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C H A P T E R   O N E

LANDSLIDES: THEIR CLASSIFICATION AND STABILITY

1.1 Landslide Classification

Landslides, described by Selby as Mass Wasting, are the downslope movement of soil or rock material under the influence of gravity, excluding the direct aid of other factors such as water air or ice. However these factors are frequently involved in reducing the internal strength of the materials involved and also creating plastic/fluid behaviour within the materials. Trying to classify such complex assortments of geomorphological phenomena involved is very hard and, ultimately, incomplete; however such systems do aid the observer in providing a broad definition before detailed description is attempted. Sharpe provided one on the earliest systems in 1938, later attractive systems have come from Varnes (1958, 1975), Hutchinson (1968) and Nemcok. (1972) Hutchinson has, to date, provided the most all- embracing system, but it is Varnes' system that has attained large scale usage, particularly in the terminology used and this is shown in Diagram 1.1. All processes can occur in bedrock or soils.

This project is particularly concerned with those mass wasting processes known as falls or, more particularly, rock avalanches. The materials involved are also described as hard rocks as they have high internal strength, with failure occurring along joints and fractures. They tend to form bare rock slopes of steep angle and are predominantly found in high mountain regions.

Diagram 1.2 shows the four different types of hard rock rock fall as defined by Nemcok. However it is rock avalanches that are of particular interest. These occur in well jointed rocks so that internal cohesion is only provided by the friction between the blocks. For loose aggregates the friction angle is 43-45° and 65-70° for densely packed aggregates. Resistance can be further reduced by weathering, the removal of lateral support, water seepage/pressure and valley deepening (so increasing the shear stress) throughout the mass.

1.2 Landslide Stability

The strength of a rock formation is its ability to resist deformation by tensile (stretching), shear (compressing) or compressive (overburden) stresses. The strength depends upon the minerals within the aggregate as well as the forces holding them together.

1.21 Cohesion

Cohesion occurs between particles by the chemical cementing of the rock, primarily by molecular and ionic bonds. However **Apparent Cohesion** can occur as well because of Capillary Stress (surface tension in water films) and the interlocking, at a microscopic level, of surface roughnesses. Capillary stresses are affected by packing (the closer the stronger), grain size (the smaller the stronger), moisture content (the drier the stronger) and the wettability (the higher the stronger).

1.22 Friction

Friction is the frictional resistance between grains in contact and so is a basic control on strength. The number of points of contact, arrangement, size, shape, voids, dilatancy and resistance to crushing are all important factors.

If a rock is placed on a flat surface, then the weight of rock on the surface (N) generates an equal and opposite reaction. (R) However if a horizontal force (H) is applied, then the magnitude and direction of R changes to accommodate the resultant combination of H and N. This consequently changes the angle of slope (ν); if H increases so does ν until the block moves. This value is known as the Angle of the Plane of Static Friction (ϕ) and has a stress acting along the plane (τ) and normal to the plane. (σ) If the fracture plane is within a rock mass then ϕ will be

$\tan \phi = \tau \div \sigma$

The volume of voids and particle then become crucial to the rock strength; water plays an important part here in that it can hold massive crystal structures together while acting as a lubricant for clay size particles. Generally the friction angle decreases with plasticity and water content.

1.23 Coulomb Equation

The **Coulomb Equation** brings together the concepts of cohesion and friction to give an overall assessment of rock strength

$s = c + (\sigma.\tan\phi)$

s = strength at failure

σ = normal stress

c = cohesion

$\tan\phi$ = coefficient of friction

This only works for dry or moist soils as it assumes a zero or negative hydrostatic head; if the area is saturated then the effect of water increases stress. A slightly different equation accommodates this:

$$s = c' - (\sigma - u).\tan\phi'$$

c' = effective cohesion

u = hydrostatic head

ϕ' = new angle of friction

1.24 Rock Strength

Although the Coulomb Equation provides a basic understanding of rock strength, there is much more involved than simply <u>intact strength</u>. Although very hard to measure, certain applications (such as in civil engineering) need to know rock strength and so classification schemes have been compiled.

The following list gives the various factors affecting strength and is taken from Selby who used the most commonly found parameters. Each one is weighted and an "r" value for the area studied can be assigned to each category to give a final score which is a measure of rock strength. Diagram shows this and the overall rating given.

The factors which affect strength are:

(1) Strength of Intact Rock

(2) State of Weathering of Rock

(3) Spacing of Partings. (joints, bedding planes etc)

(4) Orientation of Partings.

(5) Width of Partings

(6) Lateral/Vertical Continuity of Partings

(7) Gouge or Infilling Materials in Partings.

(8) Movement of Water.

Selby identified three further factors of importance:

(9) Residual Stresses Within the Rock.

(10) Angle of Internal Friction Along Partings.

(11) Waviness/Roughness Along Partings.

This is a broad basis for estimating the strength of rock mass. In a broader context it does not allow for many other factors affecting resistance and failure of that area. The failure of a rock face by cross-jointing is caused by four main factors. The first of these is the **Geological** make up for that area. This encompasses topics such as tectonic stability (earthquake triggers), the swelling of the rock and joint opening (caused by pressure release and unloading, water lubrication and weathering), angles of dip, displacement, mode of slope failure (eg from the toe) and geological structures (such as such as low strength complexes overlaying high strength ones).

Climatic factors, such as precipitation, frost, deglaciation and snowmelt can all lead to increased rock stresses. **Weathering** is important as it leads to joint opening and clay rich infilling. The last factor, the **Human Element** is still very small, however in very localised regions it can be important (Eg quarrying, transportation etc).

1.3 Rock Avalanches

Rock avalanches, or Sturtzstroms as they have been referred to by Hsu (1975), are the principle subject of this study; they can be split into two stages, that of cliff failure and then debris motion.

1.31 Cliff Failure

Particular to rock avalanches is the appearance of crown cracks and open fractures that delimit an incipient failure. Eisbacher (1979) has noted two different processes by which collapse, and its consequent streaming, can occur.
On gently-angled slopes collapse occurs and the debris is carried forward by the rotation of joint-bounded blocks in the basal rupture zone; this is also the process that crushes many blocks.
At and above gently angled slopes (thought to be around 30°) blocks cease to rotate and are more likely to slide. There is probably a transition between these two extremes. The rotating block process is thought to be seismically induced as this would be the only way by which the internal fabric of a rock mass could see the activation of roller bearings.

