Report of the Cheekye River (Ch'kay Stakw) and Fan Expert Review Panel

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Prepared for:

Province of BC
Squamish Nation
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Executive Summary

In late 2013, the Province of British Columbia, the Squamish Nation, and the District of Squamish collectively selected and appointed an independent Cheekye River and Fan Expert Review Panel (the Panel). The Panel was instructed to review all previous relevant documentation associated with geological, geomorphological, and geotechnical studies, research, reports, and publications associated with the Cheekye River and Fan, and to provide its opinion on possible future landslides, including debris flows and debris floods. Specifically, the Panel was to provide its opinions on the:

- volume and frequency of future landslides;
- the character and volume of the '10,000-year' landslide; and
- possible effects of climate change on future landslides.

This report summarizes the Panel's opinions based on a thorough review of the referenced documents and careful consideration of the unknowns, uncertainties, and assumptions, which are discussed. In carrying out its review, the Panel identified other considerations that lie outside its Terms of Reference. As requested, these considerations are also included as part of this report. This Executive Summary summarizes the Panel's opinions.

With respect to volume and frequency of future landslides, it is the Panel's opinion that the magnitude-cumulative frequency (MCF) relationships developed by BGC Engineering Inc. (2008a) (redrawn as Figure 3 in this report) are the most reliable MCF relationships currently available for Cheekye Fan. Further, it is the Panel's opinion that the part of the MCF curve representing smaller volume rainfall/surface water runoff-generated debris flows (solid line on Figure 3) is credible and could be a basis for considering debris flow mitigation strategies for this range of events. A spectrum of still smaller debris floods or stream floods, which are not shown on Figure 3, should also be considered in mitigation strategies.

With respect to the 10,000-year landslide, it is the Panel's opinion that the upper (dotted) line on the right side of Figure 3 provides a prudent estimate of the volume of debris that could be transported to Cheekye Fan during a rock slide-generated debris flow. The volume of the 10,000-year debris flow is 5.5 million m^3. This estimate is more conservative than that recommended by BGC (2008a), but is consistent with several other previous estimates, as reviewed in Section 4.2 of this report.

It is also the Panel's opinion that the 10,000-year landslide, which is conceptually comparable to a 'maximum credible earthquake' or a 'probable maximum flood', is the appropriate extreme event for estimating the largest debris flow that could affect Cheekye Fan.

With respect to possible effects of climate change on future landslides, it is the Panel's opinion that climate change will increase the frequency of debris flows and debris floods of all sizes. This expectation would shift the lines on Figure 3 to the left, although by an unknown amount. This shift would have the effect of increasing the volumes of given-year events, including the 10,000-year event. However, it is not possible at present to quantify with certainty changes in the frequency of future debris flows due to climate change. Consequently, possible climate change effects must be considered by selecting suitably

conservative parameters during the design of any mitigation, and by selecting solutions that are flexible with respect to the magnitude of potential effects.

The Panel's opinions with respect to the other considerations are as follows:

- Whether or not there is any future development on Cheekye Fan, existing development on the fan and on the west side of the Cheakamus/Cheekye river confluence including residential, public, and industrial buildings, BC Highway 99, the CN Rail line, roads and bridges, and other structures, should be protected from possible large volume (with relatively low probability of occurrence) and small volume (with relatively high probability of occurrence) debris flows, debris floods, and stream floods, and associated stream sediment movement.
- All forms of mitigation, singly or in combination, should be considered and carefully evaluated to protect existing development and to possibly allow some new development on Cheekye Fan and on the west side of the Cheakamus River opposite Cheekye Fan.

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Glossary of Some Technical Terms Used in this Report

Avulsion A sudden shift in the channel of a stream or river.

Climate downscaling The process of deriving local or regional climate data from coarser global climate models.

Debris fan A fan-shaped landform deposited at the mouth of a stream, at least in part, by debris flows. A mountain debris fan can be built by a combination of alluvial and debris flow processes.

Debris flood A high-velocity flow that is transitional between a stream flood and a debris flow.

Debris flow A high-velocity, destructive, surging flow of water-saturated sediment ranging in size from clay to boulders, including trees and other vegetation.

Dendrochronology The scientific study of annual rings of living and dead trees to determine the age of past events such as debris flows.

Ground Penetrating Radar (GPR) A geophysical technique that uses electromagnetic waves to image Earth's shallow subsurface. GPR is used to locate subsurface strata, caves, the water table, and buried pipes and tanks.

Hazard An event that can have a harmful effect on people, the environment, or the economy.

Hazard probability The probability of a hazardous event occurring.

Landslide The downward and outward movement of a body of rock or soil under the influence of gravity. The term includes rock slides and debris flows described in this report.

Lava flow A stream or sheet of molten rock that flows from a volcano or from a fissure.

LiDAR (Light Detection and Ranging) A remote sensing technique that very accurately measures distance from an airborne sensor to Earth's surface and is used to make high-resolution maps of the ground. The technique images the 'bare earth' by removing the effects of vegetation.

Linear As used in this report, a narrow elongate crack or scarp that extends across the ground surface and delineates a subsurface plane of weakness, such as a fault or an incipient landslide scarp.

Mitigation Any action taken to reduce the harmful effects of a hazardous natural event. Mitigation includes avoidance, construction to reduce the impact of the event, purchase of insurance, and education.

Natural hazard A natural event that can have a harmful effect on people, the environment or the economy.

Pyroclastic deposit An accumulation of volcanic material blown from a volcano during an explosive eruption; the material ranges from ash particles to blocks and 'bombs'.

Pyroclastic flow A turbulent, incandescent cloud of gas, ash, and rock fragments that flows close to the ground at high speed.

Risk The product of the probability of a hazardous event occurring and the expected damage if the event does occur.

Stratigraphy The field of geology concerned with the order and relative position of sedimentary layers and their relationship to the geological time scale.

Section 1: Introduction

The Cheekye River is located approximately 10 km north of Squamish, British Columbia (BC), at the head of Howe Sound, and approximately 70 km north of Vancouver, BC. The Cheekye River catchment and its associated fan complex are one of the most studied watersheds in BC, and possibly Canada. Initial geological research dates back to the 1940s. Most of the subsequent geological, geomorphological, and geotechnical studies, research, reports, and publications have been motivated by a series of proposals to develop the fan for residential and other uses, and related questions about *landslides*[1] and the associated *hazards* and *risks*.

In late 2013, the Province of BC, the Squamish Nation, and the District of Squamish collectively selected and appointed an independent 'Cheekye River and Fan Expert Review Panel' (hereafter referred to as the Panel) to review all previous relevant documentation and provide its opinion on possible future landslides, including *debris flows* and *debris floods*. Specifically, the Panel was instructed to provide its opinions on the:

- volume and frequency of future landslides;
- the character and volume of the '10,000-year' landslide; and
- possible effects of climate change on future landslides.

The relevant parts of the Terms of Reference are reproduced in Appendix A.

This report summarizes the Panel's opinions. The Panel members understand that in giving these opinions, they are assisting the Province of BC, the Squamish Nation, and the District of Squamish, and are not an advocate for any party.

1.1 Cheekye River and Fan Expert Review Panel

The Panel comprises three members who were selected and appointed by the Province of BC, the Squamish Nation, and the District of Squamish, respectively:

- Dr. John Clague P.Geo., Department of Earth Sciences, Simon Fraser University;
- Dr. Oldrich Hungr P.Eng./P.Geo., Department of Earth, Ocean and Atmospheric Sciences, University of British Columbia; and
- Mr. Douglas VanDine P.Eng./P.Geo., VanDine Geological Engineering Limited.

Collectively, the Panel has over 100 years of experience related to all aspects of landslides and associated processes. The Panel members' curricula vitae are included as Appendix B.

The Panel reported to a Steering Committee composed of senior administrators of the Province of BC, the Squamish Nation, and the District of Squamish. As the Panel member selected by the province, Dr. Clague was appointed chair of the Panel. Mr. Darren Stadel (BC Ministry of Jobs, Tourism and Skills Training) was appointed by the Steering Committee as the Project Manager.

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[1] Technical terms are italicized when first used and are defined in the Glossary

Two of the three panel members, Dr. Clague and Dr. Hungr, have participated in previous research, studies and/or reviews associated with the Cheekye River and Fan.

1.1.1 Panel Review Process

The Panel was selected and appointed in November 2013. The Panel, Steering Committee, and Project Manager initially met in late November 2013. Dr. Matthias Jakob presented a summary of the 2007 and 2008 Cheekye River landslide studies by BGC Engineering Inc (BGC 2007, 2008a, 2008b)[2]. All scientific and engineering reports and publications related to landslide hazards and risks associated with the Cheekye River and Fan, dating back to 1952, were provided to the Panel.

After individually reviewing the documents provided to it, the Panel met in camera in mid-December, thoroughly discussed the issues to formulate its opinions, and reached a consensus. In early January 2014, the Panel met with the Steering Committee and the Project Manager, verbally presented its opinions and the rationale for those opinions, and answered questions.

Between late January and April 2014, the Panel submitted several draft reports to the Steering Committee for review and comments, and met with those parties in mid-March 2014.

1.1.2 Limitations

This report is based entirely on a review of relevant previous scientific and engineering reports and publications related to landslide hazards and risks associated with the Cheekye River and Fan; other reports and publications as required; and the experience of the individual Panel members. No new studies were carried out as part of this review.

The information in this report reflects the opinions of the Panel based on the information available to it at the time the report was prepared. The Panel carried out its review and prepared this report in a manner consistent with the level of care and skill exercised by geological and engineering professionals currently practicing in BC.

This report is for the sole use of the Province of BC, the Squamish Nation, and the District of Squamish. Any use that a Third Party makes of this report, or any reliance or decisions based on this report, is the sole responsibility of those Third Parties. The Panel accepts no responsibility for damages or injury of any sort or extent, if any, suffered by any Third Party as a result of information in this report or decisions made based on information in this report.

1.1.3 Report

This report first briefly describes the Cheekye River watershed and Cheekye Fan and summarizes previous studies, research, reports, and publications related to the watershed and fan. It then addresses the issues for opinions, providing background technical information as required. For presentation purposes, the Panel addresses the issues in a slightly different order than listed in the Terms of Reference (Appendix A). The Panel's opinions are based on a thorough review of the referenced studies, research, reports, and publications, and careful consideration of the unknowns, uncertainties, and assumptions, which are discussed.

[2] References are listed at the end of the report

In carrying out its review, the Panel identified other considerations that lie outside its Terms of Reference. It brought these considerations to the attention of the Steering Committee, who agreed that they should be included as part of this report.

Section 2: Background Information

2.1 Cheekye River Watershed and Cheekye Fan

The name of the river, 'Cheekye', is derived from the Skwxwu7mesh word 'Ch'kay Stakw', which means 'dirty water'.

2.1.1 Cheekye River Watershed

The Cheekye River watershed has an area of approximately 60 km^2. The river flows westward approximately 13 km from the west flank of Mount Garibaldi and the Garibaldi glacier complex (approximate elevation 2700 m asl[3]) into the Cheakamus River (approximately elevation 50 m), and then into the Squamish River approximately 3 km downstream from the Cheekye/Cheakamus river confluence (Figures 1 and 2).

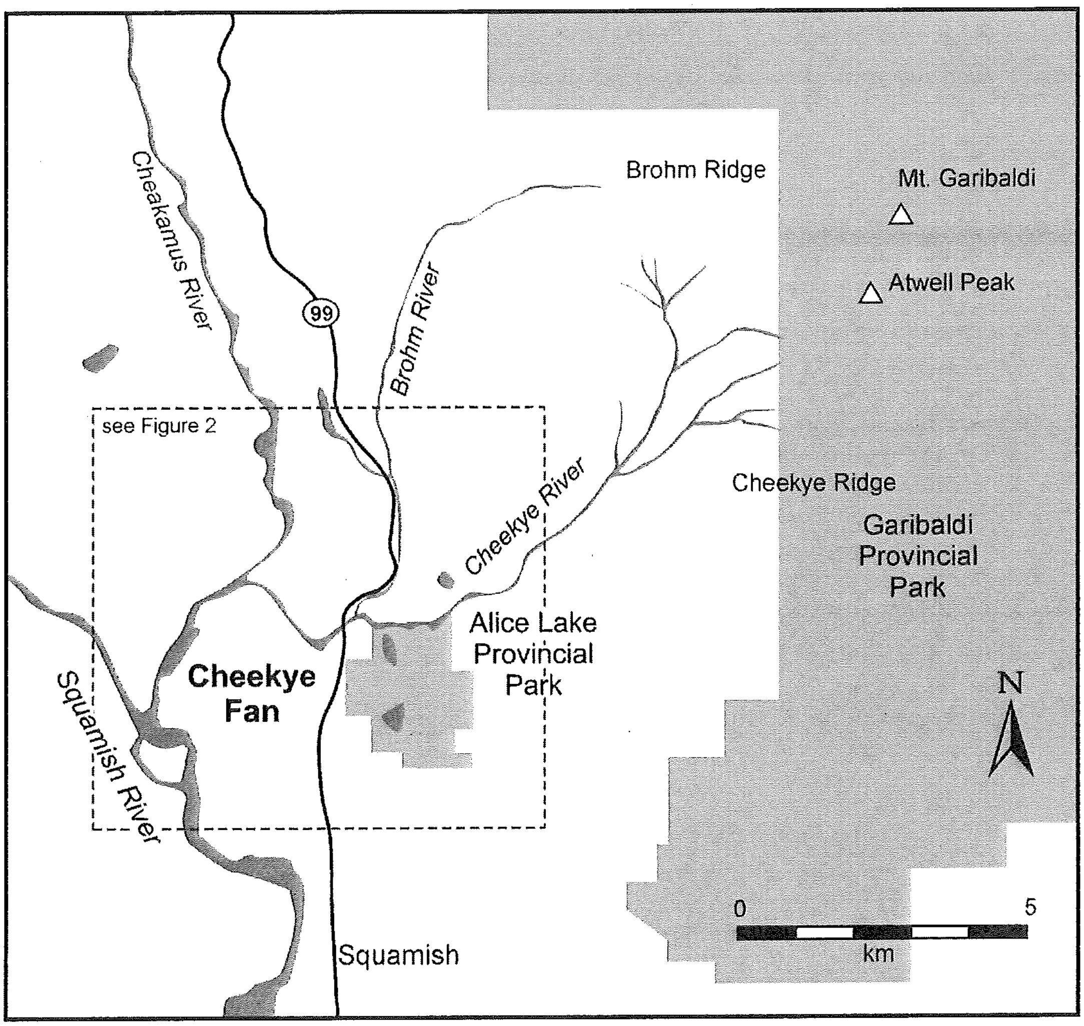

Figure 1: Location map showing the Cheekye and Brohm river watersheds and Cheekye Fan.

