Landslides in the Vancouver-Fraser Valley-Whistler region

S.G. Evans[1] and K.W. Savigny[2]

Evans, S.G. and Savigny, K.W., 1994: Landslides in the Vancouver-Fraser Valley-Whistler region; in Geology and Geological Hazards of the Vancouver Region, Southwestern British Columbia, (ed.) J.W.H. Monger; Geological Survey of Canada, Bulletin 481, p. 251-286.

Abstract: A great diversity of landslide types occur in the Vancouver region in response to high relief, steep slopes, heavy rainfall, seismicity, and a variety of landslide-prone materials. Rockfalls and small rock avalanches (less than a million cubic metres) are a significant hazard to land use development but their biggest impact has been on the transportation network and the Fraser River fishery. The deposits of larger rock avalanches (greater than a million cubic metres) are common throughout the region and have occurred along major transportation routes in the Fraser Valley and the Squamish-Pemberton corridor in the last 10 000 years. Noncatastrophic mountain slope deformation is also widespread. Such processes form linear topographic features such as cracks and fissures. Volcanic rocks of the Garibaldi Volcanic Belt are particularly prone to massive rapid landslides, some of which have blocked major rivers and formed temporary lakes upstream. Since the late Pleistocene, major collapses have taken place on the western flanks of Mount Garibaldi and Mount Cayley volcanoes. Large landslides continue to occur in the historical period and are a major consideration in land development in the Belt. Channellized debris flows within steep mountain watersheds triggered by heavy rains occur throughout the region. Debris flow defensive structures have been constructed by provincial authorities at numerous locations to protect transportation routes and/or communities. Landslides in Pleistocene sediments are also important. In addition, a number of cases of catastrophic seepage erosion have been documented. Submarine failures (outside the Fraser Delta) occur on delta fronts in both marine and lacustrine environments. The expansion of development in the Vancouver region is increasing the vulnerability of communities, transportation routes, and the resource base to landslides.

Résumé : Une grande variété de glissements de terrain se produisent dans la région de Vancouver en réponse au relief prononcé, aux fortes pentes, à l'abondance des précipitations, à la séismicité et à la présence de divers matériaux susceptibles de glisser. Les écroulements et les petites avalanches de pierres (moins d'un million de mètres cubes) constituent un danger significatif pour la mise en valeur et l'exploitation des terres, mais leur plus forte incidence a eu lieu sur le réseau de transport et les pêches du fleuve Fraser. Les grandes avalanches de pierres (plus d'un million de mètres cubes) sont survenues le long des grandes voies de transport dans la vallée du Fraser et du couloir de Squamish-Pemberton au cours des 10 000 dernières années; leurs dépôts sont communs dans toute la région. Les déformations non catastrophiques de versants montagneux sont également répandues. Ces processus créent des détails topographiques linéaires tels que des fentes et des fissures. Les roches volcaniques de la ceinture volcanique de Garibaldi sont particulièrement susceptibles de glissements de terrain rapides et massifs, dont certains ont obstrué de grands cours d'eau et donné naissance à des lacs temporaires, en amont. Depuis le Pléistocène tardif, de grands effondrements se sont produits sur les flancs occidentaux des monts Garibaldi et Cayley. De grands glissements de terrain ont continué à se produire pendant la période historique et sont un important facteur à considérer en ce qui concerne l'utilisation des terres dans la ceinture volcanique de Garibaldi. Des coulées de débris, qui sont canalisées dans des bassins hydrographiques de régions montagneuses escarpées et déclenchées par des précipitations abondantes, ont lieu dans toute la région. Les autorités provinciales ont

[1] Terrain Sciences Division, Geological Survey of Canada, 601 Booth Street, Ottawa, Ontario K1A 0E8
[2] Department of Geological Sciences, University of British Columbia, 6339 Stores Road, Vancouver, British Columbia V6T 1Z4

construit des structures en de nombreux endroits pour protéger les voies de transport ou les collectivités contre les coulées de débris. Les glissements de terrain survenant dans les sédiments pléistocènes sont également importants. En outre, de nombreux cas d'érosion catastrophique causée par des infiltrations ont été documentés. Des effondrements sous-marins (à l'extérieur du delta du Fraser) se produisent sur des fronts deltaïques marins et lacustres. L'intensification du développement de la région de Vancouver accroît la vulnérabilité des collectivités, des voies de transport et de la base de ressources aux glissements de terrain.

