University of Alberta

Klapperhorn Mountain Debris Flows

by

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Abstract

Debris flows pose a significant hazard to CN railway operations at Klapperhorn Mountain, near the Yellow Pass in British Columbia, Canada. Surficial mapping was used to describe the distribution of the geomorphic processes that contribute the to the debris flow hazard. The use of dendrochronolgy was combined with CN records to describe the frequency. Debris flows at Klapperhorn Mountain are very frequent, and have a high probability of occurrence, with the design event likely to occur several times in during the lifespan of the railway. The debris flow volume ranges from less than 50 m^3 to 5000 m^3. The surficial geology and debris flow size were combined to produce a map that rates that relative debris flow hazard at Klapperhorn Mountain. Future work may incorporate the results of this thesis in a quantitative debris flow assessment at Klapperhorn Mountain.

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My thanks go to Duane Froese and Dave Cruden for their patience and guidance throughout the course of this project. Derek Martin provided funding through the Railway Ground Hazard Research Program, which is supported by NSERC, CN, CP Rail, and Transport Canada. Tim Keegan, formerly with CN, now with BGC Engineering Inc. provided access to files, guidance in the field, and expertise gained from many experiences with the geomorphology of Klapperhorn Mountain. Emily Herd answered my many GIS related questions. Melissa Bowerman, Anna Pienkowski-Furze, and Britta Jenson helped in the field. Martin Geertsema guided me through the collection and interpretation of tree ring samples. Peter Bobrowsky (Canada Landslide Loss Reduction Project) and Roger Paulen (Alberta Geological Survey) introduced me to the world of landslides.

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Chapter 1. Introduction

1.1 Overview

Debris flows are a significant mountain hazard throughout the Canadian Cordillera. Canadian National Railway (CN) operates two tracks, the Albreda and Robson subdivisions, through the Yellowhead Pass in the Canadian Rocky Mountains. The Albreda Subdivision extends from Jasper, Alberta to Blue River, British Columbia and the Robson Subdivision runs parallel to the Albreda Subdivision in the vicinity of Klapperhorn Mountain (Figure 1.1). This corridor is the only route through the Canadian Rocky Mountains used by CN, and it provides access to ports in Vancouver and Prince Rupert. Natural hazards may result in significant losses to the railway, including direct losses due the event and indirect losses due to interruption of rail traffic. At Klapperhorn Mountain debris flows pose a significant hazard to both subdivisions. The Albreda and Robson Subdivisions cross six individual drainage basins that produce debris flows that have caused significant impact to the railway through maintenance costs, train incidents, and track outages. The overall geomorphology of Klapperhorn Mountain and the timing, size, and distribution of these debris flows are not well constrained. This research addresses each of these and summarizes the debris flow hazard. The thesis was funded by the Railway Ground Hazard Research Program (RGHRP) which is a collaborative project created to improve the management of hazards to railways in Canada (see Bunce *et al* 2005).

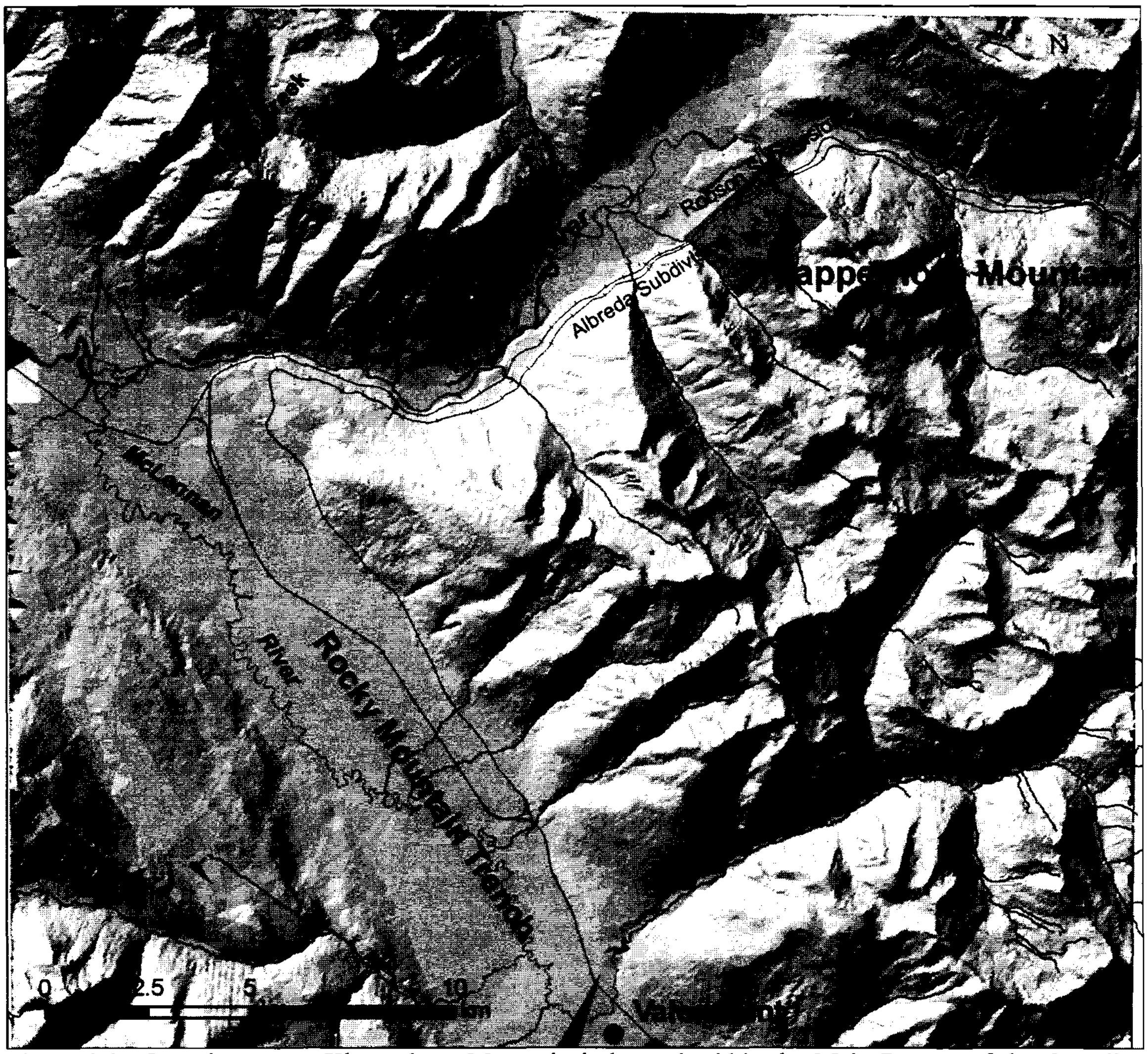

Figure 1.1. Location map. Klapperhorn Mountain is located within the Main Ranges of the Canadian Rocky Mountains. The Albreda and Robson Subdivisions run parallel along the base of the Mountain and provide CN access to the ports in Prince Rupert and Vancouver. Klapperhorn Mountain is located at 53° 00' N, 119° 13' E. The study area is highlighted. Hillshade is created from NTS 1:50 000 elevation data in ArcMap GIS software.

1.2 Debris Flow Research in the Canadian Cordillera.

Little debris flow research has been performed in the vicinity of Klapperhorn Mountain. However, debris flow processes have been studied throughout the Canadian Cordillera, particularly in southwest British Columbia and the southern Canadian Rocky Mountains. This section briefly summarizes the debris flow hazard and the history of debris flow research in the Canadian Cordillera. In this thesis, the term debris flow follows the definition of Cruden and Varnes (1996), and refers to channelized debris flows in steep mountain channels. Other terms used to describe these events in western Canada include debris torrents (*eg.* Hungr *et al.* 1984) and alpine mud flows (Winder 1965).

British Columbia

Debris flows have caused at least 70 deaths in British Columbia since 1891, and are recognized as a significant hazard (Evans 1999). Debris flows in the wet, coastal Howe Sound area have been studied extensively (VanDine 1984; Hungr *et al.* 1984). Research elsewhere in British Columbia includes regional studies of the drainage basin scale controls of debris flow processes (de Scally 2001; Jakob and Bovis 1996) and numerous detailed studies of individual debris flow locations (*eg.* Bovis and Jakob 2000; Jordan 1994; Moore and Matthews 1978).

Canadian Rocky Mountains

Debris flows are also recognized as a significant hazard in the Canadian Rocky Mountains. Perhaps the earliest published study of debris flows in the Canadian Rocky Mountains was by Winder (1965), who investigated the role of an "alpine mudflow" in alluvial cone construction at Hell's Creek and Barrett Creek along the Smoky River. Since that time, most debris flow work has been performed in the southern Canadian

Rocky Mountains. Kostaschuk *et al.* (1986), in the Banff area, and Jackson (1987) and Jackson *et al.*(1987) , in three regions in the Southern Rocky Mountains, examined regional criteria for distinguishing debris flow dominated drainage basins from fluvial dominated drainage basins. Individual debris flow events in the Rocky Mountains have been investigated by researchers including Jackson *et. al.* (1989), Podor (1992), Couture and Evans (1999), Cullum-Keynon *et. al.* (2003) and de Scally *et. al.* (2003).

Few studies of debris flows have been performed in the Klapperhorn Mountain region of the Rocky Mountains. However, there are reports of debris flows in Goslin Creek and L'Heureux Creek (Piteau Associates 1993) and Spittal Creek and Leona Creek (Ministry of Transportation and Highways 1999) to the west of Klapperhorn Mountain (Figure 1.1) which have impacted Highway 16 and residential properties. These debris flows occurred in the Rocky Mountain Trench and were much larger events than those that occur at Klapperhorn Mountain. No research has yet addressed the timing, triggers, and processes involved in debris flow activity in the Klapperhorn Mountain area of the Canadian Rocky Mountains.

1.3 Klapperhorn Mountain Debris Flow Hazard

Railway operations at Klapperhorn Mountain are exposed to several natural hazards including debris flows, rock falls and debris slides. Mitigative actions have been taken to reduce the risks to trains and track structures due to these hazards. These actions include the construction of retaining walls and rock fall catch fences to reduce the impact of events on the railway and the installation of slide detection and warning devices to protect trains and train crews from railway damage or obstruction. These measures have had some success (Keegan 2005, pers. com), especially in protecting against rock fall hazards. CN has a well-developed rock fall hazard rating system (Abbot *et al,* 1998a,b; Pritchard *et al* 2005), and rock fall processes are well understood and mitigation methods are well developed. Debris slides remain as hazards, but occur in well-defined areas and are relatively slow-moving events. Debris flows, however, continue to result in ongoing maintenance issues, have caused major disruptions to operations in the area, and are the focus of this thesis.

Effective mitigation of the debris flow hazard at Klapperhorn Mountain has been less successful because the processes that control the timing, size, and distribution of debris flows in the study area are poorly understood. This, in part, reflects the scale of the processes and a lack of extensive historical debris flow data in the study area. Debris flow impacts at track level are the result of processes that occur throughout the drainage basins, often hundreds of metres away from the track and railroad structures, but most investigations and mitigation work to date has been focused on areas adjacent to the tracks. Also, historical records of debris flows at Klapperhorn Mountain are limited and exist from only 1988 to present. These records do not include detailed information about individual debris flows and do not address the drainage basin scale transport processes, and are therefore insufficient for a complete debris flow hazard analysis. They do, however, provide some information regarding the timing and distribution of debris flow events, and is useful as a starting point for further research. These historical records are described in Chapter 2.

1.4 Setting

1.4.1 Location

Klapperhorn Mountain is in the Selwyn Range, one of the Main Ranges of the Canadian Rocky Mountains, west of the headwaters of the Fraser River. Klapperhorn Mountain lies on the southeast side of the southwest-northeast trending valley of the Yellowhead Pass, which is occupied by the Fraser River. The study area lies immediately outside of Mountain Robson Provincial Park and is on the northwest slopes of Klapperhorn Mountain (Figure 1.2).

1.4.2 Klapperhorn Mountain

Klapperhorn Mountain is 2300 m in elevation and rises 1500 m from the base of the Fraser River Valley. It is situated between Overlander Mountain to the northeast and Mount Terry Fox to the southwest. The study area at Klapperhorn Mountain includes about 3 km of each of the Albreda and Robson subdivisions, which run parallel along the base of the mountain (Mile 10 to 12 of the Robson Subdivision, Mile 53.5 to 55.5 of the Albreda Subdivision; Figure 1.2).

1.4.3 Bedrock Geology

Klapperhorn Mountain lies on the boundary between NTS 1:250 000 map sheets 83D and 83 E. The bedrock geology of the study area within 83E is mapped at a scale of 1:250 000 (Mountjoy 1980), and the study area within 83D is mapped at 1:50 000 (McDonough and Mountjoy 1990). The site is within the Proterozoic Middle Miette Group, which

Figure 1.2. Klapperhorn Mountain. The Albreda and Robson Subdivisions are shown, and the mile markers and the mileages of bridges and important structures that are referred to throughout the thesis are given. Track mileage is used as a convenient location reference throughout this thesis. Note that the photograph is rotated from north for ease of viewing. Background image 1:40 000 air photograph, 30BCB 91102 No 256, BC Provincial Airphoto and Lab Services.

includes feldspathic sandstone, granule and pebble conglomerate, siltstone and argillite (Mountjoy 1980). The Old Fort Point Formation, which is a part of the Middle Miette Group, occurs within the study area, and includes dolomitic and calcareous siltstone, limestone, and pelite. The railway runs in a southwest-northeast direction, which is perpendicular to the regional trend of major geologic structures. The bedrock geology is discussed in more detail in Chapter 3.

1.4.4 Quaternary History

The Robson Valley was glaciated during the Late Wisconsinan. The Cordilleran ice sheet advanced east toward Jasper, where radiocarbon dates provide a maximum age of approximately 29 000 years B.P. for onset of glaciation (Levson and Rutter 1996). Late Wisconsinan westward retreat of the Cordilleran Ice Sheet from the Jasper area occurred by 12 000 years BP (Bobrowski and Rutter 1992; Dirszowsky and Desloges 2004). Holocene sedimentation in Moose Lake, approximately 15 km east of Klapperhorn Mountain, began prior to 9000 years BP (Desloges 1999), suggesting that the Klapperhorn Mountain area was deglaciated after 12 000 years BP and before 9000 years BP.

1.4.5 Climate

The climate at Klapperhorn Mountain is described as moist-mild (BC Ministry of Forests 2003). Weather data for the period of May 1975 to August 1992 is available from the Robson Ranch weather station that was located near the base of Klapperhorn Mountain. During this period, average annual precipitation was about 590 mm, with the highest precipitation occurring in the months from December to January, and July to

August, with precipitation of 135 mm and 130 mm, respectively. In the December to January interval most of the precipitation fell as snow, while in the July to August interval most fell as rain. Several intense, short-lived rainstorms were observed during the 2004 and 2005 summer field seasons. The average daily maximum daily temperature between 1975 and 1992 was 8.7° C, with extremes of -29° C and 34° C.

1.5 Objectives

The overall objective of this research is to describe the debris flow processes and hazard at Klapperhorn Mountain. The specific objectives are as follows:

1) To describe the extent of the debris flow hazard at Klapperhorn Mountain using the historical record and field work (Chapter 2),

2) To use detailed terrain mapping to describe the geomorphic processes that contribute to the debris flow hazard (Chapter 3),

3) To describe specific debris flow processes that control the hazard (Chapter 4),

4) To rate the relative hazard within the study area (Chapter 5), and

5) To recommend future work that is required to develop a comprehensive risk assessment at Klapperhorn Mountain. (Chapter 6).

Chapter 2. Debris Flows at Klapperhorn Mountain

2.1 Overview

The objective of Chapter 2 is to identify and describe the debris flow drainage basins and channels at Klapperhorn Mountain and to review the historical debris flow activity in these channels. This establishes the extent of the hazard posed by debris flow activity and identifies the areas where a detailed assessment is required. Drainage basin characteristics and evidence of debris flow activity are used to identify debris flow basins. Detailed descriptions of geomorphology and debris flow processes of the areas identified in Chapter 2 are given in Chapters 3 and 4.

2.2 Methods

There are three components of this chapter: debris flow drainage basins on Klapperhorn Mountain are delineated, debris flow channels within the basins are identified, and recorded debris flow activity within these channels is described.

2.2.1 Drainage basin delineation

Drainage basins are delineated using aerial photographs and a Digital Elevation Model (DEM) of Klapperhorn Mountain that was supplied by CN. The drainage divides are well defined in the upper portions of each basin, but are more poorly defined below the Albreda Subdivision where the basins are unconfined and debris deposition areas merge or have indistinct boundaries. Therefore, drainage divides are only shown above the Albreda Subdivision. A drainage basin is defined by the area that may contribute water and debris to a portion of the Albreda Subdivision, based on distinct source areas that are separated by the topography of Klapperhorn Mountain. Relevant drainage basin parameters were calculated using ESRI (2005) ArcGIS software.

2.2.2 Debris Flow Channel Identification

Debris flow channels were identified through air photograph interpretation and field identification. Channels were recognized by the presence of debris flow features, including levees along channel banks, debris piled against the upslope side of trees adjacent to the channels, and the presence of debris flow deposits within the channels.

2.2.3 Documented Debris Flows

There are five documented debris flows at Klapperhorn Mountain. A CN ground hazard incident database documents two debris flow events that caused significant train accidents and damage to track structures. CN files describe four other debris flows.

Debris Flow Incident Database

As part of the RGHRP, CN compiled a database of ground hazard events along CN tracks that have derailed trains, damaged railway structures, or have been significant enough to require further attention (Keegan 2004). There are eight sections in the database that are available for this project. Monetary costs associated with the events are not available. The database includes the location, timing, hazard event, associated train accident, triggering conditions, health and environmental losses, and mitigation steps associated with the hazard. However, there are only two documented debris flows at Klapperhorn Mountain in this database, and there are no data for many of these fields for these events.

Additional Debris Flow records

Additional debris flow records were obtained from CN's hazard monitoring database (CN Monitoring) and geotechnical files, and provide details of debris flow activity in basins 53.6, 54.0, 54.3a and 54.7. No train incidents are associated with these records, and not all describe specific, dated debris flows.

2.3 Drainage Basins

There are six drainage basins at Klapperhorn Mountain (Figure 2.1). These basins are named for the mileage of the bridge or rockshed at which the main channel in each basin crosses the Albreda Subdivision. In basin 55.0, no structure is present, so the basin is named for the Albreda track mileage of the approximate centre of the basin. In strict watershed delineation, basins 54.3a and 54.3b could be described as a single basin, as creeks from both flow under the M54.3 bridge. For the objectives of this thesis, it is useful to define two separate drainage basins with distinct debris source areas. There are a total of 13 debris flow channels identified in these drainage basins (Table 2.1; Figure 2.1). Debris flows are documented in four of these channels (Table 2.2).

2.3.1 Basin Properties

The drainage basins at Klapperhorn Mountain are relativity small basins that range from 0.2 km^2 to 4.6 km^2 in area (Table 2.3). Basin 53.6 is the largest basin and drains the area between Klapperhorn Mountain and Overlander Mountain. The other basins all drain portions of the northwest face of Klapperhorn Mountain, and are much smaller than basin 53.6, ranging between 0.2 km^2 and 0.6 km^2 in area. Basin 53.6 also has the greatest relief, at 1720 m. The relief of the basins that drain the face of Klapperhorn Mountain ranges from 890 m to 1340 m. Melton's (1965) ruggedness number, defined as

$$R = H_b (A_b)^{-0.5} \qquad \text{eqn. 3.1}$$

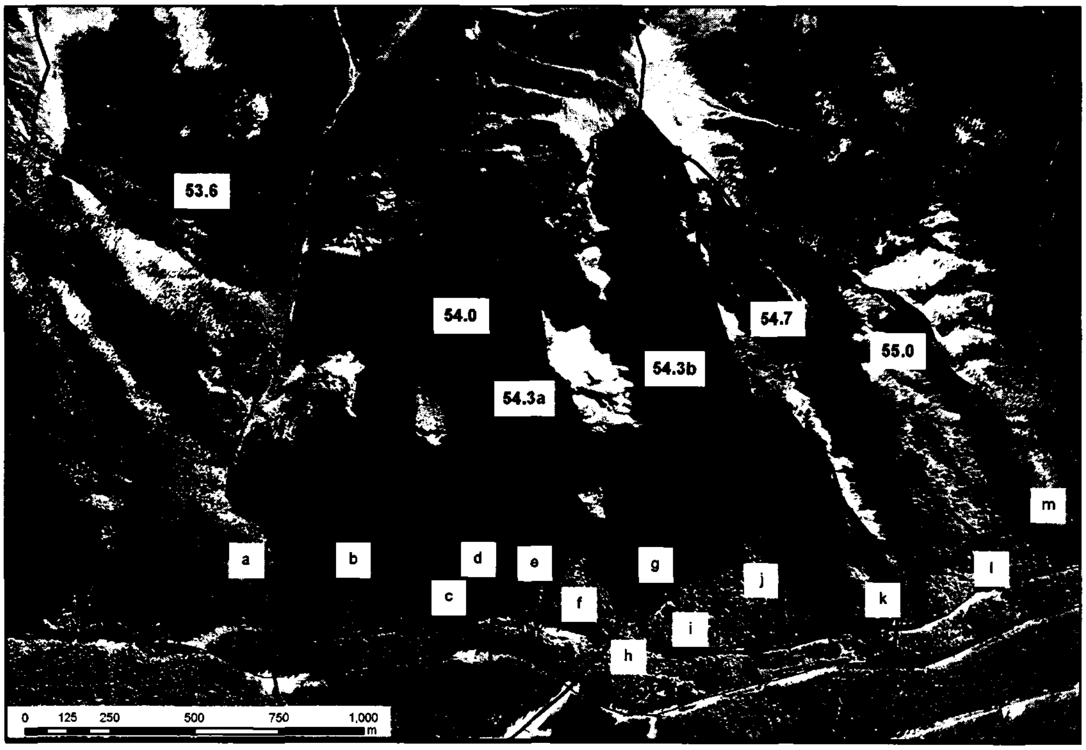

Figure 2.1. Debris flow drainage basins and channels at Klapperhorn Mountain.

Basin	Debris Flow Channels
53.6	a
54.0	b, c, d
54.3a	e, f
54.3b	g, h, i, j
54.7	k
55.0	l, m

Table 2.1. Debris flow channels within each drainage basin.