[3] Above sea level. All elevations in this report are elevations above sea level.

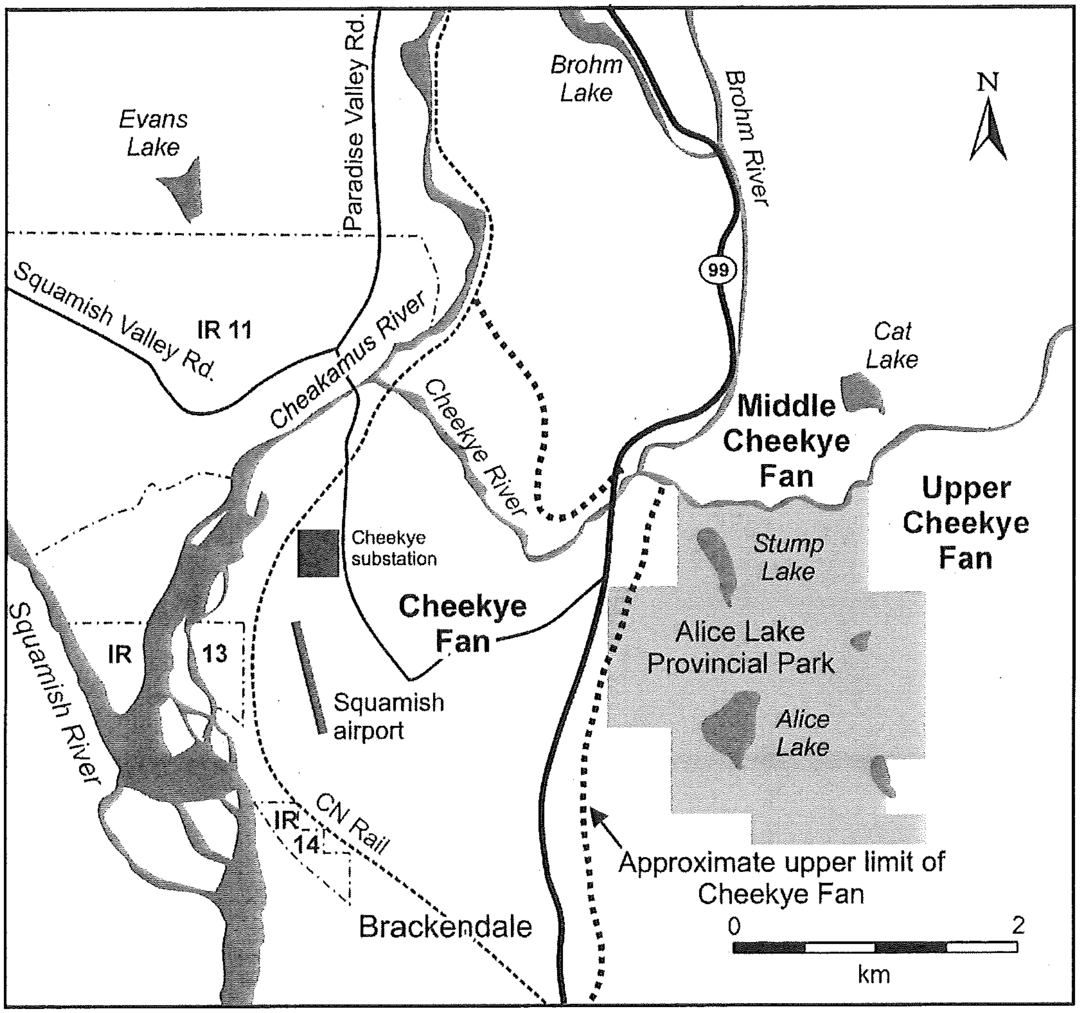

Figure 2: Map of the lower Cheekye River and Cheekye Fan.

The Cheekye River watershed drains an amphitheatre-shaped headwater area that includes, from north to south: Brohm Ridge, Mount Garibaldi, Atwell Peak, and Cheekye Ridge. The headwater slopes are very steep – up to 45°, on average, over a distance of 1-2 km from the highest points in the watershed. The main tributaries, with the exception of Brohm River, enter the main stem of the river above an elevation of approximately 500 m, approximately 8.5 km from the head of the basin.

The river then flows across approximately 2.5 km of hummocky terrain that contains a number of small lakes. Mathews (1952, 1958) referred to this hummocky terrain as the 'Upper' and 'Middle' Cheekye fans (Figure 2) and showed that they developed, in part, from thick volcanic debris (*pyroclastic deposits* and lava flows) that collapsed from the west flank of the then-active Mount Garibaldi volcano, about 13,000 years ago, and was deposited on the retreating glacier ice that filled the lower Cheakamus and Squamish valleys at that time. This hummocky terrain was subsequently incised, reworked, and redeposited, with additional material from the headwaters, to form 'Lower' Cheekye Fan.

2.1.2 Lower Cheekye Fan (Cheekye Fan)

Lower Cheekye Fan is the principal area of existing and proposed development, and is referred to as 'Cheekye Fan' in the remainder of this report (Figure 2). It is a type of fan, common to high mountainous regions, that has been formed over many milllennia by natural alluvial sedimentation as well as by deposition of episodic debris flows and debris floods. *Natural hazards* that occur on this type of fan include stream floods, deposition of sediment, erosion of new channels, *avulsions*, debris floods, debris flows, and possibly other types of landslides.

Cheekye Fan extends from its apex, approximately 0.5 km upstream of BC Highway 99, (approximate elevation 150 m) downstream approximately 3.5 km to the Cheakamus River on the north and to the Squamish River to the south. The present course of the Cheekye River changes abruptly from southwest to northwest approximately 1 km downstream of the fan apex. This point is commonly referred to in consulting reports as the Cheekye River 'dogleg'.

Brohm River is the main northern tributary of the Cheekye River and has a watershed area of approximately 16 km^2. It enters the Cheekye River downstream of the apex of Cheekye Fan, just upstream of the BC Highway 99 Cheekye River bridge. Its headwaters are in the area north of Brohm Ridge (approximate elevation 1700 m), and its watershed includes Brohm Lake on the west side of BC Highway 99 (Figures 1 and 2).

Cheekye Fan has an approximate area of 7 km^2 and an average gradient of approximately 2.5°. The fan is bordered by the Cheakamus River on the west and grades onto the Squamish River floodplain on the south. The Cheakamus and Squamish rivers are eroding the western distal margins of the fan.

Part of the community of Brackendale is located at the southwest flank of Cheekye Fan (Figure 2). A number of rural residences, the BC Hydro Cheekye substation and associated transmission lines, the Squamish airport, and some light industry are also located on the fan. BC Highway 99, a number of main and subdivision roads, and the CN Rail (the former BC Rail) line cross the fan.

Three Skwxwu7mesh villages are located on or near the western distal margins of Cheekye Fan (Figure 2):

- IR#11 Ch'iyakmesh and the associated village are located on the west side of the Cheakamus River immediately opposite the Cheekye/Cheakamus river confluence;
- IR#13 Pukwayusem and Skemin, which is currently uninhabited, straddle the mouth of the Cheakamus River immediately upstream from the Cheakamus/Squamish river confluence; and
- IR#14 Wiwk'em and the associated village are located northwest of Brackendale.

2.2 Previous Studies, Research, and Publications

As previously mentioned, the first research on the Cheekye River watershed and Cheekye Fan dates back to the 1940s, when W.H. Mathews, then a geological PhD student and later a professor of geology at the University of British Columbia, conducted his pioneering work in

Garibaldi Park (Mathews 1952, 1958). A debris flow that reached and impacted Cheekye Fan in 1958 was investigated and documented by a geologist with the BC Department of Mines (Jones 1959).

In the mid-1970s and early 1980s, the geotechnical engineering consulting firm Crippen Engineering Ltd. (Crippen)[4] carried out several investigations for the BC Department of Housing and the BC Ministry of Lands, Parks and Housing (Crippen 1974, 1975, 1981). It studied the landslide hazards and risks in the Cheekye River watershed and on Cheekye Fan, and proposed *mitigation* of such hazards and risks for the purpose of developing portions of the fan.

In the 1980s and early 1990s, Mr. Frank Baumann P.Eng., a consulting geological engineer in Squamish, carried out a number of studies on the extent and age of several prehistoric debris flows on Cheekye Fan (Baumann 1991).

In the early 1990s, Thurber Engineering Ltd. and Golder Associates Ltd. (TEL-GAL), two Vancouver geotechnical engineering consulting firms, jointly carried out a comprehensive geological hazard and risk study of the entire Cheekye River watershed and Cheekye Fan (TEL-GAL 1993). This study was commissioned by the BC Ministry of Environment, Lands and Parks, in response to Baumann's findings, new development proposals, and a review of all available information by G.C. Morgan P.Eng., a consultant to the BC Ministry of Environment (Morgan 1991). The co-authors of the TEL-GAL study subsequently published two technical papers on the investigation, the techniques used, and the results (Hungr and Rawlings 1995; Sobkowicz et al. 1995).

In the late 1990 and early 2000s, a number of geoscientists studied different aspects of the geologic history of Cheekye Fan. The results of these studies were published in a number of scientific papers (Friele et al. 1999; Ekes and Hickin 2001; Friele and Clague 2002a, 2002b, 2005, 2008; Clague et al. 2003; Ekes and Friele 2003).

In 2003, the BC Ministry of Water, Lands and Air Protection retained Kerr Wood Leidal Associates Ltd. (KWL), a water-resource engineering consulting firm located in Vancouver, to evaluate Cheekye Fan dike options in light of the TEL-GAL (1993) conclusions (KWL 2003).

In 2007, KWL investigated and developed stream flood and debris flow mitigation strategies for Cheekye Fan on behalf of the Cheekye River Development Limited Partnership (the Squamish Nation and MacDonald Development Corporation) (KWL 2007). Also in that year and in 2008, BGC Engineering Inc. (BGC), a Vancouver geological engineering consulting firm, completed a comprehensive landslide and debris flow hazard and risk study of the Cheekye River watershed and Cheekye Fan (BGC 2007, 2008a, 2008b). This study was carried out for KWL and its client, the Cheekye River Development Limited Partnership. The studies carried out by KWL and BGC, and the resulting conclusions were reviewed and approved by a Cheekye Fan Geotechnical Review Board (CFGRB) for the MacDonald Development Corporation. The CGGRB consisted of Dr. Norbert Morgenstern P.Eng. (Alberta), Dr. Oldrich Hungr P.Eng./P.Geo. (BC), and Dr. Andrew Robertson P.Eng. (BC)

[4] Now a part of the consulting firm Klohn Crippen Berger Ltd.

(Cheekye Fan Geotechnical Review Board 2007, 2008a, 2008b). Published technical papers resulting from BGC's studies include Jakob and Friele (2010) and Jakob et al. (2012).

In 2012, Golder Associates Ltd (Golder) was retained by the BC Ministry of Forests, Lands and Natural Resource Operations to review the earlier studies and research. Specifically it reviewed the 2007 and 2008 studies by KWL and BGC, and provided its opinion on the conclusions reached by KWL and BGC with respect to landslide and debris flow hazards and risks in the Cheekye River watershed and on Cheekye Fan (Golder 2013).

Section 3: Magnitude-Cumulative Frequency Relationship

Consider landslide (including debris flow and debris flood) volume estimates for a range of annual exceedance probabilities that the Panel deem relevant (i.e. evaluate the frequency-magnitude relationship proposed by BGC), identify the key sources of uncertainty, and comment on the associated confidence intervals for these volume.

3.1 Background

Many natural phenomena occur over a wide range of magnitudes. Typically, small events occur more frequently than large ones. For example, small earthquakes occur frequently, while large earthquakes are rare. Sixty years ago, earthquake scientists developed a relationship, known as the 'magnitude–cumulative frequency' (MCF) relationship, to characterize earthquake hazards (Gutenberg and Richter 1954).