1.32 Avalanche Streaming: Processes

Rock avalanches tend to be low frequency high damage events and so are often documented due to their destructive nature. They often begin as rockfalls or slides, then speed up to velocities ranging from 90-350 kph, then gathering further material as they proceed so that final volumes of material ranges from 10-100Mm^3. This type of travel and movement progresses from a rockfall to a rock avalanche; the sheer speed allows flows up and over barriers several hundred metres high.

Such large and fast movements can cover long distances and may spread out over very large areas; their efficiency can be described through the Coefficient of Friction (f). This divides the height dropped (H) by the horizontal distance travelled (L) and, for rock avalanches, can be as low as 0.11 (H/L.) This gives an indication of the type of flow involved in these masses as they have been observed to be flexible debris sheets with no gravitational sorting occurring (shown by the fact that stratigraphic sequences are preserved in the rock after the mass has come to rest).

The high efficiency attained is the result of low internal friction and so avalanches may be treated as fluids. Heim (1882) first took this idea and using fluid laws that stated that the velocity was proportional to the square root of the debris thickness, postulated that velocities would be greater in confined valleys.

The greatest area of friction is in the contact with the ground and so further theories were proposed as to how this was so low; Kent (1966) supposed it was due to trapped air, while Shreve (1968) suggested that a cushion of air carried the mass. These ideas were supported by the fact that an air blast has been observed to preceed the debris mass.

More "graphical" theories such as by Habib (1975) suggested that the shearing of debris at the base generated high enough temperatures to vapourise water and so create a cushion of steam. Kent (1965) also suggested that fluidization of coarse material in a fine grained matrix may have helped in the high velocities.

Avalanches have been discovered on the moon where there is neither fluidisation by gas nor water and so more attention is now being paid to Heim’s original work. He further noted that individual blocks take zig-zag paths making elastic impacts with their surroundings. With large aggregates of material only outer blocks may fly out and so kinetic energy is continually exchanged. This is the same mechanism that occurs in a fluid of very low internal friction. This produces high fluid viscosities when the mass is thick; it is this that prevents internal mixing and deformation and so allows the movement of the material as a thin flexible sheet of material with plastic behaviour.

When a sheet comes to a stand still, a distal rim with lateral and transverse ridges is produced, along with a hummocky texture. The presence of "molards" (debris cones) has been noted in several large avalanches. Beyond this a "splash area" can form up to 100m away demonstrating the less viscous nature of these fines which receive their momentum from the bulk of the rock avalanche behind them.

A transverse trough separating the rupture surface from the accumulation zone has been noted, accompanied by sub-parallel longitudinal debris ridges and grooves. Eisbacher (1979) has termed this a "ramp." They are more apparent in large, unconfined, sturtzstroms and are thought to represent the point where momentum was transferred from the main mass to the front. The mass behind the ramp can contain up to two thirds of the entire mass.

Other types of movement have been noted locally within the rock mass; diverging stream lines suggest a dilating sheet during movement, while the distal rims and lateral ridges suggest that a sliding motion is present when the sheet comes to a rest.

1.33 Avalanche Streaming: Description

Rock avalanches travel unusually long distances and this has been studied by several authors. It is described in the following formula (Eisbacher 1984):

$$L_e = (L - H) \div \tan 32°$$

where L and H are horizontal and vertical distances and $\tan\alpha$ the angle of friction.

Davies (1982) noted a connection between volume and excessive travel as described by

$$L_d = 9.98\ V^{0.33}$$

where L_d is the deposit length and V the volume. This has also been connected to the coefficient of friction as described above. Diagram 1.3 shows these relationships.

Velocity can also be estimated as Chow's (1959) equation demonstrates

$$v^2 = 2\ gh$$

This does not take into account friction, whereas the equation by Francis and Baker (1977) does. These are also similar to Heim's original fluid equations.

Attractive as these equations are, they provide limited practical use as they are not specific to the geology, morphology or lithology of the region, let alone the other variables previously mentioned, and so can only be used in an approximate way, for example in land hazard mapping.

1.4 Objectives

The Mt Colonel Foster rock avalanche descended into Landslide Lake causing a large tidal wave to wash down the Elk River valley. The features produced below the lake are, in many ways, similar to those found in areas where landslide dams have been breached.

The rockslide studied is, as far as can be ascertained, a landslide dam, its fall creating the lake now found in the valley.

Two important questions arise from the types of landslides that have been reviewed. Firstly, how typical is each type? Are there other types which are more prevalent? Secondly, how persistent are these forms in the landscape?

These questions can be answered by comparing the two landslides that have been reviewed and coming to conclusions about their characteristics. The area has, since the event, gone through much change and a reassessment of the region now, after it has adjusted to the impact placed upon it, is also necessary.

C H A P T E R T W O

THE 1946 MT. COLONEL FOSTER ROCK AVALANCHE

2.1 Introduction

On June 23rd 1946 at 10:13am a 7.2 magnitude earthquake struck southwestern British Columbia, Canada, causing in excess of 450 landslides (Mathews, 1979). Two of these landslides came from Mt Colonel Foster and a neighbouring peak 7km to the West of it. It is these two landslides that are the research focus for this project and so a setting of the events leading to their failure is necessary.

2.2 The Canadian Cordillera

2.21 The Cordillera

Canada comprises three major geological regions; a core of Pre-Cambrian crystalline rocks forms the shield and this is surrounded by the younger Borderlands and the submarine areas of the Pacific, Atlantic and Arctic shelves. The Borderlands comprise two rings, in segments around the core; the first ring is made up of the St. Lawrence Lowlands, Arctic Lowlands and Interior Plains, while the second ring consists of the mountains and plateaus (Cordillera, Appalachians and the Arctic Archipelago). It is the Cordilleran region that is the area of study.

2.22 The Insular Belt

The region can be further split into physiographically different belts (Cruden, 1985) with, from East to West, the Mackenzie and Rocky Mountains, the Omineca Crystalline Belt, the Intermontane Belt, the Coast Plutonic Complex and the Insular Belt. The Insular Belt, including the Vancouver Island region, contains the rock avalanches of interest.

