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Field Trip Guidebook

TRIP 15

SLOPE STABILITY AND MOUNTAIN TORRENTS, FRASER LOWLANDS AND SOUTHERN COAST MOUNTAINS, BRITISH COLUMBIA

by

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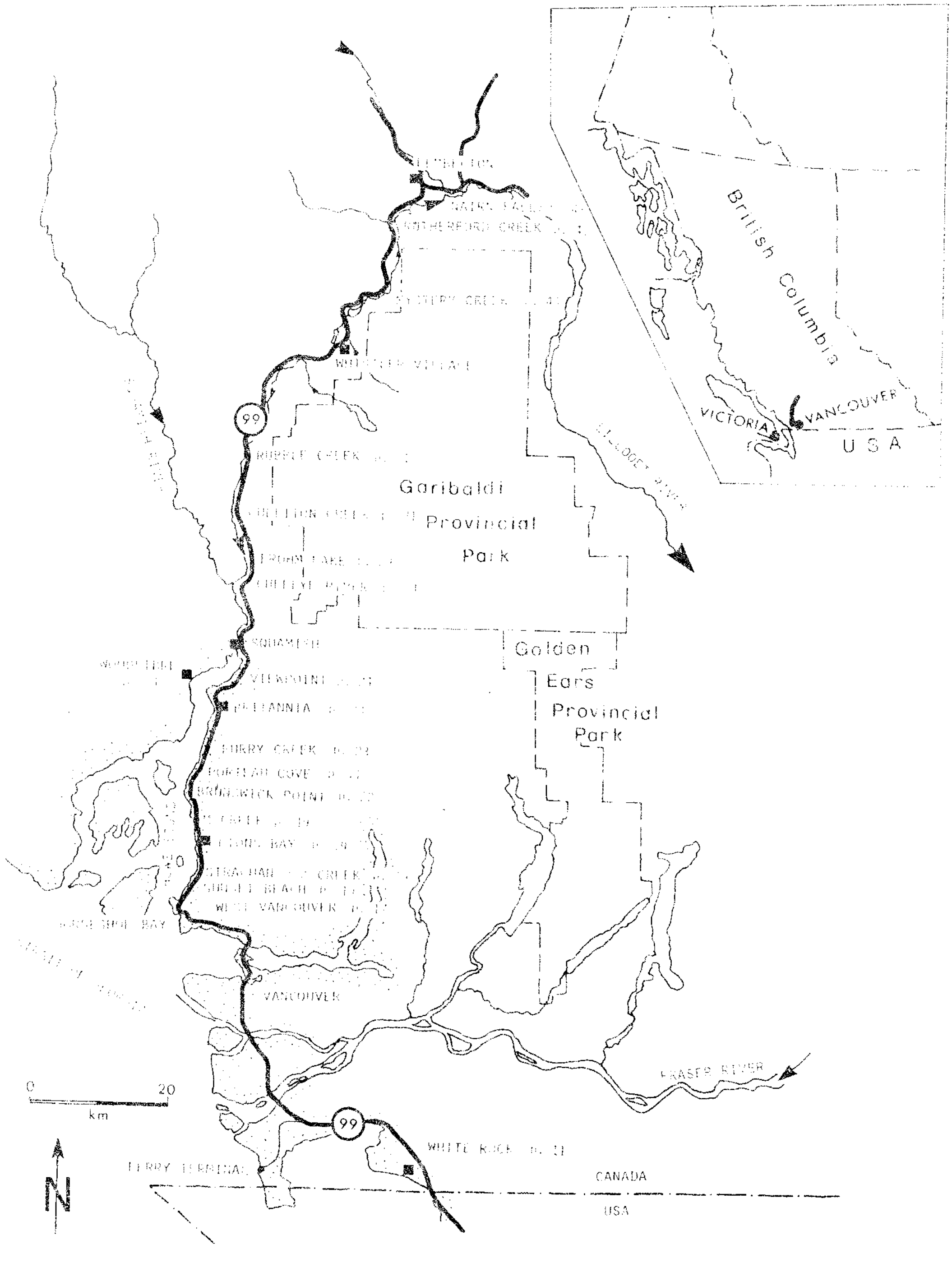


Figure 1 - Index map of excursion route which follows Provincial Highway 99.

INTRODUCTION

This guidebook provides background information for a field excursion dealing with problems of slope stability and mountain torrents encountered in the southern Coast Mountains and the adjacent urbanized Fraser Lowland of British Columbia. The south-to-north transect, spanning a distance of approximately 200 km from White Rock near the Canada-United States International Boundary to Pemberton in the Lillooet Valley, illustrates the diversity of mass movements of the Coast-Insular Zone of western Canada. This zone, characterized by steep granitic and volcanic bedrock slopes, locally mantled by surficial deposits, is subject to intense precipitation and recurrent seismic activity. On the east, some 150 km inland, the Coast-Insular Zone abuts against the Intermontane Plateau Zone which has a dry climate and therefore distinctly different slope stability problems (Eisbacher, 1979).

The excursion follows Highway 99 (White Rock-Vancouver-Horseshoe Bay-Squamish-Whistler-Pemberton) and focuses on the entire range of mass movements from small precipitation-triggered slumps in surficial deposits to huge earthquake-triggered rock avalanches. The guidebook also includes capsule accounts of historical destructive mass movements along the transect, as reported in newspapers filed at the Vancouver Public Library.

Figure 1 shows the route of the excursion with page numbers of the guidebook where specific sites are discussed in detail. The description of the sites proceeds from south to north although logistics may require some sites to be visited on the way north, others on the way south.

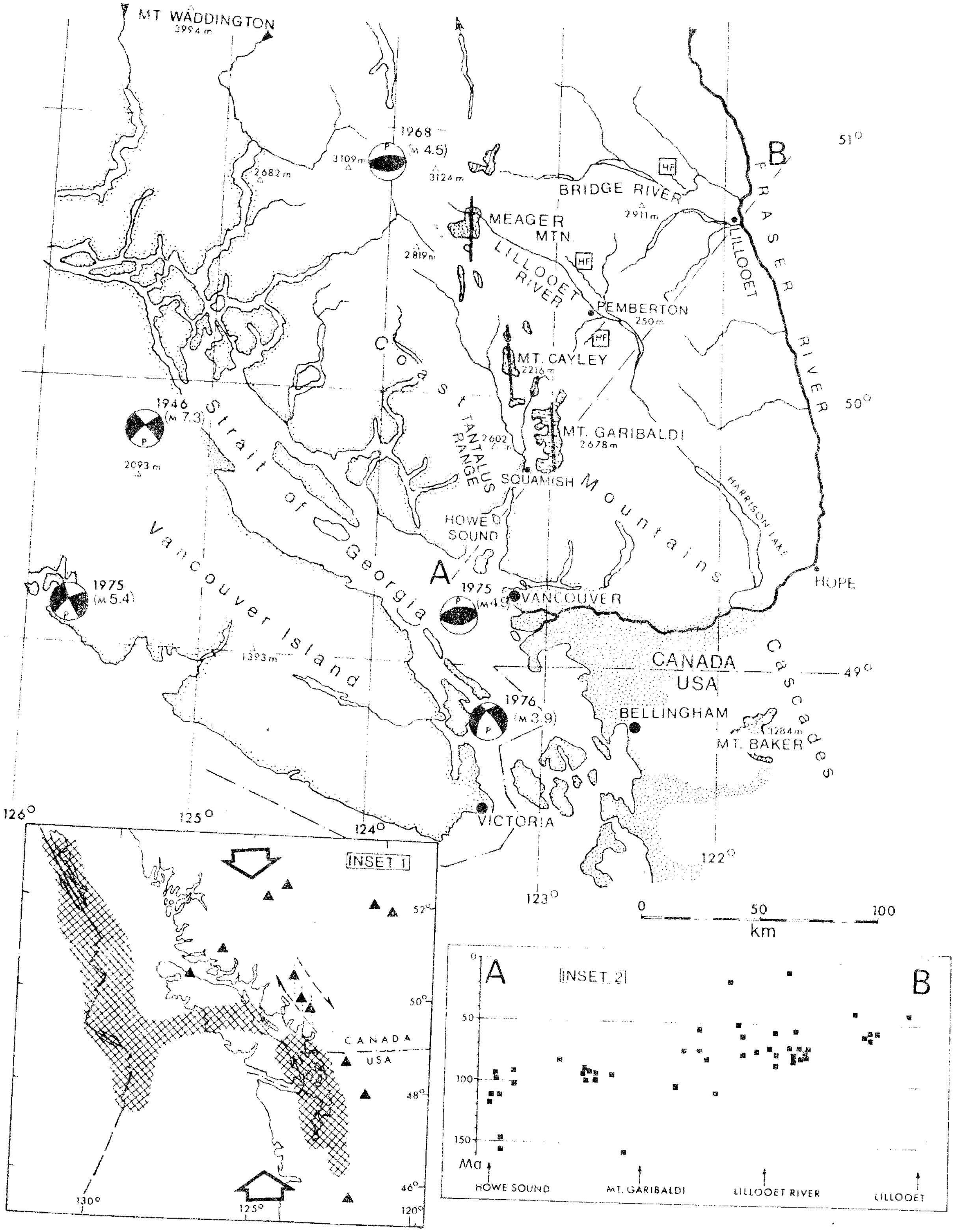
GEODYNAMIC SETTING OF THE SOUTHERN COAST MOUNTAINS AND FRASER LOWLAND

The southern Coast Mountains of British Columbia are underlain mainly by plutonic rocks of the Coast Plutonic Complex, comprising quartz diorite, granodiorite, and diorite; true granites are rare. K-Ar dates of plutonic rocks, indicating in general times of cooling, range from Jurassic to Eocene. Broadly these ages decrease from southwest to northeast. However, along a major shear zone that extends from Harrison Lake northwestwards along the Lillooet River valley several high-level intrusions have yielded Miocene K-Ar dates (see INSET 2 of Figure 2, with data from reconnaissance maps of Woodsworth, 1977, and Roddick and Woodsworth, 1979).

The plutonic rocks intrude a variety of sedimentary and volcanic successions ranging in age from late Paleozoic to Tertiary. Remnants of the sedimentary-volcanic assemblages are preserved as metamorphic septa and roof pendants strung out between the intrusive complexes and juxtaposed along major northwest-trending fault zones. Metamorphic foliation in sedimentary, volcanic, and older intrusive rocks shows predominant northwesterly trends paralleling the overall topographic grain of the Coast Mountains. Younger fracture sets, shear zones, and mafic dikes are parallel to, but also discordant with older penetrative fabrics.

