, strike of slope and bedding are parallel within 20°. Beds dip parallel to slope.

OD → Over-dip slope, same as above except slope dips steeper than bedding.

UD → Under-dip slope, same as above except bedding dips steeper than slope.

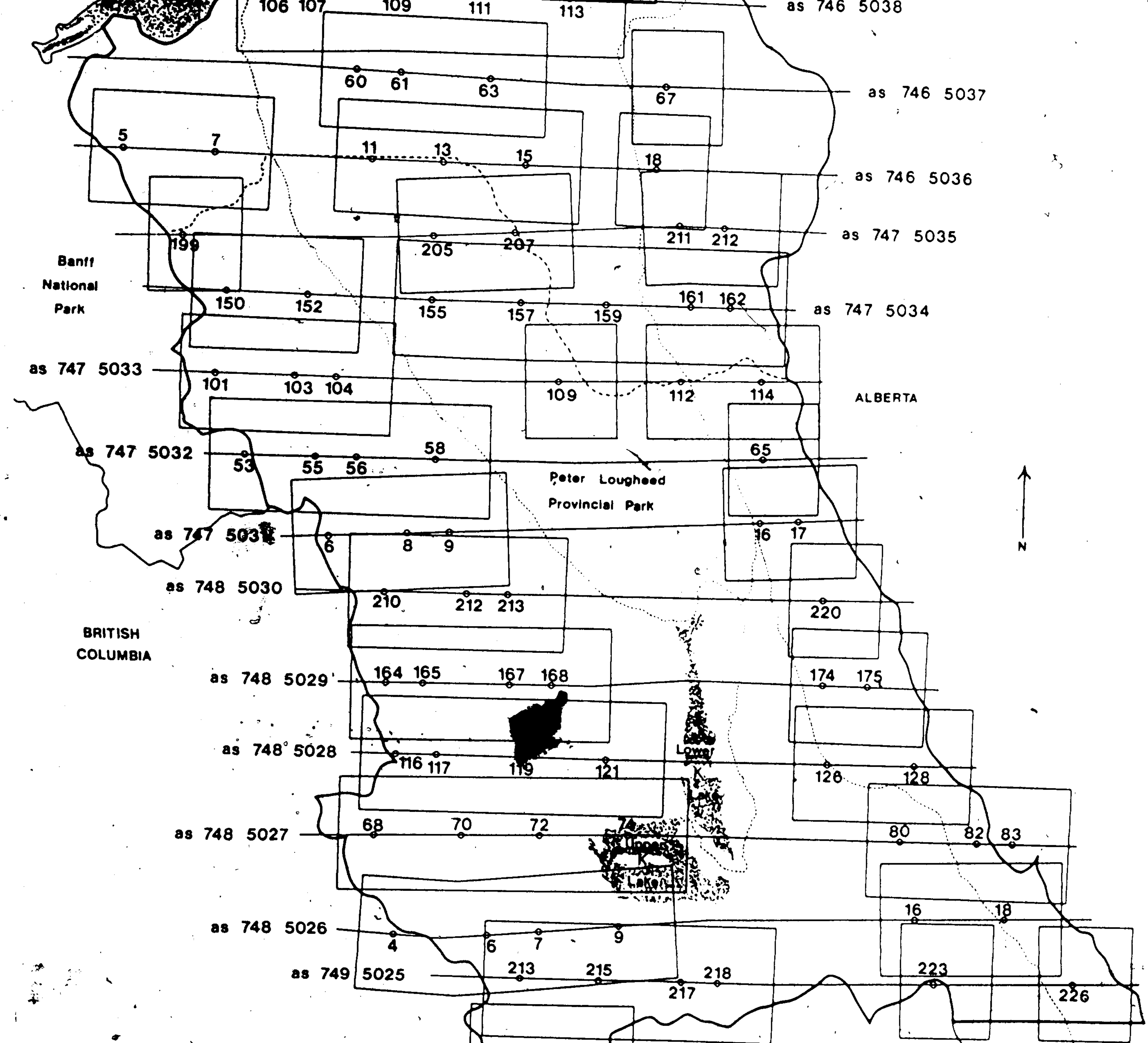
RD → Reverse-dip slope, same as above except bedding dips into slope.

S → Strike-dip slope, strike of bedding is perpendicular to strike of slope within 20°. Dip of bedding can be vertical or inclined.

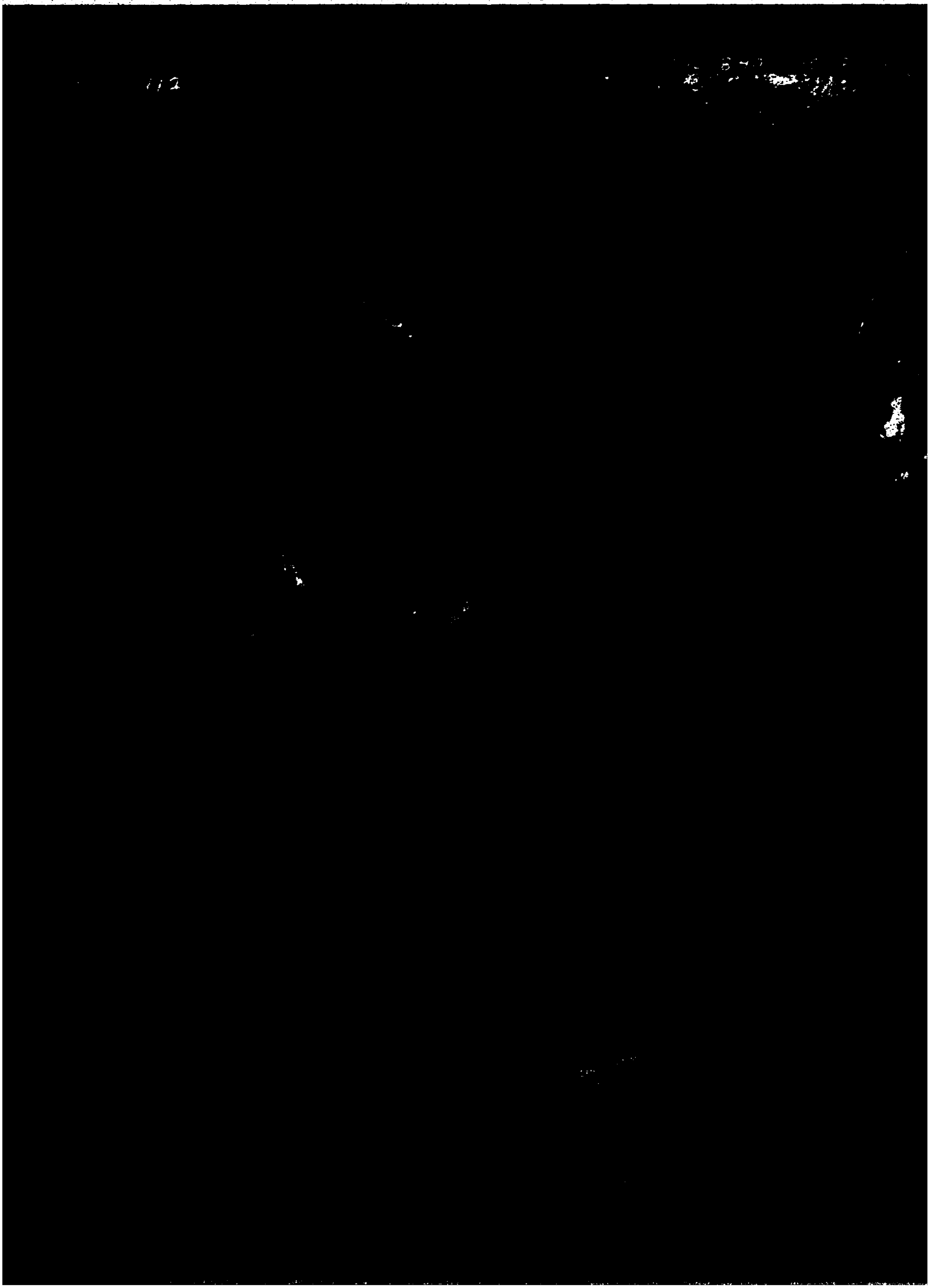
O → Oblique-dip slope, strikes of bedding and slope differ by more than 20° but less than 70°. Dip of bedding can be vertical or inclined.