Basin	Channel	Date	Description	Source
53.6	a	May 11, 1993	Debris flow in channel occurred as train was passing over the Robson Mile 10.1 bridge; bridge was "washed out" 18 cars derailed.	Keegan 2004
53.6	a	July 18, 2001	Debris flow in channel blocked drainage under Robson Mile 10.1 bridge. Water accumulated above track and saturated grade, causing an earth slide on the down-slope side of the track at Robson Mile 10.3; 2 locomotives and 14 cars derailed; intense rain trigger	Keegan 2004
53.6	a	July 18, 2003	Debris flow in channel partially blocked drainage under Robson Mile 10.1 bridge; No train incident; intense and sustained rain trigger	CN Hazard Monitoring
54.0	c	June 23, 2003	Debris flow in channel c; debris deposited in ditch above Albreda Subdivision, flowed along ditch and under Mile 54.0 bridge; intense rain trigger	CN Hazard Monitoring
54.3a	e	July 1988	Debris flow in channel that terminates at the top of the cut-slope above the Albreda Subdivision at Albreda Mile 53.2	CN Geotechnical Files 1988
54.7	k		No details of a specific debris flow event; entry recorded on August 12, 2004 describes debris flows in this channel as "frequent, every 1-2 years	CN Hazard Monitoring

Table 2.2. Historical debris flows at Klapperhorn Mountain. Notes that triggers described in the table are based on the description in the source. Specific triggering conditions based on weather data are available only for the July 1988 debris flow in channel 'e'. See text for details

Basin	Area - A (km^2)	Relief - H_b (m)	Ruggedness R	Fan Slope
53.6	4.6	1720	0.8	8.1
54.0	0.4	1040	1.6	9.6
54.3a	0.3	1050	2.1	9.8
54.3b	0.6	1340	1.7	9.9
54.7	0.3	1240	2.2	15.3
55.0	0.2	890	1.9	7.0

Table 2.3. Basin parameters for the Klapperhorn Mountain basins. $R = H_b A^{-0.5}$

where H_b is basin relief and A_b is basin area provides an area normalized measure of basin slope. This ranges from 0.8 in basin 53.6 to 2.2 in 54.7. The fans in these debris flow basins, which are described in detail in Chapter 4, range from 7.0° in basin 55.0 to 15.3° in basin 54.7 (Table 2.3).

Drainage basin properties reflect the dominant mechanism of debris transport within the basin. Kostachuk *et al.* (1986) demonstrated in the Banff region of the Canadian Rocky Mountains that basin processes and form are related, and that small, rugged basins produce steep, debris flow dominated fans. Research has shown that there are minimum values of Melton's ruggedness number and fan slope in debris flow basins, and that these parameters may be used to identify basins that produce debris flows. In the Canadian Rocky Mountains, Jackson (1987) and Jackson *et. al.*(1987) recognized that fan slopes of 4° and ruggedness numbers of 0.25 to 0.3 distinguish fluvial from debris flow dominated drainage basins. In the Cascade Mountains of British Columbia, de Scally *et al.* (2001) recognized minimum values of 4° fan slope and 0.38 for ruggedness for debris flow basins, though some fluvial dominated basins had fan slope values that exceeded 4°. Similar research in New Zealand identified minimum values of 7.5° fan slope and 0.75 for ruggedness as minimum values for debris flow basins (de Scally and Owens 2004). The differences likely reflect regional variations in factors such as geology, climate, vegetation, and material type.

The fan slope and ruggedness number values at Klapperhorn Mountain indicate that each of six drainage basins at Klapperhorn Mountain are debris flow basins (Figure 2.2). While the threshold values have not been calibrated specifically for the Klapperhorn Mountain area, the values fall well above the debris flow threshold values

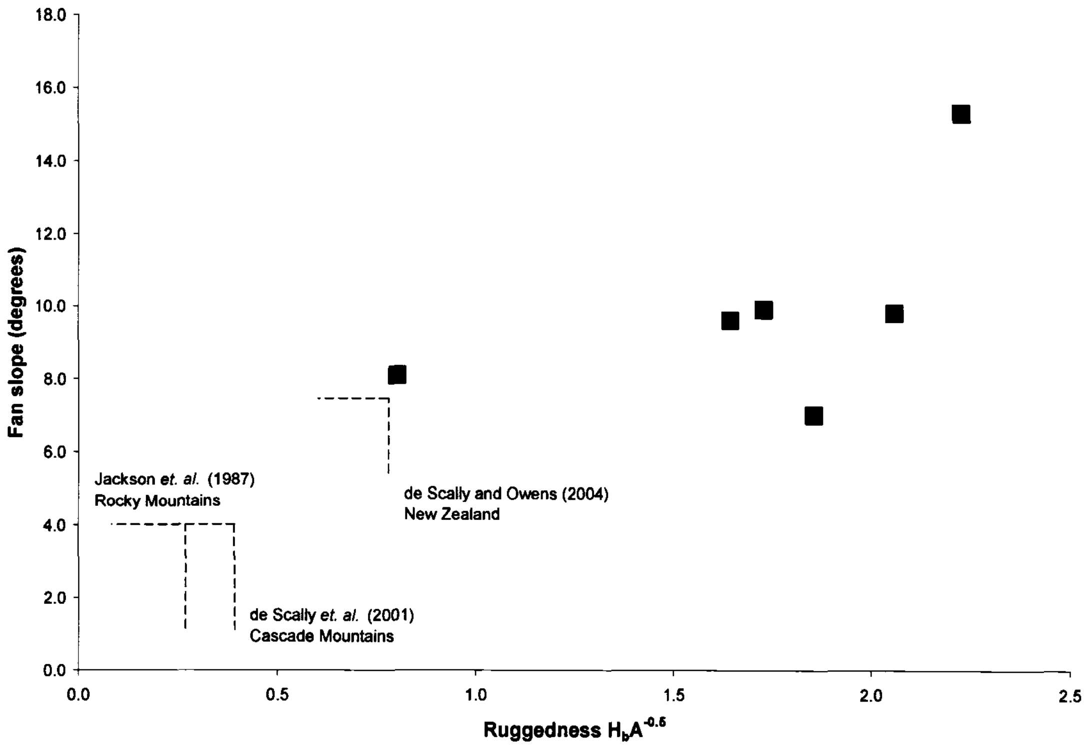

Figure 2.2. Ruggedness and deposition area values for the Klapperhorn Mountain drainage basins. Dashed lines indicate the minimum values for debris flow drainage basins in the Rocky Mountains (Jackson *et. al.* 1987), the Cascade Mountains (de Scally *et. al.* 2001) and the Alps of New Zealand (de Scally and Owens 2004)

for the Rocky Mountains (Jackson *et. al.* 1987) and the Cascade Mountains (de Scally *et. al.* 2004). The much higher slope values in basins 54.7 may reflect the impact of other depositional processes such as snow avalanches on the fans, but there are no distinct values that can effectively subdivide non-fluvial basins (Jackson *et. al.* 1987; de Scally *et. al.* 2001). The basin parameters indicate that the debris flow hazard in each of the six drainage basins must be evaluated. Debris flow channels and recorded debris flow events in each basin are described below.

2.3.2 Basin 53.6

A single channel (a) occurs in basin 53.6 and passes under the Albreda Mile 53.6 and Robson Mile 10.1 bridges (Figure 2.1). The channel is well confined above and below the Albreda Subdivision, and shows evidence of debris flow levees and deposits. Extensive channel excavation has been performed below the Albreda Subdivision to remove debris flow material.

Debris flow events in this channel derailed trains on May 11, 1993 and July 18, 2001 (Keegan 2004). The May 11, 1993 derailment was caused by a debris flow that occurred as a train was passing over the Robson Mile 10.1 bridge, which was "washed out" by the debris (Keegan 2004). The event derailed 18 train cars, and closed the Robson Subdivision for 8 days. The July 18, 2001 derailment occurred when a debris flow in channel 'a' blocked drainage at the RBS 10.1 bridge and caused water to accumulate in the ditch above the Robson Subdivision, subsequently causing failure of the track on the down-slope side of the grade. When a train passed this location, 2 locomotives and 14 cars were derailed. The length of track closure is not indicated in the records.

One other debris flow event in this basin is recorded in the historical record. On July 18, 2003 a debris flow event occurred in channel 'a', but did not cause a train derailment or damage the railway. The debris flow partially obstructed flow beneath the RBS 10.1 bridge, with water still able to pass. The trigger of this event is described as "intense and sustained rainfall" (CN Monitoring).

2.3.3 Basin 54.0

Three debris flow channels occur in basin 54.0 (Figure 2.1). Channel 'b' is a small debris flow channel that runs along the east margin of basin 54.0. Access to the upper portions of the channel was limited by dense vegetation, but a deposit of sand, silt, and clay in a 10 m length of ditch above the Albreda is similar to deposits in the distal portions of other debris flow fans. It is assumed that this deposit is the result of a small debris flow in this channel. There are no documented debris flows in the record.

Channels 'c' and 'd' run down the west margin of basin 54.0 (Figure 2.1) Channel 'd' is the main creek within the basin and passes under the Albreda Mile 54.0 bridge and the Robson Mile 10.4 bridge. Recent debris flow levees occur along the length of the channel and little to no vegetation or forest litter occurs within the channel. Channel 'c' is a secondary channel that branches from channel 'd', and reaches the ditch above the Albreda Subdivision 20 m west of the Albreda Mile 54.0 bridge. This channel reaches the Albreda Subdivision where no bridge or structure is present to control the flow. On June 23, 2003, a debris flow occurred in channel 'c' (CN Monitoring). No details of the size or triggers are available.

2.3.4 Basin 54.3a

There are two debris flow channels in Basin 54.3, which is one of two basins in which the main creek passes under the Albreda Mile 54.3 bridge. Channel 'e' (Figure 2.1) runs down the east side of the basin and terminates at the top of a 10 m high cutslope along the Albreda Subdivision. Subdued and weathered levee features line the channel and abundant forest litter occurs within the channel. Vegetation is limited to small alders in the upper reaches of the channel.

The main channel 'f' (Figure 2.1) in basin 54.3a runs down the west margin of the channel and flows beneath the Albreda Mile 54.3 bridge. There is a left-hand bend 30 m in length in the channel above the bridge. A berm runs along the right bank of the channel within this bend and is intended to ensure that debris flows are confined to the channel and pass beneath the bridge. Recent debris flow levees occur along the channel, and no vegetation and little forest litter is present within the channel.

One debris flow event in basin 54.3a is recorded in the historical record. In July 1988 a debris flow occurred in channel 'e' on the east side of the basin. (CN Geotechnical File 1988). The precise date of the debris flow is not given, but an inspection was performed on July 20, "subsequent to the most recent" debris flow. The event was observed at the top of the cut slope and is described as a "debris torrent" that occurred in a "debris chute that originates several hundreds of feet above the track" (Geotechnical File 1988). The file indicates that the July 1988 event was not unusual, but flows are "infrequent" and occur during heavy rainfall.

2.3.5 Basin 54.3b

Four debris flows channels occur in basin 54.3b (Figure 2.1). The main channel 'g' (Figure 2.1) flows down the east margin of basin 54.3 and passes under the Albreda Mile 54.3 and the Robson Mile 10.7 bridges. Extensive excavation has been performed along the length of this channel to remove debris flow deposits and to construct a berm along the outside of the right hand bend above the Albreda Subdivision. The berm is intended to constrain flows to channel 'g' along the right hand bend in the channel above the Albreda Subdivision. Two channels 'h' and 'i' occur below this bend (Figure 2.1). These channels have weathered and subdued levee features, and abundant forest litter is present. Cedar and Spruce trees of approximately 2 m in height are present within the channels.

Channel 'j' runs down the west side of basin 54.3b. Recent debris flow activity in this channel terminates approximately 200 m off of the Albreda Subdivision and channel 'j' is less than 1 m depth.

No debris flow flows events in basin 54.3b are recorded in the historical record.

2.3.6 Basin 54.7

One debris flow channel, 'k', occurs in basin 54.7 (Figure 2.1). This channel flows down the east margin of the basin and crosses the Albreda Subdivision at the Mile 54.7 rockshed and the Robson Subdivision at the Mile 11.3 bridge. Debris flow levees and deposits are present on the roof of the rockshed and along the length of the channel.

Debris flow activity in Basin 54.7 is briefly described in the historical record (CN Monitoring). An entry recorded in August of 2004 indicates that debris flows are frequent in this basin, and occur every "1 to 2 years". No indication of the size of these flows is given.

2.3.7 Basin 55.0

Two debris flow channels, 'l' and 'm', occur within basin 55.0 (Figure 2.1). Both channels occur above the Albreda Subdivision and are not seen above the Robson Subdivision. No bridge or structure is present in this basin, and both channels terminate in the ditch above the Albreda Subdivision.

Channel 'l' flows down the east margin of basin 55.0. Weathered and subdued debris flow levees occur along the channel, and lobate debris flow deposits are present immediately above the Albreda Subdivision. Abundant forest litter is present and vegetation grows in the channel.

Channel 'm', flows along the west margin of basin 55.0. Debris flow levees occur along the channel, and no forest litter or vegetation is present within the channel. The channel terminates in the ditch above the Albreda Subdivision, where a thin deposit of sand, silt, and clay is present along a 5 m length of the ditch.

2.4 Hazard Scenarios

As part of the Railway Ground Hazard Research Program, Keegan (2007) has developed a methodology for characterizing railway ground hazards by the sequence of processes that lead to track failure. Hazard scenarios for a variety of ground hazards are described using event trees that were developed using records of events throughout western Canada. The recorded debris flows at Klapperhorn Mountain may all be described according to this system.

A simplified version of the debris flow hazard scenario is shown in figure 2.3. In this scenario, there are three general ways in which a debris flow may lead to track failure. In the first branch of the event tree, a debris flow initiates and flows to the track. This flow may deposit debris on the track, strike a passing train, or damage structures such as bridges. The May 11, 1993 debris flow in basin 53.6 that damaged the Albreda Mile 53.6 bridge is an example of this type of hazard.

As shown in the second and third branches of the tree, an avulsion of the first debris flow may occur. In an avulsion, the main channel is breached and flow occurs in a secondary channel. In the second branch of the event tree, this avulsion leads to a debris flow in the second channel that may reach the track. The June 23, 2003 debris flow in basin 54.0 that reached the Albreda subdivision is an example of this type of hazard. In the third branch of the event tree, there is no debris flow in the secondary channel. In this case, water flow in the secondary channel reaches the track grade. This water may cause track failure through seepage erosion through the grade, gully erosion if the water overtops the grade, or an earth slide – earth flow as a result of elevated pore pressures within the grade. The July 18, 2001 debris flow in basin 53.6 that caused a derailment on the Robson Subdivision is an example of this type of hazard.

2.5 Triggers of Historical Debris Flow Events

The limited debris flow record and lack of complete weather data for the study area prevent a robust analysis of the triggering conditions of debris flows at Klapperhorn Mountain. However, the existing records indicate that rainfall is the primary trigger for debris flow events.

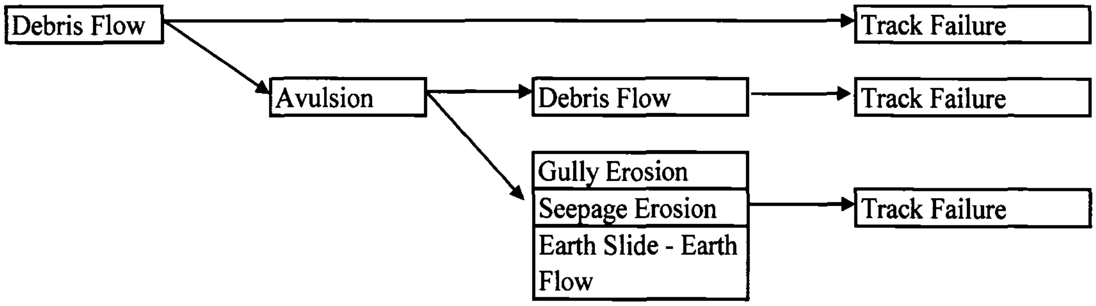

Figure 2.3. Simplified event tree for the debris flow hazard scenario (modified from Keegan, 2007). The debris flow events at Klapperhorn Mountain can be described used this hazard scenario.

An Environment Canada weather station (Mount Robson Ranch, Stn. 10952B9) was in operation at the base of Klapperhorn Mountain from May of 1975 through August 1992. Only the July 1988 documented debris flow occurred during this interval, but the data are useful for establishing average rainfall and snowfall at the base of Klapperhorn Mountain and provides insight into the triggering conditions for debris flows. Data from this weather station shows that most precipitation falls as snow from October through January, a mixture of rain and snow from February through April and as rain from May through September. Average rainfall in August is highest, at 67 mm (Figure 2.4). Only daily rainfall values are available for the Mount Robson Ranch weather station, so rainfall intensity-duration relationships are not available.

The weather data and historical record suggest that rainfall is the primary trigger for debris flow events (Figure 2.4). The number of recorded debris flows in each month show that rainfall is a likely trigger for debris flow events. Accurate snow depth data are not available for the upper regions of Klapperhorn Mountain, so snowmelt cannot be ruled out as a contributing factor in the May 1993 event. Photographs of Klapperhorn Mountain from May 2002 show snow on Klapperhorn Mountain, suggesting that snow melt may also be a debris flow trigger (Figure 2.5).

The July 1988 debris flow is the only historical debris flow that occurred between 1975 and 1992 when the weather station was operational. In July 1988, the Mount Robson Ranch weather station recorded 61.4 mm of rainfall, which is below the average of 67.0 mm for the 1975 to 1992 interval. However, in June of 1988, the station recorded 69.1 mm, which is higher than the June average of 53.4, and on July 11, 1988, 15.6 mm of rain fell, the third highest single day rainfall of 1988. The exact date of the debris flow

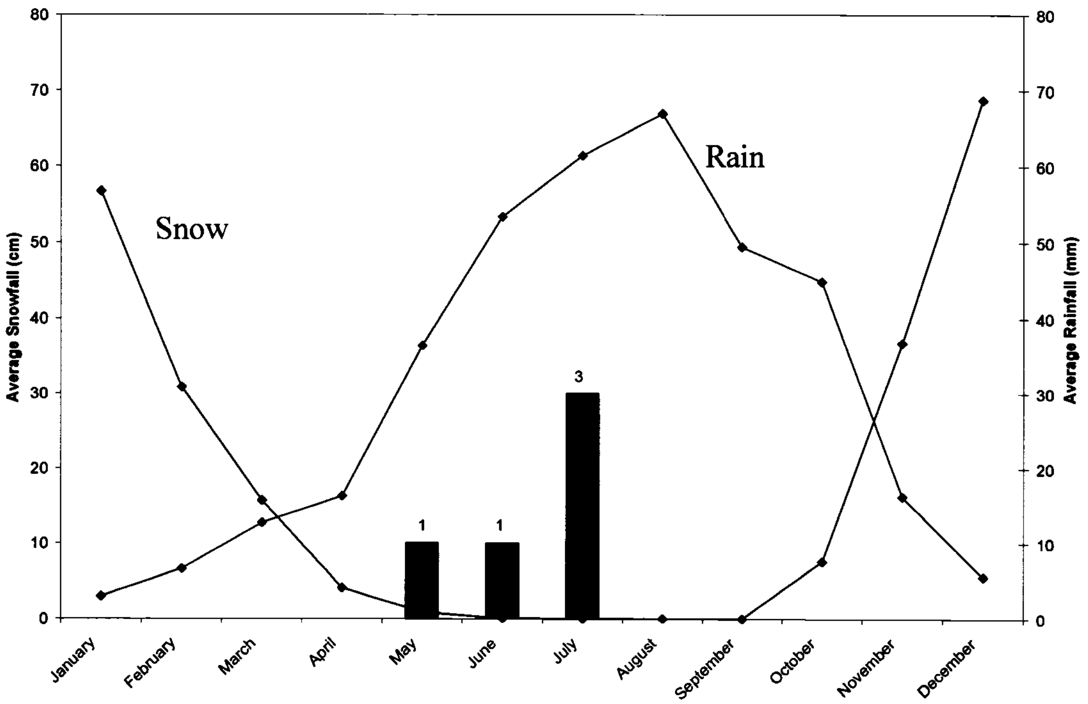

Figure 2.4. Monthly snowfall and rainfall averages at the Robson Ranch weather station at the base of Klapperhorn Mountain. Monthly averages are calculated based on data from 1975 to 1992. Columns indicate the number of historical debris flows recorded in each month. Note that only the July 1988 debris flow occurred during 1975 to 1992 weather data interval. See text for details.

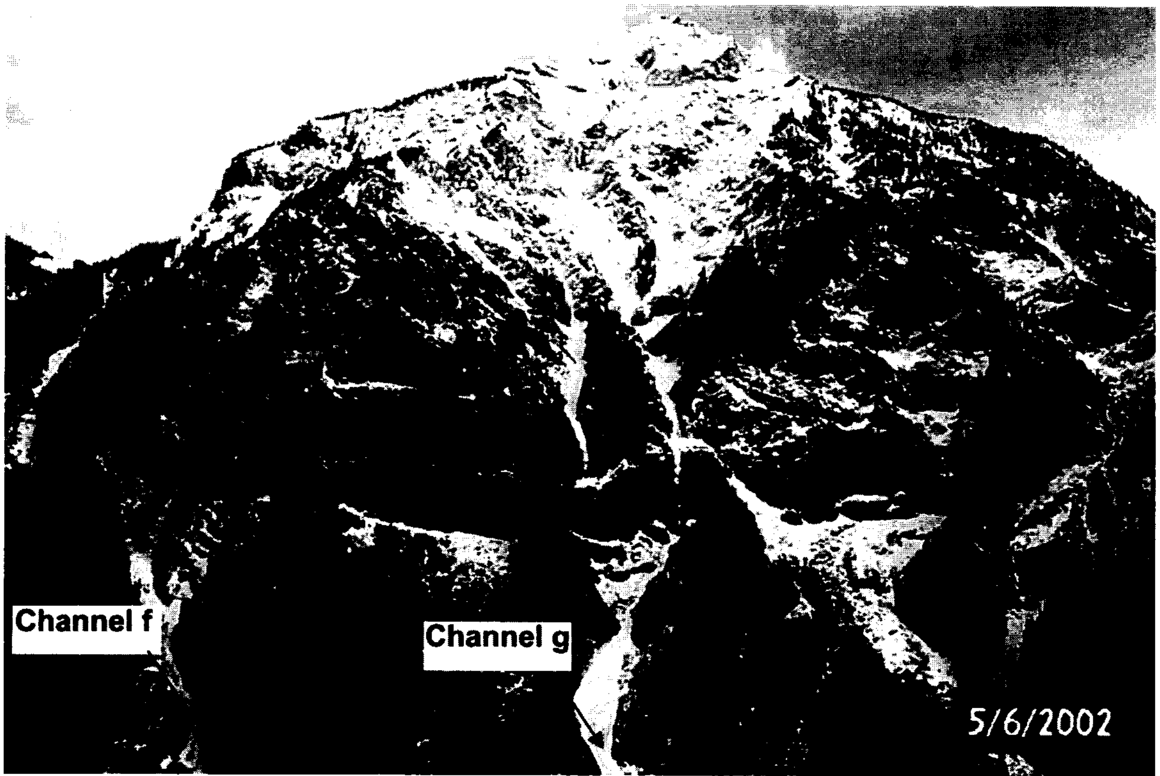

Figure 2.5. Klapperhorn Mountain on May 6, 2002. Snow is present in the upper portions of the mountain and within the visible debris flow channels, suggesting that snow melt is a possible trigger for debris flows in spring months. Accurate snow depth data for the upper portion of Klapperhorn Mountain are not available. Photo courtesy of Tim Keegan.

is not known, but the debris flow occurred before July 20, the date that the site was inspected (CN Geotechnical Files). A definite triggering event cannot be identified, but a possible trigger was a period of higher than average rainfall followed by a single day of intense rainfall.