MCF relationships can also be used to estimate the probability of landslides. A MCF relationship for landslides can be constructed for any geographic area if a continuous record of landslides for a certain period has been compiled. If the observed landslides over a period of 'N years' are ranked in the order of decreasing magnitude, from the largest to the smallest, the largest landslide has an annual probability of occurrence of 1/N, because only one such event was observed in N years. The cumulative frequency of the second largest event or larger, is 2/N, because two such events occurred in 'N years'. Similarly, the cumulative frequency of any given rank 'x' or larger, is x/N. When such MCF data are graphed using logarithmic scales, they commonly plot on a reasonably straight line.

When compiling lists of events for MCF relationship analysis, only events of similar type, nature, or process should be used. Such events are referred to as a 'population'. In the case of landslides, the events in each population must be similar in type, character, materials, and mechanics of failure and movement. Two populations that are not similar in these characteristics may exhibit different MCF relationships.

In this report, as in most other Cheekye studies, 'magnitude' is the volume of landslide debris that reaches Cheekye Fan. This value equals the sum of the volume of soil and rock detached from the very steep slopes of the Cheekye River headwaters (increased by an amount due to 'bulking' caused by fragmentation and breakage of the materials) and soil and water incorporated by the landslide as it moves downslope, minus any debris deposited before reaching the fan.

3.2 Previous Magnitude-Cumulative Frequency Relationships

Both the TEL-GAL (1993) and the BGC (2008a) studies mentioned in Section 2.2 of this report compiled MCF relationships for Cheekye Fan based on detailed investigations of the fan *stratigraphy*.

TEL-GAL (1993) produced a 1:10,000-scale topographic map of the entire Cheekye River watershed and a 1:5,000-scale topographic map of Cheekye Fan from airphotos flown specifically for the study. TEL-GAL reviewed all previous studies and research, reviewed the volcanic and seismic history of the area, re-mapped the bedrock and surficial geology of the watershed and fan, carried out seismic profiling and trenching of the *linears* on Cheekye Ridge, reviewed water well logs, excavated approximately 50 test pits across the fan, and carried out grain-size analyses and sediment age dating.

BGC (2008a) contributed additional information based on an interpretation of newly acquired *LiDAR* images and extensive additional field investigations, including new text pits and a *dendrochronological* investigation. The BGC study also benefitted from the considerable scientific research completed in the area between 1993 and 2007, including *Ground Penetrating Radar* profiling of Cheekye Fan (Friele et al. 1999; Ekes and Hickin 2001; Ekes and Friele 2003) and an investigation of sediments underlying the floor of Stump Lake on Middle Cheekye Fan (Clague et al. 2003).

As a consequence of this additional information, the inventory of past debris flows compiled by BGC is considered superior to that compiled by TEL-GAL, and it is the Panel's opinion that BGC's MCF relationships are the most reliable MCF relationships currently available for Cheekye Fan. BGC's MCF relationship curves (BGC 2008a; its Drawing 9) have been redrawn for this report (Figure 3).

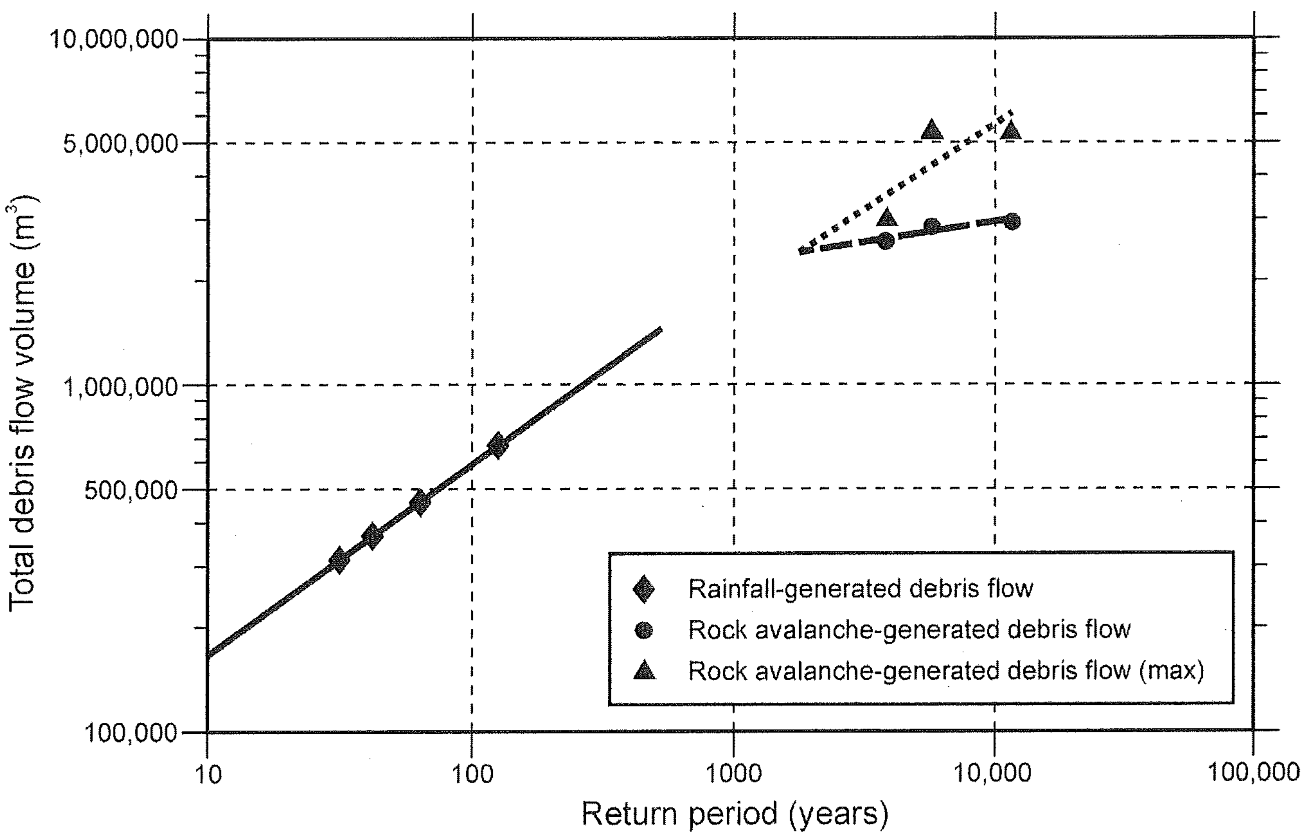

Figure 3: Magnitude-cumulative frequency relationships for Cheekye Fan (modified from BGC 2008a). BGC's return period = given-year event (of specified magnitude or larger); rainfall-generated debris flow = rainwater/surface water runoff-generated debris flow; rock avalanche debris flow = rock slide-generated debris flow. Refer to text for details.

BGC (2008a) recognized two landslide populations in the landslide inventory. It suggested that the majority of the smaller, more frequent debris flows that reached Cheekye Fan were events triggered by rainfall-generated small landslides combined with high surface water runoff. In this report these types of debris flows are referred to as 'rainfall/surface water-generated debris flows'. BGC suggested that the larger debris flows that reached Cheekye Fan were events triggered by major rock slides on the very steep headwater slopes.

After conducting a number of landslide runout analyses, BGC (2008a) concluded that it is unlikely that major rock slides from the Cheekye River headwaters would have sufficient mobility to transport debris directly to Cheekye Fan. BGC suggested, however, that such rock slides could generate large debris flows by one of two mechanisms:

- The rock slide deposit could form a landslide dam and block surface water drainage in the upper watershed. A subsequent debris flow could occur if the landslide dam were to be subsequently breached and the temporary landslide-dammed lake quickly emptied.
- A major rock slide could spontaneously liquefy saturated soil in its path and incorporate the liquefied soil into a large flow, or bulldoze the liquefied soil downslope ahead of the rock slide debris.

The above-described mechanisms have been observed at many locations around the world (e.g. Hungr and Evan 2004). In this report debris flows resulting from these mechanisms are referred to as 'rock slide-generated debris flows'.

On Figure 3, the smaller volume, rainfall/surface water-generated debris flows lie to the left and the larger volume rock slide-generated debris flows lie to the right. The two populations are separated by a gap indicating a lack of information.

BGC presented two lines for the larger volume debris flows on the right side of its MCF curve. The lower (dashed) line on Figure 3 is a 'best fit' line through the three points that BGC considered the most likely MCF relationship for larger volume debris flows. The upper (dotted) line on Figure 3 is a 'best fit' line through the three points that BGC considered maximum values for larger volume debris flows. These two alternatives are further discussed in Section 4 of this report.

3.3 Panel's Opinion

As mentioned in Section 3.2 of this report, it is the Panel's opinion that BGC's MCF relationships (redrawn as Figure 3 in this report) are the most reliable MCF relationships currently available for Cheekye Fan. The Panel agrees with BGC's interpretation and division of observed debris flows into two populations as shown on Figure 3.

It is the Panel's opinion that the solid line on the left side of Figure 3, representing smaller volume rainfall/surface water runoff-generated debris flows, is credible and could be a basis for considering debris flow mitigation strategies for this range of smaller volume events. A spectrum of still smaller events, such as debris floods or stream floods, not shown on Figure 3, should also be considered in mitigation strategies.

The lines on the right side of Figure 3, which represent rock slide-generated debris flows that could potentially transport more than 2 million m^3 of debris to the Cheekye Fan, are discussed in Section 4 of this report.

Section 4: The 10:000-year Event

Identify and characterize the landslide that corresponds to a 1:10,000 annual exceedance probability event. The intent is that the characteristics of that landslide can be used to guide the design of a suite of landslide risk reduction measures.

4.1 Background

A landslide with a 1:10,000 annual exceedance probability (or simply a 10,000-year event), is a landslide that has a 1-in-10,000 (or a 1:10,000 or a 0.0001) probability of occurring, or being exceeded, in any given year. Put in terms of a human life span and using probability theory, a 10,000-year event has an approximate 1-in-200 (or 0.005 or 0.5%) probability of occurring at least once in any 50-year period.

Risk [R], expressed in its simplest terms, is the product of the *hazard probability* [P(H)] (probability of a hazardous event occurring) and consequence [C] (the expected damage if the event does occur). Consequence includes consideration of the probability of the event affecting an area of interest (spatial probability), the probability of someone or something of interest being in that area when the event occurs (temporal probability), and a measure of the fragility vs. robustness, or exposure to vs. protection from, the event (vulnerability). In its simplest terms R = P(H) x C.

Porter and Morgenstern (2013) have recently reviewed landslide risk evaluation, including international and national practices and levels of tolerable risk.

Although in Canada there is no nationally or provincially adopted level of tolerable hazard probability or risk from landslides for residential development, over the past 40 years the 10,000-year event has become the maximum level of hazard probability tolerated by most BC provincial, regional, and local authorities in relation to major residential development expansion. The following sections (4.1.1 to 4.1.5) briefly summarize this history.

4.1.1 BC Supreme Court (1973)

In British Columbia, reference to a 10,000-year level of tolerable hazard probability is rooted in the BC Supreme Court decision on the proposed Garibaldi Estates subdivision at Rubble Creek, approximately 28 km north of Squamish (Berger, 1973). That decision upheld a BC Ministry of Highways approving officer's decision not to approve a proposed 126-lot community near the confluence of Rubble Creek and the Cheakamus River, downslope of 'The Barrier'. The Honourable Mr. Justice Berger ruled that there was a sufficient probability that a catastrophic landslide would occur during the potential several hundred-year life of the proposed 100+ lot community and that a landslide could negatively affect the community and potentially result in the loss of many lives. Although this decision has been interpreted as corresponding to a 10,000-year event, The Honourable Mr. Justice Berger did not specify that probability.

4.1.2 Fraser River Regional District (1992, 1993)

In the early 1990s, Dr. Peter Cave, a regional planner for the Fraser River Regional District, published a series of tables of tolerable hazard probabilities for a number of natural hazard types that could affect a range of residential development in the regional district (Cave 1992a, 1992b). In those tables, which are still used today, Cave selected what he interpreted from Berger's 1973 decision to be a 10,000-year event as the maximum tolerable hazard probability of a fatal landslide to a new community that could be caused by a debris flow, a small-scale localized landslide, or a rock fall. It would also be the maximum tolerable hazard probability of a major catastrophic landslide that could affect an existing community. The tables imply that these events could potentially damage, or cause fatalities in, residential developments under consideration. In other words, potential consequences are implicit within the hazard probabilities, similar to an approach used in Switzerland (e.g. Lateltin 1997).

4.1.3 BC Ministry of Transportation and Infrastructure (2009, 2013)

In 2009, the BC Ministry of Transportation and Infrastructure produced a guidance document entitled "Subdivision Preliminary Layout Review" to accompany its website "Rural Subdivision Approvals – 2.3.1.07 Geotechnical Study" (http://www.th.gov.bc.ca/DA/manual1/manpage.asp?page=2.3.1.07 Geotechnical Study.asp). The guidance document specifies a maximum tolerable hazard probability for a variety of natural hazard types that could have "life-threatening" effects. The document was updated in 2013 and now states (BC Ministry of Transportation and Infrastructure 2013):

> Where life-threatening catastrophic events are known as a potential natural hazard to a building lot the Qualified Professional is to consider events having a probability of occurrence of 1 in 10,000 years [10.000-year event] and is to identify areas beyond the influence of these extreme events.
>
> Large scale development must consider the same 10,000 year events and must also consider the total risk to the new development. When the total risk approach is used, international standards must be identified. The consultant should clearly identify the calculation procedures used.