Table C.1 List of air photograph interpretations.

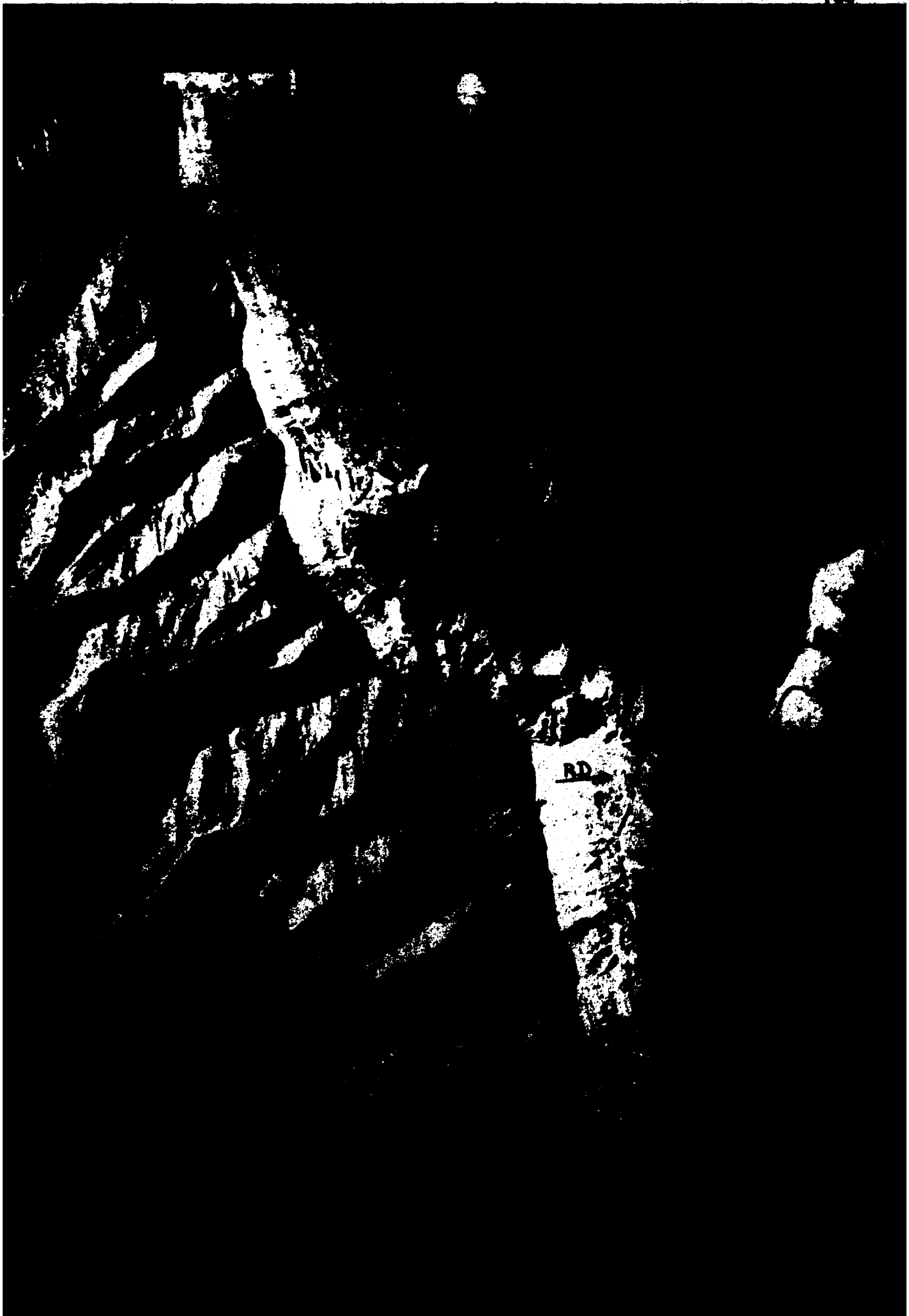
FLIGHT LINE NUMBER	PHOTOGRAPH NUMBERS
AS 749 5023	117
AS 749 5024	160, 162
AS 749 5025	213, 215, 217, 218, 223, 226
AS 748 5026	4, 6, 7, 9, 16, 18
AS 748 5027	68, 70, 72, 74, 80, 82, 83
AS 748 5028	116, 117, 119, 121, 126, 128
AS 748 5029	164, 165, 167, 168, 174, 175
AS 748 5030	210, 212, 213, 220
AS 747 5031	6, 8, 9, 16, 17
AS 747 5032	53, 55, 56, 58, 65
AS 747 5033	101, 103, 104, 109, 112, 114
AS 747 5034	150, 152, 155, 157, 159, 161, 162
AS 747 5035	199, 205, 207, 211, 212
AS 746 5036	5, 7, 11, 13, 15, 18
AS 746 5037	60, 61, 63, 67
AS 746 5038	106, 107, 109, 111, 113
AS 746 5039	153, 155, 157, 159, 161
AS 746 5040	204, 206, 208, 210
AS 745 5041	9, 10, 12, 14
AS 745 5042	54, 56, 58
AS 745 5042/43	91, 93, 95