Near Vancouver, along the southwestern flank of the Coast Mountains, Late Cretaceous to Eocene fluvial sediments onlap the deeply eroded Coast Plutonic

Figure 2 (opposite page) - Physiographic-neotectonic setting of the southern Coast Mountains of British Columbia. Note the en echelon arrangement of the Pleistocene volcanic complexes of Mt. Garibaldi, Mt. Cayley, and Meager Mountain; the heavy lines suggest the northerly trend of the principal eruptive centres in these complex.
HF indicates the location of Holocene fault scarps. Circles are first motion solutions for five recent earthquakes in the area; P is the inferred compression axis, M is Richter magnitude (from Rogers, 1979). Dots outline coastal zone and stipple pattern delineates areas of thick surficial deposits.
Inset 1: Location of offshore ridge-transform faults of the Pacific Ocean (broken line) and related zones of notable seismic activity (criss-cross pattern); Plio-Pleistocene volcanic centres are shown as triangles and the orientation of the compressive crustal stress regime is shown by bold arrows (from Sbar, 1982).
Inset 2: K-AR ages of plutonic rocks in the southernmost Coast Mountains, projected onto line A-B (data from Woodsworth, 1977; Roddick and Woodsworth, 1979).


MT WADDINGTON
3994 m
1968
(M 4.5)
P
3109m
3124m
2682 m
BRIDGE RIVER
2911m
HF
MEAGER MTN
2819m
LILLOOET RIVER
PEMBERTON
250 m
LILLOOET
B
FRASER RIVER
51°
MT. CAYLEY
2216m
MT. GARIBALDI
2678m
Coast Mountains
TANTALUS RANGE
2602
SQUAMISH
HARRISON LAKE
50°
1946
(M 7.3)
2093 m
Strait of Georgia
HOWE SOUND
A
1975
(M 4.9)
VANCOUVER
HOPE
Vancouver Island
1975
(M 5.4)
1393 m
CANADA
USA
49°
Cascades
1976
(M 3.9)
BELLINGHAM
3284 m
MT. BAKER
VICTORIA
126°
125°
124°
123°
122°
0
50
100
km
INSET 1
52°
50°
48°
46°
130°
125°
120°
CANADA
USA
INSET 2
A
B
0
50
100
150
Ma
HOWE SOUND
MT. GARIBALDI
LILLOOET RIVER
LILLOOET

Complex. Along the northeastern flank of the mountains an Oligocene(?) land surface is capped by late Miocene basaltic lava flows that range in age from 6 to 10 Ma (Parrish, 1982). The present high position of these lavas and a young cooling history revealed by fission track analysis of plutonic rocks suggest that a low-lying gently rolling, mid-Cenozoic land surface in the area of the present southern Coast Mountains was elevated 2-3 km in Plio-Pleistocene time, implying an average rate of uplift of up to 0.75 km/Ma (Parrish, 1982).

During the last 2 Ma several volcanic complexes along what is known as the Garibaldi Volcanic Belt were superimposed onto the rising pedestal of the southern Coast Mountains; they are the Mt. Garibaldi, Mt. Cayley, and Meager Mountain complexes (Mathews, 1958; Read, 1978; Souther, 1980). The eruptive centres within each complex trend slightly west of north and appear to be controlled by fracture zones separating valleys from mountain ridges of possibly pre-Pleistocene age (Fig. 2). The Garibaldi Volcanic Belt is part of a Pliocene-Recent volcanic province that extends from British Columbia southwards into the northwestern United States (see INSET 1 of Figure 2). The most recent eruptions in the southern Coast Mountains occurred about 2350 and 2000 years ago in the Meager Mountain area (Souther, 1977).

Neotectonic history and seismicity of the southern Coast Mountains are broadly linked to an offshore ridge-transform system with predominant north-directed right-lateral displacement of the Pacific plate (Milne et al., 1978; Keen and Hyndman, 1979). As indicated on INSET 1 of Figure 2, most historic seismicity has been offshore. First motion analysis of a few earthquakes with epicentres in the onshore area of southwestern British Columbia and northwestern United States suggests that this part of the North American plate presently is under north-south compressive stress (Rogers, 1979; Sbar, 1982). The largest onshore earthquake in recent history had its epicentre on central Vancouver Island and occurred on June 23, 1946. Shaking related to this seismic event caused numerous slope failures and extensive ground subsidence (Mathews, 1979; Rogers, 1980). Evidence presented in this guidebook indicates that large prehistoric earthquakes occurred within the Coast Mountains, creating fault scarps and possibly triggering large slope failures.

During Pleistocene time north-south compressive stresses may have favoured extrusion of lava from magma chambers aligned on north-trending basement fractures and accounted for part of the subsidence recorded in the extensive Pleistocene deposits of the Lower Mainland of Vancouver.

PLEISTOCENE GLACIATION(S) AND RELATED SURFICIAL DEPOSITS

The Quaternary history of southwestern British Columbia has been summarized recently by Clague (1981) and Clague and Luternauer (1982). For details and further references the reader is advised to consult these two publications.

Repeatedly during the Pleistocene, the mountains, lowlands, and parts of the continental shelf of southwestern British Columbia were covered by glaciers. At its full development the vast Cordilleran ice sheet extended more than 300 km south of the US-Canada border and reached an elevation of 2000 metres in the southern Coast Mountains. Much of the unconsolidated deposits filling the valleys and lowlands of the region were laid down during the last major glaciation

(Fraser Glaciation) and during the immediately preceding nonglacial period (Olympia nonglacial interval). The low-lying areas southwest of the mountains were sites of deposition for thick proglacial sand (Quadra Sand) between about 25,000 years and 18,000 years ago; they were subsequently covered by till and gravelly ice-contact sediments (Vashon Drift). During recession of the ice, between about 13,500 and 10,000 years ago complex successions of glaciomarine diamictons, subaqueous outwash, sands, gravels, dropstone laminites, fan delta deposits, and marine clays were laid down on coastal lowlands depressed by the weight of the ice. Isostatic uplift, locally exceeding 200 metres, was rapid and essentially complete at Vancouver about 11,000 years ago. In the Coast Mountains deglaciation was accompanied by resurgent volcanic activity, particularly in the Garibaldi area. Volcanic cliffs that had formed high above and at the contact with the glacier ice became unstable escarpments, which retreated and continue to retreat by sporadic large scale mass movements (Read, 1977; Moore and Mathews, 1978; Clague and Souther, 1982). After retreat of the glaciers and completion of isostatic adjustments, deltas, including that of the Fraser River, prograded into the Strait of Georgia and narrow fiords of the mountainous Pacific coast.

Throughout postglacial time torrents have discharged their bedload from steep catchment basins onto adjacent valley floors and into fiords. Sporadic debris flows channeled down the torrent courses have been and continue to be a significant mechanism for debris transport from the heights of the southern Coast Mountains to low-lying terrain. The ability of torrent systems to produce potentially destructive debris flows depends on the topographic-geological parameters illustrated in Figure 3: steep catchment areas, voluminous debris sources (surficial deposits or unstable bedrock slopes), narrow gorges, and depositional fans (or cones).

PRESENT CLIMATE AND VEGETATION

Moist air moving eastward from the Pacific Ocean and rising along the western slope of the Coast Mountains is generally responsible for periods of heavy precipitation in coastal British Columbia. Most precipitation falls in autumn and winter. Mean annual precipitation ranges from approximately 1500 mm in Vancouver to 3500 mm in the high mountains. Superimposed on the strong precipitation gradient from the Fraser Lowland to the Coast Mountains is the temperature-sensitive control on the position of the winter snow line along slopes facing the sea: winter snowpacks of 300 to 400 cm may accumulate above 1000 m while no snow at all may remain on the rain-swept lowlands. Thus, sudden rises in ambient air temperatures accompanied by heavy precipitation may lead to rapid snowmelts enhancing torrential runoff. On such occasions thin-skinned failure of saturated soil veneers and embankment erosion along torrent channels may combine into potentially destructive mass movements.

In their natural state the lower mountainsides of the southern Coast Mountains are covered by coast forest which is dominated by Douglas fir (Pseudotsuga menziesii), western hemlock (Tsuga heterophylla), and western cedar (Thuja plicata). Locally, stands of pine (Pinus monticula and Pinus contorta) predominate on dry ground and rocky ledges. Flood plains, torrent embankments, and snow avalanche tracks are commonly covered by thickets of alder (Alnus) and maple (Acer). The coastal belt, which includes Vancouver Island and other

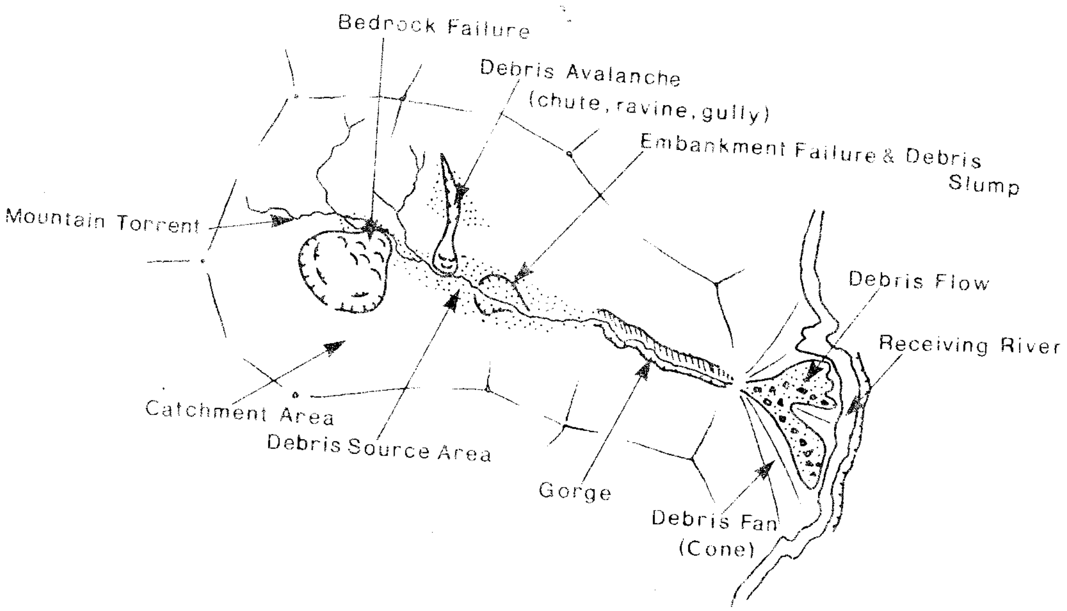


Figure 3 - Principal features of a mountain torrent showing debris-generating mechanisms.

smaller islands, is the most productive and economically significant forest region in Canada.