4.1.4 APEGBC (2012)

In 2012, the Association of Professional Engineers and Geoscientists of British Columbia published "Professional Practice Guidelines – Legislated Flood Assessments in a Changing Climate in BC" (APEGBC 2012). Although the focus is flooding, the guidelines also address several non-conventional flood-related hazards, including debris flows and debris floods. Appendix E of those guidelines suggests, with several caveats, that for large and very large subdivisions (greater than 100 single family lots, and for new subdivisions and communities), a 2500-year event should be considered for debris flow, debris flood, and landslide-dam breach hazards. Appendix J of those guidelines, however, also suggests, "For life-threatening events including debris flows, the Ministry of Transportation and Public [sic] Infrastructure stipulates in their 2009 publication *Subdivision Preliminary Layout Review – Natural Hazard Risk* that a 10,000-year return period [10,000-year event] needs to be considered" (refer to Section 4.1.3 of this report).

4.1.5 District of North Vancouver (2009)

In the past decade, there has been some movement towards assessing landslide risk [R = P(H) x C], as opposed to assessing simply the landslide hazard probability [P(H)] (see for example APEGBC 2006, revised in 2008 and 2010).

After a fatal landslide in the District of North Vancouver (DNV) in 2005, and after considerable study of international criteria (Porter et al. 2007, 2009), DNV adopted the 1:10,000 risk of an individual fatality (i.e. risk of death to a specific individual, typically the most exposed individual) per year as the maximum tolerable risk for any proposed increase in an existing residential footprint less than 25%. DNV also adopted the 1:100,000 risk of an individual fatality per year as the maximum tolerable risk for a proposed new residence or an increase in an existing residential footprint greater than 25% (DNV 2009). These criteria are similar to those used in Hong Kong (e.g. Wong 2005).

For comparison, a 1:10,000 risk of fatality per year is comparable to the annual risk of an average individual being involved in a fatal driving accident and is considerably less than the annual risk of an individual dying as a result of canoeing accident (a 500-year event) or dying from smoking (a 200-year event) (Whittingham 2008, as referred to in Porter and Morgenstern 2013).

4.2 Previous Estimates of the 10,000-year Event

Several estimates of maximum possible landslide volumes and/or 10,000-year landslide volumes in the Cheekye River watershed have been made as part of studies and research that have been carried out since the 1940s.

4.2.1 Crippen Engineering Ltd. (1974, 1975, 1981)

In 1974, Crippen carried out a literature review, helicopter reconnaissance, airphoto interpretation, ground inspection, and hydrological study of the Cheekye River watershed and Cheekye Fan for the BC Department of Housing. Based on this work, it concluded (Crippen 1974):

> ....we believe that the Fan is a creation of the geologic past, and that the conditions required for its further large scale development (the existence of huge quantities of loose and unstable landslide debris combined with the availability of a large supply of water) no longer exist.
>
> There is little doubt that no catastrophic event has occurred on the Fan in the last several centuries. Furthermore the possibility of a major natural catastrophe, which in mountainous regions always exists to some degree, occurring on the Fan in the future is low.
>
> The geometry and condition of the headwater valley slopes of the Cheekye River and its tributaries are such that blocking of the upper reaches by a major landslide, followed by ponding of water from upstream, followed in turn by failure of the blockage in the form of a mudflow, would no likely yield more that several hundred thousand cubic yards of material....
>
> ....Similarly it is not conceivable that massive rockslides on Mount Garabaldi, triggered say by a major earthquake, would progress all the way down to the Fan...

In 1975, Crippen produced a 1:12,000-scale airphoto-based topographic map of the entire Cheekye River watershed and a detailed ground topographic survey of the lower Cheekye River. It carried out further helicopter and ground traverses and additional hydrological analyses. Based on this work, it concluded (Crippen 1975):

> ....as stated in our May 1974 Report, there is no imaginable risk of a huge flow or slide comparable to the ancient events which created most of the Fan.
>
> Debris from future slides occurring in the Headwaters Area will, however, from time to time, reach the Fan area in the form of mud and/or debris flows of considerable size...

> ...any quantitative evaluation of the maximum probable mud and/or debris flow must be based largely on judgement rather than on calculations...
>
> The design event is characterized by a mud and/or debris flow emerging at the apex of the Cheekye Fan in the form of a single pulse having at Sta 90+00 [approximately 300 m upstream from Highway 99]....
>
> a. a cross section of 10,000 sq ft [929 m^2];
> b. a maximum surge speed of 14 ft/sec [4.3 m/s]
> c. a volume of 500,000 cu yd [382,300 m^3]; and
> d. a duration of about 2 minutes.

In the early 1980s, Mr. Frank Baumann P.Eng. suggested that a 30 million m^3 landslide with a probability of occurrence of 1:3,700 could originate from Cheekye Ridge. On the basis of this statement, among other reasons, Crippen was retained by the BC Ministry of Lands, Parks and Housing to review its 1974 and 1975 studies and conclusions. It investigated the area in question and conducted a literature review of similar areas in BC and elsewhere, and concluded (Crippen 1981):

> It is, therefore, our considered opinion that the enormous slide postulated by Mr. Bauman, P.Eng.., has a very low probability of occurrence, much lower that the once-per-3700 years quoted by him. Moreover, if it should occur, it would not reach the Fan. Occurrences that will reach the Fan require sufficient amounts of water so that they progress as mud flows. Since the available amounts of water are limited in volume by the topography and hydrology of the basin, the size of the catastrophic flow events remains limited as discussed in the 1974 and 1975 reports.

4.2.2 Thurber Engineering Ltd and Golder Associates Ltd. (1993)

From the stratigraphic studies described in Section 3.2, TEL-GAL (1993) estimated that the largest previous debris flow on the fan covered an area of approximately 3.76 km^2 with an average debris thickness of approximately 1.9 m, corresponding to an approximately 7 million m^3 rock slide-generated debris flow. Based on professional judgement, TEL-GAL estimated this rock slide-generated debris flow to be a 10,000-year event.

In a subsequent technical paper, several of the authors of the 1993 TEL-GAL report concluded that the maximum credible debris flow (a rock slide-generated debris flow) with a volume of 7 million m^3, would be a 90,000-year event and that the 10,000-year event would have a volume of 5.5 million m^3 (Sobkowicz et al. 1995). The 7 million m^3 estimate was based on the area of the "surface unit," which was assumed to be the deposit of a single debris flow event. With further test pitting, age dating, and interpretation of LiDAR images, BGC (2008a) confirmed that the surface unit is a composite unit and does not represent a single event.

4.2.3 Clague et al. (2003), Kerr Wood Leidal (2003), and Friele and Clague (2005)

In the early 2000s, geological researchers analyzed sediment cores collected from the bottom of Stump Lake on Middle Cheekye Fan (Figure 2) (Clague et al. 2003). They found what they interpreted to be the deposit of a single debris flow in the 10,000-year record of the sediment cores, which they dated to approximately 7,000 years ago. Based on this and other information, they estimated the volume of this debris flow to have been between 3 million m^3 and 5 million m^3.

In 2003, during its review of protective dikes designed for Cheekye Fan by the BC Ministry of Water, Lands and Air Protection, and based on Clague et al. (2003), KWL estimated the maximum debris flow volume from the 7,000-year-old debris flow to be approximately 5.4 million m^3 (KWL 2003). KWL (2003) also estimated that largest event to have affected the Cheekye Fan since the end of the last glaciation, approximately 10,000 years ago, was no larger than about 5.5 million m^3.

Based on previous work by Clague et al. (2003), Friele and Clague (2005) concluded that the Stump Lake debris flow, with a volume of approximately 5.5 million m^3, is the 10,000-year event.

4.2.4 BGC Engineering Inc. (2007, 2008a, 2008b)

Based on the studies described in Section 3.2 of this report, BGC (2008a) assigned a mean volume of 2.8 million m^3 to two rock slide-generated debris flows on Cheekye Fan, one approximately 7,000 years ago (postglacial) and the other approximately 11,500 years ago (during deglaciation). With uncertainties, BGC selected its 'mean' volume of 2.8 million m^3 from a range of 1.98 million m^3 to 5.4 million m^3, as estimated by Clague et al. (2003).

BGC (2008a) further estimated the amount of water that could be incorporated into a rock slide through entrainment of surface water, snowmelt, and rock mass porewater in order to convert a relatively dry flow into a saturated debris flow capable of flowing to Cheekye Fan. It concluded that the probability of occurrence of a debris flow with a volume of 3 million m^3 is likely greater than the 10,000-year event, while acknowledging the following compounding assumptions: i) 200-year flood event coinciding with the rock slide-generated debris flow; ii) very high debris yield rates; iii) maximum landslide dam height and impounded water volume; and iv) snow cover along the entire debris flow path length. The validity of this water budget calculation is discussed in Section 4.3 of this report.

BGC (2008a) concluded by assigning a volume of 2.8 million m^3 to the 10,000-year event.

BGC (2008a) also evaluated possible effects of future climate change, volcanic eruptions, and further deglaciation. It concluded that climate change could increase the frequency of debris flows, but that it is unclear whether debris flow magnitude would increase correspondingly. It also concluded that volcanic flows (*pyroclastic flows* and *lava flows*) could have the same, or a more serious, effect on Cheekye Fan than non-volcanic debris flows. BGC (2008a) also concluded that further deglaciation could result in a temporary increase in landslide activity.

4.3 Unknowns, Uncertainties, and Assumptions

In the above-referenced studies, a number of unknowns, uncertainties, and assumptions in estimating the 10,000-year event were enumerated. The most important of these are discussed in the following paragraphs. They relate both to estimation of magnitude and frequency of past historical debris flows on Cheekye Fan and to prediction of possible future events

In southwestern BC, the last period of glaciation ended approximately 10,000 years ago. This fact limits the length of time that geologists can 'look back' to identify, date, and estimate the volumes of past landslide events that reached Cheekye Fan. Ideally, to more accurately predict the 10,000-year event, investigators should have a record spanning many tens of thousands of years. And ideally, the geological conditions and processes over those tens of thousands of years should have been similar. Conditions that prevailed during the last glaciation are so different from postglacial conditions that they cannot be used to construct MCF relationships applicable to the present. Even during the past 10,000 years, geological conditions and processes in southwestern BC have not been constant (Friele et al. 1999; Friele and Clague 2009). Therefore, a purely statistical evaluation of anything greater than the 500-year to 1,000-year debris flow cannot be relied on, and estimates of future potential must be based, to some extent, on professional judgment.

The right side of BGC's MCF relationships (the dashed and dotted lines on Figure 3 in this report) is based on three debris flows. Only the smallest of these events was estimated with some reliability, as described in BGC (2008a). The deposits of the remaining two debris flows are buried deep in Cheekye Fan and their volumes could only be estimated with wide error margins. As estimated by BGC (2008a), the volume of either one of these debris flows could have been as large as 5.4 million m^3.

There is also the possibility that future rock slide-generated debris flows that could reach Cheekye Fan could be larger than those in the past. BGC (2008a) analyzed several scenarios, assuming a variety of potential instability and runout models. All of the models were predicated on the assumption of limited availability of water to mobilize the debris allowing it to reach the fan.

Since 2008, when BGC carried out its study, the 2010 Mount Meager landslide took place approximately 100 km north of Mount Garibaldi. This landslide occurred in rocks similar to those in the headwaters of the Cheekye River watershed, involved approximately 48 million m^3 of material, and travelled down Capricorn and Meager creeks as a rock slide-generated debris flow for distance of 12.7 km (Guthrie et al. 2012a, 2012b). One of the reasons for the extreme travel distance was the unexpected large volume of water that was present in the area. Guthrie et al. (2012a, 2012b) inferred that this water included porewater from the failed rock mass itself, talus aprons, glacial drift, and channel infillings, and that soil deposits liquefied and became entrained by the landslide. A direct comparison of landslide runout is complicated by the complex path of the Mount Meager landslide – it bifurcated (split) and ran both up and down Meager Creek along the lower part of its path. Nevertheless, the behaviour of the Capricorn Creek rock slide-generated debris flow puts into question the landslide volume limitation suggested by BGC (2008a) and used to support the lower (dashed) line on the right side of the Figure 3. The water balance calculation by BGC (2008a) mentioned in Section 4.2.4 of this report does not include adequate allowance for groundwater contained in soils that are liquefied and entrained along the path of the flow. Such groundwater was found to be important in the Capricorn Creek event.

The occurrence of the 2010 Mount Meager landslide suggests that the very steep Cheekye River headwaters could experience a similar event, larger than anything that has happened in the past. Geologically, the conditions of Mount Meager and Mount Garibaldi are similar. The volcanic rocks that are the source of the 2010 Mount Meager landslide (Read, 1977) are similar to those at the head of Cheekye River below Atwell Peak (Mathews, 1958). The former rocks are older (Plio-Pleistocene) than the latter rocks (late Pleistocene), but both are highly broken, weathered, and unstable. The Capricorn Creek and Cheekye River profiles are similar (Figure 4), and similar potential causal and trigger mechanisms exist, such as extreme precipitation events, glacier retreat, and earthquakes. One significant unknown is the amount of water contained within the rock mass below Atwell Peak.