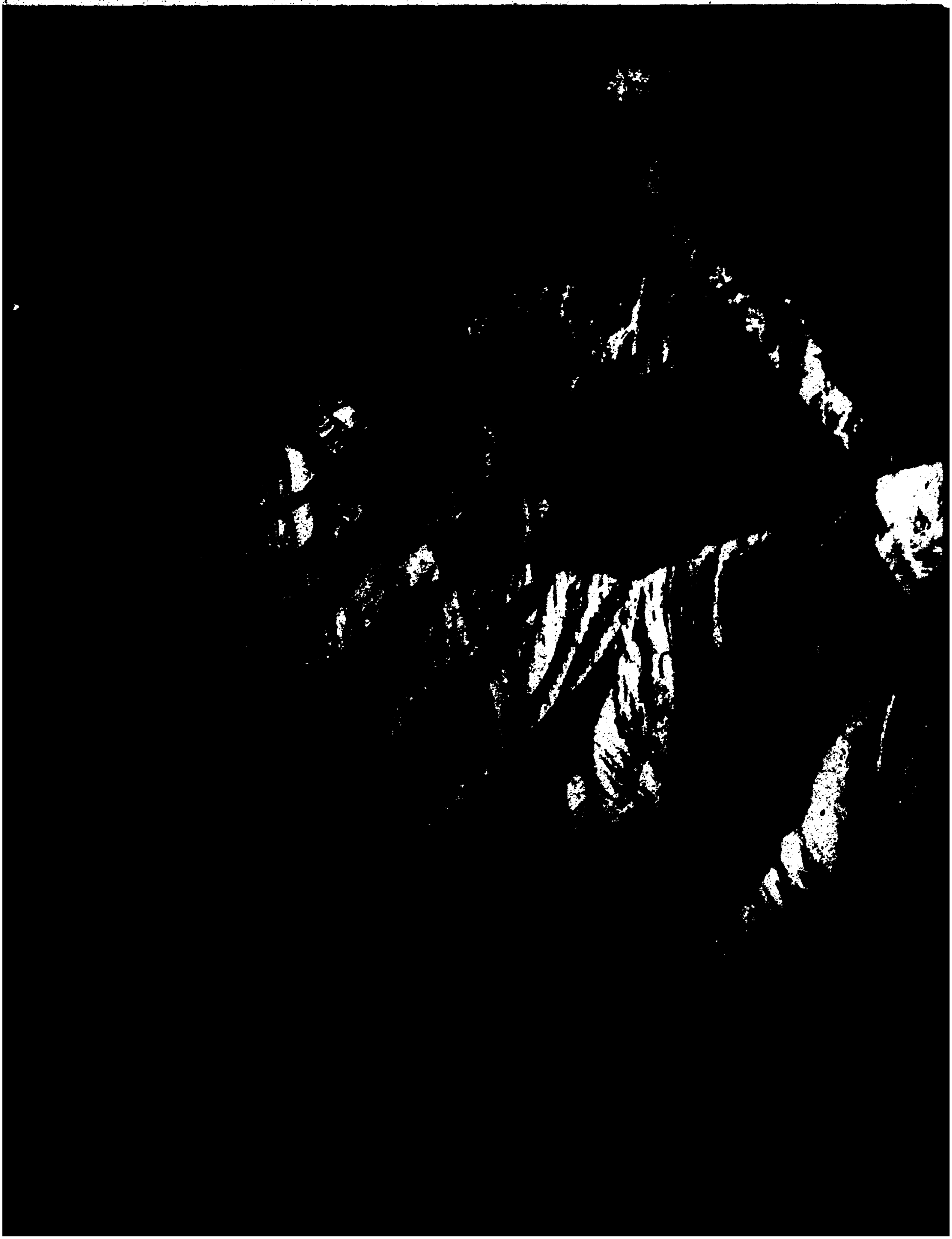


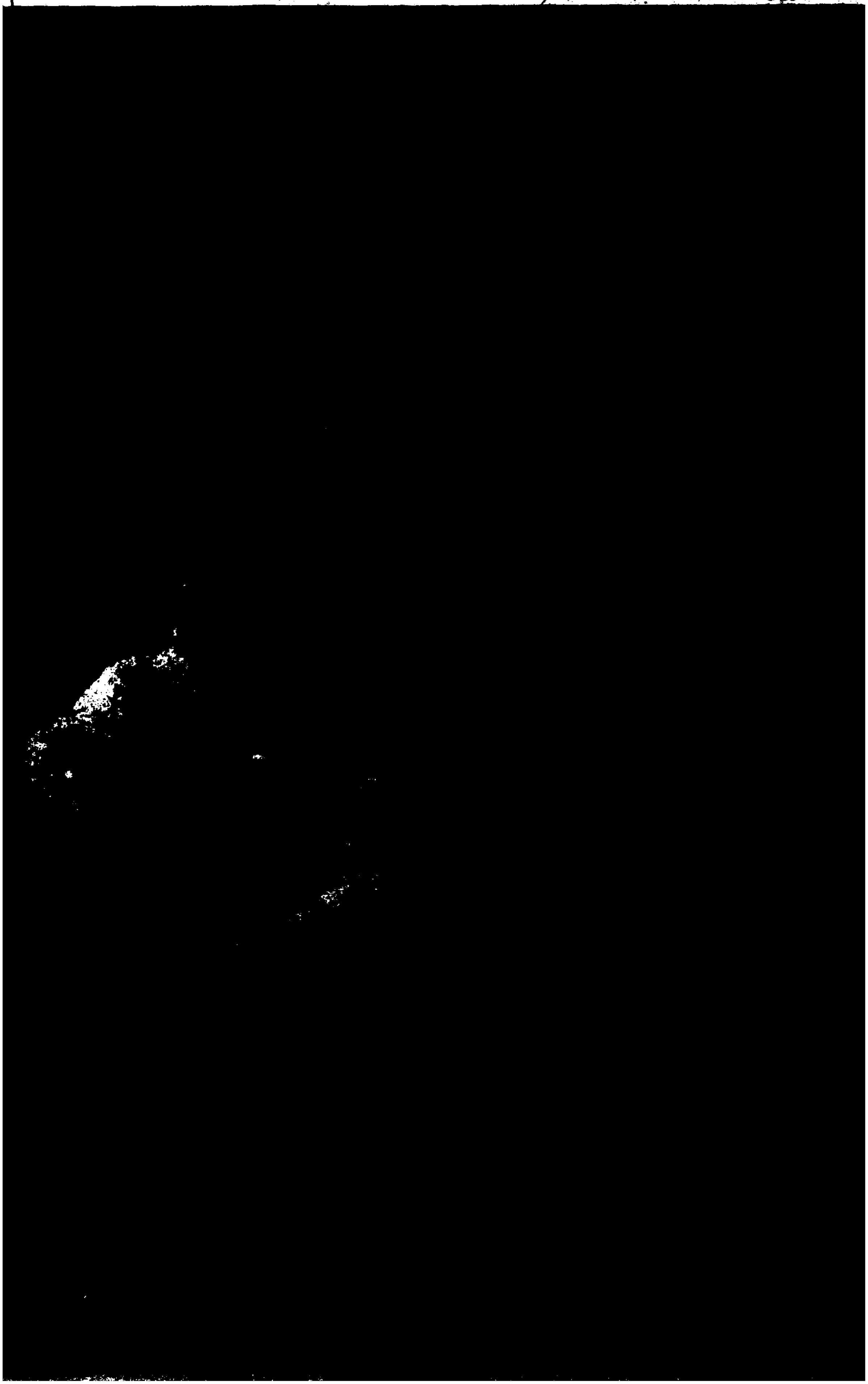
N
ALBERTA
BRITISH COLUMBIA
Banff National Park
Peter Lougheed Provincial Park
Lower
as 746 5038
as 746 5037
as 746 5036
as 747 5035
as 747 5034
as 747 5033
as 747 5032
as 748 5030
as 748 5029
as 748 5028
as 748 5027
as 748 5026
as 749 5025