INTRODUCTION

The Vancouver region (Fig. 1) is situated in the southwest corner of the Canadian Cordillera where a wide variety of landslides styles and processes have been described (Eisbacher, 1979; Eisbacher and Clague, 1984; Evans, 1982, 1984, 1990a, 1992a; Cruden, 1985; Cruden et al., 1989; Evans and Gardner, 1989; Clague, 1991; Clague and Evans, 1994b; Evans and Clague, unpublished data). Evidence for landslide activity in the prehistoric past is seen in the widespread distribution of landslide deposits throughout the region, and in the historical period (taken to be 1855 to the present), in frequent landslide events as documented by Evans and Clague (unpublished data).

The interaction between high relief, steep slopes, heavy rainfall, seismicity, a complex active tectonic history, and landslide-prone materials in the region, gives rise to a great diversity of landslide types, each with particular geotechnical characteristics, geological causes, and dynamic behaviour. This presents a considerable challenge to geoscientists who face the task of assessing the hazards posed by landslides (e.g., Eisbacher, 1982; Evans and Gardner, 1989; Morgan, 1986, 1992; Morgan et al., 1992; Hungr et al., 1993; Fell, 1994), to civil engineers in their design of engineering works to mitigate landslide hazards (e.g., Hungr et al., 1984, 1987; Hungr, 1993; Martin et al., 1984; Moore et al., 1992), and to landuse planners and legislators who face the task of regulating development in response to these hazards assessments (e.g., Lister, 1980; Cave, 1992a, b; Berger, 1973; Buchanan, 1983). Geological hazards are one of the many challenges presented by the physical environment to living in or near the mountains (Spearing, 1976).

The Vancouver region has inherent strategic importance as the gateway to transcontinental transportation corridors. In the past, landslides have had important impacts on communities, transportation routes, and on valuable forestry and fishery resources. The objective of this paper is to review the diversity of landslides that occur in the region. The review will provide background for the development of hazard mitigative strategies that increasingly have to be formulated within the context of development pressures and decreasing land availability in one of Canada's most rapidly developing regions.

LANDSLIDE TYPES

A lengthy discussion of landslide types and terminology is outside the scope of this paper. A number of landslide classification schemes are in use in the geotechnical/geological literature (e.g., Varnes, 1978; Hutchinson, 1988; Skempton and Hutchinson, 1969) and reflect, to a large extent, the regional experience of the authors. No single classification scheme has found universal application to the large variety of landslides encountered in the mountains of North America; in this paper, for example, we shall encounter especial difficulty in classifying rapid flow type movements which involve a range of materials and vary in size over several orders of magnitude.

For present purposes, landslides in rock are distinguished from those involving surficial materials. In the rock grouping those involving nonvolcanic rocks are differentiated from those involving Quaternary volcanic materials. Landslides in surficial materials include debris flows originating in colluvial and/or glacial materials in steep mountain watersheds, and landslides involving Pleistocene sediments.

An informative brochure is available describing landslide types in British Columbia (British Columbia Ministry of Energy, Mines, and Petroleum Resources, 1993).

ROCK SLOPE MOVEMENTS IN NONVOLCANIC ROCKS

Definitions

Rockfall involves the detachment of rock fragments from rock slopes and their fall and subsequent bouncing rolling, sliding, and stopping (Varnes, 1978; Hutchinson, 1988; Evans and Hungr, 1993). It may also begin by the detachment of a more or less coherent block that then disintegrates during the course of downslope movement. Rockfalls may be transitional to rock avalanches. A rock avalanche involves a very rapid downslope movement of fragments of bedrock that have become shattered and pulverized during travel which typically results from a rockfall or rockslide in mountainous terrain. It is distinguished from a rockslide by the fact that all of the debris leaves the sliding surface and travels down the valley side, generally to the valley floor, and sometimes along the valley. Rock avalanches with volumes above about one million cubic metres generally show excessive mobility and travel long distances; those with volumes below this threshold behave similarly to rockfalls (e.g., Scheidegger, 1973). Rockslides involve the movement of a rockmass on a defined shear surface or shear surfaces; most of the debris remains in contact with the sliding surface but disruption of the moved mass is considerable. Rockslides are transitional to the complex movement mechanisms associated with mountain slope deformation where discrete sliding surfaces may not be formed and the degree of disruption of the rock mass may be minimal.