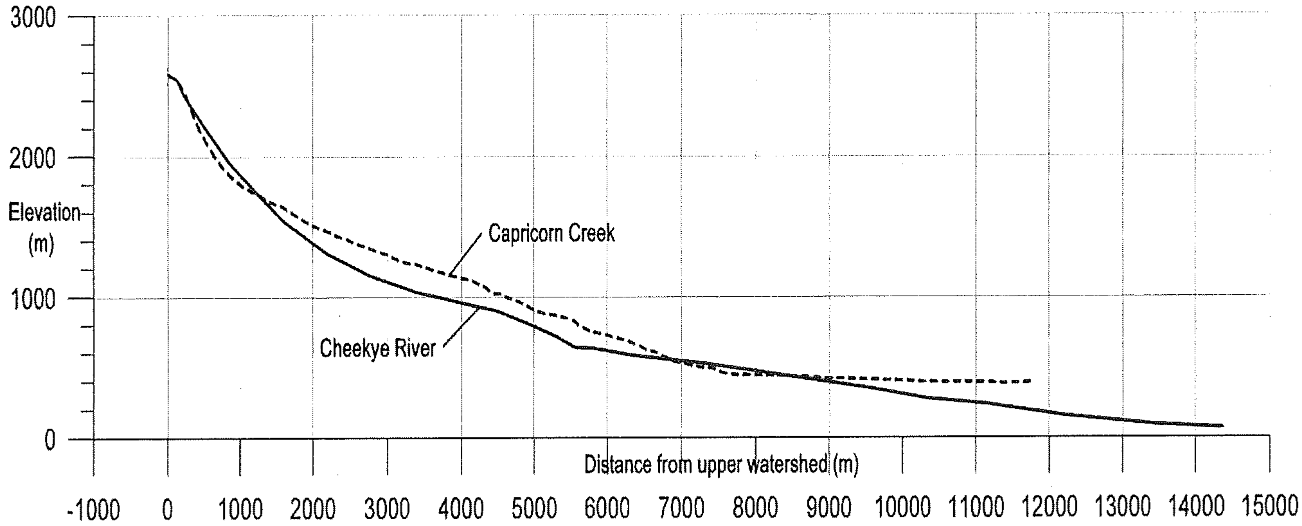

Figure 4: Comparative profiles of Capricorn Creek below Mount Meager (drawn along the runout path of the August 2010 landslide) and the Cheekye River below Mount Garibaldi (from Google Earth; 2x vertical exaggeration).

A number of areas of possible instability within the very steep Cheekye River headwaters have been identified and studied by previous investigators as potential source areas for major rock slides that could generate debris flows. Other potential source areas might exist that have not been identified and studied.

Rock slide-generated debris flows in the Cheekye River watershed were modelled by BGC (2007, 2008a). In order to simulate the complex conditions in the Cheekye River watershed, BGC had to make many assumptions about topography, geology, geomorphology, geological and geomorphological processes, and material properties during the modelling process.

The Brohm River watershed was briefly described in Section 2.1.2 of this report. The potential effects of discharges from the Brohm River watershed on Cheekye Fan were recognized as uncertainties by BGC (2007), but not included in its MCF analyses (BGC 2008a).

Unknowns, uncertainties, and assumptions associated with climate change are discussed in Section 5 of this report.

4.4 Panel's Opinion

It is the Panel's opinion that the upper (dotted) line on right side of BGC's MCF relationships (drawn as Figure 3 in this report) provides a prudent estimate of the volume of debris that could be transported to Cheekye Fan during a rock slide-generated debris flow. Therefore, it is the Panel's opinion that the volume of the 10,000-year debris flow that could reach Cheekye Fan is 5.5 million m^3. This estimate is more conservative than was recommended by

BGC (2008a), but is consistent with several previous estimates, as reviewed in Section 4.2 of this report.

It is also the Panel's opinion that the 10,000-year event is an appropriate level of hazard probability to consider for Cheekye Fan. The 10,000-year event is conceptually comparable to a 'maximum credible earthquake' (MCE) or a 'probable maximum flood' (PMF). MCE is the largest earthquake considered possible for a given area. PMF is the theoretical largest flood that could occur in a given area. Both are extreme events. The 10,000-year debris flow that could reach Cheekye Fan is also considered an extreme event. Mitigation for Cheekye Fan, however, must consider the entire spectrum of events, ranging from episodic extreme debris flows to annual stream floods. It is anticipated that risks to individuals on different parts of the fan will be dominated by events of different hazard probabilities.

These opinions consider the unknowns, uncertainties, and assumptions discussed in Sections 4.2 and 4.3 of this report.

Section 5: Climate Change

Consider the potential effects of changes to climate that could affect the scientific data and assumptions used in the proposed magnitude-frequency relationship and the design of landslide risk reduction measures.

5.1 Background

Climate change, which can be defined as long-term weather patterns that deviate from historical ranges, can have an effect on the volume and/or frequency of landslides. Much of the information in this section of the report has been gleaned from "Professional Practice Guidelines – Legislated Flood Assessments in a Changing Climate in BC" (APEGBC 2012).

Over the past two decades, the successive reports of the Intergovernmental Panel on Climate Change (IPCC) have expressed increased confidence that climate is changing around the world and will continue to do so for the foreseeable future. The physical processes driving climate change are complex and the models on which the forecasts of climate change are based are simplifications and are subject to uncertainty. Global climate models are *downscaled* to provincial, regional, and local levels by comparing the global climate models with historical provincial, regional, and local weather station data. By doing so, climate scientists attempt to forecast annual and seasonal climate changes throughout BC (Wang et al. 2006, 2012).

Even more difficult to predict are resulting changes in the volumes, frequencies, and even types of landslides, as such changes can be regarded as third- or fourth-order effects of climate change.

5.2 Expected Climate Change in BC

Climate change affects the entire hydrologic system by changing temperature; type, amount, and intensity of precipitation; evaporation; the balance between water storage as ice, snow, or liquid forms; and levels of soil moisture. The following paragraphs summarize the interpretations of downscaled BC climate models as they relate to portions of the hydrologic cycle.

By 2100, BC temperatures are expected to increase by approximately 2.8°C, including an increase in winter temperatures. Projected temperatures for an average year will be warmer than almost all of the warmest years in the recent past.

By 2100, average annual precipitation in BC is expected to increase by approximately 10% (a range between 6-17%), with the increase primarily occurring during winter months and in the mountains.

An increase in surface water runoff in the Cheekye River watershed is expected during the winter months due to a greater proportion of precipitation falling as rain. An earlier spring freshet due to warmer spring temperatures is expected. Drier conditions are expected during the summer.

Although the above-described conditions are expected to produce characteristically lower spring freshets and summer stream flows, years with severe stream floods are likely to occur in the future. For smaller coastal watersheds, which have a hybrid (snowmelt and rainfall-dominated) runoff regime, a trend towards purely rain-dominated stream floods is expected.

5.3 Expected Consequences in BC

Although the linkage between the hydrologic cycle and landslides is poorly understood, some generalizations are possible.

5.3.1 Changes in Rainfall Amounts and Intensities

The projected, approximately 10% increase in winter precipitation, combined with predicted higher temperatures during the same period, is expected to influence the extent of winter snowpack and the timing and rate of snow melt. Increased temperatures are also expected to influence the intensity of summer convective rainstorms, and the frequency of intense, long-duration winter rainfall on the coast (the so-called 'Pineapple Express'). These changes have a potential bearing on the timing and magnitude of winter storms, rain-on-snow events, spring freshets, the soil water balance, and effects of antecedent moisture on landslides.

5.3.2 Changes in Snow Cover and Glacier Ice Cover

Warmer winters will raise winter freezing levels and decrease snow cover. This effect, in combination with warmer summers, will cause glaciers in southwestern BC, including Mount Garibaldi, to thin and retreat. High-elevation snowpacks are expected to sustain glaciers, but in new equilibrium and with reduced areas. As long as temperatures continue to increase, glaciers will likely continue to thin and recede.

5.3.3 Changes in Surface Water Runoff

As a result of the above factors, surface water runoff is expected to change. Possible notable changes include:

- an increased frequency of winter stream floods in coastal BC, with the possibility of more extreme stream flows, due to both the likelihood of increased winter rains and an increased number of 'Pineapple Express' storms;
- more severe spring stream floods associated with seasonal snowmelt, due to the likelihood of more rapid snowmelt and/or an increased frequency of major rain-on-snow events;
- an increased likelihood of severe summer convectional rainstorms inducing extreme floods in basins such as the Cheekye River watershed.

5.3.4 Changes in Landslide Activity

As noted above, changes in landslide activity are third- or fourth-order effects of climate change; they are one step removed from changes in precipitation and surface water runoff. Therefore, the uncertainties associated with forecasting the effects of climate change on landslide volumes and frequencies on a regional, much less local, scale are large. The following general comments, however, can be made with specific reference to the Cheekye

River watershed:

- an increase in the amount and intensity of winter precipitation will likely increase the number and frequency of small and perhaps medium-sized landslides, specifically debris flows and debris floods;
- although individual rainstorms are not expected to have an effect on stability of rock slides in the upper watershed, increased long-term saturation of the ground in the headwaters could reduce the stability of the very steep slopes, leading to major rock slides; and
- snow and glacier ice cover mantling the Mt. Garibaldi massif, near the headwaters of the Cheekye River watershed, will decrease as temperatures increase; the effects of surface water runoff and infiltration of this additional water on slope stability are unknown, as is the overall effect of a reduced snow and ice cover.

The uncertainties at each level in the cascade of effects expected to result from climate change are large, and therefore it is not possible to quantify possible changes in the volumes or frequencies of landslides, including debris flows and debris floods in the Cheekye River watershed.

5.4 Panel's Opinion

It is the Panel's opinion that climate change might increase the frequency of smaller rainfall/water runoff-generated debris flows and debris floods, consistent with the conclusion of BGC (2008a). This expectation would shift the solid line on the left side of Figure 3 of this report to the left, although the amount of the shift is unknown. This shift would have the effect of increasing the volumes of given-year events.

It is the Panel's opinion that climate change might also increase the frequency of major rock slide-generated debris flows, which would also shift the dashed and dotted lines on the right side on Figure 3 of this report to the left. It is expected that the shift for major rock slide-generated debris flows will be less than for rainfall/surface water runoff-generated debris flows and debris floods, although this inference is by no means certain. This shift would have the effect of increasing the volume of the 10,000-year event.

It is not possible at present to quantify the possible changes in the frequency of future debris flows due to climate change. Consequently, possible climate change effects must be dealt with by selecting suitably conservative parameters during the design of any mitigation, and by selecting solutions that have flexibility with respect to the magnitude of potential effects.

Section 6: Other Considerations

The Terms of Reference (Appendix A) requested the Panel's opinions on three issues. These opinions have been presented in the preceding sections of this report. The Panel members feel they have a duty to provide additional opinions relevant to landslides and associated risks on Cheekye Fan. The following opinions are intended as guidance only. Additional studies and analyses would be required for the opinions to be translated into specific design or policy recommendations.

6.1 Existing Risks

Existing residential development on Cheekye Fan and on the west side of the Cheakamus/Cheekye river confluence, as well as other existing development on the fan, are at risk from both debris flows and debris floods, and from stream floods and associated sediment movement that may or may not be associated with debris flows or debris floods. This development includes:

- a portion of the community of Brackendale, a number of rural residences, and the inhabited First Nation reserves;
- the BC Hydro Cheekye substation and associated transmission lines;
- the Squamish airport;
- some light industry; and
- BC Highway 99, a number of main and subdivision roads, and the CN Rail line.

Any risk assessment must consider the full spectrum of flooding and landslide phenomena, ranging from large volume (with relatively low probability of occurrence) to low volume (with relatively high probability of occurrence).

It is the Panel's opinion that the above-described risks to existing development should be mitigated whether or not there is any future development on Cheekye Fan.

6.2 Mitigation

Future protection must mitigate debris flows, debris floods, stream floods, and sediment movement. Such mitigation can be accomplished in many ways, ranging from education to zoning to engineered structures, such as retention basins, stream channeling and diking, bridge improvements, or a combination of any of these options. Existing engineered protective structures include berms adjacent to the Don Ross Secondary School in Brackendale and the BC Hydro Cheekye Substation, and along portions of the lower Cheekye River.

It is the Panel's opinion that, in terms of protecting existing development and possibly allowing some new development on Cheekye Fan, and on the west side of the Cheakamus River across from Cheekye Fan, all forms of mitigation, singly or in combination, should be considered and carefully evaluated.

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Guthrie, R.H., Friele, P., Allstadt, K., Roberts, N., Evans, S.G., Roche, D., Clague, J.J., and Jakob, M. 2012b. The 5 August 2010 Mount Meager rock slide-debris flow, Coast Mountains, British Columbia: Characteristics, dynamics, and implications for hazard and risk assessment. Natural Hazards and Earth System Science, v. 12, pp. 1-18.

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KWL (Kerr Wood Leidal Associates Ltd.) 2007. Flood and Debris Flow Mitigation Strategy for Cheekye Fan, Squamish, BC. Draft Report for the Cheekye River Development Limited Partnership, 31 pp.

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Mathews, W.H. 1958. Geology of the Mount Garibaldi map area, southwestern British Columbia, Canada. Part II: Geomorphology and Quaternary volcanic rocks. Geological Society of America Bulletin, v. 69, pp. 179–198.

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Porter, M., and Morgenstern, N. 2013. Landslide Risk Evaluation – Canadian Technical Guidelines and Best Practices Related to Landslides: A National Initiative for Loss Reduction. Geological Survey of Canada, Open File 7312, 21 pp; ftp://ftp2.cits.rncan.gc.ca/pub/geott/ess_pubs/292/292234/of_7312.pdf.