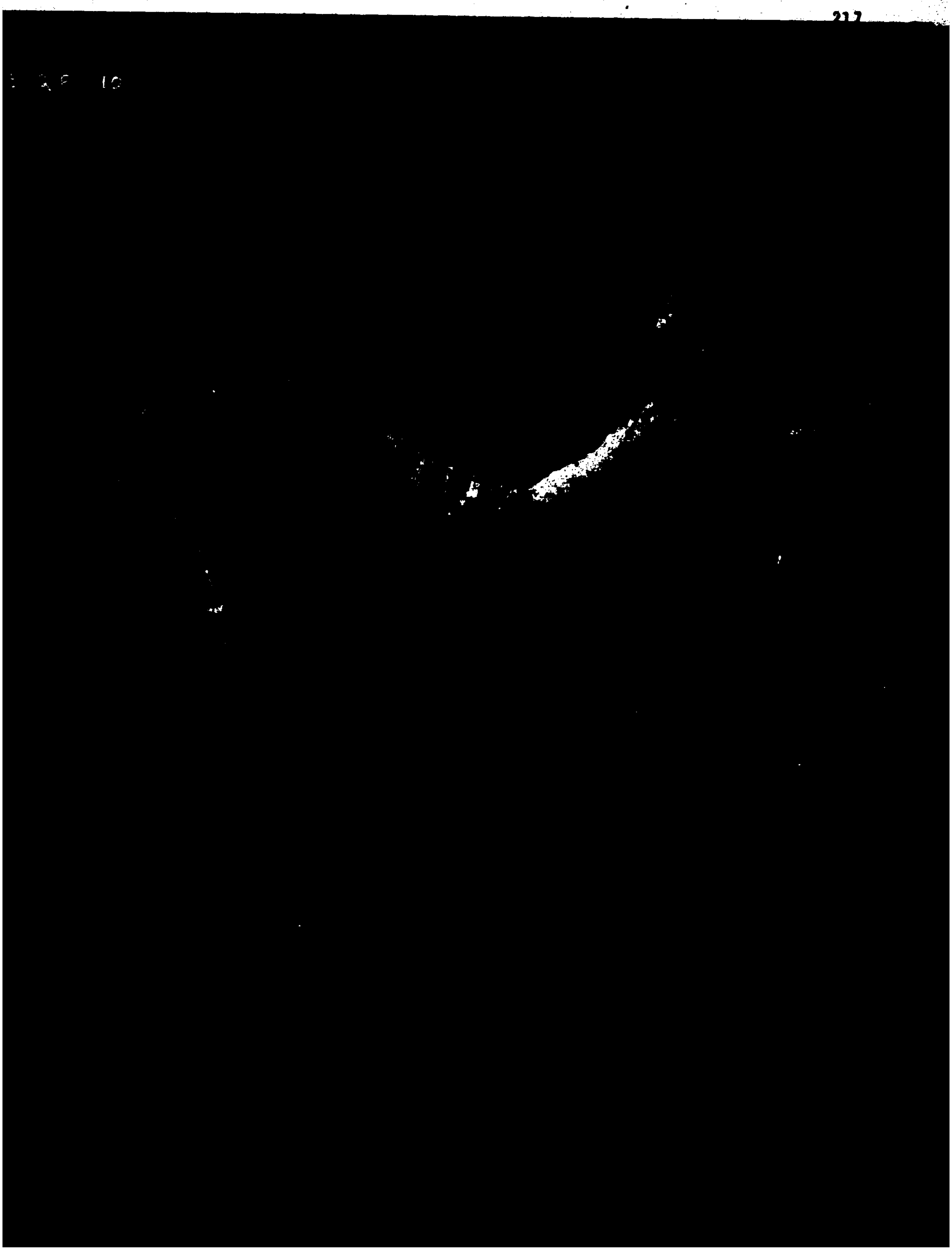

OP
P

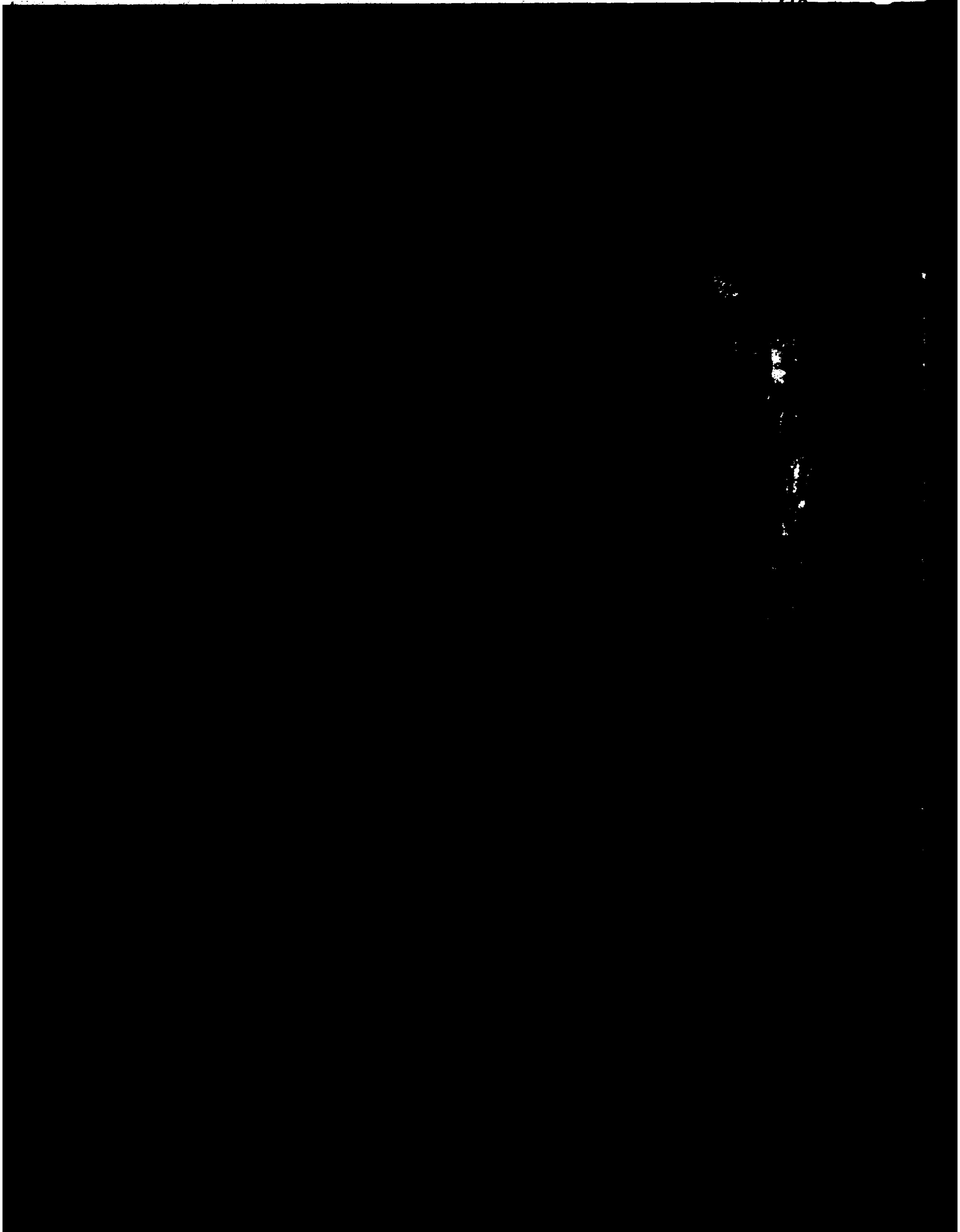