The Seismicity map of Diagram 2.1 shows that the Cordillera is one of the peak zones for earthquakes. The climate also tends to be VERY wet as air moving from East to West is blocked by the coastal ranges and so causes orographic precipitation. Many of the rock types in the region are susceptible to landsliding, particularly Quaternary volcanic areas.

Voight (1978) found that in the Canadian Cordillera, between 1855 and 1983, 84 damaging landslides occurred, of which 44% were debris flows, 17% were rock slope movements less than $10^6 m^3$ and 3.6% rock slope movements greater than $10^6 m^3$.

Eisbacher (1979) produced a landslide "behaviour belt" map for the Cordillera (Diagram 2.2) as he realised that landslides were strongly controlled by local geology and physiography.

The region is also termed the Coastal Insular Zone, this being a geological classification. It consists of high

granitic massifs and volcanic-metamorphic complexes (overlain by younger volcanics and glacial deposits).

Surface parallel joining and shear zones make up the principle discontinuities.

Rock avalanches are generally found in glacially oversteepened valleys with discontinuities pointing towards to the valley floor, with slides being caused by high water head pressures (which may lead to debris flows) or seismic shaking.

After the important effects of geology and physiography, total annual precipitation, local relief and seismicity are three further factors related to landslides. Eisbacher (1979) mapped these three factors and them combined them together to produce one map (Diagram 2.3). This final map describes regions of mass movements providing a general impression of the areas at greatest risk from landslide activity, with the Vancouver Island region in the most danger.

2.23 Geological Setting

By the nature of its position straddling the boundaries of the America and Explorer/Juan De Fuca plates, Vancouver Island is tectonically active. Diagram 2.4 shows the location of this boundary and the location of recent earthquake epicentres. The majority of the geological sequences are tectonics, and it is these two factors that leads to very unstable hill slopes.

The Mt Colonel Foster region is made up of the Karmutsen Formation, a part of the Vancouver Group. These are island arc volcanics up to 6000m thick, which unconformably overlie the Sickler Group of volcanics. They were formed by a massive extrusion of basalt between 220Ma (at the base) and 170Ma (at the top).

From the base, there is a grading upwards through several formations. At the base there is a band of red beds (containing ribbon cherts), following this there is up to 6000m of pillow lava (20cm - 1m in diameter), which is capped by sub-aerial lava flows 20m thick. The present height at which the base first appears is around 1,500m.

From the Cretaceous there were three cycles of uplift and erosion, the last one in the Pliocene forming the mountains seen today. This was then modified by the separate glaciations that took place in the Pleistocene, with the final event (the Fraser Glaciation) leaving the greatest impression. This was at its peak 19,000 years ago with the ice sheet around 1,640m thick. This means that the tops of the highest peaks, such as Mt Colonel Foster, may well have been clear of ice; these peaks have been termed Nunataks.

2.3 The 1946 Earthquake

As already mentioned, a 7.2 magnitude earthquake occurred in 1946 in southwest British Columbia. This was first discussed in the academic literature by Hodgson (1946) and was then followed by Rogers and Hasegawa (1978), before Mathews (1979) published his paper on landslides following the event.

The epicentre was located 49.76°N, 125.35°W, at a depth of around 30km, with a very steeply dipping (80°) northeasterly strike-slip motion.

Mathews mapped the location and number of landslides in the various 400km² UTM grid squares and his results are shown in Diagram 2.5. Mathews took all grid squares with values between 0 and 4 to represent a "background" value; values over and above this were thought to represent the effects of the earthquake. Interestingly the values in the area immediately surrounding the epicentre are only marginally higher than the background values, while to the west and southwest there is a very dramatic increase with a maximum around 50km away. Although not identifying a reason for this, Howes (1980) has suggested that this may be due to climatic factors, particularly the high amount of precipitation. Orientation of these slides is predominantly in this direction, whether this is connected to the fact that they face away from the epicentre is not known.

2.4 The Vancouver Island Landslides

2.41 Introduction

The earthquake of 1946 produced the rock avalanche at Mt Colonel Foster and another 7km West. Diagram 2.6 shows a topographic map of the region, with the two landslides marked. Photo 2.1 is a 1962 aerial photo of Mt Colonel Foster showing its rock avalanche and the region surrounding it. Photo 2.2 is taken just across from this and depicts the second landslide (a rockslide).

A paper Evans (1989) studied the Mt Colonel Foster rock avalanche. Information has been drawn from his work; this project will be comparing this avalanche to the one further West. It is believed that this caused the formation of a lake and so is quite different from the Mt Colonel Foster event. Results from the investigation will be presented later on and then compared.

2.42 Landslide Damming

Evans (1986) studied the effects of landslide damming, noting that large reservoirs could be formed upstream and that some geological complexes were stable, while others lead to gradual or catastrophic failure. This then has effects on inhabited areas and the local fish population.

From Evans's three-fold classification system, damming by rock slope movements is applicable. The type of fabric of

the dam is the main control on stability; for example very blocky dams are stable.

He uses the equation

$V = 0.035\ A^{1.5}$

to estimate the volume of the dammed lake (Inland Waters Directorate, 1977) to +/-15% accuracy and so from this estimate the potential for disaster from a failed dam.

2.43 The Mt Colonel Foster Rock Avalanche

The date of the avalanche has been confirmed as dating to the earthquake by dendrochronological analysis.

The avalanche detached itself from the north face of the northernmost pinnacle between 1965m and 1600m. The face is dominated by widely spaced, steeply dipping, curviplanar discontinuities which connect with the bedding planes dipping at 20°SW. Also present are discontinuities parallel to the face; this is shown in the irregularity of the detachment zone, although it is not dominant. Photo 2.3[1] shows a view of the mountain BEFORE the event and this can be compared to Picture 2.4 which is a recent (1992) view.

A mass of $1.5 \times 10^6\ m^3$ was estimated by Evans, who then went on to map the descent of the rock mass. It followed a curving path to the northeast (19° slope) between 1460m and 1080m, approximately $0.8 \times 10^6\ m^3$ was deposited abve the lake. The remainder of the mass carried on down the slope (45° slope) and entered Landslide Lake at 890m

[1] Courtesy of Ruth Masters, Courtenay, B.C.

(area 0.3 km^2).