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Sobkowicz. J., Hungr, O., and Morgan, G. 1995. Probabilistic mapping of a debris flow hazard area: Cheekye Fan, British Columbia. *In* Proceedings of the Canadian Geotechnical Conference 1995, Vancouver, BC, pp. 519-529.

TEL-GAL (Thurber Engineering-Golder Associates). 1993. The Cheekye River Terrain Hazard and Land-Use Study; Final Report, Volumes 1 and 2. Report to BC Ministry of Environment, Lands and Parks, Burnaby, BC.

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Wang, T., Hamann, A., Spittlehouse, D.L., and Murdock, T., 2012. Climate WNA – High-resolution spatial climate data for western North America. Journal of Applied Meteorology and Climatology, v. 51, pp. 16-29.

Wong, H.N. 2005. Landslide risk assessment for individual facilities. State of the Art Paper # 8. *In* Proceedings of the International Conference on Landslide Risk Management, ed. Hungr, O., Fell, R., Couture, R., and Eberhardt, E., Taylor and Francis Group, London, pp 237-296.

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Appendix A

Portion of Terms of Reference (Introduction, Panel Composition, and Scope of Review) for Expert Review Panel

Review of the Landslide Hazard and Risk Assessment of the Cheekye River and Fan November 28, 2013

Introduction
The Province of British Columbia, the Squamish Nation and its Partnership (Proponent), and the District of Squamish collectively have formed and will collaborate with an Expert Review Panel (the Panel) to review relevant background information on the landslide (including debris flow and debris flood) hazard and risk assessment of the Cheekye River and Fan. The Panel will prepare a report with key findings.

Panel Composition
The Panel will consist of three members: one selected by the Province, one by the District of Squamish and one by the Proponent. The Panel shall not include the authors of the BGC/KWL studies submitted in support of the Proponent's rezoning application, but can include previous reviewers independent from BGC and KWL.

The Panel Members will be selected on the basis of having meaningful contributions to the field of landslide (including debris flow and debris flood) hazard and risk assessment and/or their associated expertise in this field. Panel Members should have the following qualifications:

- at least 20 years of experience in the field of landslide (including debris flow and debris flood) hazard and risk assessments
- M.Sc. or M.Eng. and be registered with APEGBC, or equivalent
- ample experience nationally and/or internationally on topics of landslide hazard and risk return period thresholds for existing and proposed development
- an understanding of the historical evolution of hazard and risk tolerance criteria in British Columbia
- an understanding of landslide processes in British Columbia, including landslides in volcanic terrain, with at least some familiarity of the Cheekye River and Fan.

Scope of Review
The Panel will review scientific and engineering reports, and other information, related to landslide hazards and risks of the Cheekye River and Fan, provided by the Province, the District of Squamish, and the Proponent, and in part related to a rezoning application within the District of Squamish (see attached list of reports and information to be reviewed). This will not preclude the Panel, at its discretion, from reviewing additional information that is relevant to inform its findings.

Based on the listed reports and information, and any other additional information, the Panel will:

- identify and characterize the landslide that corresponds to a 1:10,000 annual exceedance probability event. The intent is that the characteristics of that landslide can be used to guide the design of a suite of landslide risk reduction measures.
- consider landslide (including debris flow and debris flood) volume estimates for a range of annual exceedance probabilities that the Panel deem relevant (i.e. evaluate the frequency-magnitude relationship proposed by BGC), identify the key sources of uncertainty, and comment on the associated confidence intervals for these volume estimates.
- consider the potential effects of changes to climate and geomorphic developments in the Cheekye River watershed that could affect the scientific data and assumptions used in the proposed magnitude-frequency relationship and the design of landslide risk reduction measures.

The Panel shall work towards consensus, with the final report ideally signed off by all three members.

Appendix B

Curricula Vitae of the Panel Members

John J Clague P.Geo., Ph.D.
Department of Earth Sciences, Simon Fraser University
Burnaby, British Columbia
Phone (778) 782-4924, fax (778) 782-4198
E-mail jclague@sfu.ca

CURRENT POSITION
Professor and CRC Chair in Natural Hazard Research, Simon Fraser University
Director, Centre for Natural Hazard Research

EDUCATION
Ph.D., geology, University of British Columbia, Vancouver, B.C., 1973
M.A., geology, University of California, Berkeley, California, 1969
A.B. magna cum laude, Occidental College, Los Angeles, California, 1967

AREAS OF EXPERTISE
Quaternary geology, geomorphology, engineering geology, environmental geology, sedimentology, stratigraphy, neotectonics, paleoseismology, natural hazards.

CONTRIBUTION AND IMPACT
One of Canada's leading authorities in Quaternary and environmental earth sciences; 40-years experience in surficial/terrain mapping, Quaternary stratigraphic investigations, engineering and environmental interpretations of surficial geological information, and natural hazard studies; noted for local, national, and international research collaboration with other geologists, geographers, biologists, and physicists.

I have published over 220 papers, reports, and monographs on a wide range of earth science topics of regional and national importance; my papers have appeared in 50 different international journals; prepared innovative geoscience products for educators and the public; I have given numerous television and radio interviews and newspaper and magazine article; research on earthquakes, landslides, and floods has greatly increased public and official awareness of these hazards.

PROFESSIONAL SERVICE
Councillor, Association of Professional Engineers and Geoscientists of the Province of BC (APEGBC); Former Editor-in-Chief of the *Canadian Journal of Earth Sciences*; former President of the Geological Association of Canada; former President of the Canadian Geoscience Education Network (CGEN); former President of the Canadian Geomorphology Research Group; former President of the International Union for Quaternary Research (INQUA); member of numerous national and international professional committees and commissions; Adjunct Professor - University of Fraser Valley, University of Northern BC, and University of Victoria; Associate Faculty – SFU Department of Archaeology and the School of Resource and Environmental Management (Cooperative Resource Management Institute). Serves on many graduate student committees at Simon Fraser University and the University of British Columbia; has given about 400 lectures at North American universities, professional meetings, and public venues, and reviewed scores of papers for scientific journals.

PROFESSIONAL EMPLOYMENT HISTORY

- 2003-present, Tier I Canada Research Chair in Natural Hazard Research
- 1998-present, Professor, Earth Sciences, Simon Fraser University
- 2009-present, Adjunct Professor, University of Victoria
- 2009-present, Adjunct Professor, University of Fraser Valley
- 2008-present, Adjunct Professor, University of Northern British Columbia
- 1974-1998, Research Scientist, Geological Survey of Canada
- 1996-1998, Adjunct Professor, Earth Sciences, Simon Fraser University
- 1988-1992, Editor-in-Chief, Canadian Journal of Earth Sciences, National Research Council of Canada
- 1973-1974, NSERC Postdoctoral Fellow, Geological Survey of Canada, Vancouver

POSITIONS IN SOCIETIES

- President, International Union for Quaternary Research, 2003-2007
- President, Geological Association of Canada, 2002
- Education Director, Canadian Geoscience Council, 2001-2002
- President, Canadian Geoscience Education Network, 2001-2002
- Vice-President, Geological Association of Canada, 2001
- Vice-President, International Union for Quaternary Research, 1999
- President, Canadian Geomorphology Research Group, 1998
- Vice-President, Canadian Geomorphology Research Group, 1997
- Vice-President, Canadian Quaternary Association, 1985-1987
- Councillor, Canadian Quaternary Association, 1984

EDITORSHIPS

- Associate Editor, *Journal of Quaternary Sciences*, 2006-present
- Associate Editor, *Quaternary International*, 2003-present
- Associate Editor, *Quaternary Science Reviews*, 2008-present
- Associate Editor, *Canadian Journal of Earth Sciences*, 1983-1988
- Editor-in-Chief, *Canadian Journal of Earth Sciences*, 1988-1992

PROFESSIONAL AFFILIATIONS

- Professional Geologist, Association of Professional Engineers and Geoscientists of British Columbia
- Fellow, Geological Society of America
- Fellow, Geological Association of Canada
- Member, American Geophysical Union
- Member, Canadian Geophysical Union
- Member, American Quaternary Association
- Member, Canadian Quaternary Association
- Member, Vancouver Geotechnical Society
- Member, Association of Earth Science Editors

Oldrich Hungr P.Eng./P.Geo., Ph.D.
Professor, Engineering Geology, former Director, Geological Engineering Program
Department of Earth and Ocean Sciences
University of British Columbia, Vancouver, Canada
August, 2012

Home: 4915 Almondel Rd., West Vancouver, B.C., V7V 3L6, Canada
Office: 6339 Stores Road, Vancouver, B.C., V6T1Z4, Canada
Tel: 604 822 8471 *Fax:* 604 822 6088
E-mail: ohungr@eos.ubc.ca

EDUCATION:
B.A.Sc., Civil Engineering, Geotechnical, University of Ottawa, 1972.
M.A.Sc., Civil Engineering, Geotechnical, University of Ottawa. 1975.
Ph.D., Civil Engineering, Geotechnical, University of Alberta, 1981.

EMPLOYMENT RECORD:
1996-present: Professor of Engineering Geology, University of British Columbia
1981-1996: Associate and Senior Geotechnical Engineer, Thurber Engineering Ltd., Vancouver, B.C.
1975-1977: Geotechnical Engineer, The Trow Group, Toronto, Ontario

SELECTED PROJECT EXPERIENCE:
Over 1,000 geotechnical and engineering geology assignments, including:

Review Boards:
- Member, Slope Safety Technical Review Board, Hong Kong, 2006-2009
- Member, internal review panel for the Site C reservoir hazard studies, B.C. Hydro.
- Member, Value Engineering Panel for the Fountain Slide, Fraser Valley. Ministry of Transportation, B.C.
- External Reviewer: Professional Practice Guidelines for Landslide Hazard Assessment in Residential Areas. Association of Professional Engineers and Geoscientists, British Columbia.
- Member of an advisory panel considering the stability and failure consequences for the 600m high South Spoil waste pile. Fording Coal, Elkford.
- Review Panel, waste pile stability, Porgera Mine, Papua New Guinea.
- Review Panel, rock avalanche hazard assessment, Britannia, British Columbia

Engineering geological studies for community planning:
- Development of a risk assessment framework for conducting geotechnical feasibility studies, Hong Kong Housing Authority.
- Quantitative risk analysis of landslide hazards, Geotechnical Eng. Office, Hong Kong.
- Overview study of landslide hazard zonation, Ryder Upland, Reg. District of Fraser Cheam, B.C.
- Natural hazard zoning map, Greater Vancouver Regional District Water Supply Department.
- Engineering geology overview map, City of Sault Ste. Marie, Ontario

Site investigations and hazard assessments for roads and railways:
- Review of rock cut stabilization measures in selected sections, Vancouver-Whistler highway upgrade.
- Detailed assessment of debris flow hazards, B.C. Highway 99, Vancouver to Squamish.
- C.P. Rail Beaver Valley track twinning, Glacier National Park - design of 16 km of rock cuts along the eastern approach to the Mt. MacDonald tunnel.
- Slope stability assessment, Beatton River connector, Fort St. John, B.C. - route crossing numerous active landslide areas in Cretaceous shales.
- Route selection and feasibility study, Trans-Canada Highway, Golden to Yoho, B.C.

Pipelines and transmission lines:

- Feasibility study, Trans-Adriatic Gas pipeline, Albania.
- Hazard assessment for contingency planning, Trans-Mountain Pipeline, Edmonton to Vancouver.
- Natural hazards mapping and route selection, Kemano Transmission line, Kitimat, B.C.

Dams and Reservoirs:
- Slope stability review, B.C. Hydro Site "1" reservoir, Peace River.
- 3D slope stability assessment, B.C. Hydro Hart Dam, Vancouver Island.
- Slope stability assessment, B.C. Hydro proposed Site "C" reservoir, Peace River, and Beavercrow reservoir, Liard River, including an assessment of the potential for slide - induced waves.

Landslide hazard studies:
- Silverhope area hazards study, B.C. - hazard zoning of an area subject to rockfall and rockslides.
- Cheekye Fan terrain hazard study, Squamish - detailed engineering geological mapping of an area of Quarternary volcanics, probabilistic hazard and risk assessment for planning.
- Scoping study of a landslide Quantitative Risk Assessment (QRA) in Hong Kong.
- Review consultant, Natural Terrain Hazard Study, Pat Heung, Hong Kong.
- Landslide hazard assessment, Prince Rupert Container Terminal, British Columbia

Geotechnical aspects of waste disposal:
- Assessment of behaviour in the event of failure, Syncrude Canada Ltd. Mildred Lake tailings dyke, Fort McMurray, Alberta.
- Liquefaction flow study, Sand Storage Facility, Syncrude, Fort McMurray, Alberta
- Review of stability, potential slide behaviour and remedial measures, coarse spoil storage, Suncor oil sand mine, Fort McMurray, Alberta.
- Analysis of potential failure behaviour of waste pile slides, Grasberg Mine, Indonesia.
- Waste pile stabilization and hazard assessment, Questa Molybdenum Mine, New Mexico.

Landslide stabilization:
- Stabilization of a 200,000 m^3 Bentley Rockslide on Highway 97, Peachland, B.C.
- Feasibility study of stabilization measures, Attachie Slide, proposed BC Hydro "Site C" reservoir.
- Stability assessment and unloading stabilization design (15 million tons) for a large landslide at the Placer Dome Golden Sunlight Mine, Butte, Montana.