Above elevations of approximately 800 to 1000 metres the coastal subalpine forest zone succeeds the coastal forest. The subalpine forest zone is characterized by firs (Abies amabilis and Abies lasiocarpa), and mountain hemlock (Tsuga mertensiana). Between elevations of 1800 and 2200 metres a generally narrow belt of alpine meadows leads into tundra or bare blocky debris left by mountain glaciers during their retreat from their mid-19th century Neoglacial terminal moraines.

A BRIEF HISTORY OF DEVELOPMENT

Before the first white explorers, miners, settlers, and loggers struggled up the rivers of the southern Coast Mountains, valleys and fan deltas were inhabited by bands of the Salish people. During and after the Fraser and Cariboo gold rushes in the mid-19th century trails were blazed across the densely vegetated mountains to provide access to the interior region. Late in the 19th century colonization gradually extended across the Fraser Lowland and into some of the more hospitable mountain valleys (e.g. Lillooet Valley).

In 1905 Anaconda Copper began to exploit a rich polymetallic copper deposit on Howe Sound, south of Squamish. The community of Britannia, built at the site of the mine, was serviced by boat until the mid-1950s, and thereafter by road. The mine eventually closed in 1974 and is now partly used as a mining museum.

Since 1914 a railroad has connected the town of Squamish at the head of Howe Sound with the town of Lillooet in the interior. Until the mid-1950s Squamish used to be a point of transfer for resources from the northern interior onto ships or barges.

In 1920 Garibaldi Provincial Park was established along the eastern uplands of the Cheakamus River valley to attract visitors to the region and to protect the scenic volcanic peaks from the gradually expanding forest resource use and mining exploration.

In 1956 road and rail beds, carved from the steep bedrock cliffs rising on the east side of Howe Sound, finally connected Squamish with Vancouver. A hydroelectric installation (Cheakamus Dam) was constructed in Cheakamus Valley soon thereafter, and high-voltage transmission lines were installed in the valley to transfer power from other generating plants farther north to the rapidly developing urban centres of southwestern British Columbia.

In 1965 extension of Highway 99 from Squamish to Pemberton opened this part of the southern Coast Mountains to tourists. In 1966 ski lifts and other facilities were built at Whistler Mountain serving the expanding recreational needs of Vancouver.

In the 1970s both logging and recreational activities advanced into hitherto inaccessible mountain valleys. Real estate development, continued logging, a need for more transmission line space, and intensified tourism pre-

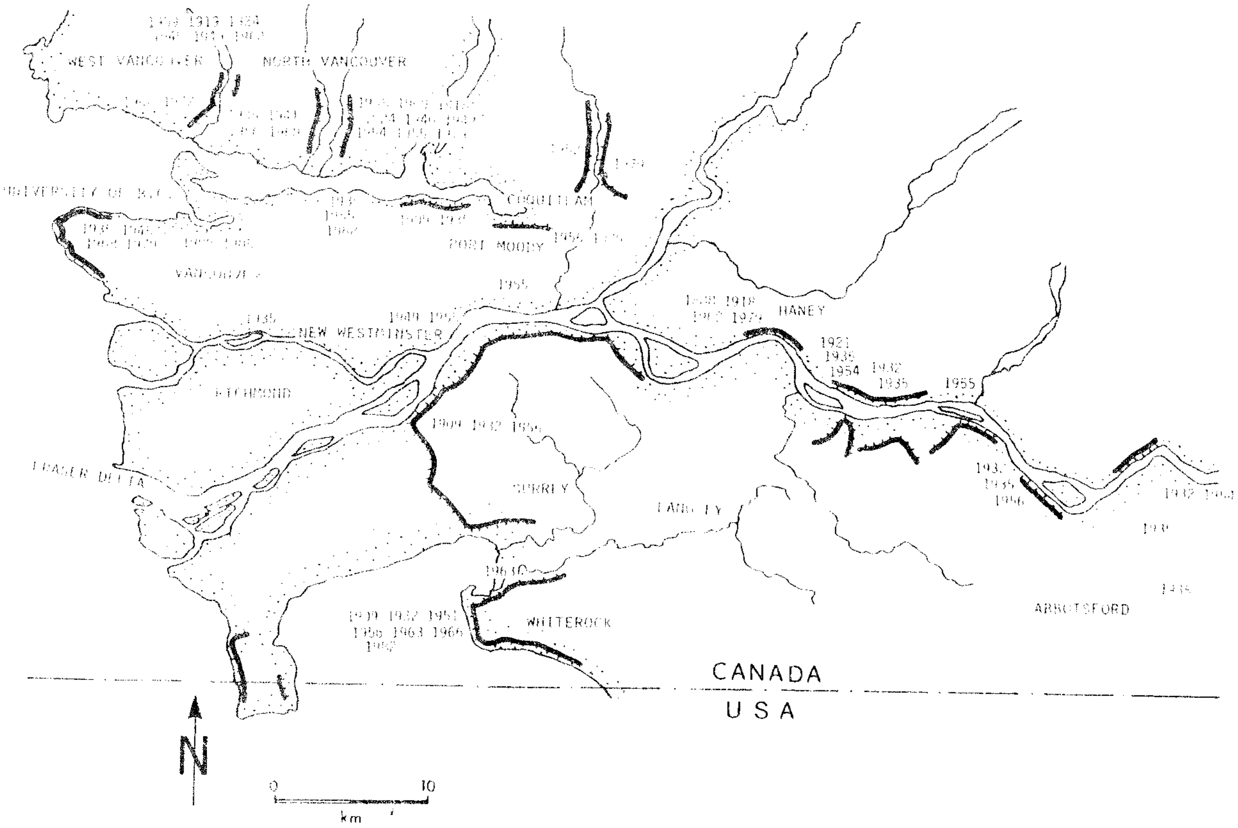


Figure 4 - Rainstorm-triggered mass movements in surficial deposits of the greater Vancouver area. Bold barbed lines indicate upland terrace rims with slope regression due to debris avalanching, slumping and gullying. Dates refer to year of mass movements (after Eisbacher and Clague, 1981).

sently pose considerable challenges to resource managers of the Squamish-Pemberton corridor.

WHITE ROCK-VANCOUVER

Urbanized Uplands

Metropolitan Vancouver spreads from the low-lying delta surface of the Fraser River onto the bedrock slopes of the southern Coast Mountains. Much of the development of Vancouver and its satellite communities has occurred on gently rolling uplands rising to about 150 metres above the sea. These terrace-like uplands consist of unconsolidated Pleistocene deposits which in general are capped by a blanket of impermeable till and stony clay. Along the sloping fringes of the uplands, natural and artificial surface changes have led to historical mass movements of considerable cumulative impact (Fig. 4). Deep gullies connect the upland surface with colluvial aprons and debris fans at the foot of well defined terrace escarpments. Throughout most of the year the gullies are either dry or carry insignificant trickles of water. However, during major rainstorms the same channels carry runoff that collects on large impermeable upland surfaces, commonly paved and insufficiently drained by storm sewers. As most gully walls and terrace rims are subject to steady creep involving a layer of tree roots, soil, or landfill to depths of 1 to 2 metres, any dramatic increase in the degree of saturation facilitates failure of thin veneers of debris that may end up blocking runoff along the narrow channels at the bottom of the gullies.

Since the turn of the century 28 storms have caused significant mass movements at the edges of the uplands within the area shown in Figure 4 (Eisbacher and Clague, 1981). These storms have been characterized by rainfall in excess of 50 mm/24 h and local intense squalls of short duration. Nearly all have occurred between the months of October and March.

The most notable mass movements occurred on 30 January 1888 (Haney), on 29 November 1909 (New Westminster), on 20-25 January 1935 (University of B.C.), on 14-17 December 1979 (Port Moody, North Vancouver), and in January and February 1982 (White Rock). Damage from mass movements is inflicted by a) retrogressive gullying which leads to undercutting of homesites located close to the terrace rims, b) debris avalanches and flows, which strike houses at the mouth of gullies or block transportation routes.

A study carried out after the serious storm of December 1979 identified the principal areas susceptible to mass movements (Fig. 4) and the critical meteorological controls (Eisbacher and Clague, 1981). This and subsequent experience shows that slide-triggering rainstorms occur when a pronounced atmospheric depression is lodged in the Gulf of Alaska causing strong southwesterly gusts, rising air temperatures, and local storm cells. Failure of gully walls and upland rims saturated with overland runoff tends to occur during the final phase of such squalls of rain.