2.6 Conclusions

Debris flows pose a significant hazard to railway operations at Klapperhorn Mountain. There are six small, rugged drainage basins with ruggedness and fan slope values that indicate that debris flows are the dominant debris transport mechanism. A total of 13 debris flow channels were identified in these drainage basins.

The distribution of the debris flow channels and the historical debris flow record indicate that there Keegan's (2007) debris flow hazard scenario effectively describes the sequence of processes that may lead to track failure at Klapperhorn Mountain.

Intense or prolonged rainfall is the most likely trigger of debris flows at Klapperhorn Mountain. The incomplete historical debris flow record and lack of weather data prevents a robust analysis of debris flow triggers, so other events such as snow melt on Klapperhorn Mountain may also be significant.

The existing historical record is insufficient for a complete hazard assessment, so terrain mapping and field data are used to supplement the existing database of recorded debris flows, to describe the geomorphology of Klapperhorn Mountain and to assess the debris flow hazard to the railway.

Chapter 3. Klapperhorn Mountain Geomorphology

3.1 Overview

Chapter 3 describes the overall geomorphology of Klapperhorn Mountain. The geomorphology is incorporated in the hazard rating (Chapter 5). A description of the geomorphology of the study area is also necessary for the appropriate design of any remediation measures. Terrain mapping is used to describe the distribution of deposits and terrain features and the results are presented in a 1:10 000 scale terrain map (Figure 3.1, map pocket) that represents the debris transport model for Klapperhorn Mountain. The distribution and characteristics of the terrain units and features are described, and the processes that control the overall geomorphology are identified. Specific debris flow controls and processes are described in Chapter 4.

3.2 Methods

The Klapperhorn Mountain terrain mapping is based on air photograph interpretation and is supplemented by ground-truthing performed during field work in the summers of 2004 and 2005.

3.2.1 Air photograph interpretation

Air photograph interpretation was used to delineate the boundaries between terrain units and to identify linear process features. Air photographs taken in 1991 are available for the entire study area at a scale of approximately 1:40 000 from the British Columbia Air Photo and Lab Services of the Integrated Land Management Bureau. These photographs provide adequate coverage of the upper bedrock portions of Klapperhorn Mountain, and were used to delineate many of the bedrock and colluvial veneer units, which are described fully in section 4.3. Two sets of air photographs from

1985 and 1997 at a scale of approximately 1:15 000 were available from CN. These photographs cover an area that extends approximately 500 m above the Albreda Subdivision and below the Robson Subdivision, and were used for delineating the colluvial cone and fan units on the lower portion of Klapperhorn Mountain. A list of the air photographs used is given in Appendix I.

3.2.2 Field Work

Ground-truthing was performed in 2004 and 2005. Due to steep terrain, only the lower colluvial units were accessible. These were investigated in detail, and a table of ground truth points is given in Appendix I. These ground truth points were used to confirm and adjust the terrain units that were identified through air photograph interpretation. In October 2004, the upper bedrock portions were observed and photographed during a helicopter flight over the study area.

3.3 Terrain Classification System

Terrain mapping is used to classify surficial materials, landforms, and geomorphological processes (Howes and Kenk 1997), and is used here to establish the distribution and relationships of the debris transport processes at Klapperhorn Mountain. This section provides an overview of the classification system and defines the terrain units and symbols used in the mapping. The terrain mapping classification system includes two parts: terrain units and linear features.

3.3.1 Terrain Units

Terrain units consist of areas on the ground with uniform characteristics. Terms and definitions from the Terrain Classification System for British Columbia (Howes and

Kenk 1997) are selected and modified for use at Klapperhorn Mountain. Terrain units consist of up to three elements: material type, surface expression and geomorphic process (Figure 3.2; Table 4.2a,b,c).

The material type term describes the type of material on the basis of the mode of deposition. The materials identified at Klapperhorn are bedrock, colluvium, and undifferentiated material (Table 4.2a).

The surface expression term describes the pattern of the material on the ground surface, including the shape of the terrain unit (cone, fan), or the depth of the material within the unit (veneer) (Table 4.2b).

The geomorphic process term describes the processes that have recently acted upon the unit, and the order of multiple process symbols reflects a subjective assessment of the relative importance of each process. Terrain units with the same primary geomorphic term are filled with the same colour on the map. The terrain unit label indicates any other process terms. It should be noted that the geomorphic process term describes recent processes. This may or may not reflect the same relative importance of the processes that initially formed the feature. Processes include mass movements, which are defined following Cruden and Varnes (1996), and snow avalanches. Avalanche processes are not differentiated, and are defined here simply as movements of masses of snow down slope under the influence of gravity (Table 4.2c).

3.3.2 Linear Features

Linear features represent features formed by processes that occur within the study area. The mapped features at Klapperhorn Mountain are snow avalanche paths, rock fall

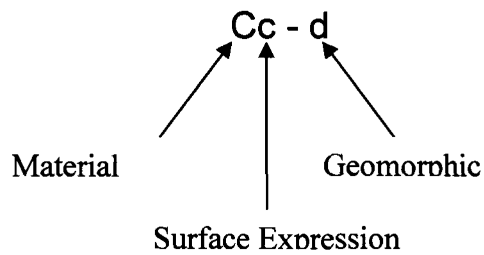

Figure 3.2. A terrain unit symbol

Symbol	Material Type	Definition
B	Bedrock	Exposed bedrock. May include discontinuous accumulations of debris less than 1 m in thickness
C	Colluvium	Material that has been transported and deposited by mass movement under the influence of gravity.
U	Undifferentiated	Material that was not described in detail. May include valley fill deposits or glacial material

Table 3.1a. Material type terms and symbols used for surficial mapping.

Symbol	Surface Expression	Definition
f	fan	Conical shaped feature with a slope of less than 20°
c	cone	Feature with a slope of greater than 20°. When not confined by topography, these features are conical, but shape may reflect the surrounding topography
v	veneer	Continuous cover of material up to 2 m in thickness. Topography reflects that of the underlying material (generally bedrock)

Table 3.1b. Surface form terms and symbols used for surficial mapping.

Symbol	Process	Definition
r	rock fall	Extremely rapid mass movement of rock type material by falling, rolling, or bouncing
ri	inactive rock fall	rock fall areas that show no evidence of recent activity
d	debris flow	Rapid movement of saturated debris type material in defined channels
s	debris slide	Movement of debris type material through sliding. Generally extremely slow to very slow
a	snow avalanche	Rapid mass movement of snow under the influence of gravity

Table 3.1c. Geomorphic process terms and symbols used for surficial mapping. The rate, material type, and movement type following Cruden and Varnes (1996)

chutes, and debris flow channels (Figure 3.1). Debris flow channels are those identified and described in Chapter 3. On the terrain map (Figure 3.1), debris flow channels are subdivided by a size classification (Jakob 2005). Chapter 5 gives a detailed description of debris flow channels, including size and frequency.

3.4 Results

A 1:10 000 scale terrain map (Figure 3.1) shows the distribution of the terrain units and features at Klapperhorn Mountain, and represents a model of the geomorphology of the study area. This section describes the characteristics and distribution of the features shown on the map, and section 3.4 describes the controls and characteristics of the individual debris transport processes.

Four general types of terrain units occur at Klapperhorn Mountain: unmodified colluvial veneer units, (Cv, grey tones), bedrock and colluvial veneer units that are modified by rock falls and snow avalanches (B, Cv-a, red tones), colluvial cone units (Cc, blue tones) that are formed and modified by rock fall, snow avalanche, and debris flows, and colluvial fan units (Cf, green tones) that are formed by debris flow deposition.

3.4.1 Colluvial Veneer Units

Colluvial veneer units that are not modified by any modern geomorphic process occur through the study area. These areas of continuous colluvium generally show mature coniferous trees, and show no avalanche tracks or debris flow channels. These unmodified units may occur on slopes up to 40°, but generally occur on slopes of less than 30°. Colluvial veneer units occur most extensively on the lower slopes of the east flanks of Klapperhorn Mountain and on the east slopes of basin 53.6. These units also occur on the convex slopes between the colluvial cone units on the north face of

Klapperhorn Mountain, and act as divides that control the distribution of debris flow processes. Colluvial veneer units that show no modification by modern geomorphic processes are considered to be geomorphically inactive areas for the purposes of this hazard assessment.

3.4.2 Bedrock and Modified Colluvial Veneer Units

Bedrock and colluvial veneer units on which rock fall and snow avalanches are active occur at Klapperhorn Mountain (Figure 3.3). The bedrock areas may show localized and discontinuous accumulations of debris, and generally occur on slopes greater than 45° to 50°. Rock fall chute features occur within these basins, and often act to funnel rock fall events to confined accumulation areas (Figure 3.4). Avalanche chutes are visible on some bedrock slopes. Generally, avalanches in the Rocky Mountains occur on slopes that range from 35° to 45°, occasionally up to 50° (Luckman 1977). Rock fall and snow avalanche processes are discussed in section 3.4.

Colluvial veneer units modified by avalanches occur on slopes of approximately 35° to 45° degrees. Continuous debris accumulates on these slopes, and may sustain vegetation growth. These slopes are steep enough for avalanches to occur, as indicated by the presence of snow avalanche tracks.

The bedrock and modified colluvial units generally occur on the upper portions of Klapperhorn Mountain, above 1200 m elevation, with occasional, smaller bedrock outcrops at lower elevations. Bedrock units are extensive on the north face of Klapperhorn Mountain in the upper portion of the debris flow drainage basins. The

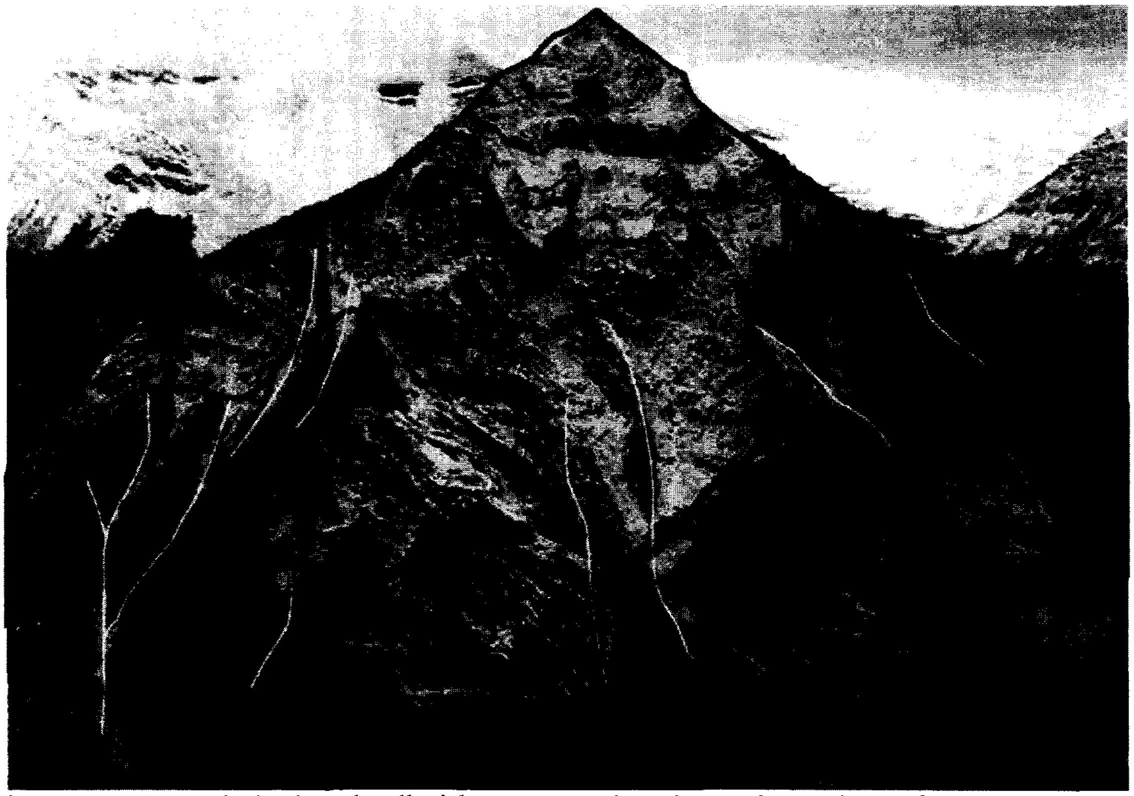

Figure 3.3. Upper bedrock and colluvial veneer terrain units on the northwest face of Klapperhorn Mountain. These units occur extensively above 1200 - 1300 m. Rock fall and snow avalanche process are important debris transport mechanisms in these units. Yellow lines are snow avalanche chutes.

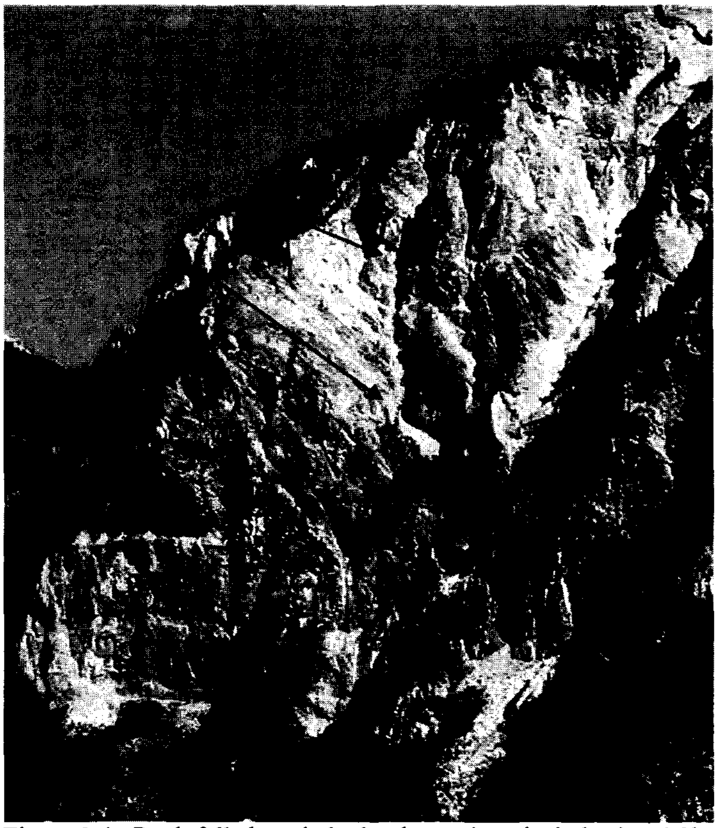

Figure 3.4. Rock fall chute in bedrock terrain units in basin 54.3b. Multiple rock fall chutes are visible. The upper arrow indicates an individual chute and the lower arrow indicates accumulation of rock fall debris at the base of the chute.

colluvial veneer units occur throughout the upper portions of the study area, including the east flank of Klapperhorn Mountain.

3.4.3 Colluvial Cone Units

Colluvial cone units occur in each debris flow drainage basin identified at Klapperhorn Mountain (Figure 3.1). These units have a generally conical shape, but may take an elongated form when confined by topography. These features have slope angles between 20° and 40°. These units are modified by multiple processes, and single cone features often consist of areas that are modified by different processes (Figure 3.5).

Colluvial cone features are subdivided on the basis of the geomorphic processes that modify the cone. A single colluvial terrain unit may show features of several geomorphic processes. In such cases each process is listed, with the order of the terms reflecting a subjective estimate of the relative importance of each process in shaping the unit. Colluvial cones with rock fall (Cc-r), avalanche (Cc-a), and debris flow (Cc-d) modification occur at Klapperhorn Mountain. Portions of these units are modified by debris slides (Cc-s). These units are distributed across the base of Klapperhorn Mountain, and generally occur below 1300 m.

Cc-r units represent rock fall deposit areas. They are generally recognized by their location beneath rock fall source areas and by the characteristics of the debris (Figure 3.6) which consists of angular, blocky and fractured boulders that are occasionally up to 5 m in size. Debris that is much larger than that associated with debris flows at Klapperhorn Mountain may occur in rock fall areas. Impact marks on trees, occasionally several metres above the ground, and on structures such as the rock shed at Albreda Mile 54.7 indicate rock fall activity. In areas in which rock fall is the only

Figure 3.5. Colluvial cone units in the lower portion of Klapperhorn Mountain. Basin 54.3a (left) and 54.3b (right) are visible. The Albreda (upper) and Robson (lower) Subdivisions are also visible in the photograph. The colluvial cone feature in each basin is subdivided on the basis of the dominant geomorphic process that modifies the terrain unit. Generally, rock fall, snow avalanche and debris flow processes occur in the upper portions of these colluvial features, and is debris flow dominated in the lower portions. The Cc-sd unit represents a portion of the colluvial cone that modified by sliding.

Figure 3.6. Rock fall modified terrain unit in basin 54.3a. Lower Arrows indicate rock fall debris, recognized by the blocky, angular, and fractured features. The largest slab (lower left arrow) is > 5m in width, while the other blocks are 0.5 m to 2 m. Note the unweathered rock fall scars (Upper arrows) in the cliff faces (R-r" terrain unit).

modifying process (Cc-r units), the deposits consist of boulder fields with debris from 1-2 m in size. Areas with no evidence of recent activity, which includes fresh surfaces with no lichen growth, are classified as inactive (Cc-ri).

Cc-a terrain units are modified by avalanche processes. Evidence on colluvial cones includes damaged and immature vegetation such as alders that may be stripped of leaves and are often bent down slope. Terrain units that occur below avalanche chute features are considered to be modified by snow avalanches. Distinct features such as boulder tongues and avalanche trails that may be associated with snow avalanches (Luckman 1977) are not generally present as the terrain units at Klapperhorn Mountain reflect formation by multiple processes that may obscure these features.

C-d units are colluvial cone units that are modified by debris flow processes, including debris flow initiation and transport. These units are recognized by the presence of debris flow channels and features. As described in Chapter 2, thirteen debris flow channels are recognized within the study area. However, relict debris flow features are also present at Klapperhorn Mountain (Figure 3.7). Weathered and subdued levee features and debris deposited against the upslope side of trees indicate debris flow modified areas. The distribution and age of the debris flow features on these terrain units are important elements of the hazard assessment, and are described in detail in Chapter 5.

Two Cc-s terrain units occur at Klapperhorn Mountain, in basin 54.3a and in 54.3b and represent colluvial cones modified by sliding. These terrain units experience very slow movement, and are characterized by bulging of the toe of the slide area that results in closing and infilling of ditches, and by cracking in the crown of the slide. The basin 54.3a Cc-s unit has been subject to ongoing maintenance including regular ditch

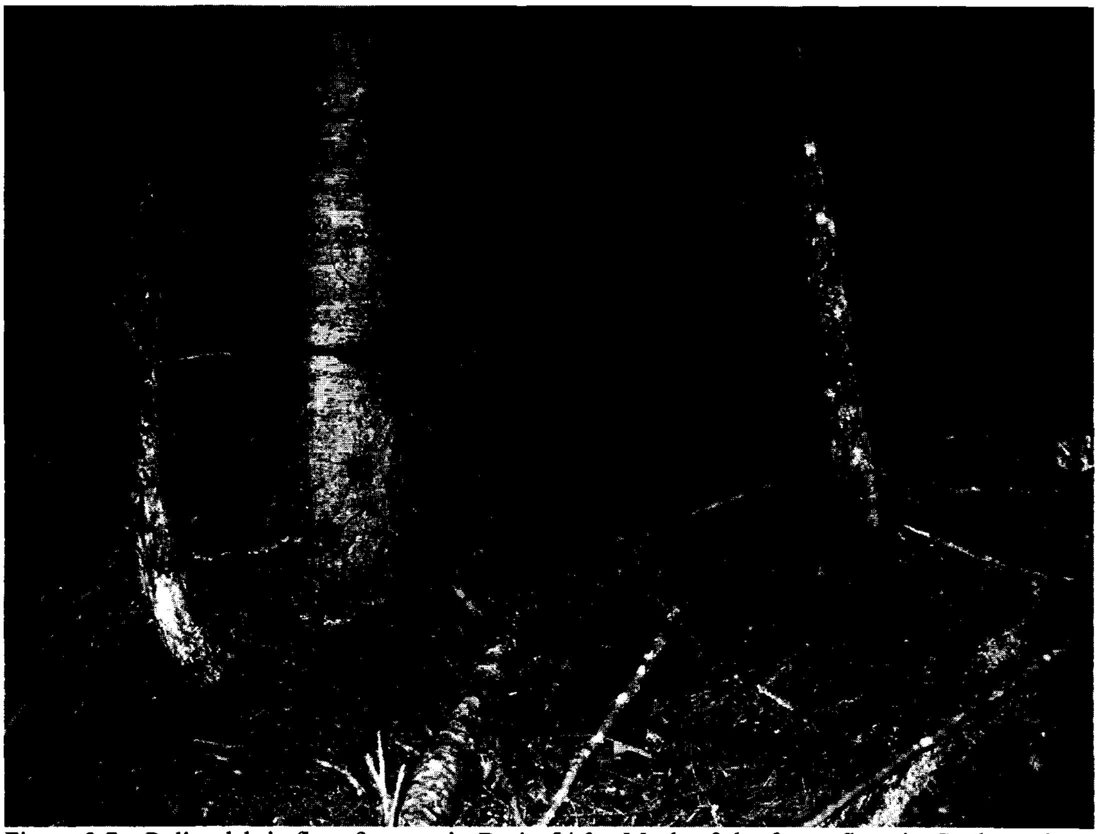

Figure 3.7. Relict debris flow features in Basin 54.0. Much of the forest floor in Cc-d terrain units is characterized by features such as those shown. Weathered and subdued levees features with vegetation growth and forest litter accumulation indicate past debris flow activity. Note the debris pile on the upslope side of the largest tree on the left side of the photograph.

excavation. The 54.3b Cc-s unit was identified during field work in 2005.

3.4.4 Colluvial Fan Units

Cf terrain units occur as accumulations of colluvium on fan shaped slopes of up to 20°. The fans at Klapperhorn Mountain are indistinct landforms that occur as the slope of the above colluvial cone terrain unit is reduced (Figure 3.8). Individual fan units merge to form an apron across the base of Klapperhorn Mountain. Boundaries between individual fans are estimated based on topography, air photographs and the extent of deposition observed during field work.