A large displacement wave was generated as a result of the avalanche entering the lake; vegetation destruction on the far side of the lake shows run up distances of 40 - 50m. An estimate of 30 m/s was achieved for wave velocity.

Large cedar trees and boulders up to 2m in diameter were carried along by the wave, which swept down the Elk River valley destroying forest vegetation up to 3km from the lake. The wave must have been at least 28.8m high as it passed in to the valley, as this is the height of the lip. The area here is hydraulically scoured and moraine deposits here have been re-deposited immediately downstream. Further sediments were stripped from the upper reaches of the valley and deposited in extensive gravel flats further downstream. The flood wave is known to have travelled at least 10km downstream as a bridge was swept away at this point.

CHAPTER THREE

OBSERVATIONS AND RESULTS

3.1 Introduction

Field observations and laboratory work involved such aspects as strength testing, obtaining descriptive values for the avalanches themselves (including bedding, dip and landslide volume), and simple aerial photogrammetry. Work was also undertaken to compile a map and producea series of stereographic pictures in order to view the development of two sites over time following the mass movement events.

3.2 Strength Testing

The rock unit involved is the Karmutsen Formation volcanics; a section of a 1:250000 Geological Map of the Alberni Region is shown in Diagram 3.1 (the map was produced in 1969). It depicts the relation of this unit to the surrounding rock types; a close up view of this unit is shown in Photo 3.1[2]. It is this unit that is the focus of the following strength tests.

Using Selby's (1980) Geomorphic Rock Mass Strength Classification, a semi-objective set of tests were used to gauge the strength of the rock unit involved in the rock

[2] All Photos are found in Appendix 2.

avalanches. All testing took place on a sample section of rock on the North Col of Mt Colonel Foster, as the actual avalanche site was too steep and dangerous to allow closer inspection.

Selby's ratings are given in Diagram 3.2, along with the allocated score gained in testing at the avalanche site. This produced an overall score of 58, which Selby rates as "Moderate" strength, although there are some particular points that require further discussion.

A Schmidt Hammer was unavailable at the time of the study, so a simple test of intact rock strength was devised. This involved impacting a selected rock with a boulder, with the test being repeated several times. (as shown in Photo 3.2) This gave a reasonably high rock strength (18) and highlighted, as Photo 3.2 demonstrates, the highly fragile nature of the rock caused by the intensity of jointing.

Weathering was estimated, as Selby suggests, by eye and gave a result which showed the rock to be resistant to weathering (9).

The spacing of joints was calculated by placing a tape measure along a section of exposed rock (Photo 3.3) and counting the number of occasions joints crossed the tape. This produced a score of 15 by Selby's classification, which shows a high level of jointing.

Joint orientations were found to be very unfavourable (a score of 5) in that they dipped steeply out of the slope; this was measured at 28°. This was worsened by the fact that the bedding was angled at 68° in and so created a very

fragile set of cross joints.

Joint widths was measured to average 1-5mm; however viewing the detachment zone from the North Col allowed large joints (up to 1m wide) approximately 3m apart to be seen (perhaps evidence of pressure release and unloading in the rock). The results together gave a score of 5. The joints were also seen to be continuous, but had no infill and so scored 5 (showing regular rock fall activity).

Finally, groundwater outflow was estimated from rainfall during the field work (scoring 1). This is by no means a reliable estimate; however, it does give some measure of outflow. From the rock itself there was no outflow, but groundwater was seen to be channelised by the jointing system.

3.3 Landslide Measurements

Data referring to the description of the two landslides in turn will be given in the following section.

3.31 Mt Colonel Foster

The detachment zone was visited (Photos 3.4) and estimates taken, using the topographic map of the region and a Thommen Altimeter (found to be accurate to 10m when ascending and descending to 2000m from 900m), of its dimensions:

Height - 460m

Depth - 90m

Width - 115m

This gives an overall avalanche volume of $4.76 \times 10^6 m^3$.

Photos 3.5 and 3.6 are views of the avalanche runout zone, just above Landslide Lake. At the top, next to the detachment zone, the slope angle is 28°. This increases to 40°, before flattening out and then increases again as it plunges over the lip of the final slope down into the lake. Photo 3.7 is taken half way down the slide looking back up to the detachment site; there is a predominance of blocks around 1m in size, however some reached upt to 4m.

Tree coring was carried out at two points in the runout zone to ascertain damage to trees at the time of the event, however results were poor due to the hardness of the trees, a blunt tree corer and the need for a large sample number. Good photographical evidence of the destructive nature of the avalanche on the forestry is demonstrated in Photo 3.8; it was noticed that, besides the obvious clearance of trees in the main avalanche path, there had been thinning of trees in the immediate avalanche vicinity.

Photo 3.9 shows the area immediately below Landslide Lake; a swath of new bush has grown since the outwash wave passed down the Elk River Valley in 1946. The has also become channelised into a notch. Photo 3.10 shows a further view of this area. Again the swath cut by the wave is evident, as well as the large amount of soil that was washed away, so allowing very slow recovery by vegetation. Photo 3.11 is close-up evidence of the scouring effect achieved by large boulders and trees as they were transported downstream. Photo 3.12 shows a view back up this section.

Further downstream there is ample evidence for deposition of debris; Photo 3.13 shows the gravel flats (with several large boulders), as well as the regeneration of vegetation in the region. Three sets of gravel flats are evident, thought to be produced by the 1946 outwash wave, and these are caused by a levelling off of the river in these two areas as it descends down valley.

3.32 Rockslide

The second part of the field work involved visiting this site and taking similar measurements. However, due to the nature of the terrain, access was impractical. Photo 3.14 shows the col that was intended as the access route over to reach it. Travel up the valley from the road was almost impossible in the time available due to the dense vegetation, whilst a helicopter drop would have been illegal in the National Park. Although this cut out the possibility of many measurements, some data were estimated as an oblique photo was obtained from high ground (Photo 3.15). Most notable is the dip of the bedding planes and this is depicted in Photo 3.16 of the mountain range on the opposite side of the valley to the rockslide.

Following Selby’s strength classification as used above, an overall score of 62 was achieved which he rates as a "Moderate" strength. This is higher than the previous score, although not substantially so. This is due to the angle of bedding, as will be seen below, so making it less susceptible to landsliding.

The variables of weathering and spacing of Joints could not be measured, but it seems likely that these would be similar to those measured on Mt Colonel Foster, although this cannot be ascertained. This would give scores of 9 and 15 respectively.