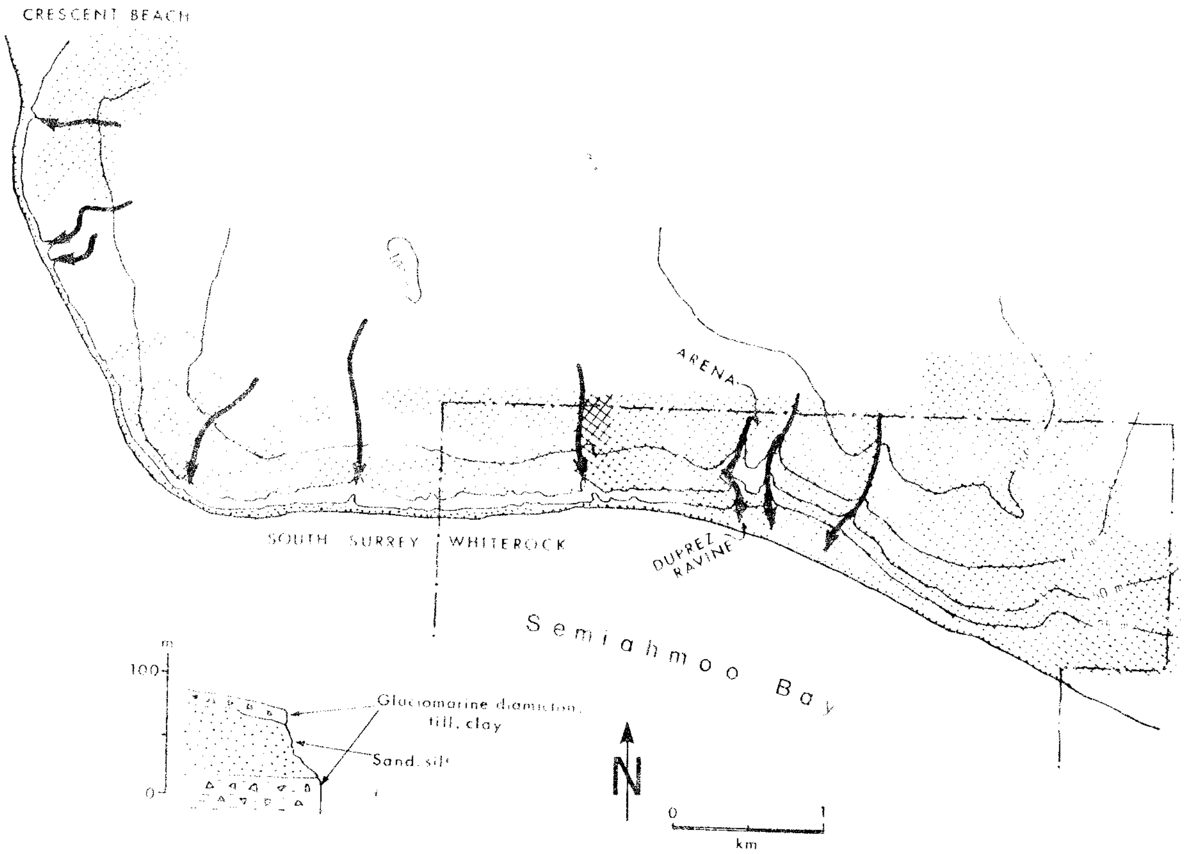


Figure 5 - The urbanized edge of the White Rock upland. A schematic cross section illustrates the geology of the rim. Major gullies are shown as arrows. Built-over terrain is indicated by a criss-cross pattern. Duprez Ravine and the gully directly to the east are accessible from the road paralleling the rail track and beach in White Rock.

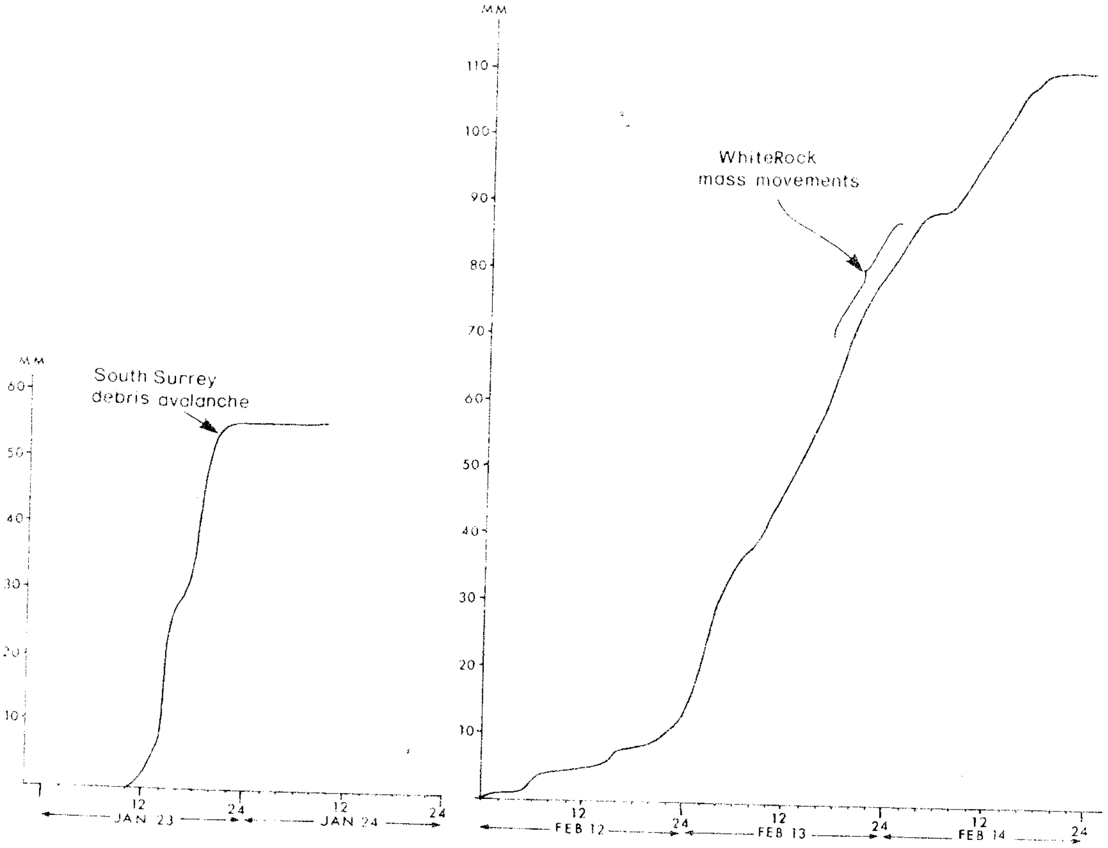


Figure 6 - Cumulative rainfall Surrey on January 23-January 24, 1982, and in White Rock between February 12 and February 14, 1982. Data from Atmospheric Environment Services, Environment Canada. Arrows indicate times of mass movements.

Examples of Destructive Mass Movements in the Vancouver area

On January 30, 1880, a 30-metre high embankment of the Fraser River at Haney failed along a head scarp approximately 300 metres long. Retrogressive slumping and outward flow of the slide mass partly blocked the Fraser River, inflicted substantial material damage and claimed one life (Evans, 1982).

On November 29, 1909, heavy rains (111 mm in 24 h) caused a blockage of a culvert along a rail bed near New Westminster. The impounded runoff from a gully saturated the fill of the rail embankment and caused its failure. The slump left a section of the tracks unsupported. A train crossing this section derailed and 22 men travelling in a box car were killed.

On January 20-25, 1935, during a period of heavy snow fall, followed by two days of torrential rain (167 mm), a minor gully on the campus of the University of British Columbia changed into a major 'canyon'. A total volume of 100,000 m^3 of sand, partly eroded by uncontrolled runoff, partly due to collapse of oversteepened embankments, swept in surges towards the sea where a fan was built (Eisbacher and Clague, 1981).

Between December 14 and 17, 1979, two separate squalls of rain triggered numerous debris avalanches and a destructive debris flow along the terrace rims of Port Moody, Coquitlam, and North Vancouver. Several houses were demolished, but fortunately there were no casualties (Eisbacher and Clague, 1981).

White Rock-South Surrey

The communities of White Rock and South Surrey are built on rolling and seaward facing uplands. The escarpment bordering this upland along the scenic Semiahmoo Bay offer good examples of the type of mass movements that threaten development of these premium sites in the Vancouver region (Fig. 5). In White Rock-South Surrey several gullies dissect a partly built-over slope that rises from the sea to an elevation of about 100 metres. Urbanization has infringed on gully walls and terrace rims which here are capped by an impermeable layer of clay or till. Haphazard tilting of many trees indicates creep of the colluvial veneer on gully walls and sporadic incipient slumps along sand-clay escarpments. A walk along the railroad tracks at the foot of the upland west of White Rock reveals numerous active and relict retrogressive ravines whose headwalls are commonly crowned by houses.

In the winter of 1982 the White Rock-South Surrey area twice was subject to intense rainstorms which followed periods of snowfall. On January 23, 1982, up to 55 mm of rain was registered within a period of 12 hours in Surrey (Fig. 6). At 8 PM, towards the end of the storm a debris avalanche near Crescent Beach demolished part of a home. On February 13, 1982, after two days of snow, the air temperature in White Rock rose; during the following 48 hours a total of 100 mm of rain fell (Fig. 6). Near the end of the storm, on the night of February 13, about 30 debris avalanches and slumps broke away along steep gullies and bowls facing Semiahmoo Bay. The failures involved natural surficial deposits, soil veneers, landfill, and trees. Their volume ranged generally from a few tens of cubic metres to 600 m^3. Some failures were triggered by oncentrated runoff from paved roads, parking lots (e.g. White Rock Arena), lugged storm sewers, and inadequate drains. The foundations of several homes ere precariously undercut when headwalls of tributary gullies failed adjacent o or below the buildings. In Duprez Ravine (Fig. 5) a mass of landfill, mud nd trees (about 150 m^3) crashed into and demolished the wing of a motel built cross the lower section of the gully. Fortunately the damaged part of the tructure was unoccupied at the time of the mishap. West of White Rock several ebris flows swept across the railroad tracks.

Because of its scenic setting, development of the White Rock-South Surrey pland will probably continue in the future. It seems that gully walls, ter- ace rims, and landfill will have to be re-enforced and runoff meticulously ntrolled if damage during future storms is to be kept within tolerable limits.

VANCOUVER-SQUAMISH

The mountains north of Vancouver consist mainly of fractured or massive artz diorite-granodiorite complexes intrusive into northwest-trending folia- d meta-argillites and volcanics. Howe Sound fiord extends 50 km inland, is to 280 m deep, and is flanked by bedrock ridges rising steeply from the sea elevations of about 1600 m a.s.l.

At the climax of the Fraser Glaciation total isostatic depression of the astal fringe of the southern Coast Mountains amounted to about 300 m (Clague, 81). During the period of rapid isostatic rebound,which accompanied deglac- tion, the initial fan delta surfaces rose to 100-200 m above present sea vel. The elevated relict fans were deeply entrenched by mountain torrents ich continued to build new fan deltas into the sea (Fig. 7). The present-day rents derive much of their bedload from embankments along these relict vio-deltaic deposits ('low-level source areas' in Figure 7) and from pockets Pleistocene ice-contact debris and Holocene rock fall talus ('high-level rce areas' in Figure 7) along the crest of steep catchment areas.

Along Howe Sound the orientation of major bedrock cliffs and torrent ges is generally controlled by northeast- or north-trending fracture zones northwest-trending metamorphic foliation.

Along their lower reaches, the torrent gorges are covered by dense forest. the upper part of torrent basins, tributary ravines are commonly also well- ured snow avalanche tracks. On north-facing slopes snow avalanche tracks ch down to approximately 300 m a.s.l.; in general, snow avalanches do not ch Highway 99.