3.5 Klapperhorn Mountain Geomorphology

The distribution and characteristics of the terrain unit and features in Figure 3.1 provide a debris transport model at Klapperhorn Mountain (Figure 3.9). In this overall debris transport model, debris is derived from bedrock weathering and rock fall processes, and is transported down slope by avalanche and rock falls. Debris accumulates on the colluvial cone units that drape the lower slopes of the mountain below 1200 - 1300 m. Debris is then mobilized primarily through debris flows and is transported to the base of the mountain, where it is deposited on fans. The morphology of basin 53.6 differs from the other basins, as it is much larger (Table 2.3) and does not have a well defined colluvial cone unit above the colluvial fan. However, the overall debris transport scenario is similar in each basin. The effect of basin morphology on the debris flow hazard is discussed in Chapter 4.

The bedrock structure and lithology at Klapperhorn Mountain likely controls the overall geomorphology. The relief of Klapperhorn Mountain is dominated by bedrock relative to the colluvial cones (Figure 3.10). The bedrock structure and lithology likely

Figure 3.8. Colluvial fan (Cf-d) terrain units at Klapperhorn Mountain. The fan units occur where the slope of the above colluvial cone is reduced to below 20°, and form an apron across the base of the mountain. The general fan form is present in basins 53.6 and 54.3b, but is less distinct in the other basins. Boundaries between each fan are estimated from DEM data, air photographs, and field work.

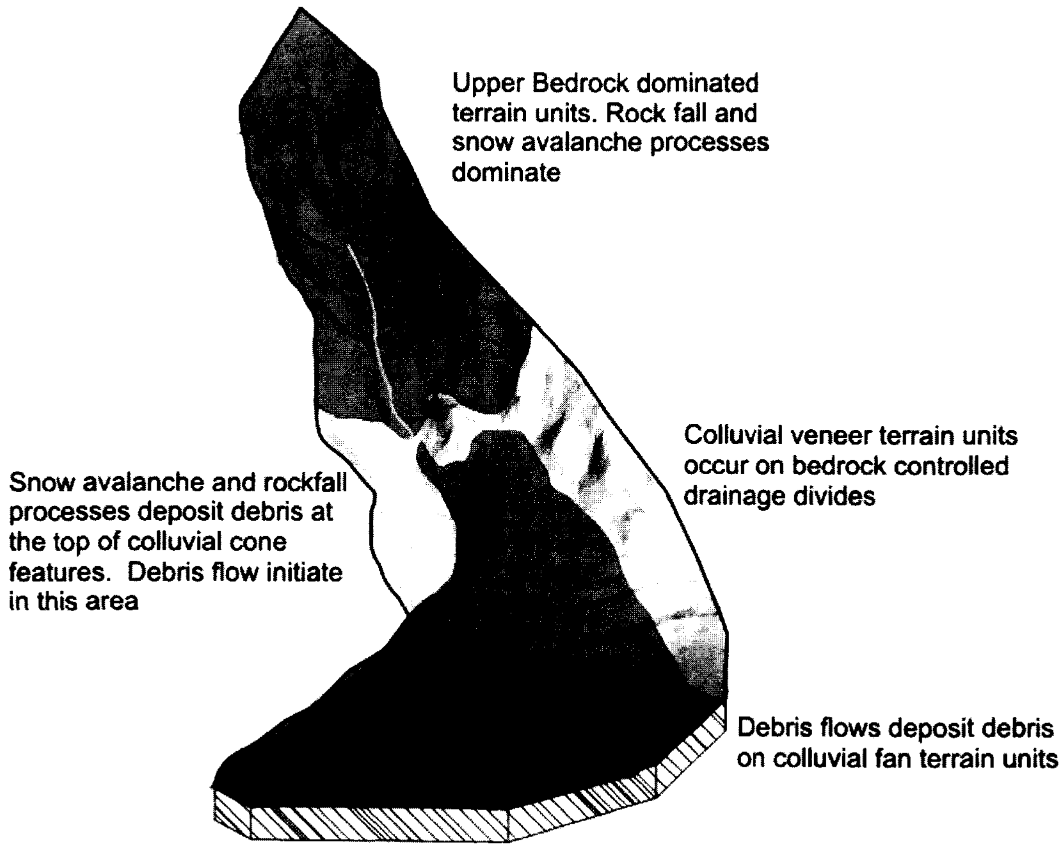

Figure 3.9. Sketch of the distribution of debris flow process within the drainage basins at Klapperhorn Mountain. The morphology and initiation processes within basins may vary (Chapter 4), but the overall transport process is similar in each basin. Yellow lines are avalanche tracks, green lines are rock fall chutes, and blue line is a debris flow channel.

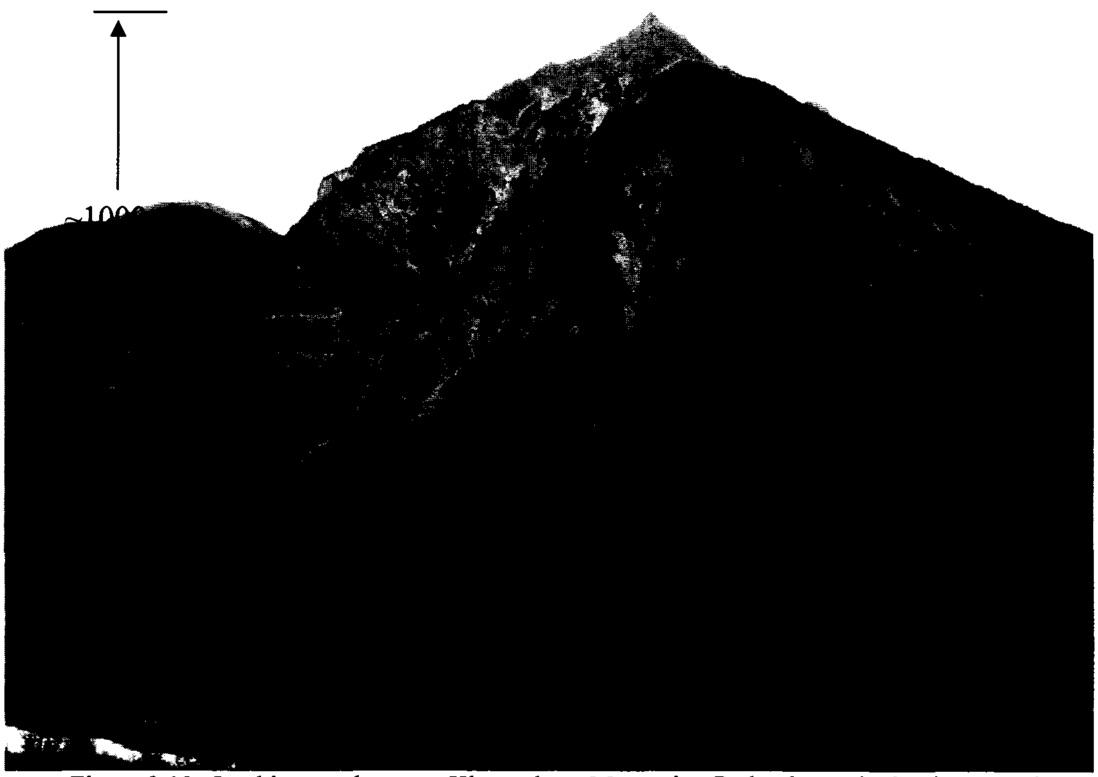

Figure 3.10. Looking southwest at Klapperhorn Mountain. Bedrock terrain dominates and controls the drainage divides, supplies debris to the colluvial cones, and controls the composition of the debris flow material. Three bedrock controlled drainage divides are visible. Arrows indicate bedrock controlled topographic drainage divides.

control the debris flow hazard in three ways: bedrock features act as drainage basin divides, rock fall processes supply debris to the colluvial cones, and the bedrock lithology controls the composition of the debris flow material.

3.5.1 Structural and Lithologic Controls

Bedrock Geology

Detailed structural geology data are not available for Klapperhorn Mountain. The study lies on the boundary between NTS maps sheet 83D and 83E and has been mapped at 1:50 00 and 1:250 000 (McDonough and Mountjoy 1990; Mountjoy 1980; Figure 3.11). Field observations and photographs identify some structural features, but most bedrock units were inaccessible.

The northwest face of Klapperhorn Mountain is perpendicular to the strike direction of the major structural features in the Rocky Mountains (Figure 3.11). Basin 53.6 may form along a syncline, while the valley to the east of Klapperhorn Mountain is formed along a fault. Klapperhorn Mountain is composed of sub-horizontal bedding with localized folding and two perpendicular joints sets that combine with bedding to form blocks (Figure 3.12). Glaciation in the Robson Valley exposed and over steepened the slopes on the northwest face of Klapperhorn Mountain. Localized folding may control the drainage basin divides.

The shape of Klapperhorn Mountain is similar to Matterhorn style peaks, which form in sub-horizontal bedding and do not produce large rockslide failures along bedding planes (Cruden and Hu 1999; Cruden 2003). However, the localized folding of Klapperhorn Mountain and exposed bedding and jointing create conditions that are suitable for frequent, low volume rock fall activity. Historical rock fall data are not available, but CN personnel indicate that rock falls on Klapperhorn Mountain can be

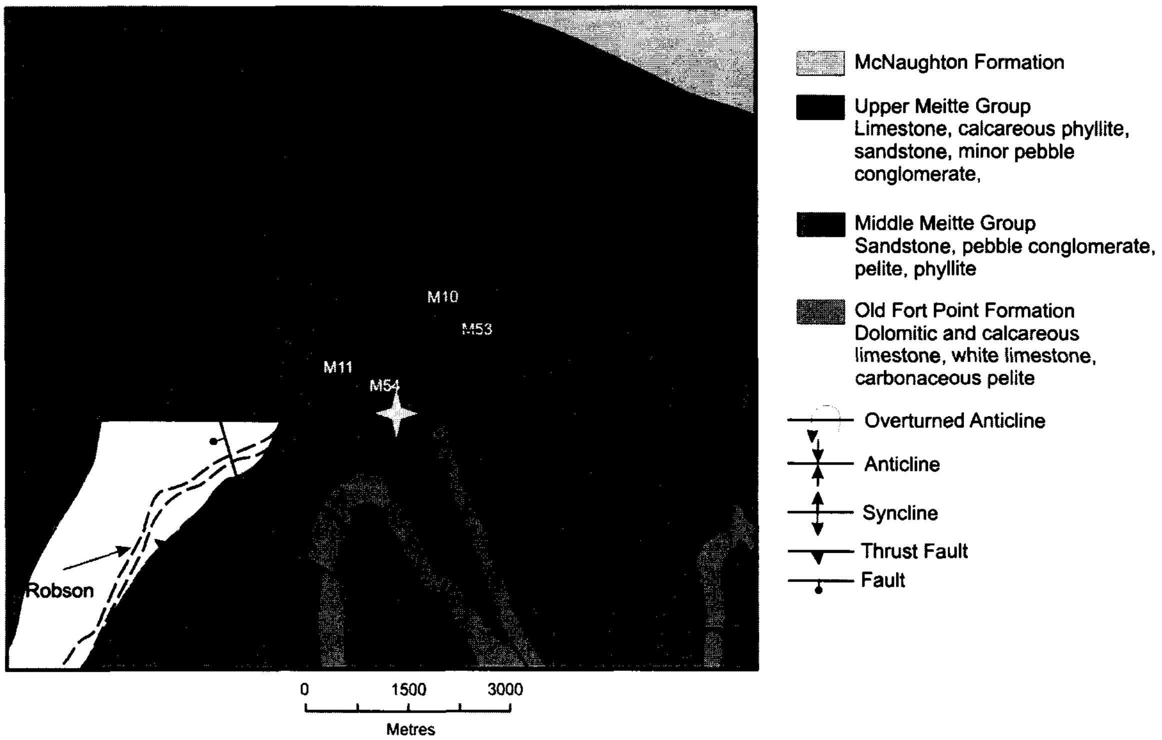

Figure 3.11. Simplified bedrock geology of the Klapperhorn Mountain region. Note that the general trend of the major structural features is perpendicular to the railway in the study area. The yellow star marks the location of the peak of Klapperhorn Mountain, and mileages on the Robson and Albreda Subdivisions are given for reference. The map is combined from two bedrock geology maps – the northern portion of the map is from Mountjoy, 1980 (1:250 000) and the southern portion is from McDonough and Mountjoy, 1990 (1:50 000).

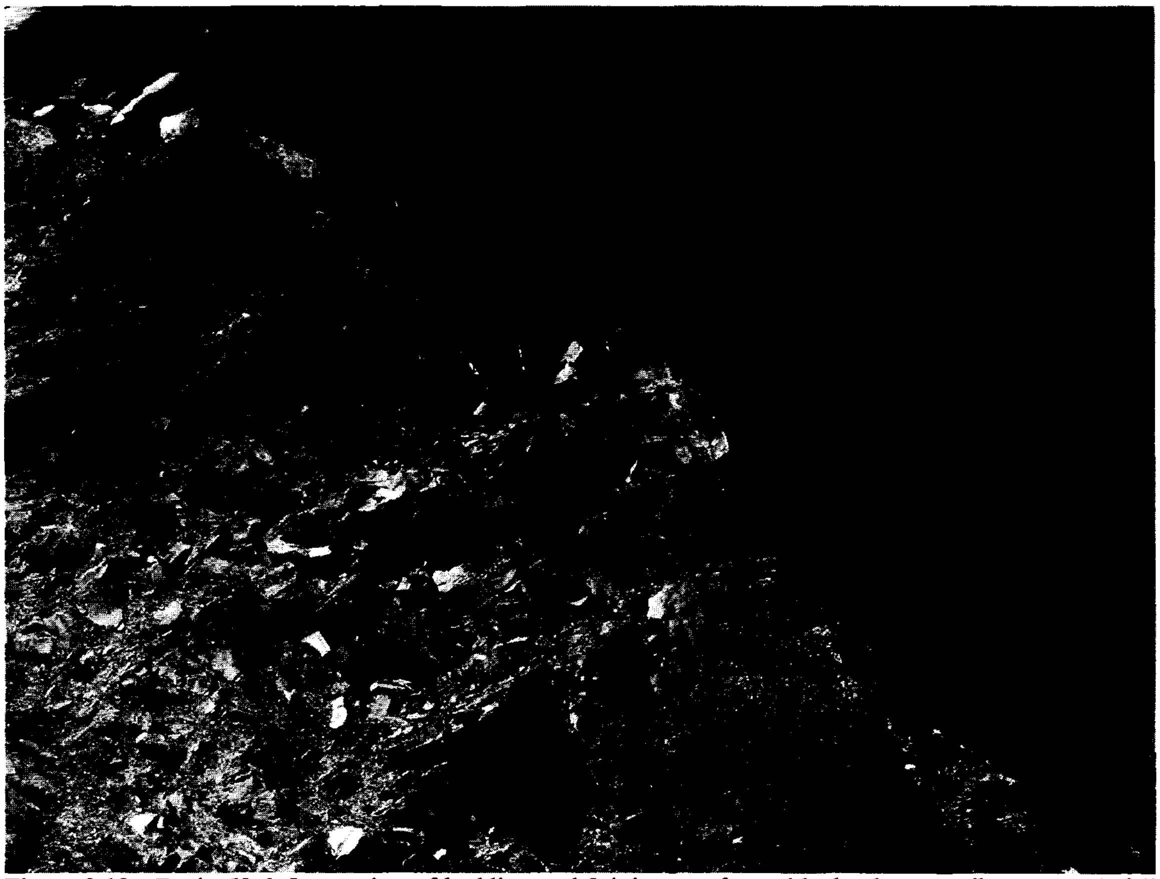

Figure 3.12. Basin 53.6. Interaction of bedding and 2 joint sets forms blocks that contribute to rock fall processes. The configuration of the joint sets ranges from oblique to near perpendicular as seen here.

heard from track level and are frequent, particularly during spring snowmelt and during periods of intense or prolonged both rainfall. (Keegan 2005, pers. com.). A small rock fall occurred in basin 54.3b between the 2004 and 2005 field seasons (Figure 3.13).

The bedrock lithology at Klapperhorn Mountain is an important control of the characteristics of the debris flows at Klapperhorn Mountain, and contributes to the relatively high frequency of the debris flow events. Studies of paleofans in the Rocky Mountains show the bedrock lithology influences debris flow characteristics, and that the Main Ranges produce less frequent, higher energy flows than those in the Front Ranges, (Levson and Rutter 2000). Klapperhorn Mountain, in the Main Ranges, produces debris flows with large clastic boulder deposits, similar to those in the Main Range paleofans. However, the Klapperhorn Mountain debris flows occur with relatively high frequency. This is likely controlled in part by bedrock lithology. The Middle Miette Group that occurs in the study area includes abundant argillite (McDonough and Mountjoy 1990; Mountjoy 1980), which at Klapperhorn Mountain has been metamorphosed to phyllite. This unit is present in each basin in the study area, and is visible in bedrock and in the debris flow deposits. The phyllite is friable and breaks easily along foliations (Figure 3.14). This unit likely weathers rapidly and produces abundant debris that is available to be mobilized in debris flow events, and may contribute to frequent rock fall and debris flow activity.

Debris Transport

Rock fall activity at Klapperhorn Mountain is frequent and likely produces abundant debris. As shown on Figure 3.1, the rock fall chutes produce a funnelling effect

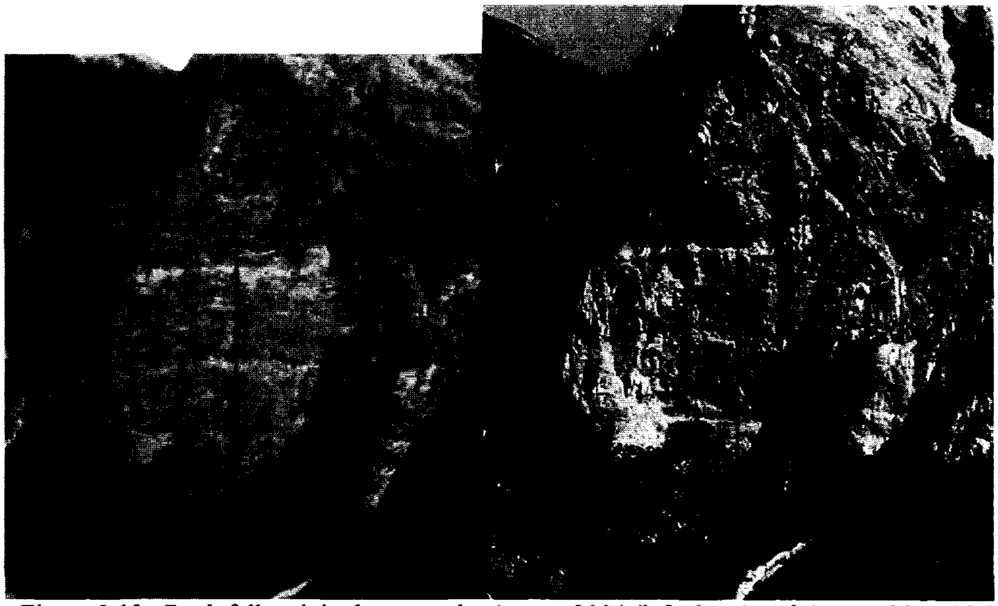

Figure 3.13. Rock fall activity between the August 2004 (left photo) and August 2005 (right photo). Channel visible in the foreground is channel 'g' in basin 54.3b. Note the enlarged deposition area below the cliff face and the freshly exposed rock fall scar on the cliff. The total volume is likely less than 50 m^3. CN employees indicate that rock fall activity at Klapperhorn Mountain is frequent, and often occurs during periods of snowmelt or intense or prolonged rainfall.

Figure 3.14. Exposed phyllite unit in basin 55.0. Note the rapid weathering to produce fine grained material. The phyllite breaks easily along cleavage planes and contributes fine fraction material to debris flow processes. Cobble size and small phyllite grains are observed in the debris flow deposits at Klapperhorn Mountain.

that concentrates debris on the upper portions of the colluvial terrain units. The narrow, upper portions of the cone features in basins 54.0, 54.3a and b, 54.7, and 55.0 are at least partially modified by rock fall deposition. In basin 53.6, rock fall activity supplies debris to the confined colluvial cone features along the debris flow channel.

Snow avalanches likely transport rock fall debris that accumulates in the upper bedrock terrain units at Klapperhorn Mountain. Terrain units that are modified by snow avalanches occur throughout the upper portion of Klapperhorn Mountain as well as on the upper portions of the colluvial units (Figure 3.1). Snow avalanches have been recognized as a significant mechanism for debris transport above the tree line in the Canadian Rockies (Luckman 1978) and may be an important process for transporting debris from the upper bedrock basins to the upper portions of the colluvial cones. Little quantitative data regarding debris transport by snow avalanche is available, but estimates in the Canadian Rocky Mountains range from 1 m^3 to 50 m^3 for individual events (Gardner 1970; Luckman 1973, in Luckman, 1978). Numerous avalanche chutes and loose rock fall debris occur on the upper slopes, which, combined with the evidence of damaged vegetation on the upper portions of the colluvial cones, suggests that snow avalanche activity is likely an important debris transport mechanism at Klapperhorn Mountain.

There are two important ways in which snow accumulation and snow avalanche processes may contribute to debris transport in the study area: direct transportation and transportation by melt water runoff. Direct transportation occurs when debris is entrained and transported in the body of the avalanche and is most effective on slopes that are covered in loose debris (Luckman 1978), such as the rock fall derived debris that is present in the upper bedrock terrain units. Debris entrained in avalanches is transported to the lower colluvial (Cc-a) units. Debris may also be transported by melt water from snow accumulations and avalanche deposits within the upper bedrock basin or within debris flow channels. This generates runoff that transports debris to the colluvial cones. During the summer field seasons, minor water flow was observed in the creek within the study area. Presumably during peak melting periods this runoff is significantly higher and may transport debris. Avalanches within the channels may block drainage and impound stream flow, and a sudden breach would cause high discharge within the channel and potentially trigger a debris flow. Together, rock fall and snow avalanche debris transport supply a significant volume of debris to the colluvial cone units on Klapperhorn Mountain. The debris flow processes on these units are described in detail in Chapter 4.

3.6 Conclusions

There are four main categories of terrain units at Klapperhorn Mountain. Colluvial veneer units on slopes from 25° to 30° are considered to be geomorphically inactive in this study. Bedrock terrain units and colluvial veneer units overlying bedrock dominate the upper portion of the mountain. Bedrock geology controls the drainage basin formation, rock fall activity and debris accumulation, and composition of the debris flow material. Rock fall and snow avalanche processes occur throughout these units and transport debris to colluvial cones. Debris flows transport material to colluvial fan units at the base of Klapperhorn Mountain. These debris flow processes on the colluvium cone units are described in Chapter 4, and the distribution of these terrain units is incorporated in the hazard assessment in Chapter 5.