RD

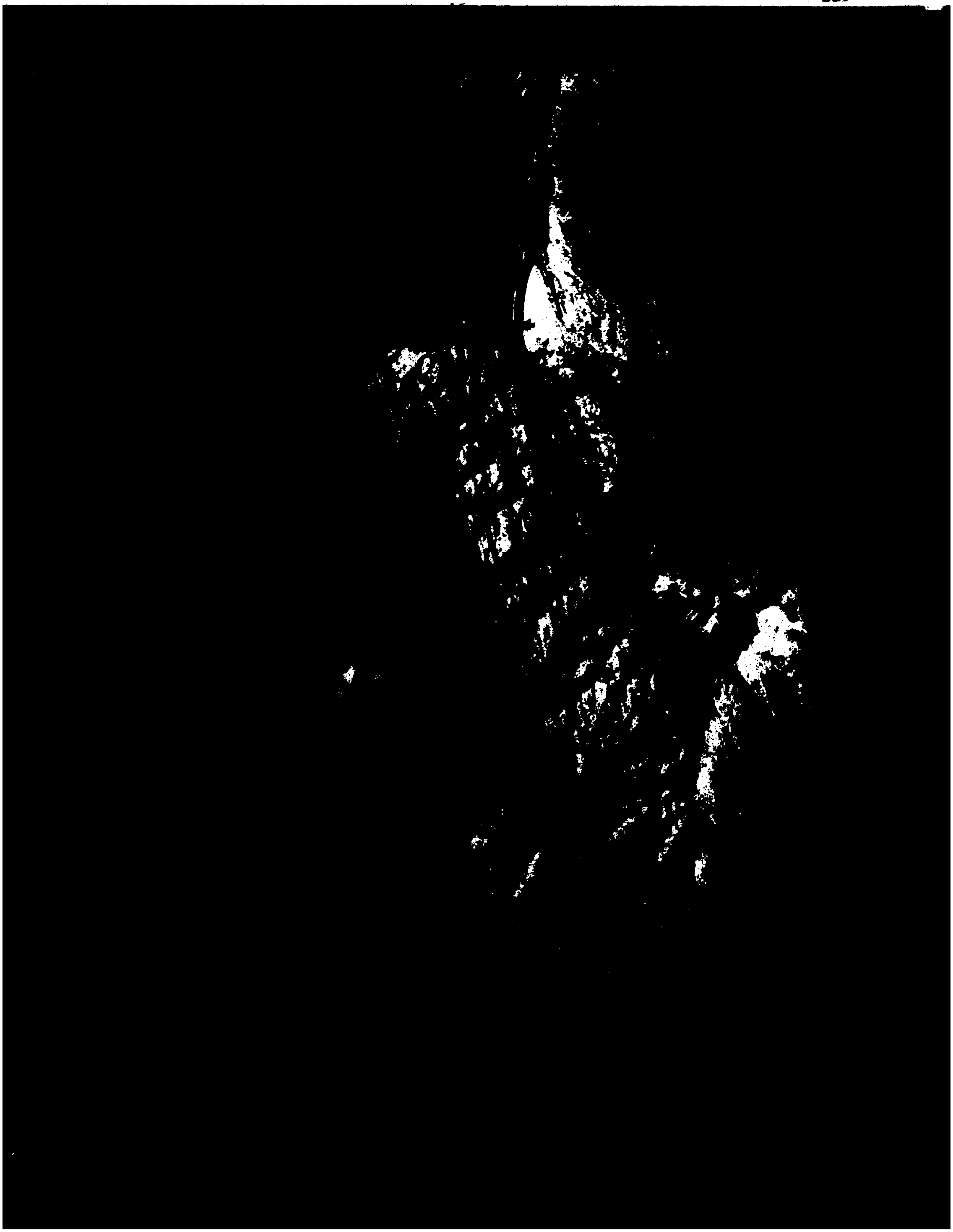


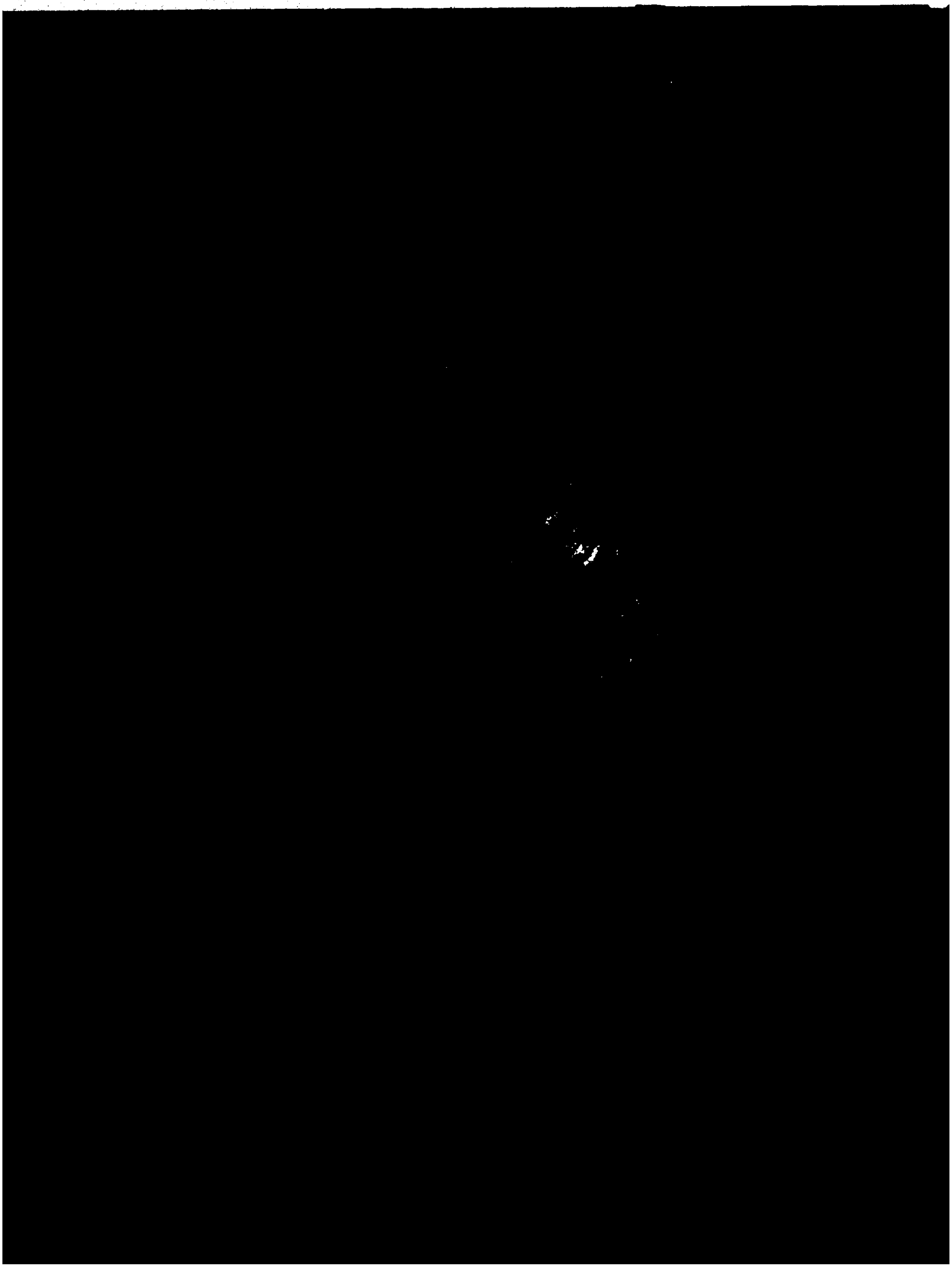