The bedding plane angle was estimated at 30° degrees, which is a moderate dip into the slope. Such a favourable angle for landsliding gives a score of 18 and it is this which greatly increases the landslide probability.

Joint width, joint continuity and groundwater outflow could not be measured, although again it is assumed that these would be similar to those seen on Mt Colonel Foster. The gentle dip of the bedding planes may, however, create high runoff coefficients and also provide a means of lubrication between bedding planes.

The slide (denoted by Nemcok (1972) a Planar Slide; Nemcok's classification of slides is given Diagram 3.3) was across five planes.

3.4 Photogrammetry and Maps

3.41 Aerial Photography

Aerial photography was acquired from local sources in Canada, the majority being Provincial; there was also a small amount of Federal run surveys. The largest set with the greatest coverage was used in the field, while sets from other years provided a means of subjective comparison and a measurement of recovery. Five sets were acquired, ranging from 1957 to 1987. The date, scale and type of photography are given in Table 3.1; photography will be referred to by number in Chapter Four.

Date	Index Number	Scale
30th May 1957	BC2096: 39-40; 71-72	1 : 31,000
7th Sept 1962	BC5056: 26-29	1 : 31,000
2nd August 1974	BC(C)95: 32-37	1 : 6,000
26th July 1980	BC80072: 44-46 106-109	1 : 20,000
13th July 1987	BC87046: 135-136	1 : 70,000

Table 3.1 Aerial Photography

3.42 Map Compilation

A simple map was produced from the photographs that were acquired (see Diagram 2.6); an Aero-Sketch was used in the compilation of this. More sophisticated technical methods of map production were unavailable for use at the time.

The only large scale map of the region, a 1:50000 topographic map, was enlarged to 1:25000 and used as a base map. The map, produced in 1976 from 1972 aerial photography was not accurate and simply compounds the problems of accuracy. The enlargement reduced the quality of the image and enlarged the deficiencies already present in the original map. The map is inadequate as it has poor contouring (every 100ft) and little in the way of features to allow photo orientation. In the original production of the map, however, it could never have been foreseen that it would be used in photogrammetrical compilation at a large scale.

One major problem was the presence of large amounts of relief displacement; for some of the photography the area of interest lay on the edges of photos and so radial displacement was a problem (this fails to take into account any tilt displacement that may also be present). Despite the problems, a fit was possible using the BC80072 run; photos 114, 110 and 111 were used in compilation. Due to the amount of displacement no other photography could be used; the map duplicates these problems, but it is still able to illustrate the main aspects of the avalanche in question.

It had originally been planned to take measurements from the aerial photography; however, due to the large amount of error present no consistent results between different sets of photography (or indeed between individual photos) could be obtained. This approach was therefore discarded.

3.43 Longitudinal-Sections

The slopes form an important part of the analysis in that they explain why there are large deposits of debris immediately below the detachment zone, as well as the presence of three large gravel flats, thought to have been produced by the rock avalanche, on the Elk River. Three longitudinal-sections were produced of the mass movements; two for the rock avalanche, with one above Landslide Lake and one below, and the third for the rockslide. These are depicted below in Diagrams 3.4 and 3.5

The cross section was completed to see if there was any connection between changes in altitude and the positions at which the gravel flats and debris deposits were formed. All measurements were taken from the previously mentioned 1:50000 topographic map; the contour interval of 100ft can give only an indication of the features present and cannot be taken as an accurate

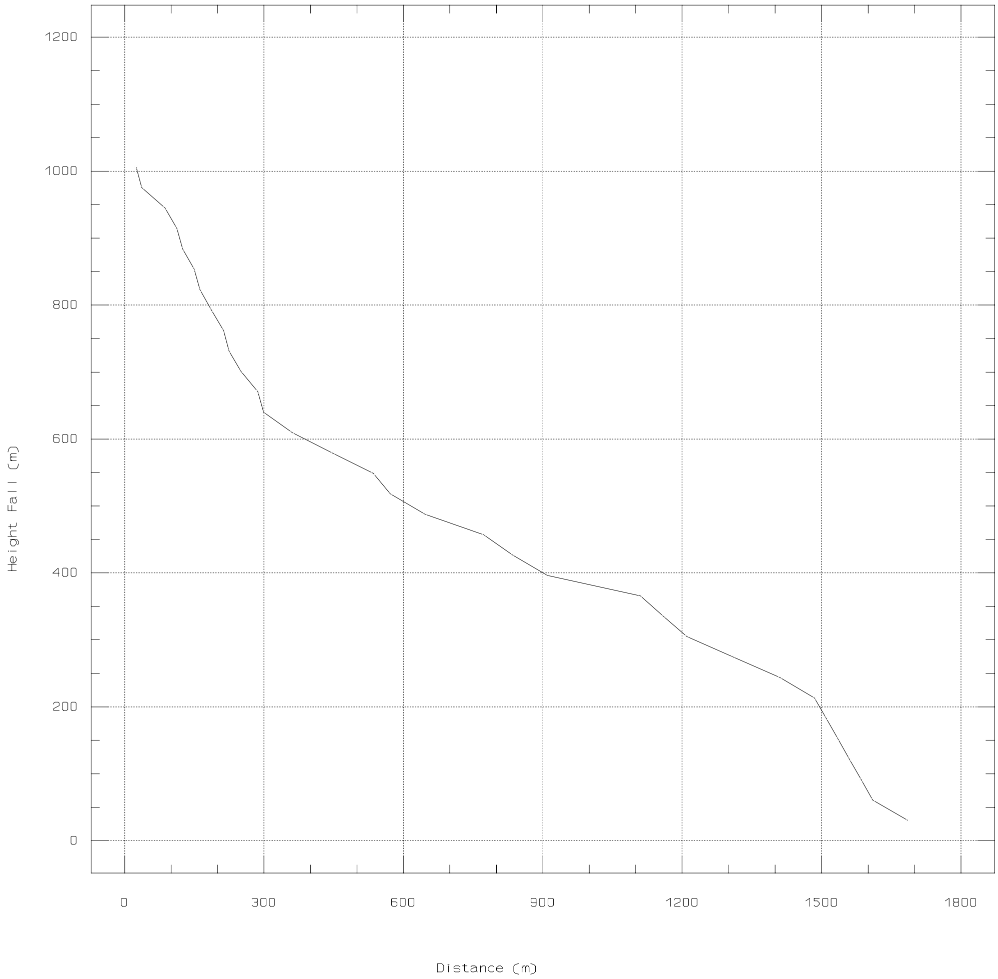

Diagram 3.4 Longitudinal section from detachment zone to Landslide Lake (horizontal scale ×1.5 vertical scale)

section.