Chapter 4. Klapperhorn Mountain Debris Flow Processes

4.1 Overview

In the overall debris transport model at Klapperhorn Mountain (Chapter 3), rock fall and snow avalanche processes above 1200 m elevation control debris deposition on the colluvial cone units, where debris flows initiate. Debris distribution and initiation processes on the colluvial cones control debris flow paths along the cones. Debris flow deposition occurs on the lower portions of the cones, or on fan slopes at the base of the mountain. These processes are described in this chapter.

The debris flow drainage basins at Klapperhorn Mountain may be divided into two general types based on the morphology of the basins. In basin 53.6, a single, well confined channel runs down the base of the gully. Multiple debris source areas supply debris to this channel. In basins 54.0, 54.3a, 54.3b, 54.7 and 55.0 a bedrock headwater portion of the basin supplies debris and water to a colluvial cone feature, where debris flows initiate. Debris flow initiation, transport and deposition control the hazard within each basin and vary between these two basin types.

4.2 Debris Flow Initiation

Understanding debris flow initiation location and mechanisms is important in developing appropriate remedial measures to reduce the debris flow hazard at Klapperhorn Mountain. However, few direct observations of the upper portions of the drainage immediately following debris flow events are available. Therefore, likely initiation zone and mechanisms are discussed based on the Klapperhorn Mountain geomorphology.

Three mechanisms for debris flow initiation are generally recognized: landslide mobilization (*e.g.* Jakob *et al* 2000; Bovis and Jakob 2000; Iverson *et al.* 1997), critical channel discharge (*e.g.* Takahashi 1991; Berti and Simoni 2005) and dam burst (*e.g.* Evans 1999). The specific processes of each are not described here, but the potential for each mechanism at Klapperhorn Mountain is discussed. Basin 53.6 is discussed separately from the other drainage basins due to differences in overall basin morphology.

4.2.1 Basin 53.6

Debris flows occur in channel 'a' of basin 53.6. This channel is well confined along its length, and debris accumulates along the channel through rock fall and avalanche processes. A tributary channel on the east bank likely contributes debris through debris flows and snow avalanches (Figure 3.1).

Debris flows likely initiate when stream discharge within the channel reaches a critical level and debris within the channel is mobilized. However, landslide initiation may occur within the Cc-dar colluvial terrain unit (Figure 3.1) that occurs along the creek. This unit slopes from 28° to 35°, and consists of poorly sorted debris that ranges from silt, clay, and sand, to boulders of up to 2 m. Stream flow is concentrated on the east margin of this terrain unit, but flowing water and saturated material was visible in August of 2005 (Figure 4.1). Under high moisture conditions, this unit may fail and mobilize as a debris flow event. Landslide activity may also form temporary dams which may burst and trigger debris flows.

Debris flows may initiate above this terrain unit. The channel profile (Figure 4.2) indicates that the slope above this terrain unit ranges from 5° to 30°. Debris flows generally initiate on slopes greater than 30° (Fanin and Rollerson 1993; Rickenmann and

Figure 4.1. Looking down the Cc-dar terrain unit in Basin 53.6. This unit slopes at up to 35°. Stream flow is concentrated on the east side of the unit (right side of photograph), but flowing water is visible throughout the unit. Landslide failures within this unit may trigger debris flows within basin 53.6. Boulders are up to 2 m.

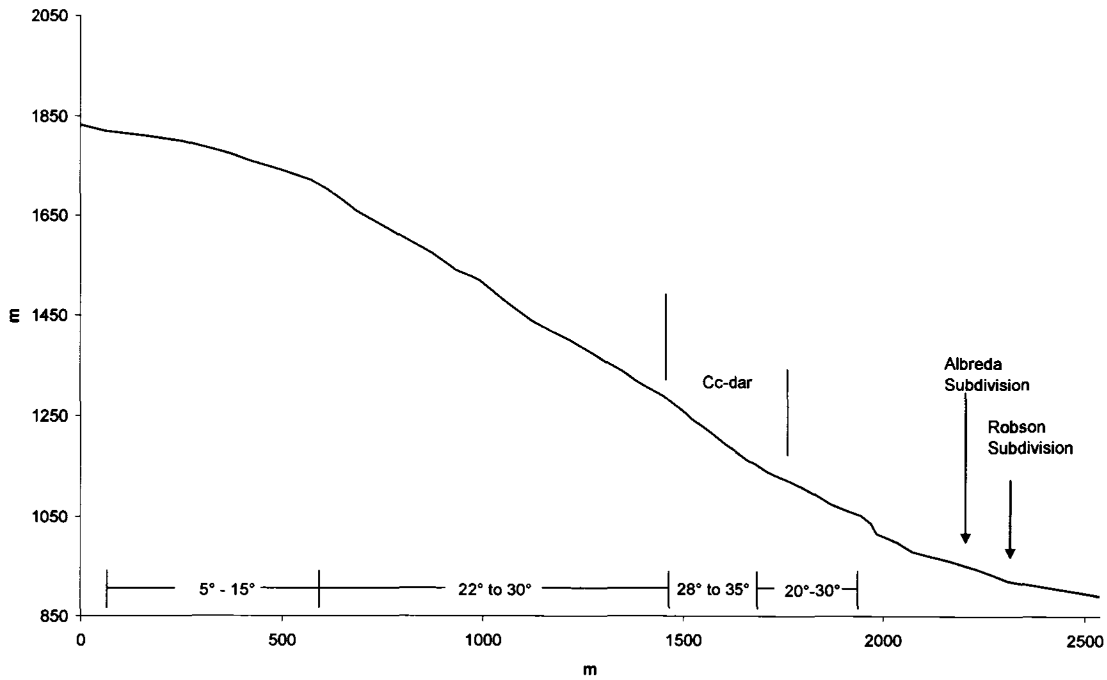

Figure 4.2. Profile of channel 'a' in basin 53.6. Recent debris flows likely initiated within the Cc-dar terrain unit that slopes at up to 35°. However, debris flows may also initiate higher in the channel.

Zimmerman 1993; VanDine 1985). However, the same research has shown that initiation angle has an inverse relationship to basin area, and in drainage basins with an area similar to that of basin 53.6 (5 km^2), initiation may occur on slopes of 20° to 25°. Therefore, debris flow initiation may occur in the upper portions of the channel. Field and air photograph evidence, however, suggests that recent debris flows have not initiated above the Cc-dar terrain unit. Debris flow levees are not evident, and trees and shrubs up to 3 m in height grow adjacent to the channel margin. This vegetation growth is visible on the 1997 CN air photographs, suggesting that most recent debris flows have initiated within or below the Cc-dar terrain unit in basin 53.6.

4.2.2 Basins 54.0 to 55.0

The overall morphology of basins 54.0, 54.3a, 54,3b, 54.7 and 55.0 differs from that of basin 53.6. Bedrock terrain units supply water and debris to colluvial cone units at the base of the mountain. The channels are not confined by topography, and multiple channels occur on single cone features.

The distribution of the terrain units suggests that debris flows in these basins initiate near the top of the colluvial cones. The alternative is that debris flow events initiate in the channels in the bedrock terrain units above the cone features and flow onto colluvial cone units, but this is considered unlikely. Several factors suggest that it is likely that debris flows initiate on the colluvial cone units.

In basins 54.0, 54.3a and 54.3a, cliffs occur immediately above the colluvial cone units (Figure 4.3). These range from 70 to 100 m in height, and slope at up to 70°. If debris flows initiated above these cliff features, they would need to maintain their channelized form as they flowed over the cliffs and onto the colluvial cone, which is

Figure 4.3. Steep cliffs above the colluvial cone terrain units in basins 54.0, 54.3a, and 54.3b. The presence of these cliffs indicates that debris flows initiate on the colluvial cones, rather than initiating above and maintaining there channelized form. Also, little debris accumulates on the upper bedrock units. Scale is approximately 1:12 000 (1997 CN air photograph)

unlikely. Also, particularly in basins 54.3a and 54.3b, there is little debris accumulation above these cliffs (Figure 4.3), nor is there spattered debris at the base of the cliffs. In these basins, the slope of the upper portions ranges from 50° to 60° and little debris accumulation is visible on air photographs or field photos. In basin 54.0, debris accumulation is visible, but it is likely that this is transported by rock fall and snow avalanche processes to the upper portions of the colluvial cones.

The distribution of channel features in basins 54.7 and 55.0 indicates that debris flows initiate within the colluvial cone terrain units. In these basins, upper portions of the colluvial cones are confined by bedrock and are 30 m to 40 m in width and elongated (Figure 3.1). Channel and levee features are absent at the top of the colluvial units and begin approximately 50 m from the upper portions of the cones suggesting that debris flows initiate within the colluvial cone terrain units (Figure 4.4). This direct evidence of initiation in the colluvial cones, combined with the presence of the cliffs and distribution of debris in basins 54.0, 54.3a and 54.3b, suggests that debris flow initiation occurs within the colluvial cones units at Klapperhorn Mountain.

Critical discharge within the debris flow channels is a likely initiation mechanism within these drainage basins. The initiation zones within these basins correspond to Rickenmann and Zimmerman's (1993) Type 2, slope type starting zones, in which initiation by "progressive erosion" of the channel occurs. In this basin type, debris flows initiate on steep colluvial cones or talus slopes below a rock wall. Drainage from the colluvial cone is often concentrated to the initiation area by "grooves" in the rock wall. At Klapperhorn Mountain, channels within the bedrock direct water to the upper portions

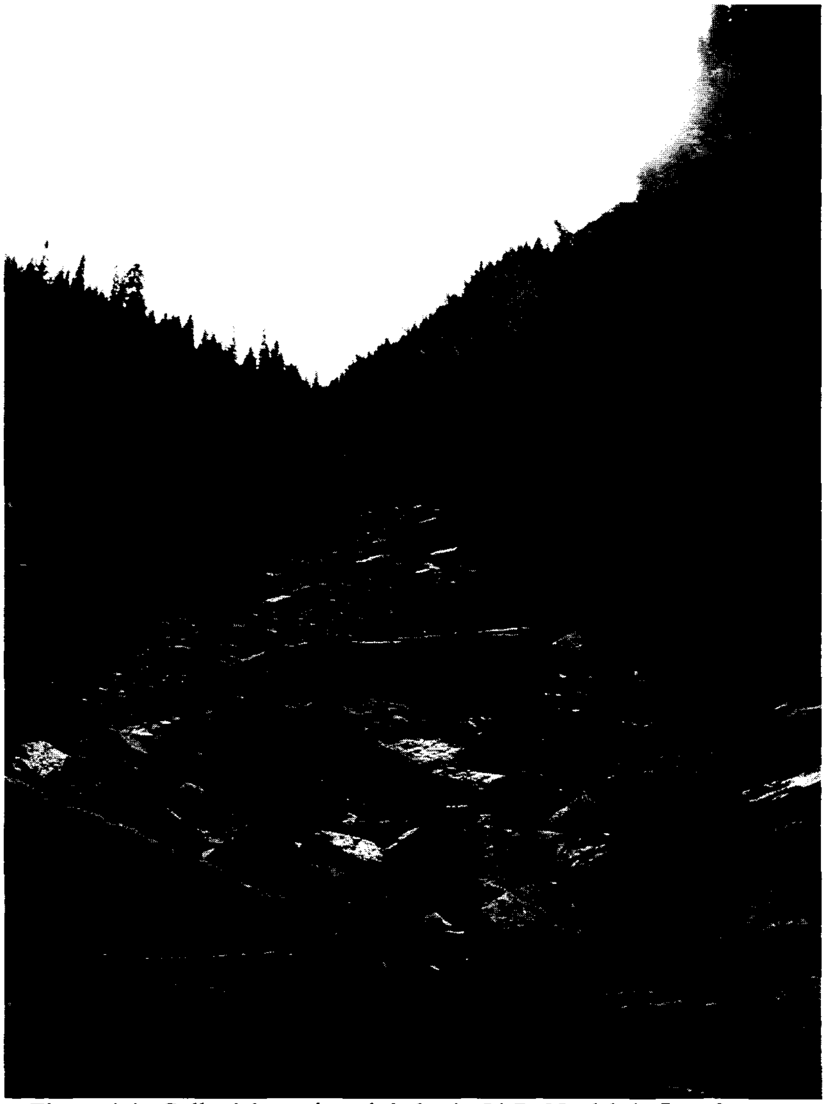

Figure 4.4. Colluvial terrain unit in basin 54.7. No debris flow features such as an incised channel or debris flow levees are present in this area. Such features occur below the location of the photograph, indicated that debris flow initiate within the deposits on the upper portion of the colluvial cone terrain units.

of the colluvial cones where debris flows likely initiate within the channel. In similar basins in the Italian Alps, critical discharge is a common initiation mechanism (Berti and Simoni 2005).

While initiation within the channels is likely most common, landslide mobilization may also occur. Debris masses adjacent to the channels occur in the upper portion of the colluvial cone, and there is evidence of shallow landslide activity in some of these areas (Figure 4.5a, b). The upper portions of the colluvial cone units range from 30° to 37° in slope, which is sufficiently steep for landslide mobilization (Iverson *et. al.* 1996). During high moisture conditions, landslide failure may occur due to increased pore pressure. Accumulation of debris from the upper terrain units may trigger landslide failure through loading of this material (*e.g.* Wilson *et. al.* 2003). Impulsive loading (Bovis and Dagg 1992) may also trigger debris flows when a landslide event transfers momentum to the colluvium. This mechanism cannot be confirmed as a debris flow trigger at Klapperhorn Mountain, the frequent and extensive rock fall activity (section 3.3) suggests that it is possible.

4.2.3 Debris Availability

Debris supply conditions are an important factor in the initiation of debris flows. Debris flow drainage basins may be classified as weathering limited or transported limited based the availability of debris (Bovis and Jakob 1999). The debris flow colluvial cone terrain units at Klapperhorn Mountain consist of abundant debris and are transported limited. In transport limited basins, debris flow magnitude and timing are not affected by the time since the previous event, as channel debris recharge is not necessary (Jakob *et. al.* 2005). In each basin within Klapperhorn Mountain, significant debris is available.

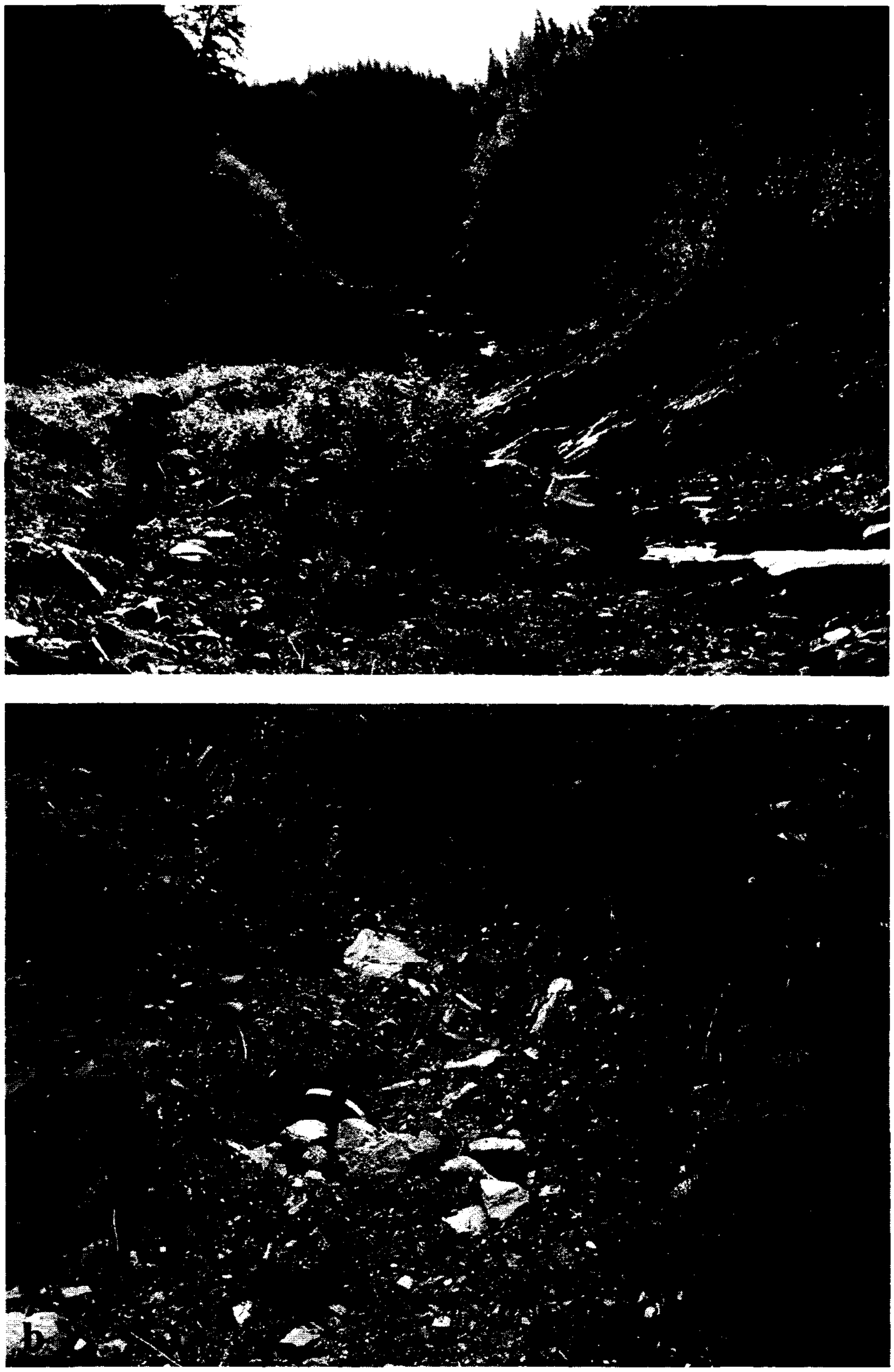

Figure 4.5. Upper portion of colluvial cone terrain unit in basin 54.0. Photo a shows a debris accumulation of approximately 2 m in depth on bedrock adjacent to channel 'd' (right side of photograph). Photo b shows evidence of a shallow landslide within that debris. The slide is 1.5 m in width and 2 m in length.

Rock fall and snow avalanche processes that supply to debris to the top of the colluvial cones are frequent, and there is abundant debris on these cones This suggests that debris flow triggering is dependant primarily on external events such as snow melt and rainfall, and channel recharge is not required to produce debris flows. Therefore, as shown in Chapter 5, debris flows at Klapperhorn Mountain are frequent.

4.3 Channel Migration

Channel migration across the colluvial cones is an important element of the debris flow hazard at Klapperhorn Mountain. The main creeks within each drainage basin are generally well incised and contain most of the recent debris flow activity within a basin, as shown by the presence of long term structures including bridges and the rock fall shed. However, the presence of surface features such as multiple debris flow channels, relict debris flow levees (section 3.3) and exposed buried soils (Figure 4.6) indicate that debris flows occur across the width of the colluvial terrain units. A sequence of three buried soils, exposed in the left bank of channel ‘c’ in basin 54.0, indicates periods in which no debris flow deposition occurred, and soil profiles were able to develop, followed by debris flow activity which buried the soils. The inactive, soil forming periods may represent times of overall debris inactivity at Klapperhorn Mountain, but likely represent periods of inactivity within channel ‘c’, while other channels on the colluvial terrain units may have been active. Mechanisms of channel migration and the implication for the hazard assessment at Klapperhorn Mountain are described.

Figure 4.6. Sequence of buried soils in the left bank of channel 'c' in basin 54.0. The base of the channel is approximately at the base of the photograph. Each white marker in the photograph indicates the top of a soil, with the upper marker indicating the present day forest floor. The weathering and soil development are clearly visible in the photograph. The visible portion of the section is approximately 75 cm in height.

4.3.1 Mechanisms

There are likely two mechanisms that may result in activation of channels within a drainage basin. Channel avulsion within a main channel may activate secondary channels such as those in basins 54.0 and 54.3b, or the initiation processes described above may occur in the upper portions of the colluvial terrain units. Each scenario is discussed.

Channel avulsion occurs when a debris flow event breaches the banks of its channel and results in the activation of another channel. Channel 'c' in basin 54.0 is activated by avulsion in channel 'd' and channels 'h' and 'i' in basin 54.3b are activated by avulsion in channel 'g' (Figure 2.1). The chaotic nature of debris flow events prevents a detailed analysis of the avulsion processes and distribution at Klapperhorn, but two likely mechanisms occur: avulsion in channel bends due to flow superelevation and avulsion in areas of reduced gradient. In basin 54.3b, avulsion has resulted in flow in the now inactive channels below the right hand bend in the main channel above the Albreda Subdivision. This avulsion likely occurred when superelevation of the flow through the curvature of the main channel exceeded the height of the channel banks, but recent construction and the age of the inactive channels (>25 years) prevents a detailed analysis. The avulsion in channel 'd' in basin 54.0 is not associated with a channel bend, as the avulsion point occurs along a straight portion of channel. Scarred trees indicate that channel 'c' has been active at least three times (section 5.2) and is likely active when the depth of a debris flow exceeds that of the channel banks at this location. The average slope of the main channel 'd' in this portion of the basin is 28°; however, the channel avulsion point occurs at the top of an 8 m length of channel in which the slope drops to an average of 17°. This section of lower gradient likely reduces flow velocity, causes local deposition and increases flow height resulting in avulsion and flow in the secondary channels (Figure 4.7). A third possibility is that coarse woody debris may temporarily block channels during debris flow events. Logs and branches are visible in some debris flow channels and on debris flow fans, but there is no direct evidence that they have caused channel avulsion.

Initiation processes in the upper portions of the colluvial terrain units likely also control the distribution of active debris flow channels at Klapperhorn Mountain. A landslide failure in the thin (~2 m) colluvium that overlies bedrock may mobilize as a debris flow. When this occurs in above inactive channels they may become reactivated (Figure 4.8).

4.3.2 Hazard Implications

The processes that control the activation of individual channels suggest that the more recently active channels are most likely to be active again when debris flow triggering conditions occur. Runoff occurs in the incised, more recently active channels, making debris flow mobilization by critical channel discharge more likely in these channels. Channel avulsion occurs when discharge within active channels is sufficiently high to exceed the capacity of the channel, making debris flows less likely to occur in the secondary channels. Landslide mobilization may cause debris flows, but vegetation growth may stabilize areas of less recent activity (Reoring *et. al.* 2003), making landslides less likely to occur. The 'channel age' factor described in Chapter 5 accounts for these conditions in the debris flow hazard assessment.

Figure 4.7. View down channel ‘c’ immediately below the avulsion point in channel ‘d’. Note the large levee features and poorly incised channel, indicating debris flow deposition. Avulsion likely occurs along an 8 m length of channel ‘d’ that has a reduced slope of 17°. Localized deposition causes increased flow depth that exceeds the height of the channel banks.