Recurrent destructive mass movements along the narrow shore zone of Howe d include a) debris flows and debris floods from high- and low-level deb- source areas, b) submarine slope failures in unconsolidated deposits, and rock falls from natural cliffs or artificial cuts.

The section of Highway 99 connecting Vancouver and Squamish is divided four parts with regard to the salient slope stability problems: West ouver, Horseshoe Bay-Brunswick Point, Brunswick Point-Porteau Cove, Porteau -Squamish. Pullouts and parking lots along this heavily travelled road may

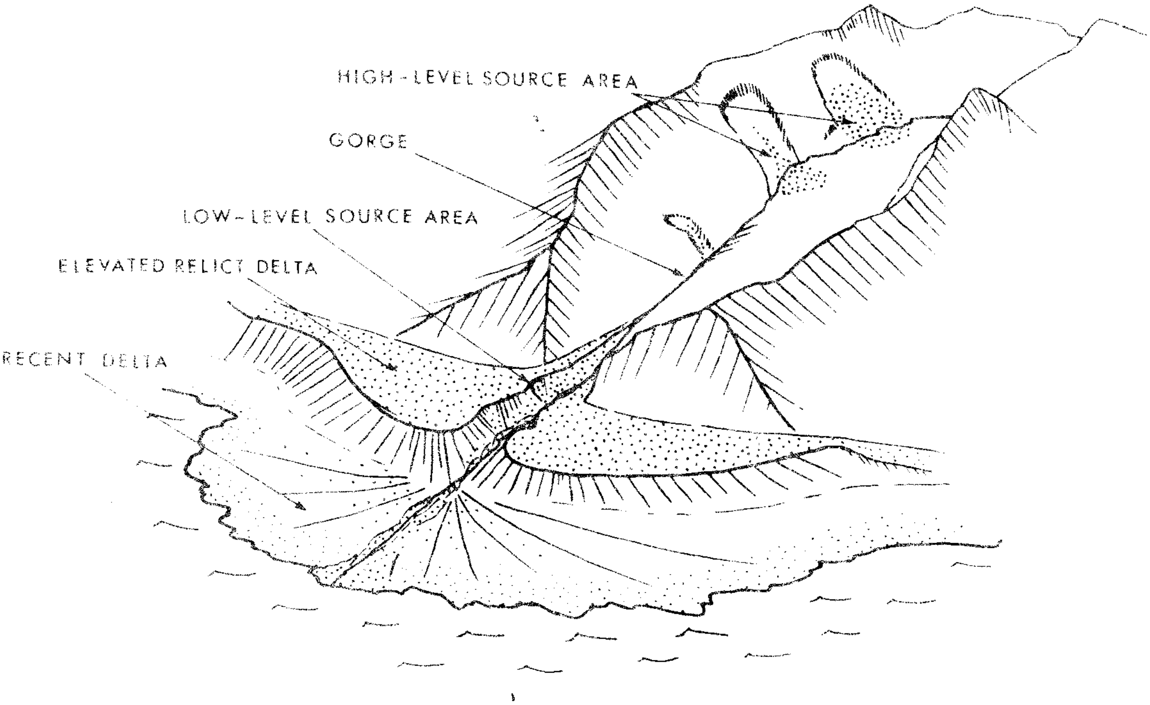


Figure 7 - Diagrammatic illustration of debris sources along torrents discharing across fan deltas into fiords of the southern Coast Mountains.

not be suitable for certain vehicles and discretion should be exercised when crossing the highway.

West Vancouver

The slopes above the north shore of Vancouver are densely populated and comprise the two municipalities of North Vancouver and West Vancouver. The Capilano River is the municipal boundary between the two communities and its fan delta is a conspicuous gravel flat just west of Lions Gate Bridge. The Capilano River flows from the Capilano water reservoir which meets one third of Vancouver's drinking needs (the other two thirds being met by wine).

Several mountain torrents with gradients between 14% and 18% (11^{o} and 12^{o}) descend from forest-covered bedrock slopes that are mantled by only thin unconsolidated sediments (generally till). Below the 200-metre contour the torrent channels are cut into late Pleistocene fan delta deposits. During severe storms unprotected channel embankments are subject to erosional scour. Bouldery debris from low-level sources may block culverts and cause serious flooding on built-over debris cones and shoreline flats below. In addition, terrace rims are susceptible to shallow debris slides.

On July 12, 1972, a freak summer rainstorm dumped more than 95 mm of rain onto the slopes of West Vancouver; several torrents overflowed and debris mobilized from a construction site was propelled down Rogers Creek inflicting considerable erosional damage to roads and properties. Several retention basins have since been built in West Vancouver to delay flood runoff from storm sewers.

During the night of October 30/31, 1981, a regional rainstorm deluged the north shore mountains. One of the West Vancouver torrents (Lawson Creek) locally undercut its bouldery embankments and plugged a narrow culvert with debris eroded along the embankments. Debris and flood water soon spilled over the culvert and onto the inconspicuous cone of the torrent which is completely built over. Damage from this debris flood was estimated between $500,000 and 1,000,000.

In recent years there has been apprehension concerning potential erosion and flood damage along other creeks as well. Effective stabilisation of channel walls by revetments may be required to protect properties along the normally tranquil mountain streams during phases of severe storm runoff.

Horseshoe Bay-Brunswick Point

At Horseshoe Bay Highway 99 turns sharply to the north and enters Howe Sound (Fig. 8). This stretch illustrates the hazard from mass movements, set off along high-level debris sources and channeled through bedrock ravines onto small bedrock promontories, debris cones, and fan deltas which have been subdivided for residential development. Torrent channels and dry ravines along the mountainside terminate upwards in bedrock cliffs or snow avalanche tracks. Their inclination generally exceeds 15^{o}. Some of the fringing slopes were logged in the 1960s; enhanced debris movement resulting from these activities

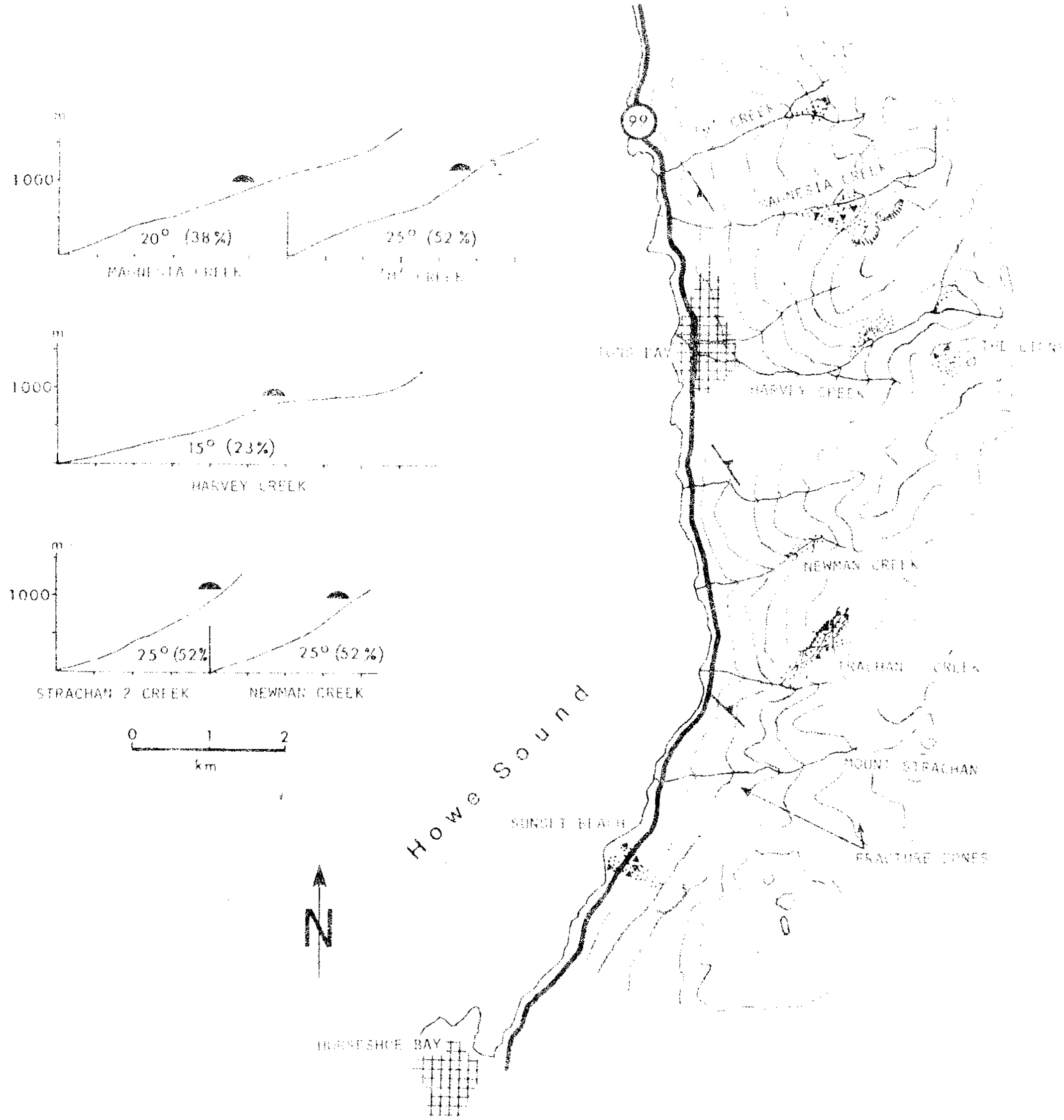


Figure 8 - Sketch map of the steep eastern shore of Howe Sound north of Horseshoe Bay. Profiles of five torrents with debris flow potential are plotted on the left; inverted-cup symbol above the torrent profiles indicates location of high-level potential debris sources.

has been demonstrated by O'Loughlin (1972).

Sunset Beach (2.5 km north of Horseshoe Bay) straddles a bedrock spur that projects into Howe Sound. Its upper part is covered by a conical rock avalanche deposit consisting of angular quartz diorite slabs. Since mature forest covers the blocky lobe it is at least 300 years old. The total volume of the lobe is approximately 300,000 to 400,000 m^3; its source is a fracture-controlled cliff face at an elevation of 600 m a.s.l. Most of the surface of the bedrock spur and the fringe of the rock avalanche deposit have been subdivided and built over with residential buildings.