Landslide protection works:
- Engineering geology input into the design of debris flow protection structures, Squamish Highway - barriers, passage channels, bridges.
- Debris flow hazards assessment and design of defensive measures, Coquihalla Highway, Hope to Merritt - 12 retention basins and deflecting dykes.
- Design of a debris flow protective barrier, Tsin Yan housing development, Hong Kong.
- Dynamic analysis, debris flow structure at Sham Tseng San Tsuen Village, Hong Kong.
- Debris flow hazard assessment and design of protective barriers, Whistler, B.C.
- Design review, MacKay creek debris flow protection structure, North Vancouver.
- External review, Standard Barrier Design Development Study, GEO, Hong Kong
- Hazard assessment and protective measures, East Gate landslide, Glacier Park, Canada.
- Review consultant, debris avalanche protection measures for three sites, Hong Kong.
- Preliminary design of debris flow/avalanche protection, Prince Rupert Container Terminal, B. C.

Excavations:
- Highwall slope design, Gulf Canada Obed-Marsh coal mine, Hinton, Alberta.
- Pit landslide stability assessment, Cardinal Coal, Red Deer, Alberta.
- Robson Place building excavation, downtown Vancouver- design and monitoring.

Tunnels:
- Site investigation for the 15 km MacDonald Tunnel in Rogers Pass, B.C., including a 300 m deep ventilation shaft.
- Site investigation for the North Diversion tunnel, Ryiadh, Saudi Arabia.
- Site investigation for the 3 km power tunnel at Mamquam, north of Vancouver, B.C.
- Design review of tunnel modifications and station caverns, Vancouver rapid transit.

Expert testimony:

- Expert witness representing the B.C. Ministry of Highways and other parties in five separate cases involving fatalities and injuries caused by rockfall on B.C. highways.
- Testimony regarding the influence of logging on triggering a debris flow, Vancouver, B.C.
- Expert testimony regarding a rock fall accident near Larissa, Greece.
- Expert testimony regarding a major fatal landslide accident in Papua New Guinea.

SELECTED PROFESSIONAL ACTIVITIES:
- Registered Professional Engineer / Geoscientist of British Columbia (P.Eng./P.Geo.)
- Member, Association of Professional Engineers and Geoscientists (APEGBC Board of Examiners.
- Member of the Editorial Board, Engineering Geology, Elsevier, Amsterdam
- Associate Editor, "Landslides", Journal of the International Landslide Consortium, Kyoto, Japan.
- North American Representative – IASMGE, IAEG and ISRM Joint Technical Committee on Landslides and Engineered Slopes
- Canadian Representative, UNESCO-Kyoto University "Round Table for Landslide Hazards Mitigation", 3 day meeting, Tokyo, January, 2006.
- Chair, Task force on the promotion of geological engineering and engineering geology in Canada, Canadian Geotechnical Society, Engineering Geology Division, 2001-2002.

INVITED AND KEYNOTE LECTURES:
- Keynote speaker, ROCEXS-2011, International Workshop on Rock Fall Hazard Engineering, Innsbruck, Austria, May 2011.
- Keynote speaker, 5th International Conference on Debris Flows, Padova, Italy, July 2011.
- Coordinator, Benchmarking Exercise on Landslide Dynamics at the International Forum on Landslide Management, Hong Kong, December, 2007
- Invited speaker, JTC-1 ("Joint Technical Committee on Landslides") Workshop on Mechanics and Velocity of Large Landsides, Courmayer, Italy, September 25-29, 2006.
- Invited speaker, Workshop on guidelines for landslide susceptibility, hazard and risk zoning, 18th to 21th September 2006, Technical University of Catalonia, Barcelona, Spain
- Invited lecture, Hong Kong Institution of Civil Engineers (December 2006)
- State-of-the-Art Lecture, Theme 5, Int. Conference on Landslide Risk Management, Vancouver, May 2005.
- 57th Canadian Geotechnical Conference, Quebec City, October 2004
- NATO Advanced Workshop on Landslide Dams, Bishkek, Kyrghistan, July 2004.
- "Flows 2003", International Conference, Sorrento, Italy, June 2003.
- "Natural Terrain Hazards, a Constraint to Development?" Annual Meeting of the Institution of Mining and Metallurgy, Hong Kong Branch, Hong Kong, November 2002.
- NATO Advanced Workshop on Massive Slope Failure, Celano, Italy, June 2002.
- Workshop on Landslide Hazards and Risk Management in Canada, Geological Survey of Canada. Ottawa, November 16-18, 2001
- Co-Author, State-of-the-Art Lecture "Cuts and Fills in Soil" at the GeoEng 2000, International Conference on Geotechnical and Geological Engineering in Melbourne, November 2000.
- Second Pan-American Symposium on Landslides, Rio de Janeiro, November 1997.

AWARDS:
- Fellow, Geological Society of America (2010)
- Meritorious Achievement Award, B.C. Association of professional Engineers and Geoscientists (2010)
- Geological Society of America Burwell Award in Engineering Geology (2009)
- Schuster Medal awarded jointly by the US Association of Environmental & Engineering Geologists and the Canadian Geotechnical Society. This medal recognizes excellence in research on geohazards (2008)
- Fellow, Engineering Institute of Canada (2008)

- Visiting Foreign Researcher Award, Institut de Physique du Globe de Paris
- Earth and Ocean Sciences, UBC, Faculty Teaching Prize (2006).
- "Innovation" Editorial Board Award, Association of Professional Engineers and Geoscientists of BC (2005).
- Association of Engineering Geologists (US) AEG Publication Award (2001).
- The Canadian Geotechnical Society Prize (1995).
- The Thomas Roy Award, Engineering Geology Division, Canadian Geotechnical Society (1990).
- Member of a project team that received the Canadian Consulting Engineering Award of Merit for the design of a series of debris flow protection structures near Vancouver (1986).
- Research Award for Foreign Specialists, Science and Technology Agency, Japan (1989).
- Canada - France Science and Technology Cooperation Program Award (1990).

TEACHING:

UBC courses:

- Third and fourth year courses on Geological Engineering, Geomorphology and Field School, graduate course on Advanced Geotechnics, Coordination of B.A.Sc. theses.

Short courses on landslide hazards engineering:

- Vienna Polytechnic, Austria, 2010
- Milano Polytechnic, Italy, 2009
- APEGBC, Vancouver, 2006 and 2008)
- University of Rome La Sapienza, July 2005 and April 2006
- ETH Zurich, April 2006
- Washington State Department of Transportation, Seattle, September 2004
- Vienna Polytechnical Institute, Austria, May 2003
- University of Taranto, Italy, June 2003
- Slope stability and runout analysis training course, Freeport GrasbergMine, Indonesia, April 2010
- Short course on landslide hazard assessment, Geological Survey of Canada project "Geoscience for Andean Communities, Mendoza, Argentina and Caracas, Venezuela. Oct. 2003, February 2004
- Seminar on slope stability analysis, Syncrude Canada Ltd., Fort McMurray, December 1990

SELECTED SERVICE TO THE UNIVERSITY

- Mentor, E. Eberhardt
- Director of the Geological Engineering Program (from August 1, 1998 to August 1, 2002)
- Geological Engineering Student Advisor (1998-2002)
- Chair of the Board of Study (1996-2002)
- Chair of an ad hoc committee preparing a curriculum change to eliminate options from the Geological Engineering program (2001-2002)
- Department representative, Graduate Council (since September 2003)
- Ex Officio Member, Head's Advisory Committee, 1998-2000

CONFERENCE ORGANIZATION:

- Member of the Technical Committee, 2012 International Symposium on Landslides, Banff.
- Member of the Organizing Committee, Chair, Scientific Program Committee, Vancouver Conference on Landslide Risk Management, 2005
- Co-Chair, Scientific Program Committee, Member of the Organizing Committee and field trip leader, 8th Congress of the International Assoc. of Engineering Geology, Vancouver, B.C., September 1998
- Member of the Organizing Committee, Chair of the Papers Subcommittee, 48th. Canadian Geotechnical Conference, Vancouver, B.C., September 1995

SELECTED RECENT PUBLICATIONS (from 2000 only):

Bourrier, F. and Hungr, O., 2011. Rock fall dynamics: a critical review of collision and rebound models. Chapter 6 in Lambert Stéphane, Nicot François (eds.), Rock fall Engineering, John Wiley & Sons, New York, ISTE Ltd, London.

Mancarella, D. and Hungr, O., 2010. Analysis of run-up of granular avalanches against steep, adverse slopes and protective barriers. Canadian Geotechnical Journal 47:827–841.

Evans, S.G.,Tutubalina, O.V., Drobyshev,V.N., Chernomorets, S.S., McDougall, S., Petrakov, D.A. and Hungr, O., 2009. Catastrophic detachment and high-velocity long-runout flow of Kolka Glacier, Caucasus Mountains, Russia in 2002. Geomorphology 105:314–321.

Willenberg, H., Eberhardt, E., Loew, S., McDougall, S. and Hungr, O., 2009. Hazard assessment and runout analysis for an unstable rock slope above an industrial site in the Riviera valley, Switzerland. Landslides 6:111-116.

Hungr, O. and McDougall, S., 2009 Two numerical models for landslide dynamic analysis. Computers & Geosciences 35: 978–992.

Hungr, O., 2008. Simplified models of spreading flow of dry granular material. Canadian Geotechnical Journal 45:1156-1168.

Sosio, R., Crosta, G.B. and Hungr, O., 2008 Complete dynamic modeling calibration for the Thurwieser rock avalanche (Italian Central Alps). Engineering Geology, 100:11-26.

Hungr, O., 2008. Numerical modelling of the dynamics of debris flows and rock avalanches. Geomechanik und Tunnelbau 1 (2008), Ernst und Sohn, Berlin, Heft 2:112-119.

McDougall, S. and Hungr, O., 2008. Two numerical models for landslide dynamic analysis. Computers and Geoscience (in press).

McDougall, S., Pirulli, M., Hungr, O. and Scavia, C., 2008. Advances in landslide continuum dynamic modeling. Invited Special Lecture at the 10th International Symposium on Landslides and Engineered Slopes, Xian, China (in press).

Hungr, O. and Wong, H.N., 2007. Landslide Risk Acceptability Criteria: Are F-N Plots Objective? Geotechnical News 25:47-50.

Hungr, O., 2007. Dynamics of Rapid Landslides. Chapter in "Progress of Landslide Science", H. Fukuoka, Editor, Springer Verlag, Heidelberg.

Welkner, D., Eberhardt, E., Hungr, O. and Hermanns, R., 2007. A dynamic analysis of prehistoric rock slope failure events in the central Andes of Chile. Proceedings, 60th Canadian Geotechnical Conference, Ottawa.

Hungr,O., McDougall, S., Wise, M. and Cullen, M., 2007. Magnitude-frequency relationships of debris flows and debris avalanches in relation to slope relief. Geomorphology (in press).

Rose, N.D. and Hungr, O., 2007. Forecasting potential rock slope failure in open pit mines using the inverse-velocity method. International Journal of Rock Mechanics and Mining Science 44:308–320

McDougall, S., Boultbee, N., Hungr, O., Stead, D. and Schwab, J.W., 2006, The Zymoetz River landslide, British Columbia, Canada: Description and dynamic analysis of a rock slide – debris flow. Landslides, 3:195-204.

Geertsema, M., Hungr, O. Evans, S.G. and Schwab, J.W., 2006. A large rock slide – debris avalanche at Pink Mountain, northeastern British Columbia, Canada. Engineering Geology 83: 64–75.

McDougall, S. and Hungr, O., 2005. Modelling of landslides which entrain material from the path. Canadian Geotechnical Journal 42:1437-1448.

Hungr, O., 2005. Prospects for prediction of landslide dam geometry using dynamic models. Keynote Paper, NATO Advanced Workshop on Landslide Dams, Bishkek, Kyrghistan. Kluwer NATO Science Series (in press).

Hungr, O., 2005. Rock avalanche occurrence, process and modelling. Springer NATO Science Series, IV. Earth and Environmental Sciences, 49:243-266.

Hungr, O., 2005. Book review: "Dépôts de Pente Continentaux; Dynamique et Faciès, by P. Bertran. Géographie physique et Quaternaire 57:256-257.

Hungr, O., Corominas, J. and Eberhardt, E., 2005 .State of the Art Paper #4, Estimating landslide motion mechanism, travel distance and velocity. In Hungr, O., Fell, R., Couture, R. and Eberhardt, E., Eds.. Landslide Risk Management. Proceedings, Vancouver Conference. Taylor and Francis Group, London.

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Revellino, P., Hungr, O., Guadagno, F.M. and Evans, S.G., 2003 Velocity and runout prediction of destructive debris flows and debris avalanches in pyroclastic deposits, Campania Region, Italy. Environmental Geology 45:295-311.

Hungr, O., 2003. Flow slides and flows in granular soils. Keynote Paper. L. Picarelli, Editor, Procs., Occurrence and Mechanisms of flow-like Landslides in Natural Slopes and Earthfills. International Workshop, Sorrento, Italy, Patron Editore, Bologna, pp. 37-44.

Hungr, O., Dawson, R., Kent, A., Campbell, D. and Morgenstern, N.R., 2002. Rapid flow slides of coal mine waste in British Columbia, Canada. In "Catastrophic Landslides" Geological Society of America Reviews in Engineering Geology 15:191-208.