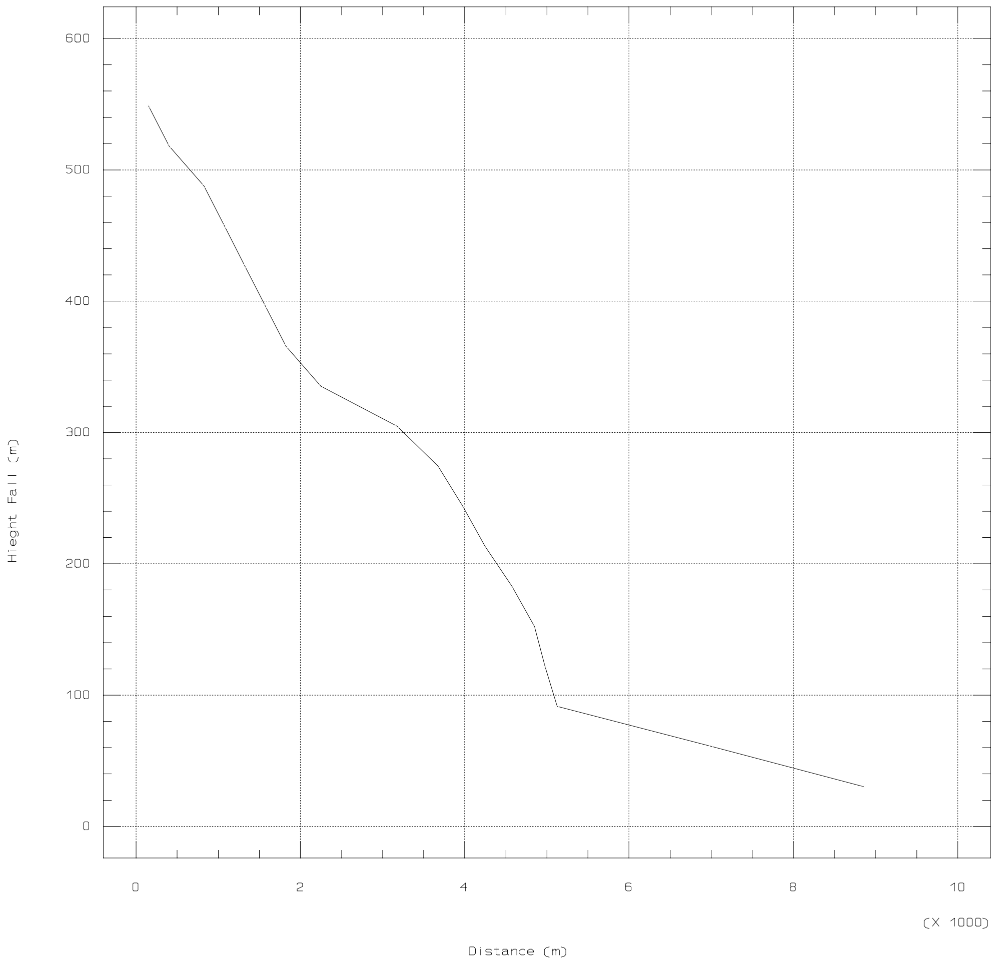

Diagram 3.5 Longitudinal section from Landslide Lake to beyond gravel flats (horizontal scale ×10 vertical scale)