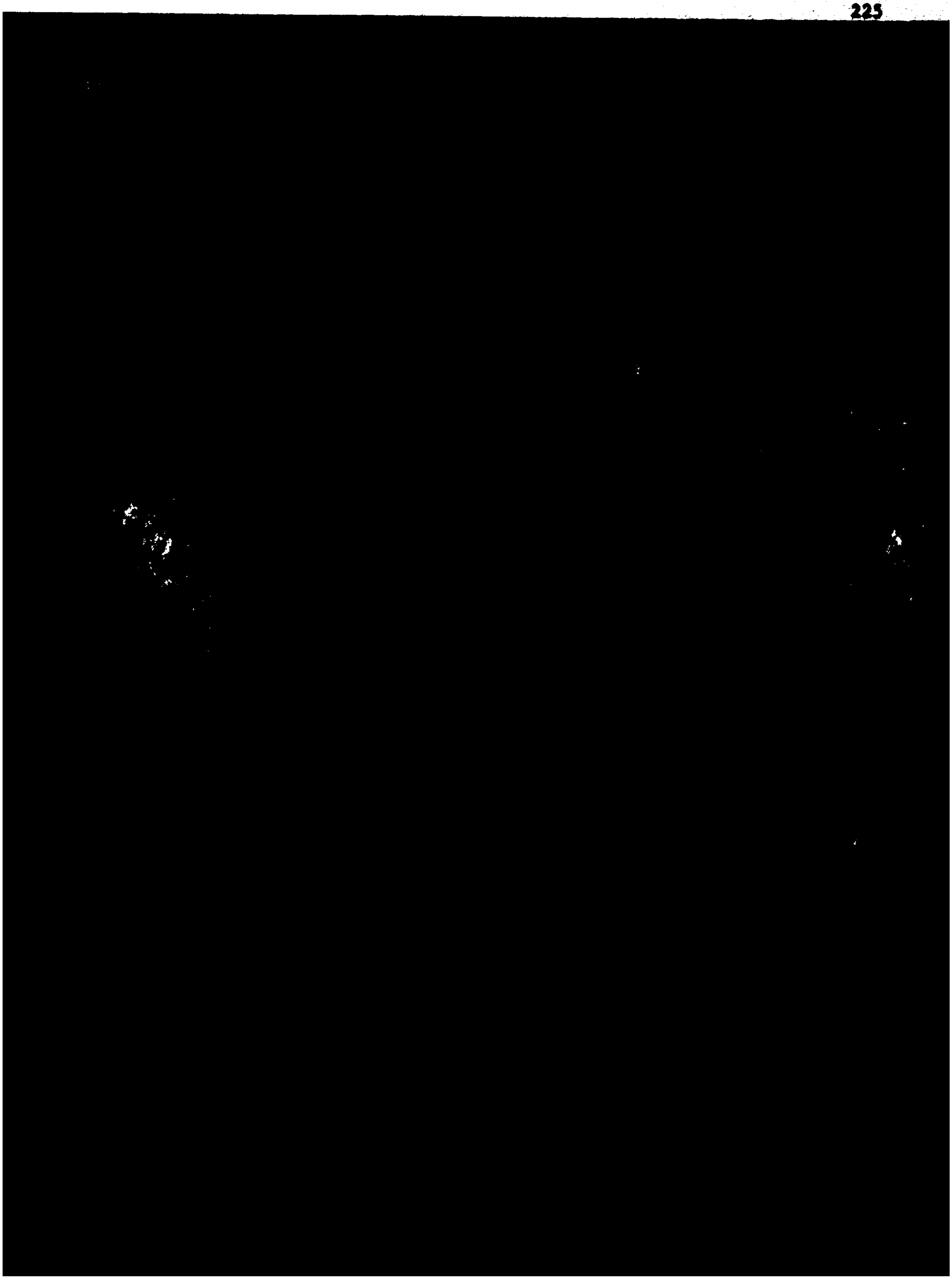
[redacted]