Strachan-2 Creek (4 km north of Horseshoe Bay) is a high-gradient torrent (52%) whose northern tributary branch is a northeast-trending fracture-controlled rock fall chute at an elevation between 800 and 1000 m a.s.l. Mobilization of blocky debris from this rubble-filled ravine produces debris flows that gather momentum in the gorge below and subsequently burst onto the steep debris cone bordering Howe Sound.

On September 18, 1969, during a local rainstorm, a boulder flow of several thousand cubic metres swept away the highway bridge and dislodged the railroad bridge across the torrent. Two cars plunged into the gaping hole in the highway, but the four occupants survived. One car and its driver disappeared along this stretch of road, and presumably were carried to sea by the debris flow. The winter of 1968/69 had been characterized by cycles of abnormal freeze-thaw activity (see Porteau Cove); massive rock falls into the upland ravine of Strachan-2 Creek may have provided an unstable source of granitic rubble which was mobilized during the September storm. A strong steel concrete bridge was constructed across Strachan 2 Creek after the debris flow.

On December 4, 1981, a squall of rain (approximately 20-30 mm/5 h) coupled with rapid snowmelt at higher elevations mobilized some 30,000 to 40,000 m^3 of debris, including blocks with diameters of more than 2 metres, from the rubble-filled Strachan-2 upland ravine. Fortunately, the highway bridge withstood the pressure of the slow-moving boulder lobe and blocked its further advance onto the debris cone where several residences had sprung up in the 1970s. Nevertheless, one person was killed during the hasty evacuation. At present, four bridges cross the apex of the cone, providing some protection to the houses located below.

Lions Bay is a community built mainly on the shoulders of an incised relict delta cone. However, some buildings also flank the only slightly incised channel on the recent fan delta.

During the storm of September 18, 1969, when several other torrents in the area spilled bedload into the sea, Harvey Creek (gradient 23%) was flowing at bankfull stage and carrying a substantial load of trees and boulders derived from a high-level point source in unconsolidated deposits. The peak of the debris flood, estimated at more than 100 m^3/sec (Russell, 1972) damaged several homes on the delta cone. A large clearcut, stretching across most of the catchment area, may have intensified runoff that mobilized the main pulse of debris.

M Creek (2 km north of Lions Bay) is a high-gradient creek (gradient 48%), flowing from an elevation of about 1300 m a.s.l. to a small fan delta on Howe Sound. On October 27, 1981, near midnight, a small avalanche consisting of sur-

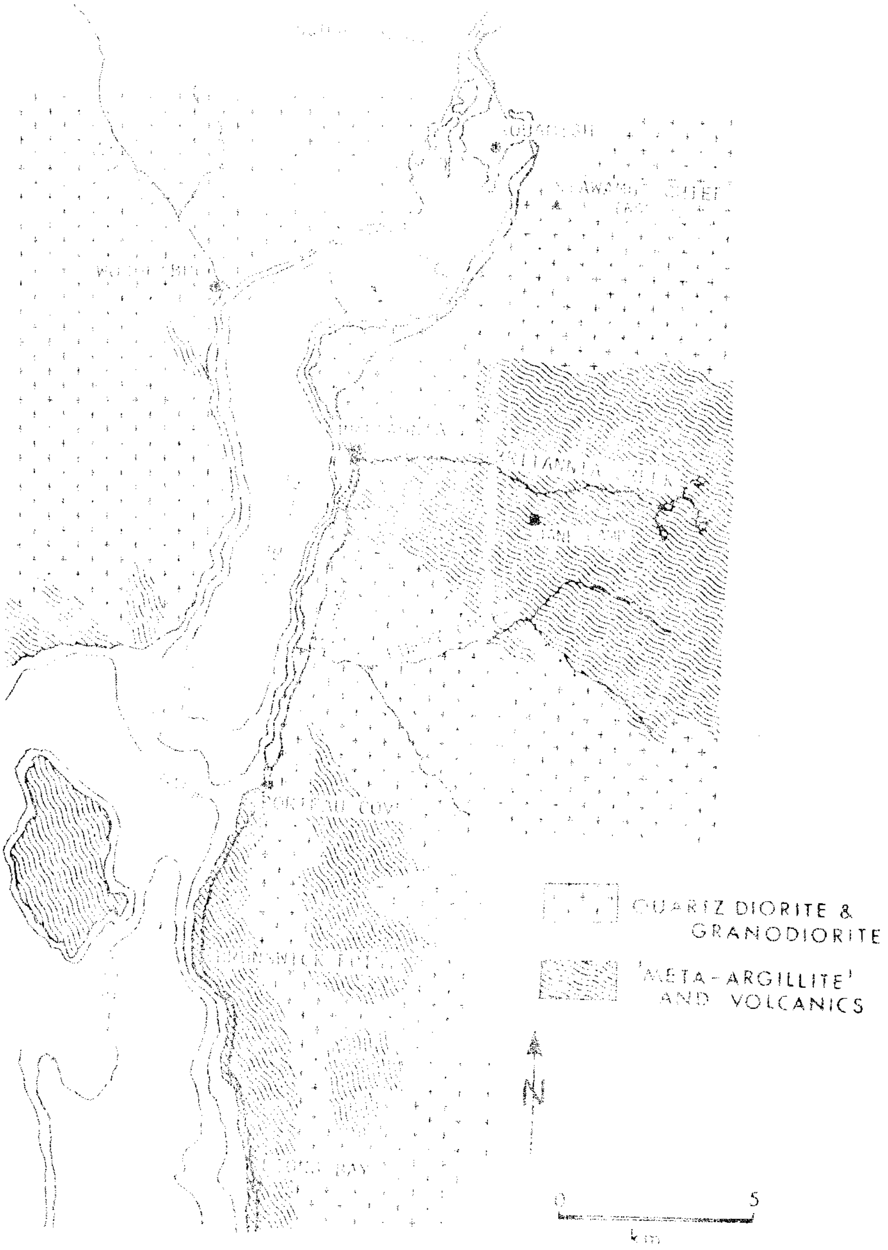


Figure 9 - Sketch map showing the two predominant bedrock types along Howe Sound between Lions Bay and Squamish: the generally massive to weakly foliated igneous rocks (quartz diorite, granodiorite) and the strongly sheared, foliated, and intensely fractured meta-argillites, greywackes and volcanics. Submarine contours outline the morainal sill extending across Howe Sound near Porteau Cove.

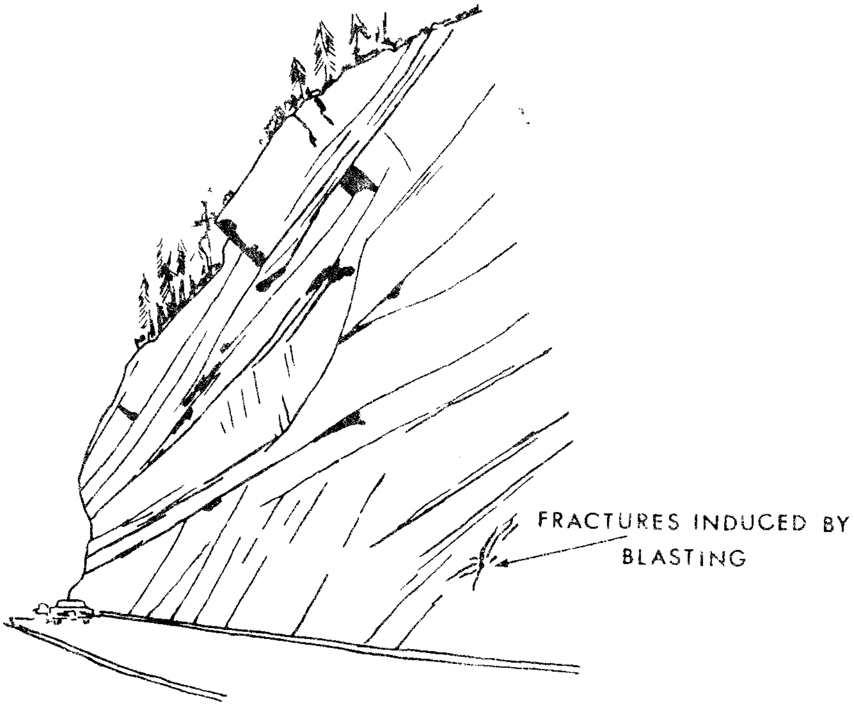


Figure 10 - View of the sheeted structure in weakly foliated quartz diorite along Highway 99 at Porteau Cove. Note that there are two sets of joint sets, both roughly parallel to the surface.

ficial debris and fractured bedrock failed along a steep tributary draw along the margin of an old clearcut at 1150 m a.s.l. The debris temporarily blocked the main rain-swollen bedrock channel, then descended to a logging-road crossing where it burst across a log jam and swept downwards into the gorge, growing to a volume of approximately 15,000 m^3. The boulder front, having gained a velocity of several tens of metres per second had sufficient momentum to knock out the central wooden support columns of the highway bridge, slicing an 18-metre chasm across the road bed. An unoccupied residential building on the fan delta was carried to sea. Several vehicles approaching the bridge in rain-swept darkness plunged into the gap and disappeared in the debris streaming towards the sea. The accidents claimed 9 lives. In 1982/83 a new free-span steel-concrete bridge was being completed across the torrent.

Brunswick Point-Porteau Cove

For approximately 5 km between Brunswick Point and Porteau Cove, Highway 99 passes through one of the most serious rock fall zones in southwestern British Columbia. Excavation of the railroad track and highway bed in the late 1950s resulted in vertical cuts which locally are more than 100 m high. The bedrock consists of intensely fractured northwest-trending meta-argillite and volcaniclastics in the Brunswick Point area, and massive quartz diorite, characterized by a weak foliation and widely spaced, surface-parallel fractures ('sheeting'), north of Porteau Cove (Fig. 9).

The Brunswick Point meta-argillite section has experienced repeated rock falls ranging from individual small blocks to large wedge failures. The large failures are generally preceded by breakout of smaller rock fragments along pre-existing fracture zones.

On February 13, 1969, a fall of 6000 m^3 closed the highway; on August 25, 1976, a fall of 1500 m^3 closed the highway for two days and also caused the derailment of a train; on January 16, 1982, when heavy snowfalls brought traffic on the road to a standstill a single block fell from one of the cliffs on a stopped car, killing one person. In 1972 one of the most notorious cuts through the meta-argillite was stabilized by the application of a blanket of wiremesh and shotcrete 5 to 10 cm thick. Horizontal drains were drilled above road level. Effective scaling of this and other meta-argillite cuts has proven to be extremely difficult.