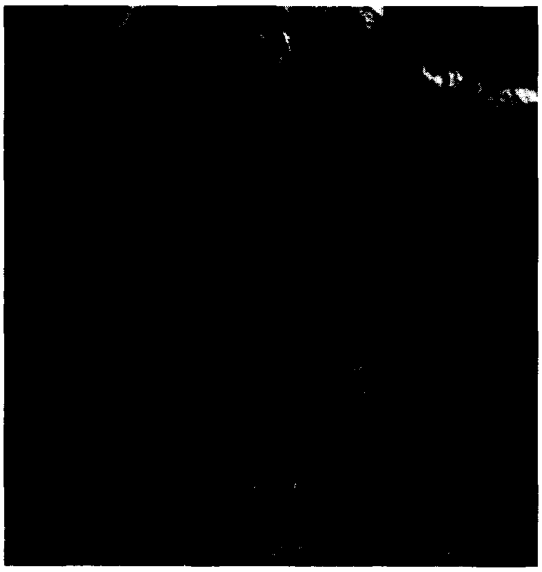

Figure 4.8. Initiation area in basin 54.3a. The main channel, 'f' runs along the west side of the drainage basin. An older channel, 'e' runs along the east side of the basin. Channel 'e' is not well incised, and stream flow and most debris activity occurs in channel 'f'. A landslide failure in the narrow colluvial unit d above channel 'f' may result in activation of the channel. Scale is approximately 1:9:000.

4.4 Debris Flow Deposition

Debris flow deposition at Klapperhorn Mountain occurs on the lower portions of colluvial cones, and on the colluvial fans. In channel 'g' in basin 54.3b, channel banks have been constructed below the Robson bridge to constrain flows to the east side of the fan. There is no evidence of recent debris flow deposition below the Albreda Subdivision in channel 'j' in basin 54.3 and channels 'l' and 'm' in basin 55.0, indicating that these debris flows deposit material on the colluvial cones rather than on the fans.

The form of debris flow deposition may affect the debris flow hazard. As described in Chapter 3, the Robson Mile 10.1 has been "washed out" (Keegan 2004) by a debris flow, indicating that the debris was in motion when passing under the bridge. In a separate debris flow event, drainage beneath the bridge was blocked, indicating that deposition had occurred at and above the bridge (Figure 4.9). These likely represent differing modes of deposition that occur within debris flow channels. In addition to levees, debris flow deposits generally consist of either complete or partial plugs within the channel, or lobate sheet deposits on the fan (VanDine 1996). Debris flows that deposit material at or above the bridges represent plugs within the channel, while larger debris flows that deposit on the fans below the bridges represent the sheet deposits. Partial plugs of debris within the channels that do not cause an avulsion are a maintenance issue, rather than a hazard to the track and trains.

The debris deposited on the fans varies along the fan profile. In the upper portions of the fan, the largest material is deposited, including boulders of up to 2 m in size. These are deposited along the channel and in lobes on the fan surface. (Figure 4.10). These deposits are likely associated with the bouldery front of debris flow events that are deposited as the gradient is reduced. The distal debris flow deposits consist of

Figure 4.9. Debris flow deposition within channel ‘d’ in basin 54.0 on July 18, 2001. Similar deposition channel ‘a’ in basin 53.6 caused track failure (Chapter 2). Photo courtesy Tim Keegan.

Figure 4.10. Upper portion of the Cf-d terrain unit in basin 54.0, approximately 15 m below the Robson Subdivision. Boulders of 1 m to 1.5 m are deposited in this area.

finer material from clay to gravel. This finer material is likely associated with sediment rich water flows that occur behind the bouldery front and run out onto the distal portions of the fans (Figure 4.11). Deposition of these larger boulders may block bridge drainage, and the sediment rich water flows may accumulate behind the bridges and cause grade failure.

4.5 Conclusions

Understanding debris flow processes including initiation, channel migration, and deposition are important for the design of appropriate remedial structures, and estimating the debris flow hazard to the railway.

Landslide mobilization and critical channel discharge are the likely initiation mechanisms for debris flows at Klapperhorn Mountain. The occurrence of these processes may affect other processes, such as debris flow channel migration. The drainages basins at Klapperhorn Mountain are transport limited basins and therefore channel recharge is not a significant factor in debris flow initiation.

In basin 53.6, the debris flow channel is well confined at the Albreda and Robson Subdivisions, and avulsion related hazards are unlikely. In basins 54.0 to 55.0, multiple debris flow channels and debris flow features indicate that channels migration occurs on the debris flow fans. This migration occurs due to channel avulsion or landslide mobilization in the upper portions of the terrain unit. This migration is an important component of the debris flow hazard in basins 54.0, 54.3a, 54.3b, 54.7 and 55.0. The processes that control channel migration indicate that debris flows are most likely to occur in channels that have had most recent debris flow activity.

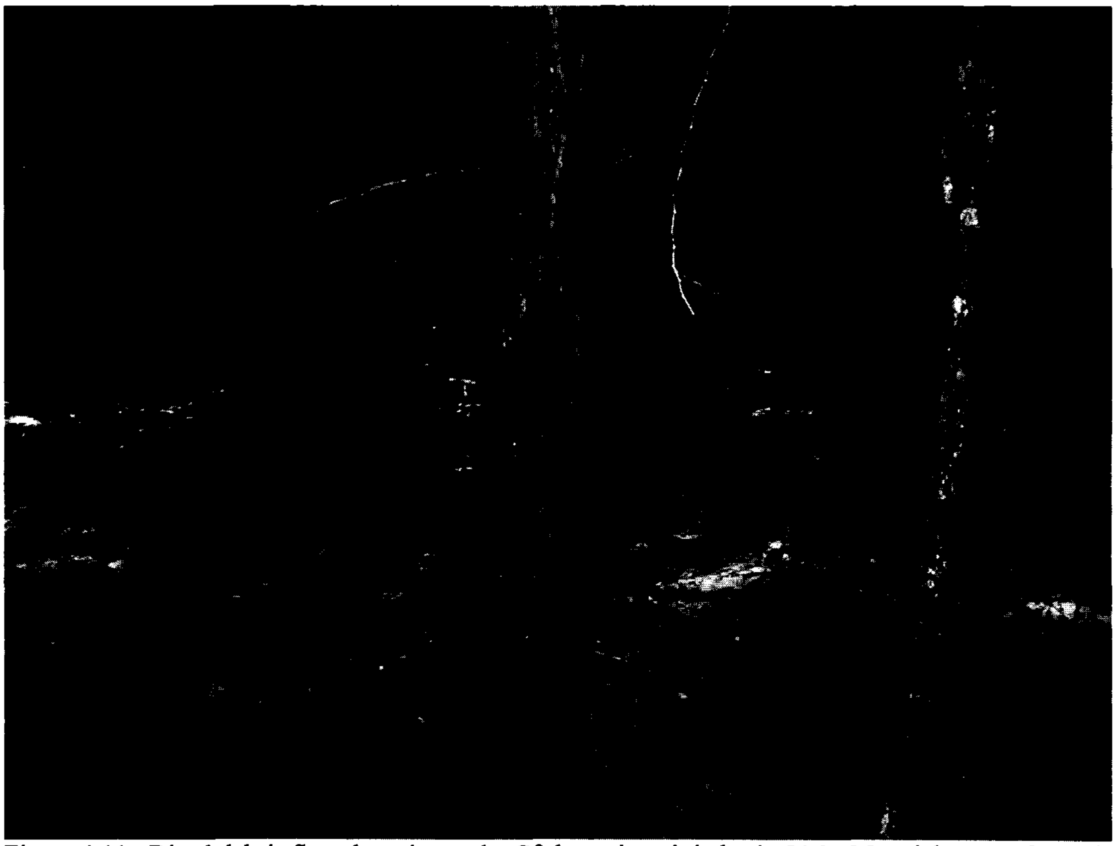

Figure 4.11. Distal debris flow deposits on the Cf-d terrain unit in basin 54.0. Material ranges from clay to gravel and is likely deposited by the sediment rich after-flow that follows the bouldery front of debris flow events. For scale, tree in centre foreground is approximately 50 cm in diameter.

Debris flow deposition affects the hazard to the railway. When debris flow deposition occurs as a plug within the channel, the sediment rich after-flow and stream flow may cause water to accumulate on the upslope side of the railway and cause failure. In larger flows that run out past the Albreda and Robson bridges, debris may damage bridges and cause train accidents.

Elements of these debris flow processes are combined with size and frequency estimates to rate the relative debris flow hazard at Klapperhorn Mountain (Chapter 5).

Chapter 5. Klapperhorn Mountain Debris Flow Hazard

5.1 Overview

The debris flow hazard to the railway is summarized based on the distribution, timing, and size of debris flow events at Klapperhorn Mountain. Debris flow timing and size are estimated for each channel and relative hazard of each is rated.

Debris flow size and frequency are not well-constrained at Klapperhorn Mountain. The documented debris flows are insufficient for a complete frequency analysis, and no direct measurement of the size of debris flow events exists. Debris is often removed from the channels immediately following debris flow events and no records of the volumes of debris are available. Individual debris flow deposits on the fan features generally cannot be distinguished due to vegetation growth and erosion. More recent deposits that may be distinguished have been excavated, preventing volume estimates.

Debris flow size and frequency are essential components of a hazard assessment (Jakob 2005b), and are estimated for the Klapperhorn Mountain debris flow channels. Frequency is estimated using documented debris flows, photographic evidence, dating of tree scars, and field work to compile a record of years with debris flow events. Debris flow size is estimated using the geometry of the debris flow channels and existing empirical debris flow size relationships. The methods used do not allow the size of individual debris flow events to be identified, so no frequency-size relationship may be established.

5.2 Debris Flow Timing

5.2.1 Methods

Years in which debris flows occurred are identified using CN records, tree scar age estimates and field evidence. CN records were used to compile the record of documented debris flows (Chapter 2), and CN photographs provide several additional dates.

The age of debris flow scars on living trees is estimated using the pattern of ring growth over the scar. This is an effective dating method that is commonly used in natural hazard studies (Jakob 1996; Stoffel *et al.* 2005). When a tree is damaged, ring growth continues over the damaged area, leaving a distinctive ring pattern that may be used to determine the year in which the debris flow occurred (Figure 5.1). Wedges were obtained from damaged trees along channels and in depositional areas of debris flow basins. To minimize the likelihood of mistaking trees damaged by other events, only trees that occurred immediately on channel banks or were closely related to debris flow deposits were sampled. Time and weight constraints prevented extensive sampling of trees within the study area, so only trees that clearly showed scars were sampled. No suitable trees occurred within basins 53.6 or 54.3b, and few occurred along the channels within basins 54.7 and 55.0. Ten trees were sampled in total. Debris flow dates obtained from tree rings were considered to be valid if they are repeated in multiple trees in a single channel, or if the scar on a single tree is distinctive.

Field work in 2004 and 2005 identified three channels in which debris flows occurred between field seasons. While these debris flow events may have occurred at any time between August 2004 and August 2005, most known debris flow activity at

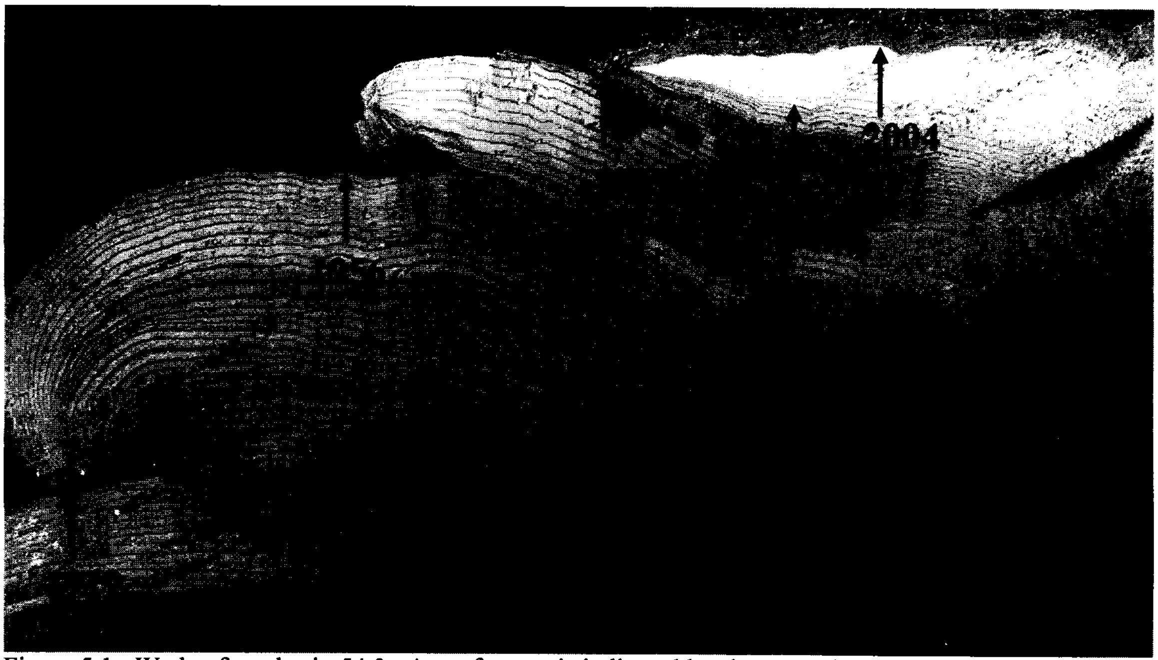

Figure 5.1. Wedge from basin 54.0. Age of a scar is indicated by ring growth. Five scars are dated in this wedge. The outer ring represents 2004, the year that the wedge of obtained.

Klapperhorn Mountain occurs between May and July (Chapter 2). Therefore, these are recorded as 2005 events.

Biases

The methods used to compile the debris flow record at Klapperhorn Mountain are more likely to identify larger events, as is common in debris flow records (Bovis and Jakob 1999; Marchi and D'Agostino 2004). Railway records, including the incident record, monitoring documents and geotechnical files, consist of debris flows that have caused train accidents or had significant costs or potential costs. These are probably the larger events within the study area. The tree ring record is also biased toward larger events as debris flows must be large enough to impact and damage trees adjacent to the channel. The exceptions are the 2005 debris flow events recognized during fieldwork. These were small flows that may not have otherwise been recorded as they did not damage or pose a direct hazard to the track. These debris flows were also too small to scar trees.

The debris flow record is also biased toward more recent events. The documented debris flows at Klapperhorn Mountain occurred after 1988. Tree scar dating also identifies more recent events. The age of trees at Klapperhorn Mountain gives a maximum age of debris flow events that can be recognized as 100 years. However, sampling of trees was limited by time and other logistical factors, therefore only trees that showed surface evidence of scarring were sampled in the field. Also, extraction of wedges by both chainsaw and handsaw resulted in a tree ring record that generally extends to the 1950s, with one tree providing a date of 1919. Both the temporal and size bias should be considered when assessing the record of debris flow activity at Klapperhorn Mountain.

5.2.2 Results

A frequency-size relationship cannot be established for the debris flows at Klapperhorn Mountain based on the available data, as there is insufficient evidence to assign sizes to individual debris flow events. Therefore, the following is a discussion of the intervals between recorded debris flow events based on the available data, and does not present frequency-size relations.

Dated debris flow events are available for ten of the thirteen debris channels at Klapperhorn Mountain (Table 5.1). The intervals between successive debris flow events are given for each channel in which more than one event is known. Where the years of three or more events are known, the average of the intervals between debris flows is also given.

The intervals between successive debris flows ranges from 2 to 47 years (Table 5.1). However, the longer intervals may reflect lack of debris flow evidence rather than a lack of debris flow events, and should be viewed with caution. In channels with 3 or more debris flow events, the average intervals are 5 years (channel a), 24 years (channel c), 12 years (channel d) and 25 years (channel f). However, for channels c and f, these average values are obtained from one relatively short interval and one relatively long interval, indicating that the average values may reflect lack of data, rather than actual debris flow intervals.

Channel d in basin 54.0 is the only channel with more than three debris flows, with a total of 8 known debris flow years between 1919 and 2005. In this basin the

Basin	Channel	Debris Flow Year	Years Since Previous Flow	Average Interval
53.6	a	2003 (D)	2	5
		2001 (D)	8	
		1993 (D)		
54.0	b	-	-	-
	c	2003 (D/T)	41	24
		1962 (T)	6	
		1956 (T)		
	d	2005 (F)	4	12
		2001 (P)	4	
		1997 (T)	12	
		1985 (T)	6	
		1979 (T)	12	
		1967 (T)	11	
		1956 (T)	37	
		1919 (T)		
54.3a	e	1988 (D)	9	9
		1979 (T)		
	f	2005 (F)	2	25
		2003 (T)	47	
		1956 (T)		
54.3b	g	2001 (P)	6	6
	h	-	-	-
	i	-	-	-
	j	2005 (F)	-	-
54.7	k	2003 (T/P)	12	12
		1991 (T)		
55.0	l	1976 (T)	-	-
	m	2005 (F)	-	-

Table 5.1. Years with debris flows in the Klapperhorn Mountain channels. D – documented debris flow, T – tree ring date, F – field, P – photographic evidence.

average interval is 12 years. There is a larger interval (37 years) between the 1919 event, which was recorded in only one sampled tree, and the 1956 event. This interval may reflect a lack of data for this period, which is likely given the temporal bias of the data discussed above. Omission of this date gives an average interval of 8 years. Five other debris flow channels have only 2 known events, with intervals that range from 6 to 12 years.

These dates suggest that successive debris flows in individual channels may occur within two years, but on average, intervals range from 6 to 25 years. Given the limitations of the 24 and 25 year intervals, the data suggest that the average interval between debris flows in each creek is 6 to 12 years.

An estimate of the return period of debris flow activity at Klapperhorn as a whole may be calculated using the debris flow record. There are 15 years since 1919 in which at least one debris flow event has occurred at Klapperhorn Mountain (Figure 5.2). The average interval is 6 years and the intervals range from 0 to 37 years. Omission of the 1919 event gives an average interval of 4 years, with a range of 0 to 9 years. These dates suggest that the average interval between debris flows at Klapperhorn Mountain is 4 to 6 years, but intervals range from 0 to greater than 9 years.

5.2.3 Hazard Implications

Relative Probability of Occurrence

As described above, the available data at Klapperhorn Mountain are insufficient for the construction of quantitative frequency –size relationships. However, there are sufficient data to define a relative probability of occurrence. VanDine

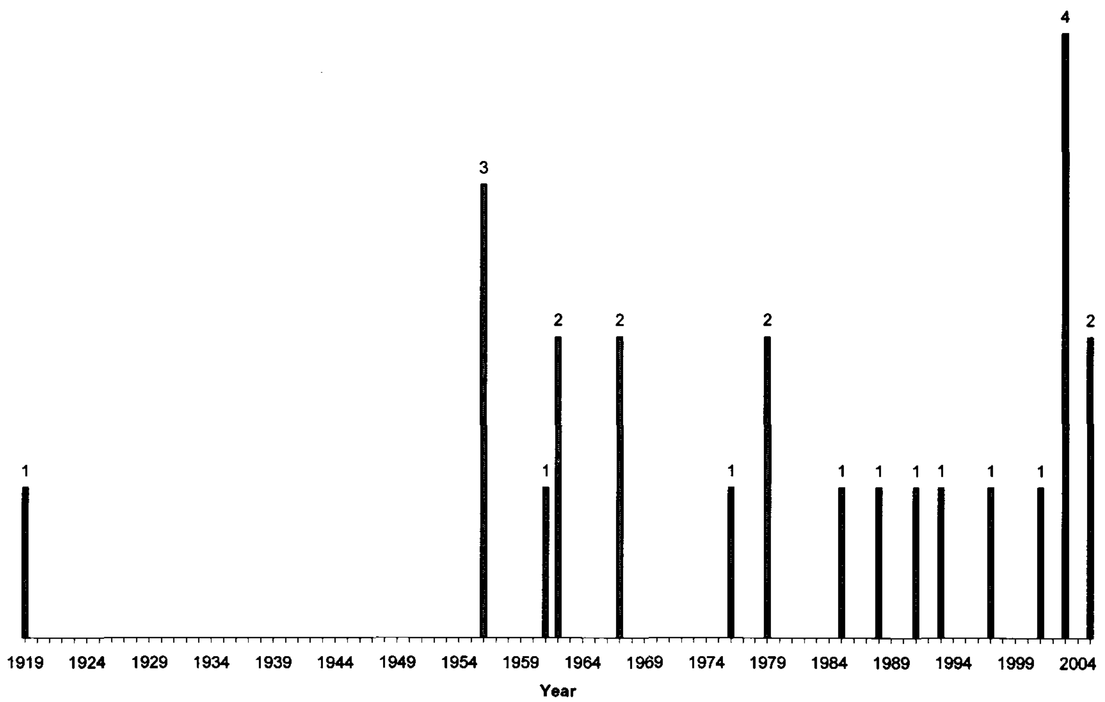

Figure 5.2. Years with debris flow events at Klapperhorn Mountain. Bar height indicates the number of debris flows in a given year. There were 15 years between 1919 and 2005 in which at least one debris flow event occurred at Klapperhorn Mountain.

(1985; 1996) describes five categories of debris flow probability (Table 5.2) that have been applied to debris flow hazard assessments in western Canada.

Based on the debris flow record and field evidence, the debris flow channels at Klapperhorn Mountain are Category 4, or very high probability channels. Debris flows occur frequently during high runoff conditions, and the design debris flow event (section 5.3) is likely to occur in the short term. The debris flow record indicates that debris flows frequently occur at Klapperhorn Mountain, and the incident record indicates that debris flows that are large enough to cause train incidents have occurred recently. This indicates that in lifespan of the railway, the design event is likely to occur several times.

Channel Age

The debris flow record is not sufficient to assign frequency estimates to individual debris flow channels. However, the channels may be assigned to a channel age category that reflects the length of time since debris flow activity within the channel. As described in section 4.3, the debris flow initiation processes at Klapperhorn Mountain suggest that debris flows are more likely to occur in recently active channels. The drainage basins are transport limited, indicating that channel recharge is not an important factor in debris flow initiation (Jakob *et. al.* 2005). Therefore, debris flows are most likely to occur in more recently active channels, and channel ages provides a useful hazard estimate.