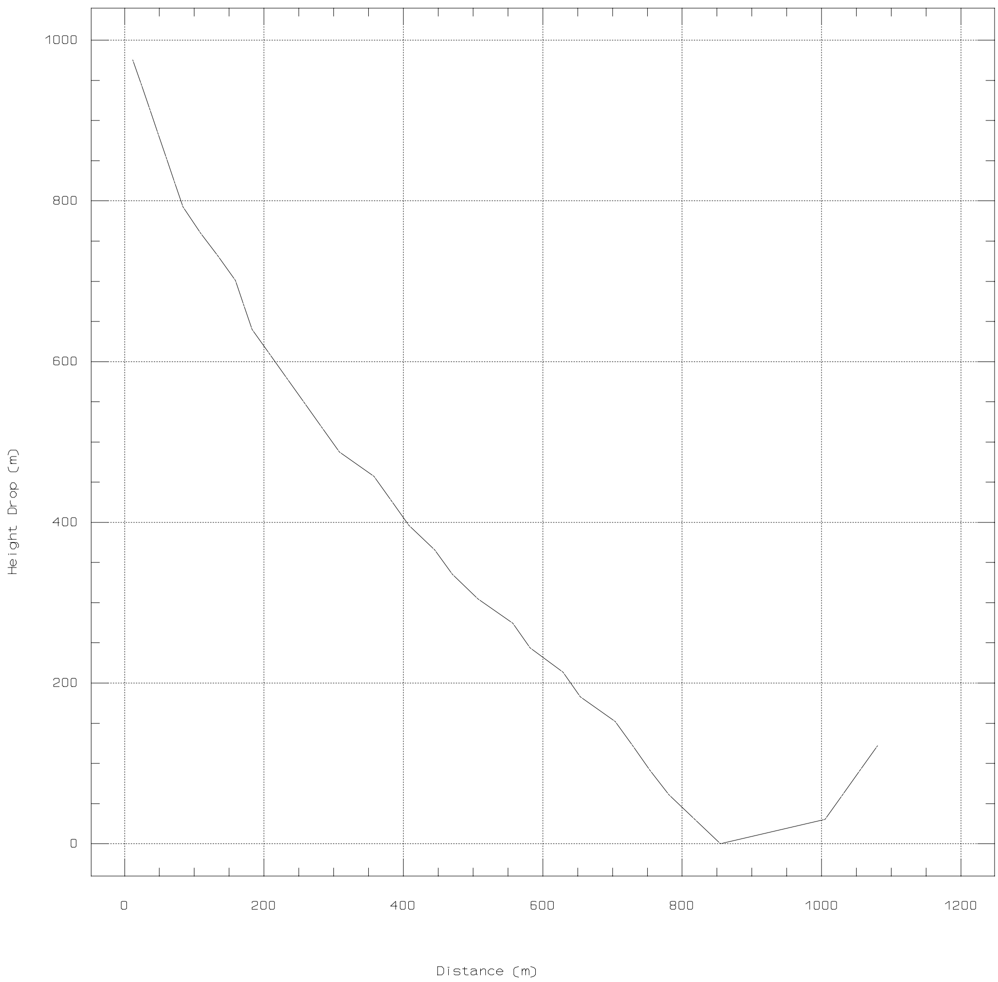

Diagram 3.6 Longitudinal section of rockslide

3.44 Stereoscopic Images

A series of stereoscopic images are presented in Appendix 1; these are intended as an aid to assessing the features of the rock avalanche and rockslide, as well as the amount of regeneration that has taken place since the event.

Copies were taken on a colour laser copier to achieve greater definition. Images were then cut and glued into position to allow stereoscopic viewing. Due to the large amounts of relief displacement, the 3-D field of view is very much reduced (particularly noticeable on the 1987 photography of Mt Colonel Foster). As far as possible, a similar scale (approximately 1:30,000) has been achieved between different sets of photograpy by enlarging or reducing them. This inevitably leads to problems of definition with small scale photographs, such as BC87046 at a scale of 1:70,000.

The areas presented are from the rock avalanche, rockslide and area of gravel flats immediately below landslide lake throughout the five sets of aerial photography.

CHAPTER FOUR

DISCUSSION

4.1 Introduction

A short review of current thinking on rock avalanches complete, including classification, description and motion has been completed. A description of the field work carried out at the site of the Mt Colonel Foster rock avalanche, and laboratory work completed, is also finished. This chapter focuses on a discussion of matters arising; the research will be tied into current scientific thought and perceptions related to the field area.

4.2 Rock Strength

The Karmutsen volcanics are common to both the Mt Colonel Foster rock avalanche and to the rockslide. Within the larger context of Strength Testing, this has major implications for the susceptibility of this area to mass movements.

Evans (1989) describes the Karmutsen Formation as a "particularly landslide-prone geological unit"; a view supported by Howes (1980) who found it to be the most unstable unit in his study area, strength testing in the field confirming this result.

Strength involves more than the geological unit, as

Selby’s classification attests. The review in Chapter 1 demonstrated how important the effects of weathering, jointing and groundwater are. The effects of water were not considered in this study due to the presence of summer cyclones. For a value judgement, records of rainfall and discharge values from rock units would have to measured and correlated with known landsliding activity.

Mt Colonel Foster falls in Zone 2 of Howes’ (1980) regions of precipitation, with a range of 2000-3000mm yearly, decreasing eastward due to the rain shadow effect created by the mountains. Howe identifies intense storm events as the major cause of landsliding activity by either increasing hydrostatic pressure or reducing shear strength. Water plays an important role; however it cannot be considered within the context of the two mass movements.

Triggering of the movements was by an earthquake, a common occurrence in this region and a major cause of activity according to Howes.

The rock unit was seen to be unweathered due to its relative youth and mode of formation. Weathering has little effect on the strength of the rock formation.

This study identified the presence of jointing as the greatest influence upon the strength of the unit. Photo 3.1, a close-up of the detachment site, depicts the steep out-dip of the finely bedded volcanic rock, along with the more irregular cross-joints. Small and large scale jointing were seen to permeate the rock structures on Mt Colonel Foster making it susceptible to any mechanism that reduces rock strength, whether that be the effect of pore water or earthquake activity. Due to the angle of the bedding planes the landslide to the West was thought to be particularly susceptible to the effects of water. Which ever method causes failure it is the incidence of jointing that is the single largest cause of mass movements within this rock unit.

4.3 Mt Colonel Foster Rock Avalanche

This study estimates the volume of the rock avalanche at $4.76 \times 10^6 m^3$, compared with the estimate by Evans (1989) of $1.5 \times 10^6 m^3$. The difference in these values is accounted for by the fact that Evans *et al* only viewed the detachment zone from a helicopter using the helicopter's altimeter and topographic maps to ascertain the various dimensions. In this study the actual site was visited and a complete view afforded of the detachment zone. The altimeter had been tested for its accuracy and was used on a meteorological stable day.

The avalanche track down into Landslide Lake is shown in the longitudinal-section of Diagram 3.4a and, as supported by Photos 3.6 and 3.7, this depicts the region where a portion of the debris was deposited. By reference to topographic maps and aerial photo BC5056-029 it has been estimated that, with a ground debris depth of 2m, 0.825 ×

$10^6 m^3$ was deposited, with the remainder ($3.935 \times 10^6 m^3$) travelling on down into Landslide Lake. This deposited value has good correlation with Evans (1989).

One point of interest is the presence of off-shoots from the main avalanche body; there is one main off-shoot (area $0.038 km^2$) clearly visible and a smaller one just above. These are both on the same side of the runout zone and so may have been caused by the presence of small climbs on the downhill side of the slope. This would cause them to take off and gain enough momentum to leave the avalanche body. The thinning of trees from the surrounding forest, particularly the downhill side, is evidence of smaller blocks breaking free and shooting away from the main body.

Although the majority of the rock mass descended in to Landslide Lake, the "travel distance" was estimated to see how comparable it was to other avalanches. With an estimated Length of 3,800m and a Height Drop of 1,250m, a Coefficient of Friction (f) of 0.32 was attained. This suggests a highly mobile avalanche that would have been extremely destructive if it had not travelled in to Landslide Lake. The consequences for such a movement in habitated areas would be devastating.

Velocity was estimated at 156 m/s, meaning the mass would have reached Landslide Lake in 11s.

L_d (travel distance) was calculated as 1595m; this is considerably lower than that estimated from aerial photos and could be attributed to the huge loss in height, and so gain in momentum, of the avalanche mass. The distance L_e

was calculated but gave an anomalous result; this again is due to the unusually large drop in height.