For 500 metres north of Porteau Cove the highway has undercut a quartz diorite cliff with widely spaced (1-5 metres) and surface-parallel joints that dip approximately 50° to the west. Blasting during construction probably opened several incipient 'sheet' joints in the weakly foliated but otherwise massive rock mass. The fact that the rock is internally stressed is well illustrated by a set of blasting fractures at the bottom of the cliff at Porteau Cove (Fig. 10). The fractures are roughly perpendicular to the weak foliation and parallel to the 'sheet' joints.

On November 26, 1964, several thousand cubic metres of rock slid from the Porteau Cove cut onto Highway 99; on February 9, 1969, a slab landed on a car moving along the highway, killing three people; on February 17 and March 4, 1969, other slides were triggered due to repeated freeze thaw cycles. On July

25, 1970, another slab, described as 'big as a house', blocked the highway. Rock bolts, scaling, and drainage have since improved the stability of the slope; however, winter temperatures in the 1970s have also been more balanced. During the extremely variable and wet winter of 1981/82 individual blocks again came loose near the toe of the road cut.

Porteau Cove-Squamish

In the northern part of Howe Sound the Squamish River and three major torrents with low-level debris source areas (Furry Creek, Britannia Creek, Mill Creek) have built substantial fan deltas into the deep waters of the fiord. At Porteau Cove the fiord is crossed by a submerged moraine that forms a sill dividing Howe Sound into two basins (Fig. 9).

Furry Creek (gradient 12%) is incised into a relict fan delta which for years has been mined for aggregate and therefore has almost disappeared along Highway 99. Deposits farther upstream provide a steady source of debris to the channel of the torrent. During intense rainstorms such as those of winter 1982 pulses of blocky-bouldery debris are capable of washing out the low highway bridge crossing Furry Creek.

Britannia Mine used to exploit a polymetallic copper deposit located in a northwest-trending and steeply southwest-dipping shear zone composed mainly of volcaniclastics. The mine operated between 1905 and 1974; it is presently the site of the B.C. Mining Museum.

In the early days of mining, much of the mine's staff was housed on the an delta of Britannia Creek (gradient 17%), although camps were also scattered hroughout the upland basin of this torrent. Judging from contemporary photos Ramsay, 1967) a large proportion of the Britannia Creek basin had lost its orest cover during initial exploration and development activities related to ineral exploration. Logs and debris from unstable embankments clogged the hannel at narrow passages.

On October 28, 1921, heavy rainfall created even more serious blockage of he channel near low-level debris sources. When one of several log-debris jams urst, a deluge of bouldery debris and uprooted trees fanned over Britannia, rushed many buildings, swept others into the sea, and claimed 37 casualties. t is possible that during this event a small failure along the delta front aused retreat of the shore face near the mouth of the torrent. Several large locks deposited during the catastrophe are still scattered about in the vic-nity of the highway bridge crossing Britannia Creek.

Stability of bedrock slopes in the vicinity of mine adits also created erious problems. In 1914 tunneling may have contributed to a progressive det-ioration of an unstable bedrock ridge approximately 300 metres above Jane mp. A near-vertical crack on the ridge crest above Jane Camp was observed id photographed before March 22, 1915 (Ramsay, 1967, p. 34). On this day a lume of possibly more than 100,000 m^3 of rock and water-saturated snow failed d ploughed into the bunkhouses of the camp where 50 to 60 men, women, and ildren perished. Traces of the rock avalanche can still be seen near the old mp. Bedrock slopes to the west of the abandoned camp also show signs of incipient failure.

Woodfibre is a major pulp mill located on the Holocene fan delta of Mill Creek, along the west side of Howe Sound across from Britannia Mine. The plant and related warehouse-wharve complex were constructed more than 60 years ago. At that time measures were taken to control the channel of Mill Creek where it flowed across the delta fan and over the years had built a regular delta front composed of sand and gravel.

On August 22, 1955, a major slump at the shore face dislodged a warehouse and dock about 30 m seaward. At the head of the slump water depths increased by about 10 m and the disturbed part of the delta front apparently extended to about 150 m below sea level. The slump occurred during low tide, the fiord waters experiencing tidal ranges up to 4 metres. In a classic paper on submarine slope failures, Terzaghi (1956, p. 17-22) analysed this failure and concluded that the subaqueous slide 'consisted in the descent of a body of sediment which was perched on the slope and the seaward slope of this body must have been very much steeper than the normal slope of the delta front'. The normal slope of the delta front is between 27° and 28°. Terzaghi (1956, p. 22) concluded that the abnormal slope had been created by the accumulation of suspended sediment swept backwards against the shore face from a promontory artificially created at the mouth of Mill Creek. More recently Prior et al. (1981) carried out a side-scan sonar survey of the delta slope off Woodfibre; it revealed chutes, hummocky topography, and scarps. It also indicated traces of submarine mass movements beyond the area affected in 1955.

Five kilometres south of Squamish, a Viewpoint along Highway 99 affords a magnificent panorama of the eroded edifice of Mt. Garibaldi (2670 m), which is the source area of the torrential Cheekye River. Figure 11 is a sketch of the view in case the excursion reaches this stop during a downpour or in fog. Beyond the viewpoint and just south of Squamish, Highway 99 skirts the foot of Stawamus Chief (650 m), a sheer glacially scoured wall of massive granodiorite fringed by Holocene blocky talus and late Pleistocene delta gravels.

CHEEKYE RIVER

Setting

Located 5 km north of Squamish, the torrential west-flowing Cheekye River drains a basin of 58 km^2. Its mean monthly discharge, based on two years of measurements in the 1950s, ranges between 2 and 8 m^3/sec. During Holocene time numerous instabilities in the uplands of the basin have led to voluminous debris transport towards the confluence of the Cheakamus and Squamish rivers (Fig. 12).

The crest of the Cheekye basin is the rugged and partly glacier-covered Mt. Garibaldi (2670 m), a complex of dacite tuff breccia and ash flows, mainly of late Pleistocene age. The present Mt. Garibaldi-Diamond Head ridge is the remnant of an explosive volcanic dome; its western part probably was built out over Pleistocene glacier ice (Mathews, 1952a) and wasted away together with the Cordilleran ice sheet. The preserved eastern part rests on a pedestal of quartz diorite. Between 1200 and 2400 m a.s.l. the unstable west-facing wall

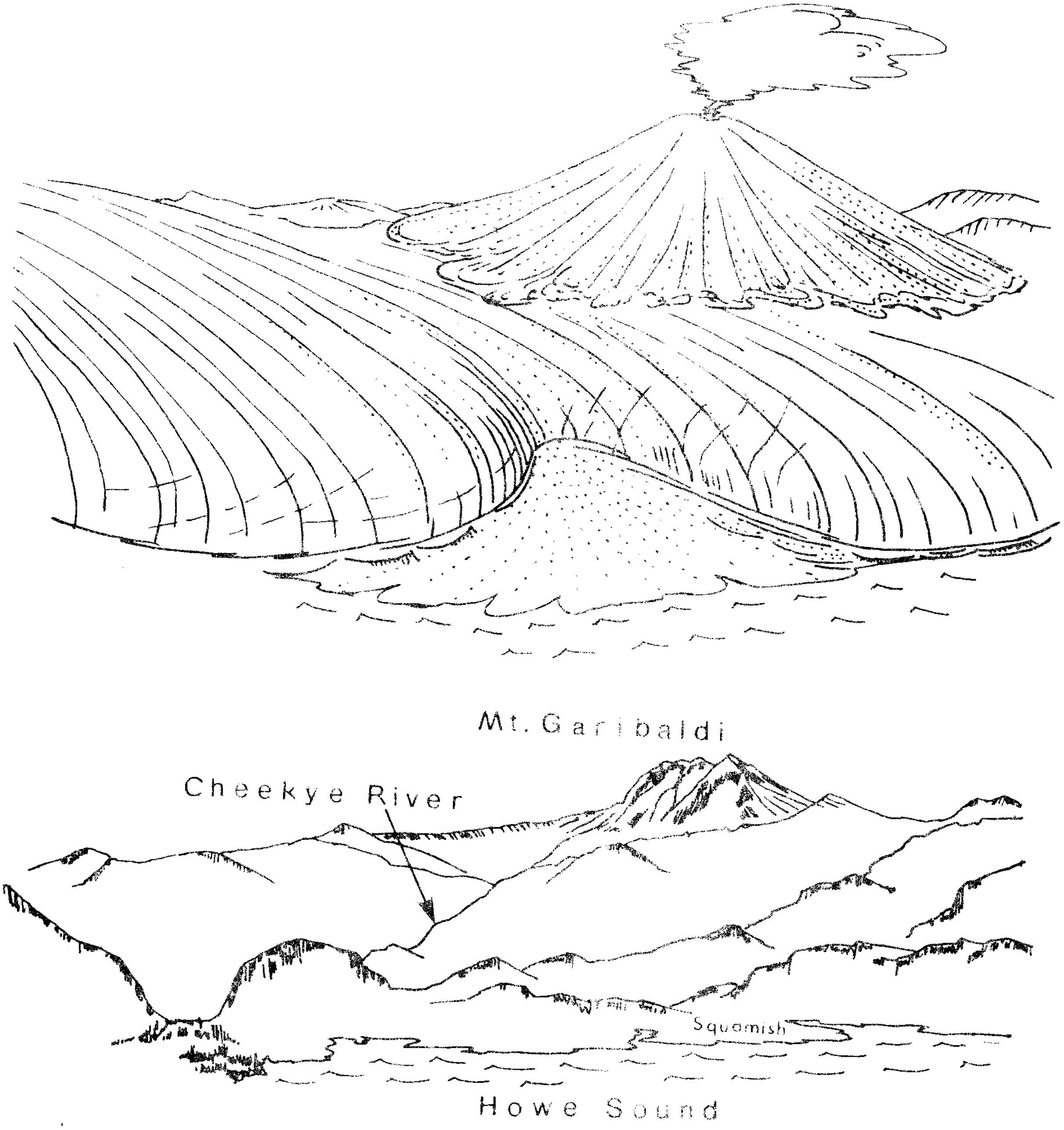


Figure 11 - Below: Panorama of the volcanic edifice of Mt. Garibaldi (2670 m) as seen from Viewpoint 5 km south of Squamish.
Above: Cartoon of late Pleistocene Mt. Garibaldi erupting in contact with remnants of the Cordilleran ice sheet.