Rockfall

Rockfall is a common process in the mountainous terrain of the Vancouver region, where its continued occurrence has formed talus slopes, and it is also common on rock slopes adjacent to linear transportation facilities. Although, as described by Evans and Hungr (1993), rockfall hazards have affected land-use development at the base of talus slopes, as in the example of Silverhope (Fig. 1), the main impact of rockfall in the Vancouver region has been on transportation routes (Hungr and Evans, 1988, 1989; Peckover and Kerr, 1977; Piteau and Peckover, 1978; Theodore, 1986; VanDine, 1992) and on the fisheries resource of the Fraser River (Evans, 1986).

Howe Sound

Rockfalls are common along the Squamish Highway (also known as the Sea-to-Sky Highway) and the adjacent B.C. Rail track along the east side of Howe Sound (Nasmith, 1972; Moore, 1983; Hungr and Skermer, 1992; Fig. 1) where they have frequently caused road and rail traffic interruptions for example, a rockfall in October 1990, near Loggers Creek (Fig. 2) involved 10 000 m^3 of debris and blocked the highway for 12 days thus severing the road link between the communities in the Squamish-Pemberton corridor and Vancouver. The cost of the rockfall, involving repairs and the construction of preventative structures, was approximately \$7 million (British Columbia Ministry of Energy, Mines, and Petroleum Resources, 1993). In addition, in response to this event, the