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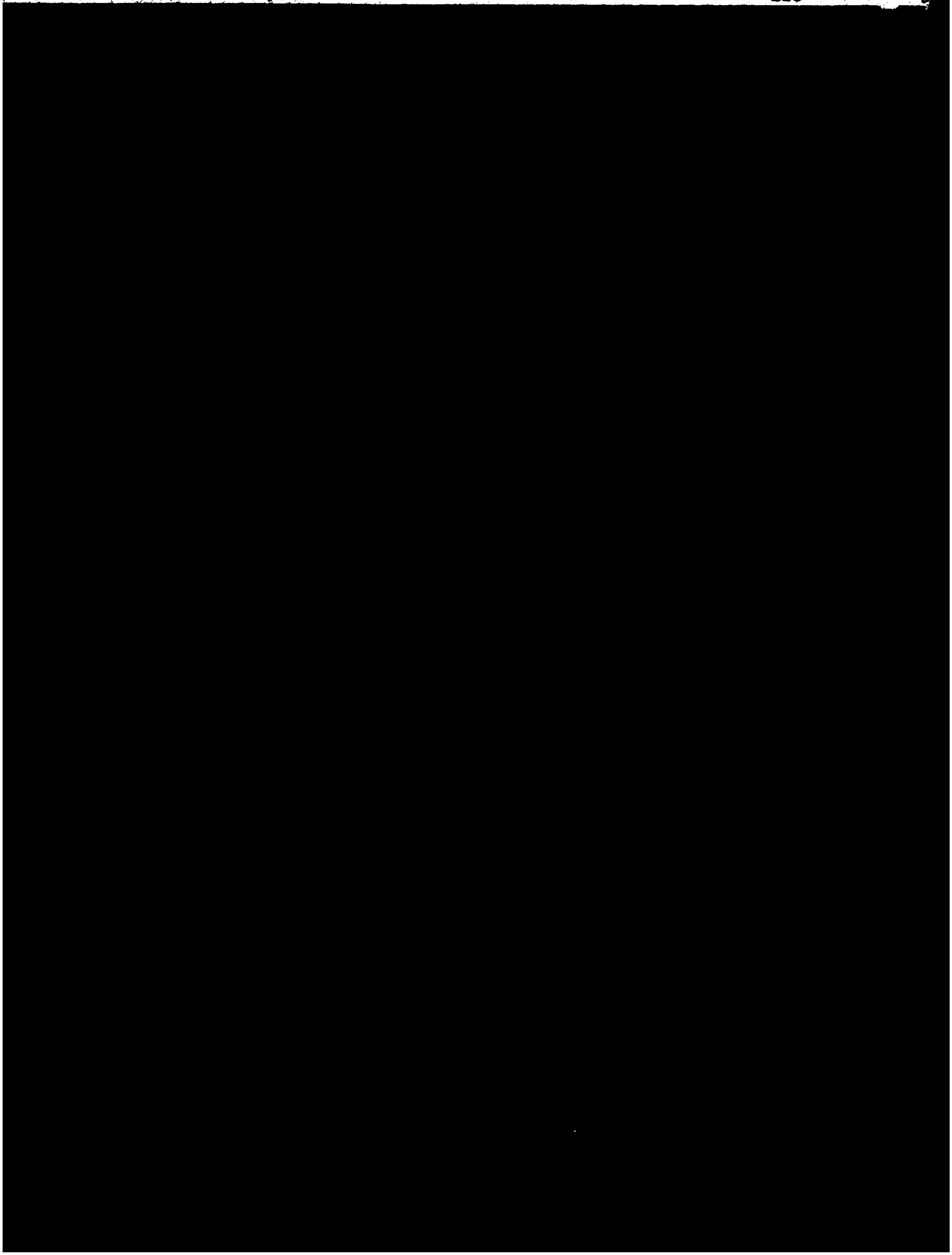