There are 4 channel age categories at Klapperhorn Mountain (Table 5.3). Age is given relative to 2005, and the two 2005 debris flows have an age of zero years. A description of the debris flow features and vegetation within channels of each age class is

Category	Description
4	Very high probability of occurrence. Indicates that debris flows of less than the design magnitude can occur frequently with high runoff conditions, and the design debris flow should be assumed to occur in the short term.
3	High probability of occurrence. Indicates that debris flows of less than the design magnitude will occur less frequently than under category 4, but the design debris flow should still be assumed to occur within the short term. It is applied to creeks that have a history of a single debris flow, or creeks with no known history of events, but possess significant physical characteristics that are comparable to category 4 creeks
2	Moderately high probability of occurrence. Indicates that the design debris flow should be assumed to occur during the life of a significant long term structure (such as a bridge or a house). It is applied to creeks that have significant physical characteristics that fall well within the threshold where debris flows are possible, although not in the range of category 4. There is no recorded history of debris flows.
1	Low probability of occurrence, Indicates a low potential for the design debris flow. It is applied to those creeks whose physical characteristics place them at or close to the threshold where debris flows are possible. Although a debris flow is possible during the life of a long term structure, it would require an unusually high (and thus infrequent) runoff condition.
0	No risk. Indicates that there is virtually no potential for large debris flows to occur. It is applied to channel reaches whose physical characteristics fall well below the threshold where debris flows are possible.

Table 5.2. Categories of probability of debris flow occurrence from VanDine (1985; 1996).

Category	Age (years)	Calendar Years	Description
1	0-5	2000-2005	Debris flow features show no vegetation growth, minimal forest litter may be present. Mud lines and splash marks may remain on trees and rocks within the creeks.
2	5-15	1990-2000	Debris flow levees and deposits present, but no mud lines or splash marks. Abundant forest litter is present. Little or no vegetation
3	15-25	1980-1990	Debris flow levees and deposits present, but no mud lines or splash marks. Abundant forest litter is present. Deciduous trees and shrubs may occur within the channel.
4	> 25	pre 1980	Debris flow features present, but may be weathered, and less distinct. Coniferous trees may occur within the channel

Table 5.3. Debris flow channel age categories.

given. Coniferous trees may occur in Category 4 channels. Ecesis estimates for coniferous trees throughout the Rocky Mountains range from 20 to 30 years (McCarthy and Luckman 1993; Leonard 1997; Osborn *el. al.* 2001) and no conifers grow within channels at Klapperhorn Mountain that are dated as than less than 25 years in age. Therefore, the presence of conifers indicates that the channels are greater than 25 year in age.

Most debris flow channels at Klapperhorn Mountain are age category 1 channels (Table 5.4). These are generally the main channels within each basin that pass under the existing bridges. However, channel 'j' is a small debris flow channel that was identified in 2005 and does not reach the Albreda Subdivision. Debris flows at Klapperhorn Mountain are most likely to occur within these age category 1 channels. Category 2, 3, and 4 channels are recently inactive channels within the basins and pose a lesser debris flow hazard. The presence of conifers of greater than 20 years in age within channels 'h' and 'i' suggest that there has been no significant debris flow activity within these channels in more than 45 years. These channels occur below the bend in channel 'g', and a berm has been constructed to prevent avulsion of this channel.

5.3 Debris Flow Size

5.3.1 Methods

There are insufficient data to assign volumes to individual debris flow events within each channel as the deposits and features of individual debris flows can not be distinguished. Therefore, the size estimated for each debris flow is based on the largest debris flow features of each channel which are likely formed by the largest debris flows

Channel age category	1	2	3	4
Channels	a	b	e	h
	c			i
	d			l
	f			
	g			
	j			
	k			
	m			

Table 5.4. Debris flow channels in each age class.

that have occurred within each channel. This provides an estimate of the channel design event which is defined as the largest event that is likely to occur during the lifetime of a structure within the area of interest (e.g. VanDine 1996; Jakob and Jordan 2001). Recent debris flow levees that are the product of one or more debris flow events may occur within a larger channel (Figure 5.3). The geometry of the largest channel, excluding the more recent deposits, is used to estimate debris flow size.

Velocity, discharge, and total event volume are important size criteria for debris flow events as they are significant for design considerations and affect the magnitude of the hazard to railway operations. Estimates for each are provided based on channel geometry and empirical relations between debris flow parameters.

Channel Geometry

Longitudinal channel profiles were measured using a handheld Laser Technology Inc. Impulse 200 XL Laser Ranger Finder (LRF). This measures horizontal and vertical distance up to 2200 m with an accuracy of 1 m, and measures slopes with an accuracy of 0.1° l (Laser Technology Inc users manual, 2003).

Channel cross-sections were also measured in the field. Precise cross-sections were not required, and weight and time restrictions prevented the use of precise survey instruments. Therefore, they were measured using a Mastercraft construction laser level which was mounted on a tripod and placed on the bank of the channel. This provided a horizontal reference line from which the depth the channel was measured using a survey rod. This method was used in channels 'c', 'd', 'f', and 'k'. Stream flow in channel 'a' prevented the use of this method, so simple cross-sections were estimated using a tape

Figure 5.3. Recent debris flow deposits within larger set of debris flow levees in channel 'd' in basin 54.0. Size estimates are based on the geometry of the largest channel.

measure and visual estimates. In the small channels 'e', 'l', and 'm', the dimensions of the channel cross-section were visually estimated. Channel 'g' in basin 53.6 has been extensively excavated, and the existing channel geometry does not represent the debris flow processes within the channel. The cross-section is estimated based on pre-excavation photographs. Channel slope at each cross-section was estimated using a handheld compass clinometer.

Velocity

Debris flow velocity is estimated based on the depth and slope of the debris flow channel. There are several debris flow models that are used for calculating average velocity including Newtonian laminar flow, Newtonian turbulent flow, dilatant grain shearing, and numerous locally calibrated empirical relations (see Rickenmann 1999; Jakob 2005a,b). The Newtonian laminar flow equation (eq. 5.1) provides reasonable estimates for debris flows in the Canadian Cordillera (Hungr *et al.* 1984; Jordan 1994) and is used at Klapperhorn Mountain. The Newtonian laminar flow equation is

$$v = \gamma S h^2 / k\mu \qquad \text{eq. 5.1}$$

where v is the average flow velocity, γ is the unit weight of the debris, S is the channel slope, h is the flow depth, k is a channel shape coefficient and μ is the dynamic viscosity of the debris. Unit weight and viscosity of the debris at Klapperhorn Mountain were not estimated directly. Debris flow unit weight generally ranges from 20-23 kN/m^3 and dynamic viscosity of coarse debris flow is approximately 3 kPa·s (Hungr 1984; Jakob and Jordan 2001). A unit weight of 23 kN/m^3 is used here to provide a conservative estimate of velocity. The shape factor, k, is 3 for a wide rectangular channel, 5 for a trapezoidal channel, and 8 for a semicircular channel (Hungr 1984).

Discharge

Discharge is simply the product of debris flow velocity and the cross-sectional area of the channel:

$$Q = vA \quad \text{eq. 5.2}$$

where Q is discharge and A is cross-sectional area. A subjective estimate of the cross-section area can be based on the measured cross-sections and an estimate of the amount of recent channel material within the levees (Figure 5.3). When the amount of recent debris was difficult to determine, estimates that provided larger cross-section areas were used to provide conservative discharge values.

Volume

The volume of the largest debris flow events is difficult to estimate directly. Deposits of older events are obscured by more recent events, and are difficult to distinguish. Also, material is often excavated from channels and fans by CN following debris flow events. Therefore, debris flow volume is not estimated directly.

There is an empirical relation between debris flow peak discharge and volume of bouldery debris flows in southwestern British Columbia. (Bovis and Jakob 1999). Total volume of a debris flow event, V, is related to peak discharge, Q, by the relationship

$$V = 36Q^{1.1} \quad \text{eq. 5.3}$$

This relationship is based on a dataset of debris flows that generally have discharge values above 10 m^3/s, and is not calibrated for the Klapperhorn Mountain region. Volumes of debris flow events follow this general relationship, but may vary by an order of magnitude among individual debris flows. Therefore, the calculated volume values are useful for assigning channels to a debris flow size class when combined with discharge estimates, but should not be used directly for design considerations.

Size Classification

The calculated discharge and volume values are used to classify the largest likely debris flows in each channel. The Jakob (2005a) classification system is used (Table 5.5). In this classification system, debris flows are divided into categories that are useful for assessing the hazard due to a debris flow of a given size. There are 10 size classes that have corresponding debris flow sizes for both bouldery debris flows and volcanic debris flows, and have associated potential consequences. Classes 6 through 10 describe debris flows that are large enough to be produced only in volcanic settings, and have no bouldery debris flow equivalent.

5.3.2 Results

Debris flow size

Debris flow velocity, discharge and volume estimates are available for 9 of the 13 identified channels at Klapperhorn Mountain (Table 5.6). Velocity and discharge values range from 0.3 m/s and 1.0 m^3/s in channel 'm' in basin 55.0 to 5.0 m/s and 90 m^3/s in channel 'g' in basin 54.3b. Volume values based on the Bovis and Jakob (1999) relationship range from 40 m^3 to 5050 m^3. These values correspond to Jakob (2005) size classes of 1 to 3. (Figures 5.4, 5.5). To provide conservative estimates, size classes are assigned based on the largest discharge and volume values in channels with multiple cross-sections. In channels with multiple cross-sections, size estimates vary by up to a factor of three. This variation likely reflects erosion and deposition along the length of the channel and the chaotic nature of debris flow processes.

Size Class	V range (m^3)	Q range (m^3/s)	Potential Consequences
1	$<10^2$	<5	Very localized damage, known to have killed forestry workers in small gullies, damage small buildings
2	$10^2 - 10^3$	5-30	Could bury cars, destroy a small wooden building, break trees, block culverts, derail trains
3	$10^3 - 10^4$	30-200	Could destroy larger buildings, damage concrete bridge piers, block or damage highways and pipelines
4	$10^4 - 10^5$	200-1500	Could destroy parts of villages, destroy sections of infrastructure corridors or bridges, could block creeks
5	$10^5 - 10^6$	1500-12 000	Could destroy parts of towns, obliterate valleys or fans up to several tens of km^2 in size, dam rivers

Table 5.5. Debris flow size classifications for bouldery debris flows. V is total volume and Q is peak discharge. From Jakob (2005a).

Basin	Channel	Shape Factor	Width (m)	Depth (m)	Area (m^2)	Slope Angle	Gradient	Velocity (Hungr et.al. 1984)	Discharge m^3/s	Volume (Bovis and Jakob 1999)	Size Class (Jakob 2005a)
53.6	a	3	10	2	20	11°	0.19	1.9	39	2000	3
	a	3	16	2	32	15°	0.27	2.8	88	5000	
54.0	b	-	-	-	-	-	-	-	-	-	1
	c	5	2	1.1	2.1	20°	0.36	0.7	1.4	53	1
	d	5	4	1.5	5.3	30°	0.58	2.0	11	480	3
	d	5	3	2.3	9.2	25°	0.47	3.8	35	1790	
	d	3	5	1.5	7.5	25°	0.47	2.7	20	970	
	d	3	4	1.6	5.2	30°	0.58	3.8	20	970	
54.3 a	e	3	3	1.5	3.0	20°	0.36	2.1	6.0	270	2
	f	5	3	2.0	4.8	30°	0.58	3.5	17	810	2
	f	3	2	1.8	3.9	20°	0.36	3.0	12	540	
	f	5	2	2.3	4.2	20°	0.36	3.0	12	570	
54.3b	g	5	6	3.0	18.0	20°	0.36	5.0	90	5050	3
	h	-	-	-	-	-	-	-	-	-	-
	i	-	-	-	-	-	-	-	-	-	-
	j	-	-	-	-	-	-	-	-	-	1
54.7	k	3	6	1.6	9.1	25°	0.47	3.1	28	1390	3
	k	3	5	1.5	8.7	28°	0.53	3.1	27	1330	
	k	3	4	2.0	9.4	28°	0.53	5.4	51	2730	
55.0	l	3	5	1	5	25°	0.47	1.2	6.0	260	2
	m	5	1.5	0.75	5	20°	0.36	0.3	1.0	50	1

Table 5.6. Debris flow channel size parameters. Width given is the approximate average width of the channel. Debris flow velocity discharge, and volume estimates, and the corresponding size classification for the Klapperhorn Mountain channels. Channels d, f, and k have multiple cross-sections.

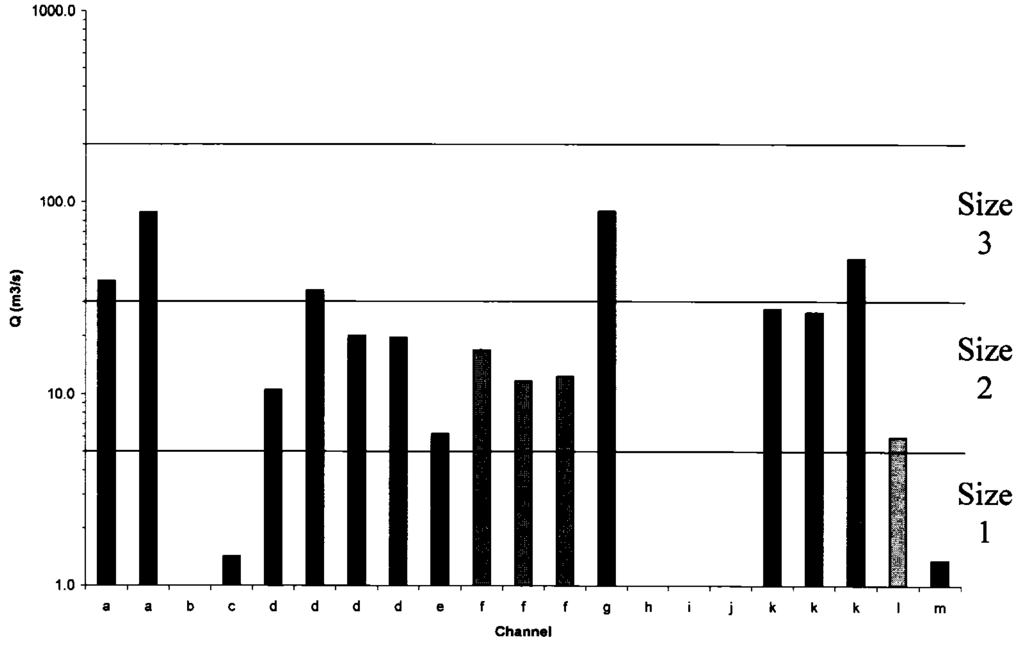

Figure 5.4. Channel discharge estimates. Jakob (2005a) size classes are shown.

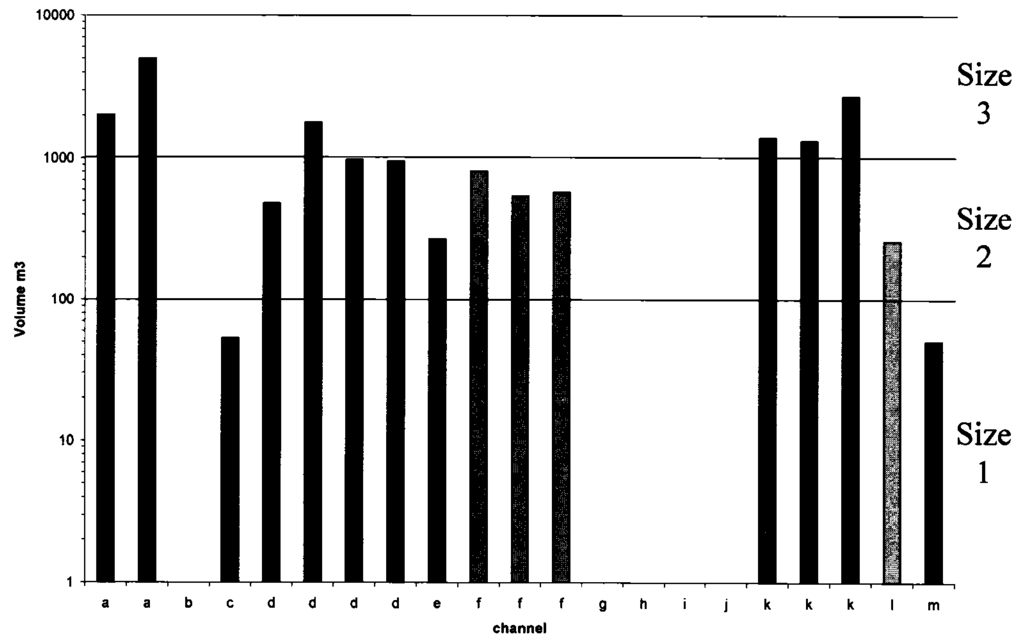

Figure 5.5. Channel volume estimates. Jakob (2005a) size classes are shown.

No cross-sections are available for channel ‘b’ in basin 54.0, or for channels ‘h’, ‘i’, or ‘j’ in basin 54.3b. Channel ‘b’ is a small channel associated with a minor debris flow deposit above the Albreda Subdivision (Chapter 2). This channel is assigned a size class of 1 based on the small size of the debris flow deposit (> 100 m^3). The entire volume of the debris flow in this basin was contained by the ditch above the Albreda Subdivision, and there is no record of larger debris flows in this channel. Channels ‘h’ and ‘i’ in basin 54.3b are channels with weathered debris flow features and abundant vegetation growth including coniferous trees (Chapter 2). No cross-sections are available, and a size class is not assigned. The debris flow in channel ‘j’ in basin 54.0 occurred between the field seasons in 2004 and 2005. No cross-section of the channel is available, but the debris flow event terminated 200 m upslope of the Albreda Subdivision and the volume of the associated deposits is less than 100 m^3, therefore this channel is assigned a size class of 1.

Class 3 debris flows occur in channel ‘a’ in basin 53.6, channel ‘d’ in basin 54.0, channel ‘g’ in basin 54.3b, and channel ‘k’ in basin 55.0. Each is the main channel within the basin and passes under a bridge, or over the rockshed. The largest debris flows occur in channel ‘g’, though a single cross-section estimated from photographs was used to estimate size. In channel ‘a’, the estimates vary by a factor of 2.5, with the lower value obtained from a cross-section immediately above the Albreda bridge, and the higher value obtained in the upper portion of the basin. The discharge and volume at each are within the class 3 range. Channel ‘k’ in basin 54.7 produces class 3 debris flows. Volume estimates at each cross-section fall within the class 3 range and one discharge value falls within the class 3 range. Two cross sections produced discharge values in the upper range of size class 2 indicating that class 3 debris flows are likely. In channel 'd' in basin 54.0, debris flow size values are estimated at four cross-sections. The values at one cross-section lies within the class 3 range, while the others are within the class 2 range (Figures 5.4, 5.5). The higher values suggest that the creek may produce class three debris flows, and it assigned to class 3.

Three class 2 debris flow channels occur at Klapperhorn Mountain. Channels 'e' and 'f' in basin 54.3a produce debris flows with velocity and discharge values that are within the class 2 range. Channel 'l' in basin 55.0 also has produced class 2 debris flows.

Four class 1 debris flow channels occur at Klapperhorn Mountain including channel 'c', which branches from channel 'd' in basin 54.0 and channel 'b', which runs down the east margin of the colluvial cone in basin 54.0. Both debris flow events that occurred between the 2004 and 2005 field seasons, in channels 'j' and 'm' were class 1 debris flows.

Debris flow channels of differing sizes occur within several individual basins. This may reflect processes such as channel avulsion, as in channel 'c' in basin 54.0, or be caused by debris flow initiation processes. In basins 54.0 and 54.3b, smaller, class 1 debris flows initiate in separate debris sources areas (Figure 3.1, terrain map). There are no distinct channels that supply water directly to these initiations areas, which may prevent initiation of large debris flows events. In basin 55.0, two debris flow channels initiate in the same source area. Channel 'm' was active in 2005, and produced a class 1 debris flow. The channel geometry of Channel 'l' indicates that this is a class 2 debris flow channel. This suggests that the initiation zone in basin 55.0 is capable of producing debris flows of size class 2, and a larger debris flow is possible in channel 'm'.

5.4 Debris Flow Hazard

5.4.1 Distribution

The relative debris flow hazard varies at Klapperhorn Mountain. Channel age (section 5.3) provides an estimate of the relative probability that a debris flow will occur within a channel, and the debris flow size class (Table 5.5) describes size of the largest debris flow likely to occur within the channel. These are used to describe the distribution of the debris flow hazard at Klapperhorn Mountain.

The debris flow hazard is assessed on terrain units that are modified by debris flows as described in Chapter 3 and 4. Areas not modified by debris flows are considered to have no debris flow hazard. Areas that are modified by debris flows but do not have an identified debris flow channel are considered areas of low debris flow hazard. Areas where debris flow channels are present have a higher hazard that is assessed based on the age and size class estimates (Figure 5.6). Higher debris flow hazard occurs in the most recently active class three channels, while smaller, less recently active debris flow channels are a lesser hazard. Eight of the thirteen debris flow channels at Klapperhorn Mountain have a channel age of 1 (Table 5.4). Therefore, debris flow size is the primary hazard factor in most channels at Klapperhorn Mountain.

The highest hazard is associated with the size class 3 debris flows in basins 53.6, 54.3b, and 54.7 (Figure 5.6). Size class 1debris flow channels, even those with a channel age class of 1, pose a relatively low hazard. Size class 2 debris flows of channel age 1, 3, and 4 occur, with the highest hazard associated with the age class 1 channels. No size class is available for channel 'h' and 'i'. These are both described as size class 3 channels on the hazard map due their relation with channel 'g'.