The forestry below Landslide Lake was devastated by the outwash wave that poured over the lip of Landslide Lake. Massive boulders and logs were carried within the outwash and at three points further downstream (Aerial Photo 2) gravel flats were deposited which can be seen today. Diagram 3.4b shows a longitudinal-section of this region; two of the gravel flats were deposited at point 1, while the third was deposited a point 2. These areas are confluences and so at this point the valley widens. Consequently there is a rapid drop in height (depicted) followed by a flat. The river loses energy and drops its load.

4.4 Rockslide

The rockslide is very different from the avalanche that took place on Mt Colonel Foster. Occurring in the same rock unit it suffers from the same problems of jointing as the other. However the angle of the bedding planes makes this much more susceptible to mass movement.

The angle of dip out of the slope of the bedding planes was measured at 30°, with the rockslide going to a depth of five major planes. After the seismic shaking, these then slid down into the valley and 50m up the far slope, blocking the valley and causing a lake to form behind it.

This is feature seen today and has a river draining out of the northern end. Diagram 3.5 is a longitudinal-section of this slope, showing slope uniformity.

The area at the south end of the lake, as BC5056-029 shows, has dried out. The lake is therefore shallow here, whereas the end blocked by the landslide is deeper. BC(C)95 in Appendix 1 gives high definition detail of this region and shows large blocks of rock within the lake, as well as the lake bottom and original vegetation beneath the water surface.

The slope is also marked by numerous fresh scars and these are thought to be caused by snow avalanches during the winter.

The rockslide volume is much harder to calculate, particularly the depth of deposit, as the site has not been visited. This is estimated at 20m for the dam area and this produces a volume of $1.25 \times 10^6 m^3$. The coefficient of friction is calculated to be 1.1; an expected value for a rockslide.

The velocity, when calculated, gives a very high value (140m/s); this is because the equation was designed originally for fluids. This operates well for rock avalanches which have a similar motion, but not for rock slides.

The equation L_d operates very well with an expected travel distance of 1026m, compared with an actual distance of 1050m.

A rockslide operates under different process to a rock avalanche, sliding en masse as a single unit down the slope; many characteristics, however, are similar. One major difference is the very much shorter excessive travel distances (due to the sliding) and so a lower coefficient of friction. This can also be noted in the landscape as less fragments of rock escape the slide, so that the forest immediately surrounding the slide is relatively untouched. This is the case here, although it should be noted that a large off-shoot departed the slide approximately half way down.

The presence of debris cones on the west side of the lake may have been deposited in pre- or immediate post-slide times as they appear on BC2096. They may even have occurred at the same time. Without closer inspection nothing more can ascertained. They could represent snow avalanches that carried down large amounts of soil and debris (very much like a debris flow) or other slides.

A final point of interest is the massive amount of gullying taking place on the exposed site of the avalanche track. Even by 1957 this was very evident in the lower portion of the slope and this emphasises the vulnerability of soils on high mountain slopes that have undergone recent glaciation.

4.5 Rejuvenation

Both areas have undergone rejuvenation in the last 45 years, this clearly depicted in the stereographic photos in Appendix 1.

Just above Landslide Lake, both BC2096 and BC5056 show little evidence of re-growth, however by 1980 (BC80072) large portions of the lower slide area have new bush growing upon them. The front cover, taken in 1990, shows evidence of this. Areas of no-growth are steep rock slopes and boulder strewn areas. These are being colonised, but with a lack of soil this is only beginning to take place from cracks and crevasses. It can be assumed that a natural response time of at least 30 years is necessary before rejuvenation of an area can begin. This process is much clearer in the stereographic photos of the rockslide; the difference between BC80072 and BC5056 is very striking. A large amount of gullying and only the beginnings of growth in 1957 is replaced by virtual coverage of the whole slide area in 1980. The areas that remain exposed are boulder strewn or gullied. This has been arrested though and will require a longer period to be fully covered.

It was noted that deciduous trees were growing naturally and had reached a height of 2-4m. From information of forest re-growth after logging, it would seem that a further period of 80 years is required before forest cover is regained; however this still leaves soils that are damaged and less fertile. Information from dateable extreme events such as these would be invaluable in calculating the effects of logging on the landscape; areas that have seen multiple events could, if dating was possible, be used to calculate the effects of second and third cuts.

Re-growth of the river region below Landslide Lake has also taken place. However the response time has been much longer due to the massive scouring effect of the swash wave. BC(C)95 shows how far this had progressed by 1974, while the oblique photos taken this summer (1992) demonstrate the further growth that has taken place.

C H A P T E R   F I V E

CONCLUSIONS

5.1 The Future

The high mountain environment is a delicate natural system that is constantly modifying itself. In understanding the processes at work in such a landscape it becomes possible to predict future events making a degree of accuracy in land hazard mapping possible. Two future problems are present and are discussed below.

It is clear from this study that the Karmutsen volcanics are a highly unstable rock unit and seismic activity and high precipitation in these glacially oversteepened valleys causes a high occurrence of mass movement activity. Evidence in the landscape confirms this. This is not a problem in unpopulated areas; however the consequences of such a set of circumstances in populated areas would be devastating. The amount and orientation of jointing is seen as a major contributor to the type of mass movement and an understanding of this is essential in predicting any type of future movement.

A landslide dam has been created at the site of the rockslide, the stability of which is of great importance. If the dam were to fail then a sudden discharge of a large volume of water could have destructive effects further downstream (similar to the tidal outwash created by the Mt Colonel Foster avalanche). This is particularly important in habitated areas.

Failure could occur by mass movement collapse into the lake creating a tidal wave, the lubrication of the debris through high precipitation levels or another seismic event. Piping is a major form of de-stabilising such a feature and this is more likely in debris that is matrix supported.

5.2 Conclusions

Rock avalanches are rare events (Voight 1978), the Mt Colonel Foster case especially so due to the occurrence of the lake outwash.

Rockslides are very common phenomena, with the formation of lakes not at all uncommon. Such frequency with the possibility of moderate devastation deserves greater study; however the low frequency, high damage events always provoke interest.

Smaller mass movements are more common, although their overall effects are minimal in terms of hazard mapping. What are of consequence are medium frequency, medium damage events such as seen here. Although not spectacular and low in damage, the potential for disaster is still there and over time the probabilities of further similar movements are greater.

The effects of such movements need further consideration, but are outside the scope of this investigation. A further concern, landslide damming, is now receiving greater attention from the academic community.

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