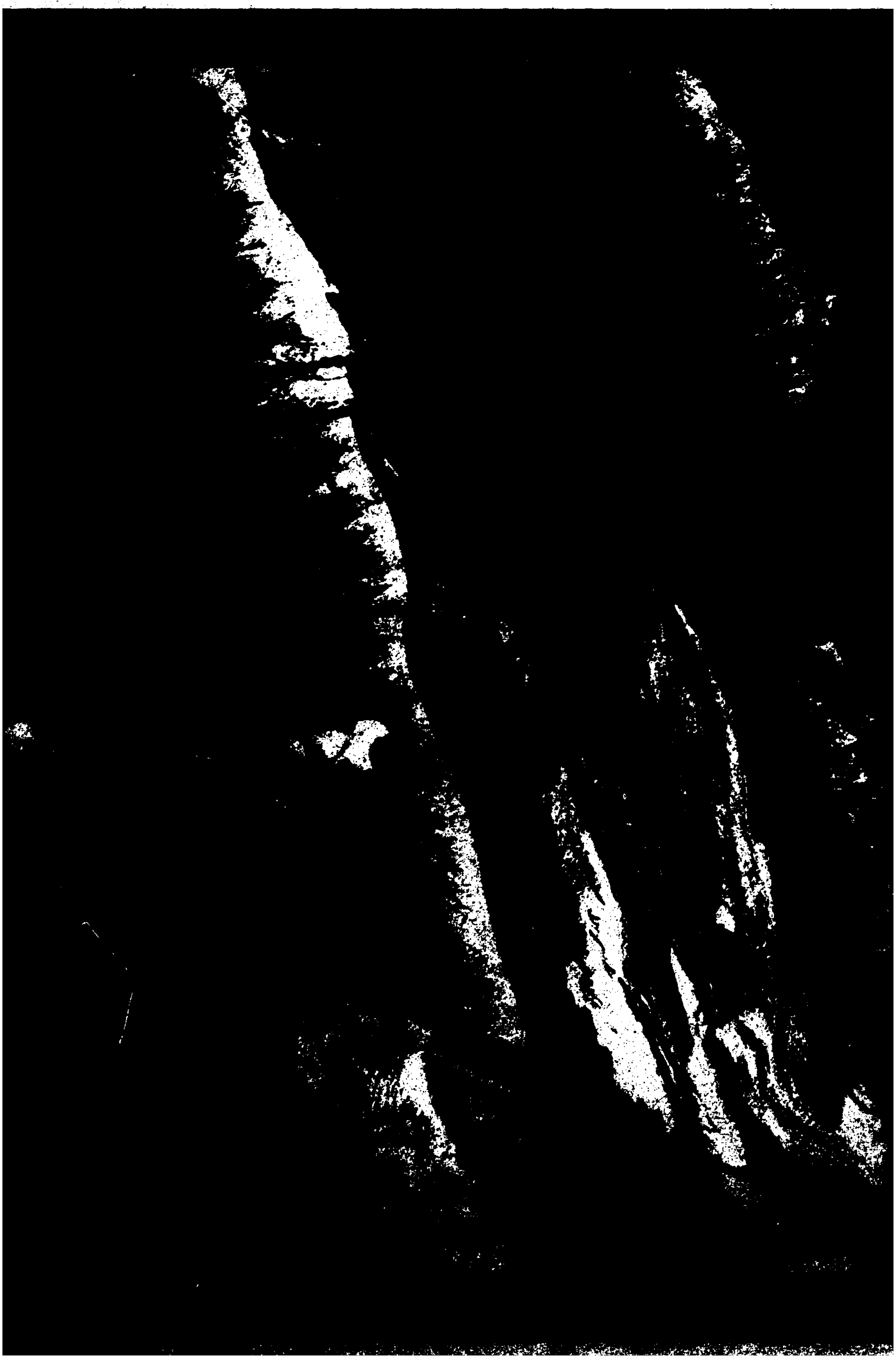

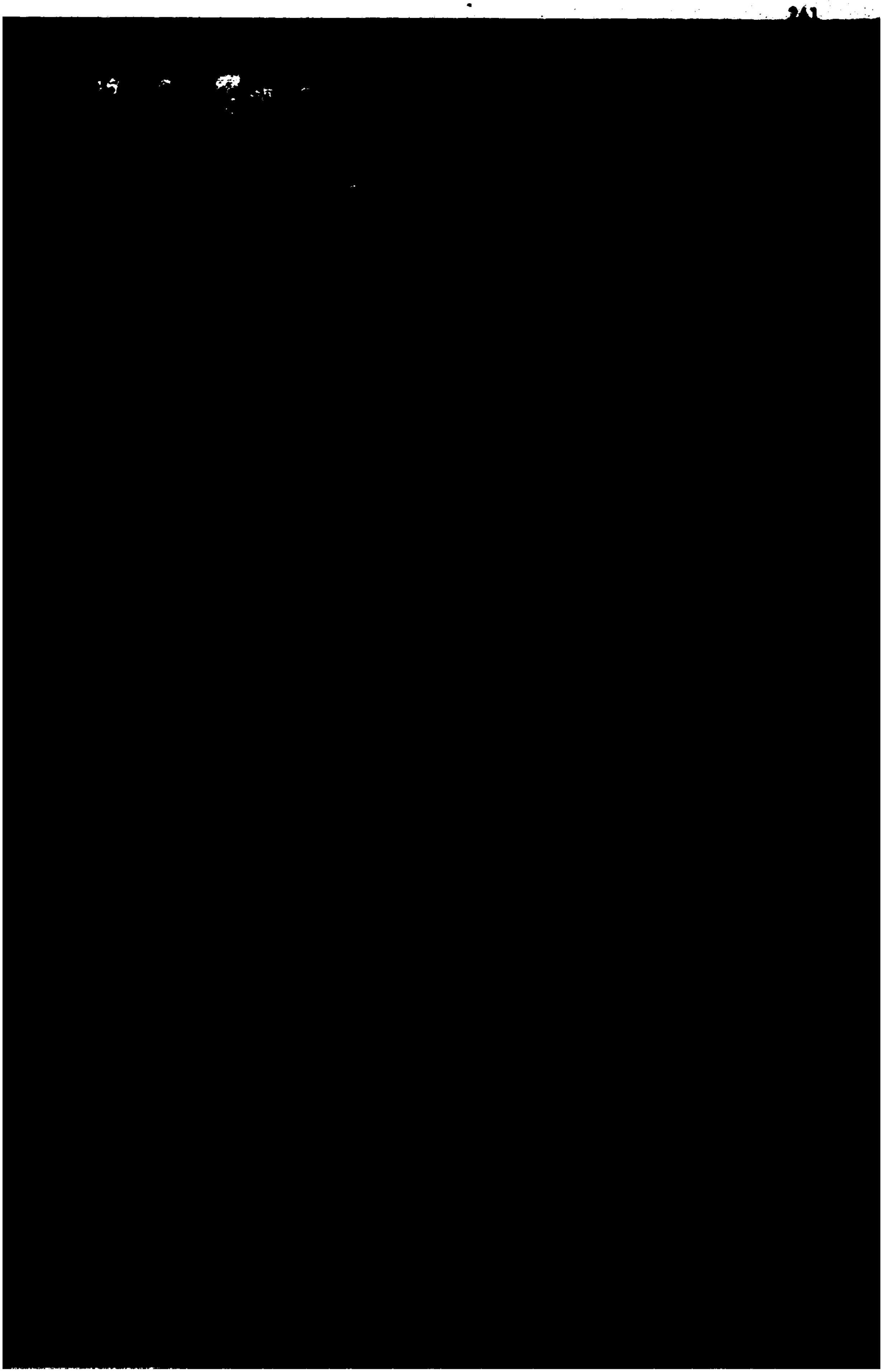

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