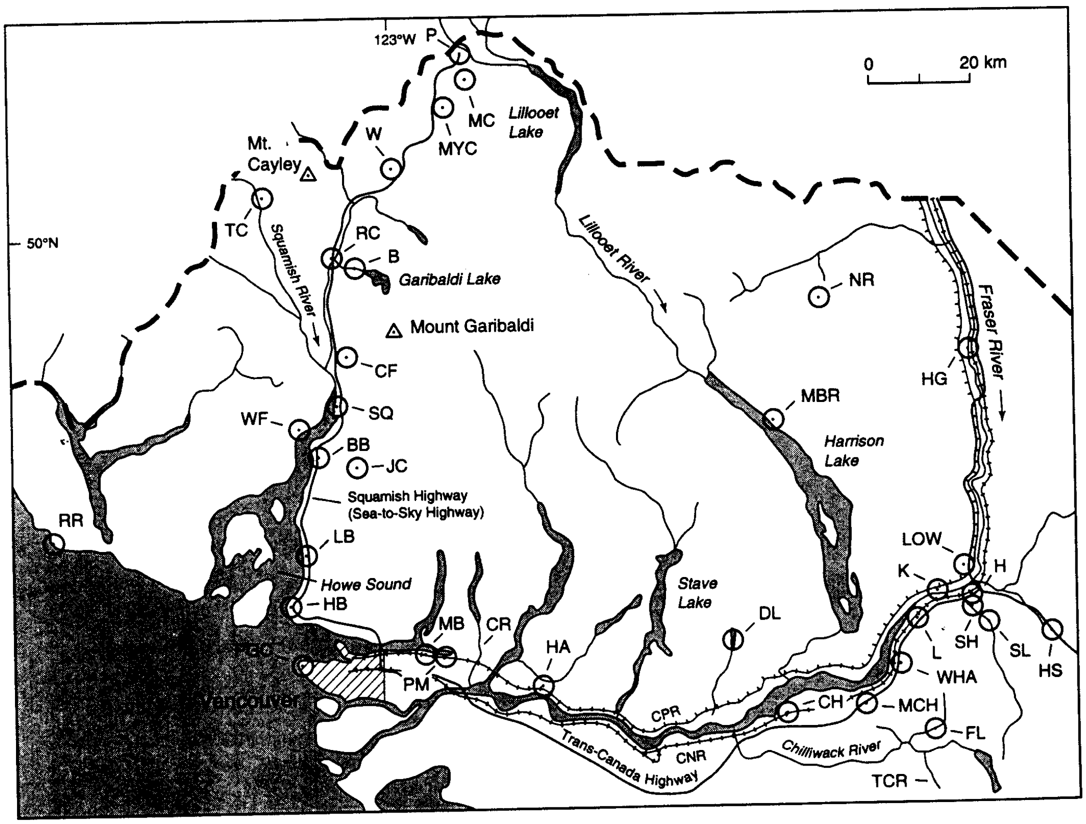

Figure 1. Location map of region showing localities discussed in text. Key: B = The Barrier, BB = Britannia Beach, CF = Cheekye Fan, CH = Chilliwack, CR = Coquitlam River, DL = Dickson Lake, FL = Foley Lake, H = Hope, HA = Haney, HB = Horseshoe Bay, HG = Hell's Gate, HS = Hope Slide, JC = Jane Camp (former site of), K = Katz slide(s), L = Laidlaw, LB = Lions Bay, LOW = Lake of the Woods (also known as Schkam Lake), MB = Mount Burnaby, MBR = Mount Breakenridge, MC = Mount Currie, MCH = Mount Cheam slide(s), MYC = Mystery Creek, NR = Nahatlatch River, P = Pemberton, PGC = Point Grey Cliffs, PM = Port Moody, RC = Rubble Creek, RR = Redroofs escarpment, SH = Silverhope, SL = Silver Lake, SQ = Squamish, TC = Turbid Creek, TCR = Tamihi Creek, W = Whistler, WF = Woodfibre, WHA = Whaleach Power Station; dashed line represents boundary of study area.

provincial government constructed an emergency ferry terminal to be used should the highway be blocked by a similar landslide in the future.

Rockfalls have resulted in the deaths of several motorists on the Squamish Highway since 1969. One such rockfall accident occurred in January 1982 when a single block fell off a rock face above the highway and killed a passenger in a car. The trajectory was analyzed (Fig. 3) by Hungr and Evans (1988) who calculated that the boulder had an impact velocity of 28 $m \cdot s^{-1}$.

Fraser Canyon

Rockfalls are also common in the Fraser Canyon (Peckover and Kerr, 1977; Piteau, 1977) and have impacted upon the Trans-Canada Highway and both intercontinental railway lines, Canadian Pacific Railway (CPR) and Canadian National Railway (CNR) (Fig. 4, 5), causing traffic delays, derailments, and numerous deaths. Since the 1960s, the B.C. Highways Department and both railway companies have spent many millions of dollars to mitigate the rockfall hazard, either by rock slope treatment (e.g., scaling, rock bolts, shotcrete, buttresses, and drainage) or the construction of protective measures such as sheds, catch fences, meshes, ditches, and warning devices (Peckover and Kerr, 1977; Wyllie, 1991).

Data provided in Theodore (1986) shows that the Mountain Region of Canadian National Railways spent almost $2 000 000 per year between 1971 and 1986 on rock slope stabilization work, mostly between Hope and Kamloops. Since the inception of a major rockfall protection program in 1971 the number of derailments has been substantially reduced despite a significant increase in traffic densities.