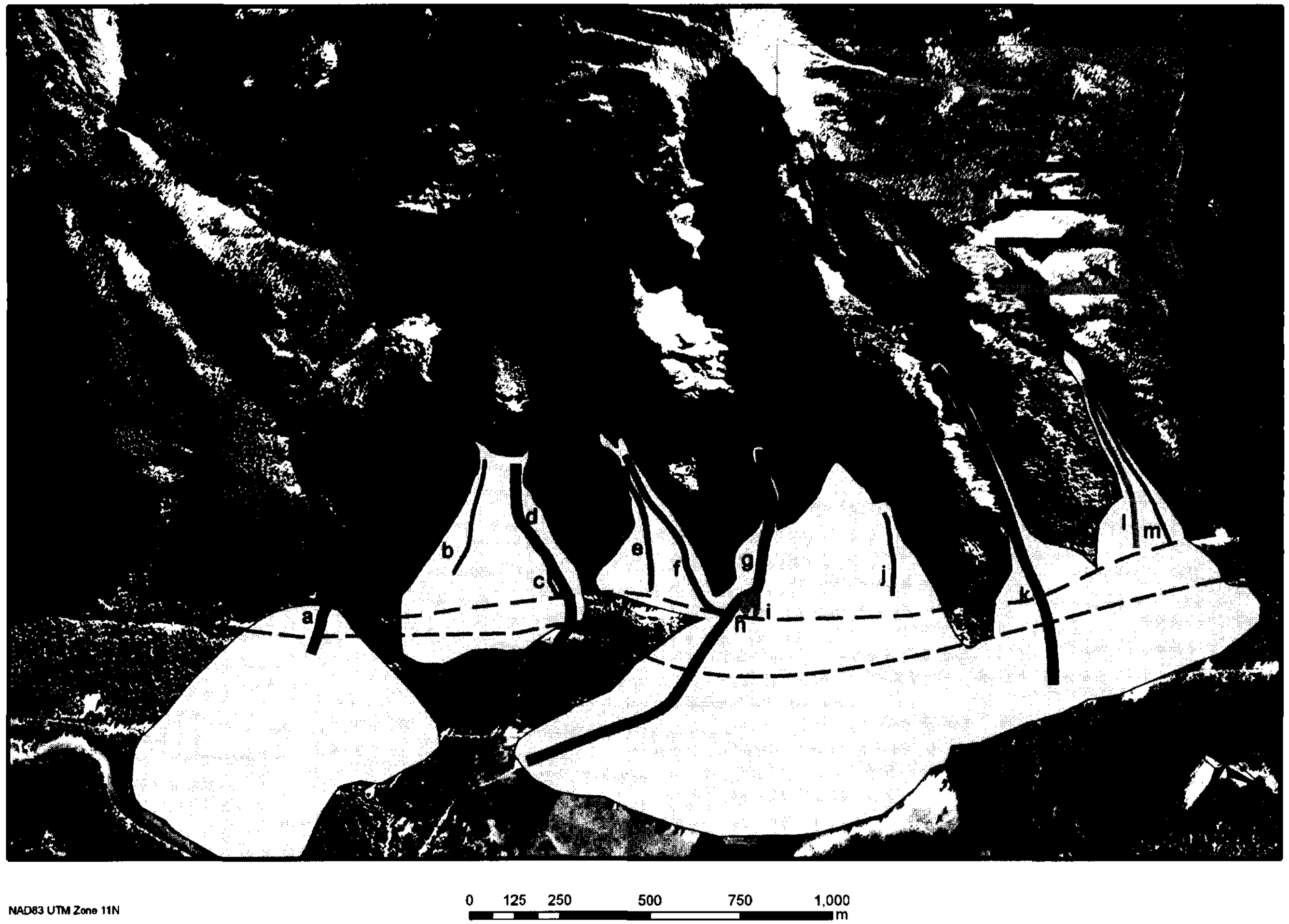

Figure 5.6. Debris flow hazard at Klapperhorn Mountain. Channels are classified according to the size of the largest debris flows that are known to have been produced (line thickness), and by the channel age (line colour). Larger, darker channels represent the highest debris flow hazard areas on in the study area. The yellow areas represent colluvial cone or fan features that are modified by debris flow processes. No existing channels occur but the landforms suggest that there is a potential for debris flow in these areas

5.4.2 Potential Consequences

Jakob (2005) lists potential consequences for each debris flow size class (Table 5.5). At Klapperhorn Mountain, debris flows of each size class present a specific hazard to the Albreda and Robson Subdivisions. Potential hazards associated with each size class are described, and are based on field evidence and estimates of the ability of each to impact the railway.

Class 1 debris flows are not likely a significant hazard to the railway at Klapperhorn Mountain. Each observed class 1 debris flow channel terminated above the Albreda Subdivision, either on the colluvial cone or in the ditch above the railway. In rare instances a class 1 debris flow may deposit debris on the track, and could potentially derail a train, but generally class 1 debris flows are a maintenance issue rather than a train hazard. Channel 'c' in basin 54.0 is the largest class 1 debris flow, and is the most likely to impact the railway.

Class 2 debris flow channels pose a hazard when they occur along the Albreda Subdivision where no bridge is present. There is little evidence that debris flows occur between the Albreda and Robson Subdivisions, with the exception of those within the existing channels that pass beneath the bridges. This suggests that debris flows that reach the Albreda tracks do not remain channelized and do not reach the Robson Subdivision. Therefore, class 2 debris flows likely pose a hazard to the Albreda Subdivision. Class 2 debris flows would pass under bridges, but where no structure is present, such as in channels 'e' and 'l' these may deposit sufficient debris on the track to derail a train.

Class 3 debris flows pose a hazard to bridge, particularly along the Robson Subdivision. There is no evidence of class 3 debris flows in channels that do not pass under the existing bridges at Klapperhorn Mountain. In rare events, avulsion may cause a class 3 debris flow to reach the track, but there is no evidence that this has occurred. The historical record suggests that bridges on the Robson Subdivision are most susceptible to debris flows, as the bridges along the Albreda Subdivision have higher clearances than those on the Robson. In basin 54.7, there is no bridge on the Albreda Subdivision as the track is protected by the rock shed at Mile 54.7.

5.5 Conclusions

Debris flows occur at Klapperhorn Mountain occur with high frequency. Frequency estimates for individual creeks are not available, but the data indicate that the Klapperhorn Mountain debris flows have very high probability of occurrence and the design debris flow event in each channel is likely to occur several times over the lifespan of the railway.

The debris flow channels are classified by channel age, which describes the time since the last debris flow activity within the channel. Based on processes that control debris flow distribution on the colluvial cone units, debris flows are most likely to occur in more recently active channels. Therefore, channel age provides an estimate of the channels that are most likely to produce debris flows

Debris flow size at Klapperhorn Mountain ranges from Jakob (2005) size class 1 to 3. Size class 3 debris flows occur in the main channels in basins 53.6, 54.0, 54.3b, and 54.7, and pose a hazard at bridges. Class 2 debris flows occur in basins 54.3a and 55.0, and pose a hazard along the Albreda Subdivision where no bridges are present. The five class 1 debris flow channels are largely a maintenance issue, but in rare circumstances may deposit material on the track, particularly at channel ‘c’ in basin 54.0

The highest debris flow hazard at Klapperhorn Mountain occurs where channels are present, but a hazard exists on all debris flow modified terrain units. The presence of debris flow channels increases the hazard, and recently active size class 3 channels are areas of highest hazard.

Chapter 6. Conclusions and Future Work

6.1 Conclusions

Debris flows threaten railway operations and infrastructure on the Albreda and Robson Subdivisions in the Yellowhead Pass region of the Canadian Rocky Mountains. This thesis provides the first description of the surficial geology and geomorphologic processes involved in the debris flow hazard, and provides and assessment of the size and timing of individual debris flow events.

Debris flows occur in six drainage basins at Klapperhorn Mountain. These are recognized by drainage basin characteristics and by the presence of debris flow channels and deposits. A total of thirteen debris flow channels are identified within these basins. The debris flow hazard may be described using Keegan's (2007) debris flow hazard scenario, in which a sequence of processes lead to track failure. At Klapperhorn Mountain, debris flows may cause train failure directly, or a sequence of events including avulsion, secondary debris flows, seepage erosion, gully erosion and earth slides my lead to track failure.

Terrain mapping is used to evaluate the debris flow hazard at Klapperhorn Mountain by establishing the distribution of the geomorphic processes that control debris flow activity. Rock fall and snow avalanche processes dominate in the upper two thirds (>1200 elevation) of the mountain, which is composed of bedrock and colluvial veneer terrain units. These processes deposit material on colluvial cones on which debris flows are the dominant transport mechanism. Material is then transported by debris flows to fan features at the base of the mountain. The structure and composition of the bedrock at Klapperhorn Mountain ultimately controls the distribution of debris on the colluvial cones and the locations of the drainage basin divides.

Debris flows at Klapperhorn Mountain are relatively frequent events. The debris flow record indicates that there have been 15 years since 1919 in which at least one debris flow event occurred in the study area. The data suggest that debris flows within each creek have a very high probability of occurrence, and the design event should be assumed to occur in the short term, relative to the lifespan of the railway.

Given the high probability of occurrence of debris flows, the distribution and size of the debris flows are the primary controls of the hazard at Klapperhorn Mountain. Debris flow occurrence is controlled by drainage basin morphology and the distribution of the colluvial units within the basins. In basin 53.6, both subdivisions cross the debris flow channel where it is well confined by topography, so debris flow size is the main hazard consideration. In the other basins, the tracks run across the colluvial cones on which debris flows occur. In these basins, debris flow channelization is an important influence on the hazard. Multiple channels occur on the colluvial cones, and debris flows migrate across the cones through time. Currently, the largest debris flow channels in the study area pass under the existing bridges, and the hazard is controlled by the size of the debris flows. Based on the geometry of the largest channel features, these channels may produce debris flows up to class 3 (10^3 to 10^4 m^3), in size. Several class 2 (10^2 to 10^3 m^3) debris flow channels occur on Klapperhorn Mountain. These channels pose a hazard where no bridge or structure is present, particularly on the Albreda Subdivision. Class 1 ($>10^2$ m^3) debris flows are largely a maintenance issue, as they may be contained by ditches above the Albreda Subdivision. However, in rare cases, and particularly in channel 'c' in basin 54.0, class 1 debris flow may deposit debris on the tracks.

The debris flow hazard assessment at Klapperhorn Mountain demonstrates the importance of understanding drainage basin scale processes in effective risk management. Prior to this work, debris flows in this area had been addressed at the track level by excavating debris from the channels following debris flow events, and by installing warning devices in areas of concern. This research demonstrates that processes that occur throughout the drainage basins control the debris flow hazard at track level, and that understanding these processes may allow for more effective hazard mitigation.

6.2 Future Work

This thesis describes the processes that control debris flows at Klapperhorn Mountain. While some questions regarding the geomorphology remain, there is sufficient data to begin the development of a debris flow hazard and risk rating system using Keegan's (2007) methodology for risk analysis of railway ground hazards. The following sections describe the aspects of the geomorphology that would benefit from further research, and outlines the steps required to integrate this research into an overall risk management program.

6.2.1 Triggers

The limited debris flow record and lack of weather data prevent an assessment of triggering conditions. Detailed records of future events should be made to describe the date, size, location and characteristics of the debris flows, as well as the weather conditions at the time of the event. This will provide a more extensive debris flow dataset. In October 2004, a weather station was installed on a peak adjacent to Klapperhorn Mountain that will provide quantitative weather data that can be used to describe the weather prior to debris flow events. If a large enough debris flow dataset is generated, this weather data may be used to identify threshold weather conditions, and potentially will provide an early warning of debris flow activity.

6.2.2 Frequency-Size

Frequency-Size relationships are essential for natural hazard risk assessments. This thesis describes the timing of debris flow activity based on limited data in several creeks, and identified a very high relative probably of occurrence for debris flow activity at Klapperhorn Mountain. However, it does not define the frequency-size relationships of individual debris flow channels. If, as suggested above, detailed records of future debris flow events are kept, these relationships may be generated. In addition, trenching and detailed mapping of the debris flow fans, which was beyond the scope of this project, may provide data about the size of past debris flow events.

6.2.3 Risk Management

As part of the Railroad Ground Hazard Research Program, Keegan (2007) has developed a methodology for managing the risk posed to railways by all ground hazards. The research at Klapperhorn Mountain may be incorporated into this risk management system. There are seven steps in the risk management system:

1. Develop a risk library
2. Hazard Identification
3. Risk Communication
4. Risk Estimation
5. Risk Evaluation
6. Risk Control
7. Action and Monitoring.

A risk library database is in development, and will be used to store hazard data in a consistent format. In addition to its role in the overall risk management process, this database will store relevant debris flow data for Klapperhorn Mountain and as a larger dataset is developed, may allow the specific triggering conditions to be identified and for true frequency-size relations to be determined.

This research fulfills the hazard identification requirement of the risk management system at Klapperhorn Mountain, and suggests that criteria such as Melton's Ruggedness number and fan slope may be used to identify other debris flow drainage basins in the region. The detailed description of the Klapperhorn Mountain geomorphology presented in this thesis will allow the debris flow hazard scenarios to be populated.

This Klapperhorn Mountain research may be incorporated into the development of a debris flow risk assessment system that will fulfill the risk estimation component of the program. Three risk assessment systems currently exist: the CN Rockfall Hazard and Risk Assessment System (RHRA) for rock falls (Abbott *et al.* 1998a, 1998b), the Beaver Activity Hazard Assessment (BAHA) for hazards related to beaver activity (Keegan 2007, pers. comm.) and the River Attack Track Risk Assessment System (RATRAS), for river erosion hazards (Porter *et. al.* 2005). These are attribute based systems that use relevant attributes to generate hazard likelihood, track vulnerability and consequence ratings that can be used to evaluate and compare the risk along the CN network. The detailed overview of the Klapperhorn Mountain geomorphology may assist in the development of a similar rating for debris flow hazard. This risk rating would allow for effective prioritization and decision making and would enable the risk evaluation, risk control, and action and monitoring components of the risk management methodology to be performed effectively.

6.3 Summary

This thesis provides the first description of the drainage basin scale processes that control the debris flows that pose a hazard to railway operations at Klapperhorn Mountain and provides a preliminary hazard assessment. The distribution and timing of rock fall, snow avalanche, and debris flow processes are described, and the size of debris flows in the study area is estimated. Future work would allow this research to be incorporated into an overall ground hazard risk management system to effectively manage the debris flow risk at Klapperhorn Mountain and elsewhere along the railway network.

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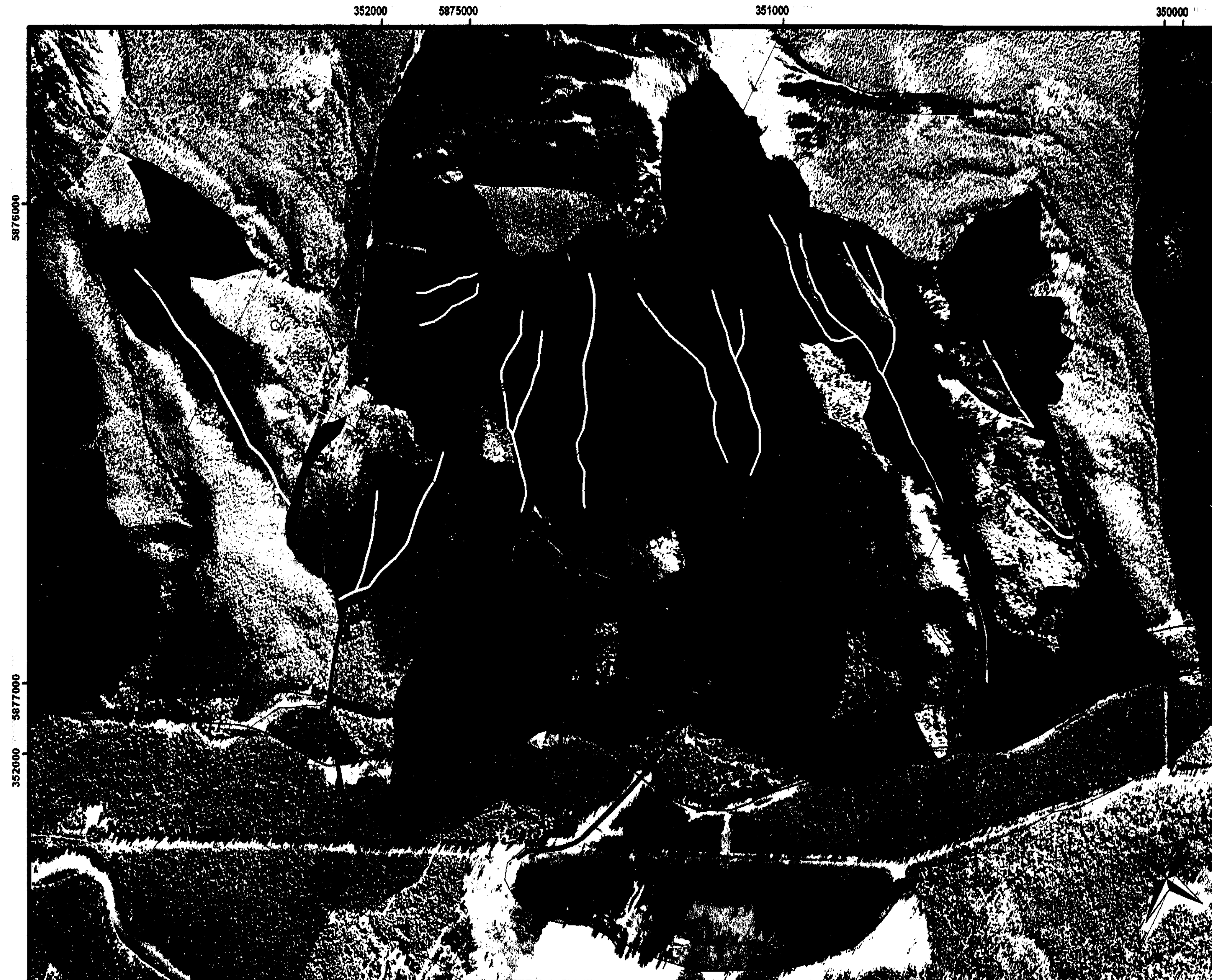
Appendix – Terrain Mapping

Photo Number	Source	Year	Scale
NW11685 LN 15 99	CN Rail/Northwest Survey Group	1985	1:15 000
NW11685 LN 15 100	CN Rail/Northwest Survey Group	1985	1:15 000
NW11685 LN 15 101	CN Rail/Northwest Survey Group	1985	1:15 000
NW11685 LN 15 102	CN Rail/Northwest Survey Group	1985	1:15 000
NW11685 LN 15 103	CN Rail/Northwest Survey Group	1985	1:15 000
NW11685 LN 15 104	CN Rail/Northwest Survey Group	1985	1:15 000
NW11685 LN 15 105	CN Rail/Northwest Survey Group	1985	1:15 000
NW11685 LN 15 106	CN Rail/Northwest Survey Group	1985	1:15 000
NW11685 LN 15 107	CN Rail/Northwest Survey Group	1985	1:15 000
NW11685 LN 15 108	CN Rail/Northwest Survey Group	1985	1:15 000
IAS(97) 54256 - 110	CN Rail/IAS	1997	1:15 000
IAS(97) 54256 – 111	CN Rail/IAS	1997	1:15 000
IAS(97) 54256 – 112	CN Rail/IAS	1997	1:15 000
IAS(97) 54256 – 113	CN Rail/IAS	1997	1:15 000
IAS(97) 54256 – 114	CN Rail/IAS	1997	1:15 000
IAS(97) 54256 – 115	CN Rail/IAS	1997	1:15 000
IAS(97) 54256 – 116	CN Rail/IAS	1997	1:15 000
IAS(97) 54256 – 117	CN Rail/IAS	1997	1:15 000
IAS(97) 54256 – 118	CN Rail/IAS	1997	1:15 000
30BCB 91102 No 256	BC Air Photo & Lab Services	1991	1:40 000
30BCB 91102 No 257	BC Air Photo & Lab Services	1991	1:40 000
30BCB 91102 No 258	BC Air Photo & Lab Services	1991	1:40 000
30BCB 91102 No 259	BC Air Photo & Lab Services	1991	1:40 000
30BCB 91103 No. 1	BC Air Photo & Lab Services	1991	1:40 000
30BCB 91103 No. 2	BC Air Photo & Lab Services	1991	1:40 000
30BCB 91103 No. 3	BC Air Photo & Lab Services	1991	1:40 000
30BCB 91103 No. 4	BC Air Photo & Lab Services	1991	1:40 000
30BCB 91103 No. 157	BC Air Photo & Lab Services	1991	1:40 000
30BCB 91103 No. 158	BC Air Photo & Lab Services	1991	1:40 000
30BCB 91103 No. 159	BC Air Photo & Lab Services	1991	1:40 000
30BCB 91103 No. 160	BC Air Photo & Lab Services	1991	1:40 000
30BCB 91103 No. 161	BC Air Photo & Lab Services	1991	1:40 000
30BCB 91103 No. 162	BC Air Photo & Lab Services	1991	1:40 000

Air photographs used for terrain mapping (Chapter 3)

Point	Easting	Northing	Basin	Terrain Code
1	351545	5876344	53.6	Cc-r
2	351657	5776155	53.6	Cc-dar
3	351449	5876506	53.6	Cv
4	351091	5876844	53.6	Cc-d
5	351271	5876671	53.6	Cf-d
6	351077	5876500	54.0	Cc-d
7	351115	5876346	54.0	Cc-d
8	350885	5876174	54.0	Cc-d
9	350763	5876237	54.0	Cc-d
10	350837	5876222	54.0	Cc-d
11	351063	5876036	54.0	Cc-dar
12	350834	5876187	54.0	Cc-d
13	350687	5876358	54.0	Cc-d
14	350671	5876474	54.0	Cf-d
15	350656	5876099	54.3a	Cc-ad
16	350520	5876168	54.3a	Cc-s
17	350473	5876093	54.3a	Cc-d
18	350597	5875988	54.3a	Cc-d
19	350889	5875851	54.3a	Cc-adr
20	350737	5785894	54.3a	Cc-adr
21	350416	5876232	54.3b	Cc-ri
22	350354	5876119	54.3b	Cc-d
23	350294	5876088	54.3b	Cc-d
24	350395	5875787	54.3b	Cc-dr
25	350515	5785632	54.3b	Cc-r
26	350137	5876216	54.3b	Cf-d
27	350422	5876215	54.3b	Cf-d
28	350526	5876530	54.3b	Cf-d
29	349975	5875852	54.3b	Cc-s
30	350050	5875736	54.3b	Cc-ad
31	349695	5875658	54.7	Cc-dar
32	349623	5875832	54.7	Cf-d
33	349849	5875446	54.7	Cc-dar
34	350108	5875267	54.7	Cc-dar
35	349512	5875332	55.0	Cc-dr
36	349769	5875090	55.0	Cc-ard
37	349468	5875265	55.0	Cc-dr
38	349408	5875524	55.0	Cf-d

Selected terrain mapping ground truth points (Chapter 3) Points were accessed during field mapping in 2004 and 2005.



Map Scale: 1:10 000
NAD83 UTM Zone 11N

Figure 3.1. Surficial Geology of Klapperhorn Mountain

Terrain Units

Bedrock

Bedrock at surface. May be modified by snow avalanche (-a) and rock fall (-r")

Colluvium

Colluvial Cone - Conical landform with a slope > 20 degrees

Co-a — Colluvial cone unit modified by snow avalanche processes. May also be modified by debris flow (-d) and rock fall (-r)

Colluvial cone unit modified by rock fall processes. May also be modified by snow avalanche (-a). Rockfall area may be inactive

Colluvial cone unit modified by debris flowprocesses. May also be modified by snow avalanche (-a) and rock fall (-r)

Colluvial cone unit modified by debris slide processes

Colluvial Fan -Fan shaped landform with a slope < 20 degrees

Colluvial fan unit modified by debris flow processes

Colluvial Veneer - Continuous cover of colluvium on bedrock up to 2 m in thickness

Cv — Colluvial veneer unit, not modified by any active geomorphologic processes

Colluvial veneer unit, modified by snow avalanche processes

Undifferentiated

U — Undifferentiated material. May include till and valley fill deposits.

Linear Features

Debris Flow Creeks

Size Class 1 debris flow creeks

Size Class 2 debris flow creeks

Size Class 3 debris flow creeks

Size classification is used here to distinguish debris flow creeks. For a description of this classification, and a further differentiation of the debris flow creeks, see Chapter 5.

Snow avalanche Paths

Rock Fall Chutes

Figure 3.1 continued. Terrain Map Legend. See Chapter 3 for detailed descriptions of terrain units.