Fletcher, L., Hungr, O., and Evans, S.G., 2002. Contrasting failure behaviour of two large landslides in clay and silt. Canadian Geotechnical Journal 39:46-62.

Nichol, S., and Hungr, O. 2002. Brittle and ductile toppling of large rock slopes. Canadian Geotechnical Journal 39:1-16.

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Hungr, O., 2000. Analysis of debris flow surges using the theory of uniformly progressive flow. Earth Surface Processes and Landforms 25:1-13.

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BOOKS EDITED:

Wieczorek, G. and Hungr, O., Eds., 2007. "Debris Flows". Special Issue, "Landslides", Journal of the International Consortium on Landslides, Kyoto University, Japan, (in press).

Jaramillo, M., Oyeda-Moncayo, J., Fauqué, L. and Hungr, O., Editors, 2007. Movimentos en Masa en la Región Andina: Una Guía para la Evaluación de Amenazas. Nacional Resources Canada, Vancouver, 325 pp (Translated to Spanish, in press)

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Moore, D.P. and Hungr, O., Eds., 1998. Engineering Geology, a Global View from the Pacific Rim. Proceedings, 8th Congress, International Association of Engineering Geology and the Environment, Vancouver, B.C. Balkema Publishers, Rotterdam (6 volumes).

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RESUME **November 2013**

EDUCATION
BSc(Eng), Geological Engineering, 1972, Queen's University, Kingston, Ontario, Canada
MSc (Eng), Civil Engineering (Geotechnical), 1975, Queen's University, Kingston, Ontario, Canada

EXPERIENCE
1984-present: VanDine Geological Engineering Limited, Victoria, British Columbia, Canada
Mr. VanDine provides specialized geological and geotechnical engineering consulting for civil engineering developments and the forestry industry. His areas of expertise include: landslide and debris flow studies and associated mitigative design work; geological engineering mapping; terrain mapping and route location; geological hazard and risk analyses; mineral aggregate location and evaluation; technical review, forensic engineering, expert witness; and education and training. Mr VanDine has been a member of numerous federal, provincial and professional committees on engineering and geoscience. He has taught courses associated with geological and geotechnical engineering at University of British Columbia (Vancouver, BC), University of Victoria (Victoria, BC), Camosun College (Victoria, BC), BC Forestry Continuing Studies Network (Vancouver, BC), Institute of Engineering (Kathmandu, Nepal), and University of the West Indies (Kingston, Jamaica). Mr VanDine has been involved both in developing and carrying out both compliance audits for the BC Forest Practices Board, and General and Technical Professional Practice Reviews for the Association of Engineers and Geoscientists of the Province of British Columbia. He has participated in a number of expert panels and review panels, both in Canada and Hong Kong. In 2010 he was appointed a panel member of the BC Environmental Appeals Board, Forest Appeals Commission and Oil and Gas Appeals Tribunal.

1982-1984 and 1974-1976: Thurber Consultants Ltd, British Columbia and Alberta, CANADA
Mr. VanDine carried out a wide variety of projects including major reservoir shoreline stability studies of BC Hydro's Peace River developments, engineering terrain assessments of rail lines for CN Railway, and land use planning, aggregate and groundwater studies. He had major input into the Sea to Sky and Coquihalla highways debris flow investigations and mitigative studies for the BC Ministry of Transportation and Infrastructure.

1978-1982: Assistant Professor, Geological Engineering, Queen's University, Kingston, Ontario, Canada
Mr. VanDine taught courses in Engineering Geology, Site Investigation, Airphoto Interpretation, Engineering Terrain Analysis, Urban Geology, and Geology for Engineers. His areas of research included slope stability, aggregates, geotextiles and engineering terrain analysis. During this period Mr VanDine was a consultant on projects in Ontario and the Maritimes, in the USA, and in Guyana, South America.

1976-1978: Gartner Lee Associates Limited, Ontario, Canada
Mr. VanDine conducted a number of mineral aggregate assessments, hydrogeological studies, subdivision planning studies and engineering terrain studies in Ontario and Manitoba. Major projects

included the Northern Ontario Engineering Geology Terrain Studies for the Ontario Geological Survey, and a sand and gravel resources study for 12,000 km^2 in central Manitoba.

1972-1973: Geological Survey of Canada, Northwest Territories and British Columbia, Canada
Mr. VanDine was involved in the Granular Resources Inventory Mackenzie Valley project, permafrost degradation studies in the same valley, and a study of natural and human-induced landslides along the Thompson and Fraser rivers, BC.

1971: Terra Scan Limited, Ontario, Canada
This work involved drill inspection, instrumentation, construction supervision and laboratory testing for a variety of geological and geotechnical engineering studies.

MEMBERSHIPS

Professional Engineers and Geoscientists of British Columbia (P.Eng. and P.Geo.)
Professional Engineers of Alberta and Ontario (P.Eng. resigned member in good standing)
Professional Engineers of Nova Scotia (P.Eng. resigned licensee in good standing)
Canadian Geotechnical Society (CGS); Engineering Geology Division (EGD); International Association of Engineering Geology (IAEG)

APPOINTMENTS

President-Elect (2014), Canadian Geotechnical Society
Panel Member, BC Environmental Appeals Board, Forest Appeals Commission and Oil and Gas Appeals Tribunal (2010-present)
Member, Association of Professional Engineers and Geoscientists of British Columbia, President's Awards Committee (2008-2013); Chair (2010-2013)
Scientific Editor and Member of Advisory Panel, Canadian Technical Guidelines and Best Practices related to Landslides: a national initiative for loss reduction, Geological Survey of Canada, (2010-2013)
Member, Association of Professional Engineers and Geoscientists of British Columbia, Task Force on Geotechnical Engineering Definition and Competencies (2009-present)
Series Editor, The Geology of the Federal, Provincial and Territorial Parliament Building of Canada, *Geoscience Canada* (2001-2009)
Member, Advisory Committee, International Debris-Flow Hazards and Mitigation Society (2000-2009)
Trustee, Canadian Foundation for Geotechnique (1999-2013); Vice President and National Fund Raising Chair (2005-2008); President (2008-2013)
Director, Institute of Forest Engineering of British Columbia (1996-1997)
Member, National Mapping Program Coordinating Committee, Geological Survey of Canada (1995-2001)
Member, Joint Practice Board (JPB), Association of Professional Engineers and Geoscientists of British Columbia/ Association of British Columbia Professional Foresters (1995-1998); Chair (1995-1996)
Executive, Division of Engineers and Geoscientists in the Forest Sector (DEGIFS), Association of Professional Engineers and Geoscientists of British Columbia (1995-1998)
Member, Canadian Geoscience Council Committee on the Future of Geosciences in Canada (1994-1995)
Member, Earth Science Task Force of the British Columbia Resources Inventory Committee (1993-1998)
Member, Advisory Committee, British Columbia Geological Survey Branch, Surficial Geology Unit (1989-1995)
Associate Editor, Canadian Geotechnical Journal (1988-1990)
Member and Treasurer, Canadian Geoscience Council (now known as the Canadian Foundation for Earth Sciences) (1984-1988 and 1990)

Chairman, Engineering Geology Division, Canadian Geotechnical Society (1984-1986)

RECOGNITIONS

Geoscientists Canada (formerly Canadian Council of Professional Geoscientists), Fellow (FGC 2013)
Engineers Canada (formerly Canadian Council of Professional Engineers), Fellow (FEC 2009)
Engineering Institute of Canada, Fellow (FEIC 2006)
Association of Professional Engineers and Geoscientists of British Columbia, CJ Westerman Award (APEGBC's premier award for professional geoscience) (2005)
Forest Engineering Award of Excellence, Association of Professional Engineers and Geoscientists of British Columbia and Association of British Columbia Professional Foresters (2003)
Association of Professional Engineers and Geoscientists of British Columbia, Professional Service Award (1998)
Canadian Geotechnical Society, Engineering Geology Division, Thomas Roy Award (1998)
8th Canadian Geotechnical Colloquium Speaker of the Canadian Geotechnical Society (1984)
Engineering Society Teaching Award, Queen's University (1981)

NON-TECHNICAL COMMUNITY CONTRIBUTIONS

Board of Directors for the Victoria U-JAM (Jazz) Society (2010-present)
Volunteer gallery actor and docent, Royal BC Museum, Victoria, BC (2002-2006)
Board of Directors and volunteer for the Victoria Bluegrass Association, Victoria, BC (2001-present)
Board of Directors, Beckley Farm Lodge (Intermediate Care Facility), Victoria, BC (1984-1985)

PUBLICATIONS, PRESENTATIONS AND FIELD TRIPS

Mr. VanDine has authored or co-authored over 60 refereed papers, conference papers and presentations, major reports and book reviews. These cover the fields of geological hazards and risks, landslides, terrain mapping, aggregates, geological engineering education, geotechnical history and professional practice. He has led numerous technical field trips along the Sea to Sky Highway, in the Fraser Valley, by raft down the Thompson River, and on Vancouver Island, all in British Columbia. A listing of some of Mr. VanDine's recent publications follows. A full listing is available upon request.

Cruden, D. and VanDine, D.F., 2013. Classification, Description, Causes and Indirect Effects – Canadian Technical Guidelines and Best Practices Related to Landslides: A National Initiative for Loss Reduction, Geological Survey of Canada, Open File 7359, 22 pp.

VanDine, D.F. and Savigny, K.W., 2012. Requirements for professional landslide studies in Canada, in Proceedings of the International Symposium on Landslides and North American Symposium on Landslides, Banff, Alberta.

VanDine, D.F., 2012, Risk Management – Canadian Technical Guidelines and Best Practices Related to Landslides: A National Initiative for Loss Reduction. Geological Survey of Canada Open File 6996.

VanDine, D.F., 2011, Professional Practice and Insurance Issues – Canadian Technical Guidelines and Best Practices Related to Landslides: A National Initiative for Loss Reduction. Geological Survey of Canada Open File 6981.

Couture, R., Blais-Stevens, A., Bobrowsky, P., Wang, B. and VanDine, D., 2011. Canadian technical guidelines and best practices related to landslides; a national initiative for loss reduction. Proceedings 5th Canadian Conference on Geotechnique and Natural Hazards, Kelowna, BC, May 2011, Paper 118.

VanDine, D.F. and Lister, D.L., 2011. The much misunderstood '1:475 landslide'. Proceedings 5th Canadian Conference on Geotechnique and Natural Hazards, Kelowna, BC, May 2011, Paper 179.

Santi, P.M, Hewitt, K, VanDine, D.F. and Manolo Barillas Cruz, E, 2010. Debris-flow impact, vulnerability, and response, Natural Hazards, v. 52, August 2010.

VanDine, D.F., Gerath, R.F., Jakob M., and Mitchell, P. 2008. Natural hazard legislation and professional landslide guidelines in British Columbia, Canada. Invited paper for inclusion in the session on Legislation on Landslide Mitigation for Infrastructure and Residential Development at the First World Landslide Forum, Japan, November 2008.

Arksey, R, and VanDine, D., 2008. Example of a debris-flow risk analysis from Vancouver Island, British Columbia, Canada. An invited paper in *Landslides* (Theme issue "Debris Flow Hazards", editors G. Wieczorek and O. Hungr), v. 5, pp. 121-126.

Association of Professional Engineers and Geoscientists of British Columbia (co-author) 2006 (updated in 2008 and 2010). Professional Practice Guidelines for Legislated Landslide Assessments for Proposed Residential Development in British Columbia. Association of Professional Engineers and Geoscientists of British Columbia.

VanDine, D.F., Rodman, R.F., Jordan, P., and Dupas, J. 2005. Kuskonook Creek, an example of a debris flow analysis. An invited paper in Landslides (special issue, editors J. Corominas and C. Bonnard), v. 2 ,pp. 257-265.

Fannin, F., Moore, G., Schwab, J. and VanDine, D., 2005. Managing landslide risk through application of different model codes of forest practice: an example from British Columbia, Canada. In Proceedings, International Conference on Landslide Risk Management, Vancouver, BC (editors O. Hungr, R. Fell, R. Couture, and E. Eberhardt), pp. 299-320.

Skermer, N.A. and VanDine, D.F., 2005. Debris flows – A historical perspective. Chapter 3 in Debris Flows and Debris Avalanches – A Practically-Oriented Overview of the State of the Art (editors M. Jakob and O, Hungr), Springer-Praxis Books, pp. 25-52.

Bichler, A., VanDine, D.F. and Bobrowsky, P., 2004. Landslide hazard and risk mapping – a review and classification. Invited paper in GeoQuebec 2004, 57th Canadian Geotechnical Society Conference, Session 5C, pp. 1-12.

Couture, R. and VanDine, D.F., 2004. Field Trip Guidebook, Geological Hazards along the Sea-to-Sky Highway, British Columbia. Geological Survey of Canada Open File 4642, 84 pp.

Wise, M., Moore, G.. and VanDine, D.F. (co-author and co-editor), 2004. Landslide Risk Case Studies in Forest Development Planning and Operations. Land Management Handbook #56, BC Ministry of Forests, Research Branch, 199 pp.

Cullum-Kenyon, S,, Heinz, H.K., Sobkowicz, J.C., VanDine, D.F. and Kerr, D., 2003. Debris flow hazard at Five Mile Creek, Banff, Alberta.