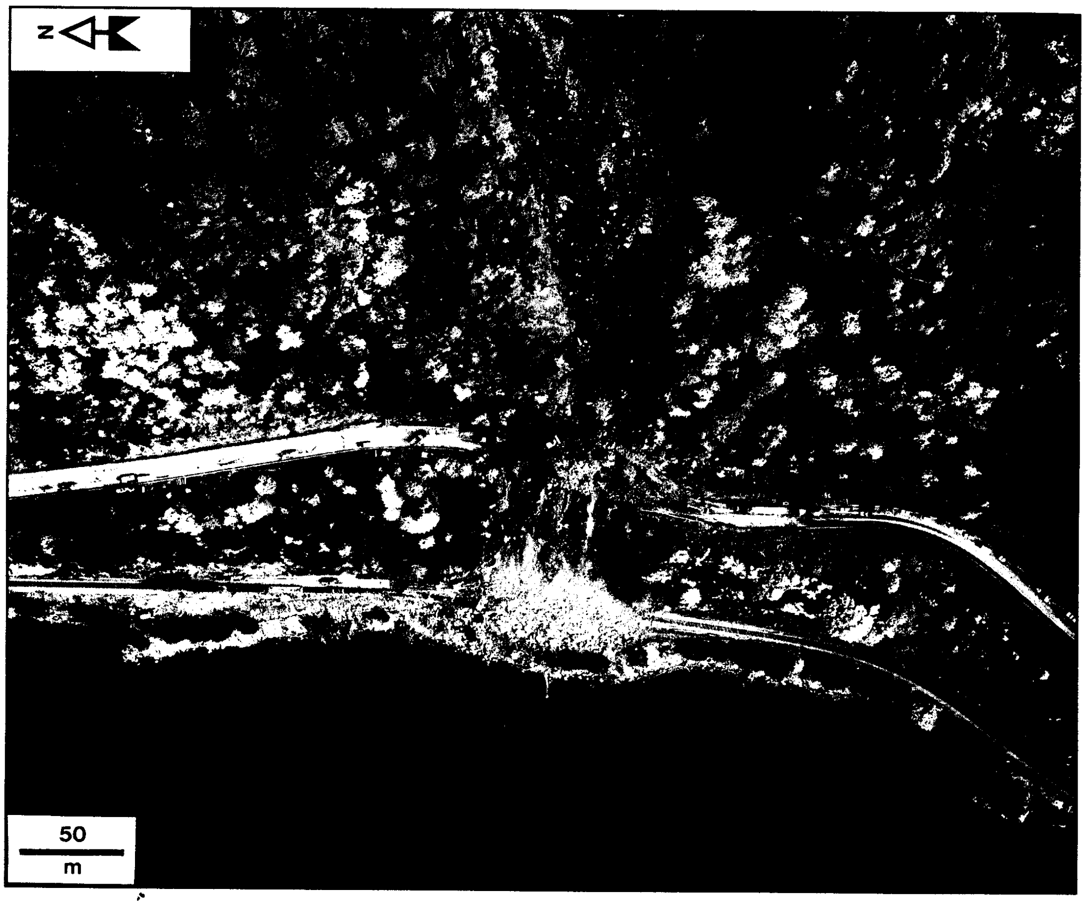

Figure 2. Aerial photograph of rockfall which covered the Sea-to-Sky Highway and B.C. Rail tracks, 4 km north of Lions Bay, October 1990 (Photo courtesy of Selkirk Remote Sensing, Richmond, British Columbia; negative number SRS 4466-5).

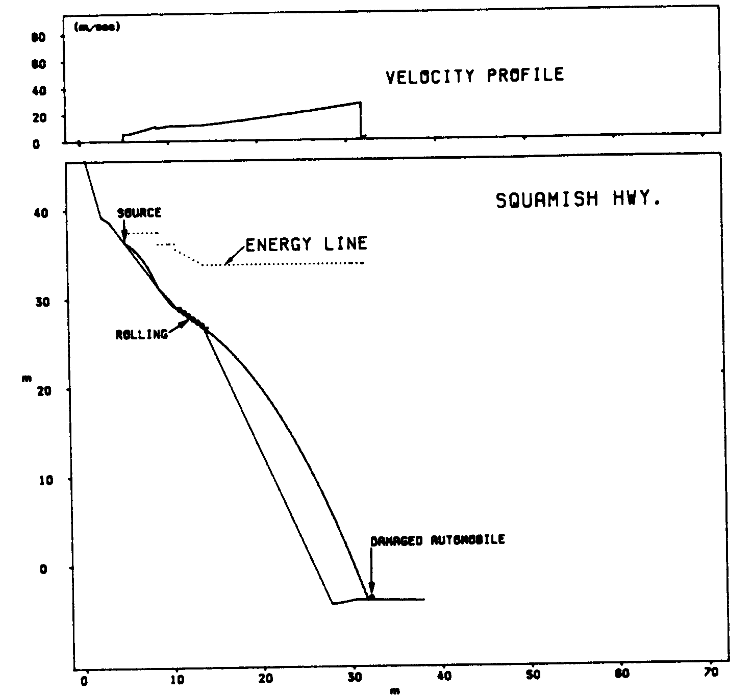

Figure 3. *Simulated trajectory of a single boulder which caused the 1982 rockfall accident on Sea-to-Sky Highway, 22 km north of Horseshoe Bay (from Hungr and Evans, 1988).*

Figure 4. *Rockfall on Trans-Canada Highway, Fraser Canyon, near Yale (courtesy of D. Wyllie).*

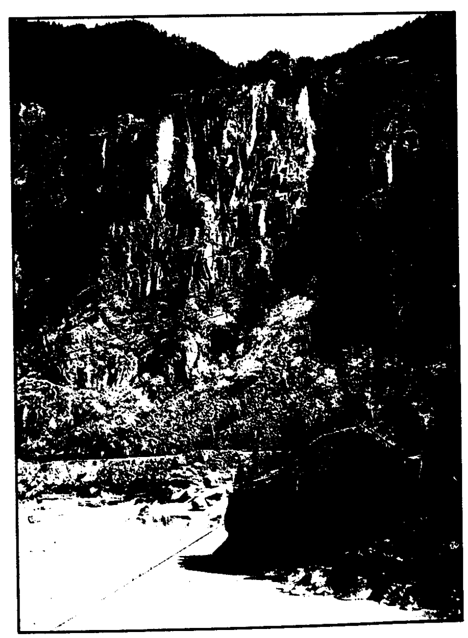

Figure 5. *Typical steep jointed rockslope in the Fraser Canyon, which is subject to rockfall. Canadian National Railway tracks run acoss the base of the slope which is located just south of Siwash Creek. GSC 1994-709A*

Rockfall frequency shows a marked correlation with the weather (Peckover and Kerr, 1977; Fig. 6). Figure 6 shows data for rockfall frequency on Canadian National Railway tracks in the Fraser Canyon. The highest frequency is found in January, February, and March, the time when freeze-thaw cycles are most frequent, thus reflecting the role of frost wedging in rockfall release. When the mean monthly temperature is above zero (March-November), the number of rockfalls per month varies more or less directly in proportion to mean monthly precipitation (Peckover and Kerr, 1977).

A rockfall (estimated volume 75 000 m^3) at Hell's Gate in the Fraser Canyon (Fig. 1), caused by railway construction activity in 1914, had a major impact on the Fraser River salmon fishery from which it has not yet recovered (International Pacific Salmon Fisheries Commission, 1980; Evans, 1986). The debris greatly increased an obstruction that had been initiated by previous railway construction activity in 1913 and prevented many migrating salmon from returning to their spawning grounds in the vast Fraser watershed, covering about a quarter of the province of British Columbia, above Hell's Gate. The rockfall has had a major impact upon salmon returns in subsequent years; in 1978 dollars and landed values, the loss to sockeye fishery alone, resulting from a diminished return in 1914, amounted to $1.7 billion between 1951 and 1978 (International Pacific Salmon Fisheries Commission, 1980). Fishways were constructed between 1944 and 1966 (Fig. 7), at a cost of $1.36 million, to provide passage for the salmon past the obstruction in an attempt to restore the sockeye and pink salmon runs to their historical abundance.

Rockfall is not confined to steep mountain slopes in the Vancouver region. It may also occur on steep, rocky, coastal cliffs such as along the Stanley Park seawall from Prospect Point to Siwash Rock (Armstrong, 1984).

Small rock avalanches (less than one million cubic metres)

Rock avalanches of less than one million cubic metres are common in the Vancouver region (Fig. 8). In 1915, a rock avalanche involving about 100 000 m^3, killed 56 people at Jane Camp (Fig. 9), a mining community in the Britannia Creek watershed (Evans and Clague, unpublished data). Although this event is Canada's second largest landslide disaster (after the 1903 Frank slide) little is known about the rock avalanche, except that cracks were inspected above Jane Camp several days before the landslide took place but the danger was not realized (Ramsey, 1967).

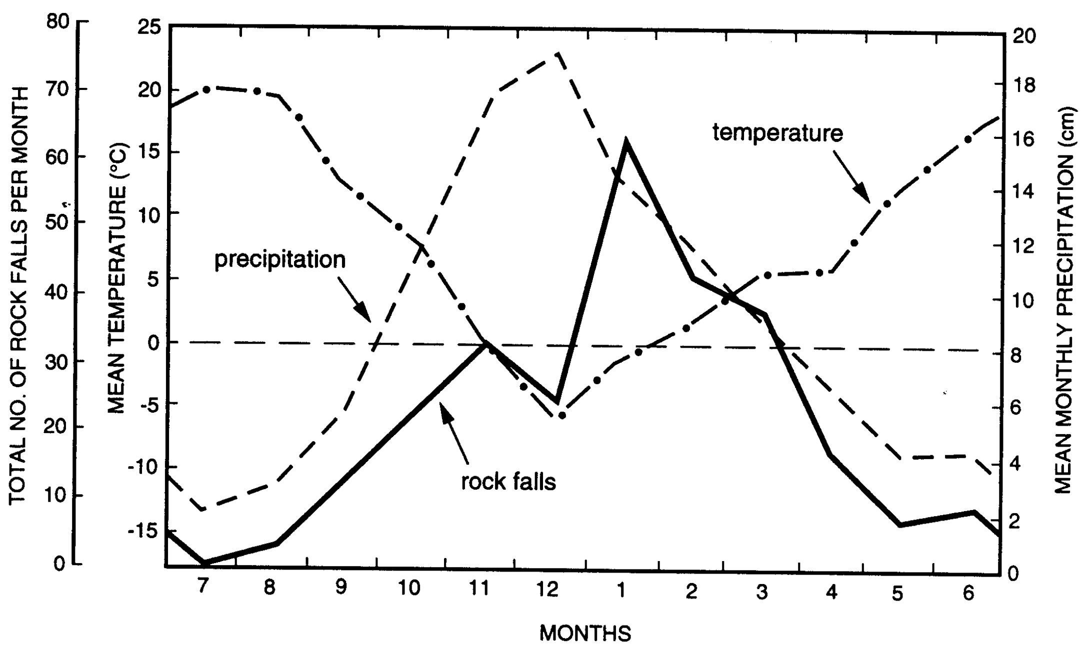

Figure 6. Rockfall frequency and weather over the period 1933-1970, Fraser Canyon, Yale subdivision, Canadian National Railway (modified from Peckover and Kerr, 1977).

Large rock avalanches (greater than one million cubic metres)

Rock avalanches are relatively common in certain geomorphic and geological environments in British Columbia (e.g., Clague and Evans, 1987; Cruden, 1985; Cruden et al., 1989; Eisbacher, 1979; Evans, 1984, 1988, 1989a, b, c, 1990a; Evans and Clague, 1988; Evans and Gardner, 1989; Evans et al., 1989).

A complex set of structural factors, detachment mechanisms, and triggers leads to the occurrence of a rock avalanche. Detachment is favoured on steep rock slopes where planar structural elements, such as joints, bedding planes, and foliation, combine to form a detachment surface that may consist of a single surface (as in rock avalanches involving dipping sedimentary rocks of the eastern part of the Cordillera) or multiple surfaces (which are typical of the rock avalanches found in the plutonic and metamorphic rocks of the Coast and Cascade Mountains) that result in more complex movement mechanisms.

Four rock avalanches, which have occurred in major modern transportation corridors, and that are illustrative of the scale and nature of this landslide type in the Vancouver region, are described below.

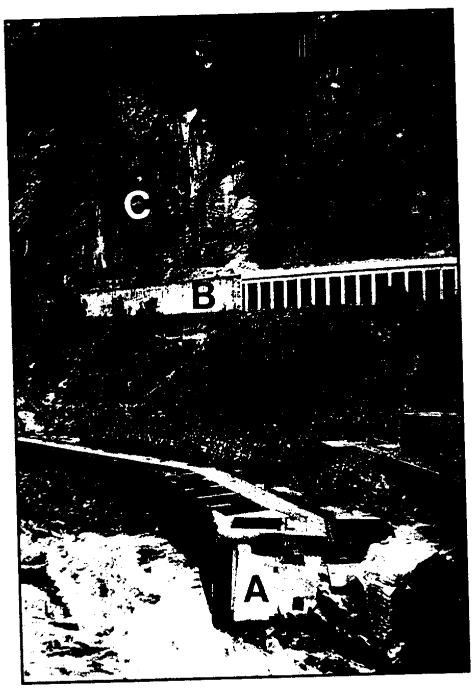

Figure 7. *View of Hell's Gate fishways, **A**) looking upstream from the west bank of the Fraser River in 1985. Note Canadian National Railway rockfall protection structure, **B**) and steep jointed rock slope of Fraser Canyon wall above **C**) source of 1914 rockfall. GSC 1994-709B*

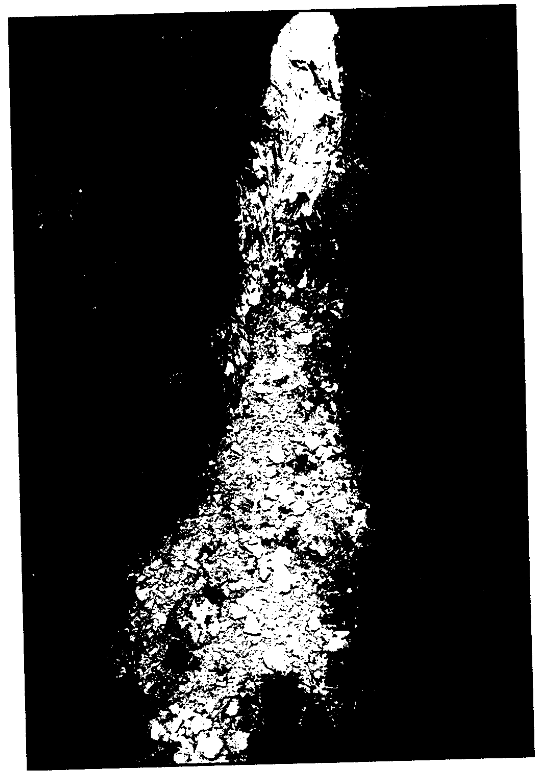

Figure 8. *Typical small rock avalanche (estimated volume 20 000 m^3) in jointed plutonic rock, north side of Fraser Valley, 2 km northwest of Hope. GSC 1994-492G*

Figure 9. *Destroyed buildings and rock debris at Jane Camp, Britannia mine, following the 1915 rock avalanche which resulted in 56 deaths. The Jane Camp tragedy is Canada's second largest landslide disaster, after the 1903 Frank Slide (photo by British Columbia Museum of Mining).*

Hope Slide

The 1965 Hope Slide (Fig. 1, 10) is the largest historical rock avalanche known to have occurred in Canada. It involved 48 000 000 m^3 of rock which descended the southwestern slope of Johnson Peak in two phases separated by about 3 hours. The landslide inundated several kilometres of the Hope-Princeton transportation corridor (Fig. 10), burying three vehicles and claiming four lives.

As noted by G.M. Dawson, the first Geological Survey of Canada geologist in the region (Dawson, 1879), Johnson Peak was the site of a prehistoric rock avalanche. A radiocarbon date obtained from organic material found beneath the debris yielded a radiocarbon age of 9680 ± 320 BP (GSC-1433) (Mathews and McTaggart, 1978), representing a minimum age for the landslide, which was of comparable size to the 1965 events. The 1965 events deepened the prehistoric slide surface and extended the headscarp almost to the top of the ridge. The rock avalanche developed mainly in greenstone belonging to the Hozameen Complex of Permian to Jurassic age. Felsite intrusions occur as sheets within the greenstone that dip toward the valley; some of these made up part of the sliding surface (Mathews and McTaggart, 1978; Von Sacken, 1991). Contacts between the felsite and the greenstone are sharp and are commonly marked by a weathered clay gouge.

As documented by Von Sacken (1991), the 1965 failure occurred on multiple discontinuity surfaces that dip toward the valley bottom at variable angles. The failure surface in the lower portion of the slope was controlled largely by felsite sheets (Fig. 11A) whereas steeply dipping intersecting joints controlled the upper portion (Fig. 11B).

The 1965 event was proposed by Mathews and McTaggart (1978) to have been triggered by two small earthquakes recorded at approximately the same time as the landslide in the pre-dawn hours of January 9. The possibility of a seismic trigger was further investigated by Wetmiller and Evans (1989) who re-examined the seismic records associated with the landslide. Their attempt to demonstrate an indisputable seismic trigger for the Hope slide was inconclusive. A re-analysis of the 1965 Hope Slide by Weichert et al. (1990, in press), in the light of the seismic signatures generated by the collapse of an open pit mine slope in the interior of British Columbia in 1990, however, suggests that the "earthquakes" associated with the landslide may have been generated by two phases of the landslide itself. Von Sacken (1991) and Von Sacken et al. (1992) found field evidence to support the two slide scenario. It is thought that the debuttressing of the upper slope by the first slide event, as a result of failure along felsite sheets in the lower part of the slope, led to the second event a few hours later. This scenario eliminates an obvious trigger for the Hope slide.

Analysis has shown that the prefailure slope was in a stage of limiting equilibrium before the 1965 slide (Bruce and Cruden, 1977; Wetmiller and Evans, 1989; Von Sacken, 1991) yet it had withstood substantial seismic accelerations in the past including the M = 7.4 North Cascades earthquake of 1872 (Wetmiller and Evans, 1989). It is not clear how the slope that failed in 1965 withstood such forces since, according to slope stability analysis (Wetmiller and Evans, 1989; Von Sacken, 1991), modest seismic forces should have been high enough to result in detachment.

Katz slides

The Katz slide is located on the north side of the Fraser Valley between Hope and Chilliwack (Fig. 1). Linear facilities occupying this section of the Fraser Valley transportation corridor include Canadian National and Canadian Pacific rail lines, the Trans-Canada Highway, trunk gas and oil pipelines owned by Trans Mountain Pipe Line Company Ltd. and Westcoast Energy Inc., respectively, the B.C. Tel fibre optics telecommunications line and several B.C. Hydro power grids; severance of these lines by a modern Katz slide would have a major impact on Vancouver and the Lower Mainland. As indicated on Figure 12, the corridor has been partially inundated by two prehistoric rock avalanche events. These have not been studied in detail. The following description is taken from preliminary accounts by Naumann (1990) and Savigny and Clague (1992).

Figure 10. Oblique aerial photo of 1965 Hope Slide; view to northwest. (Photo by K.W. Savigny).