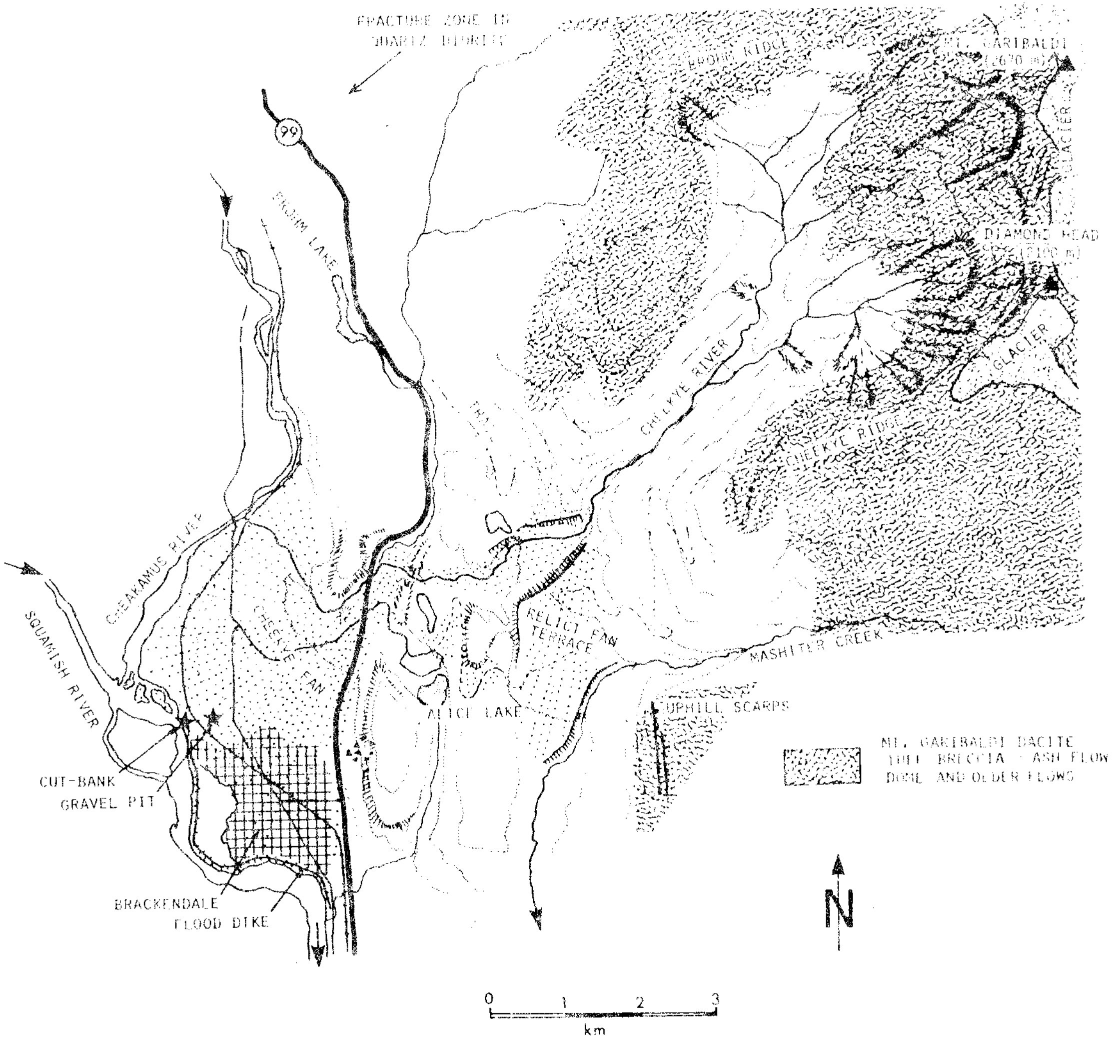


Figure 12 - Sketch map of the Cheekye River basin; note volcanic source area below Mt. Garibaldi, incised relict fan terrace, bedrock knolls east of Highway 99, and Holocene fan west of Highway 99.

f the volcanic edifice is scarred by erosional ravines and snow-avalanche racks. Open cracks along the serrated crest of the escarpment attest to inipient instabilities and the potential for sporadic failures of the volcanic liff. Below the tributary ravines of the Cheekye River runoff and debris from he uplands collect in a bedrock gorge; temporary blockage of logs and volcanic ebris along this gorge probably accounted for the generation of massive flows o the fan.

Fan

At the mouth of the Cheekye gorge a relict fan terrace, older than the ain Holocene Cheekye fan, is preserved between Cheekye River and Mashiter reek (Fig. 12). The apex of the block-strewn surface of this relict fan abuts gainst the Cheekye gorge at an elevation of 500 m a.s.l.; at its outer peripery this fan possibly aggraded against stagnating late Pleistocene valley ice. isappearance of the glacier ice, isostatic rebound, and a waning supply of ebris caused the Cheekye River to incise these older deposits, a process that ontinues to this day. The unruly Cheekye locally undercuts the older fan deosits along embankments up to 90 metres high. Downcutting of the Cheekye hannel also has exhumed several bedrock knobs on the valley floor.

The apex of the Holocene Cheekye fan is at the mouth of a short bedrock orge at an elevation of 200 m a.s.l. east of Highway 99. The Holocene fan xtends from this point west to the junction of the Squamish and Cheakamus rivrs, and south to Brackendale (Fig. 12). Part of the aggradation history of his fan is recorded in a cut-bank of the Squamish River northwest of Brackendale nd in a gravel pit near the railroad tracks in the same area (Figs. 12 and 13).

Cut-bank and Gravel Pit

Approximately 300 m south of its confluence with the Cheakamus River, the quamish River has eroded the toe of the Cheekye fan, exposing a cut-bank of up o 13 m of sediments dipping gently to the south (Fig. 13). The section reeals five units from the river level up:

1) 1-2 m of buff to rusty-weathering sandy gravel with abundant subrounded volcanic boulders and lenses of laminated clayey-organic silt; organic material in the silt layers yielded a C_{14}-date of 5890±100 years B.P. (GSC -3256; coll. by F.W. Baumann, G. Banks, R. Price).
2) 2.5 m of grey, angular, volcanic blocks (up to 1.5 m diameter) and similar smaller components arranged without obvious stratification and probably debris flow deposits.
3) 2 m of buff, parallel-bedded sand and gravel with rounded volcanic and plutonic cobbles.
4) 2.5 m of massive bouldery deposits containing volcanic slabs up to 1 m in diameter; probably debris flow deposit.
5) 3.5 m of well-bedded to lenticular channel gravels containing lenses of crossbedded sand. Imbrication of cobbles indicates average paleoflow to

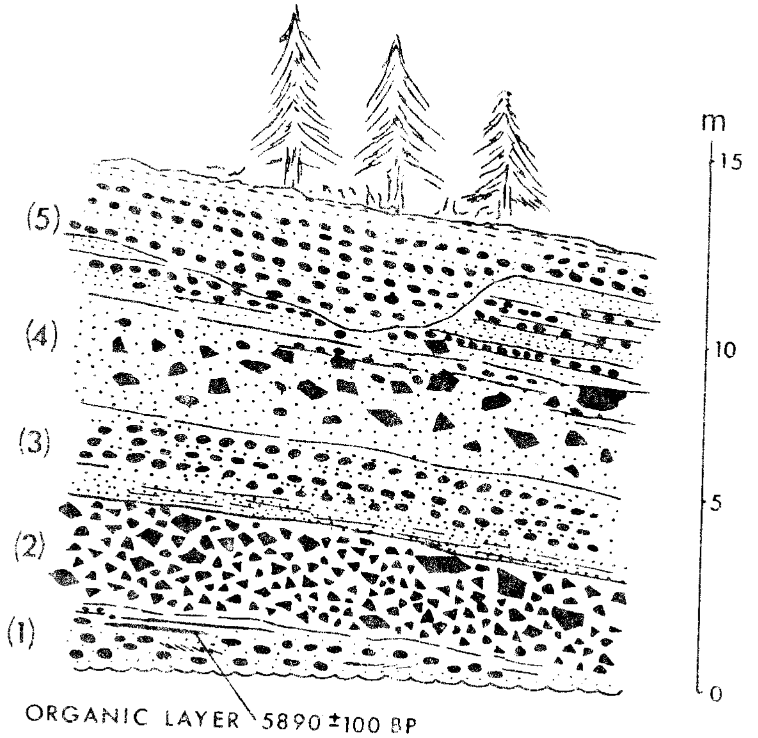


Figure 13 - Squamish River cutbank exposing debris flow and fluvial deposits at the toe of the Cheekye fan (see Figure 12 for location).

the SSW (S 25° W). This unit is also exposed in gravel pits east of the railroad track.

The section records two cycles of rapid aggradation, each characterized by the emplacement of a massive debris flow (units 2 and 4), and a subsequent phase of fluvial deposition in braided channels (units 3 and 5). The present surface of the fan is covered by well developed soil and mature forest, except in the immediate vicinity of the Cheekye River channel.

Recent Debris Flows

The channel of the Cheekye River hugs the northern flank of the fan, guided locally by exhumed spurs of quartz diorite. The braided channel floor is 10 to 20 m wide, and is flanked by erosional embankments 2 to 5 m high and by bouldery depositional ridges up to 3 m high.

In August 1958, 'following a sudden rainstorm, thousands of yards of tuff breccia debris and logs rushed down the Cheekye River and built a fifteen-foot high dam across the Cheakamus River .... Eyewitnesses say that the mudflow moved at 5 miles per hour near the mouth of the Cheekye, flowed for several minutes, and appeared to be about 10 feet high' (Jones, 1959). From these scant data it is estimated that the debris lobe had a total volume of 50,000 to 100,000 m^3. According to accounts by local inhabitants, an even larger flow occurred 'about 30 years' prior to 1958 (Jones, 1959). Thus debris flows with volumes in the order of 100,000 m^3 probably sweep down Cheekye River more than once every 100 years, on the average.

Development

The lower Cheekye fan hosts the expanding community of Brackendale, rail tracks, an airstrip, and a large transformer station. Brackendale extends onto the floodplain of the Squamish River, but is protected by a flood dike. The upper fan is still covered by mature forest. Highway 99 crosses the Cheekye River below the apex of the fan; above the bridge the 15-metre wide channel is incised only slightly into the apex of the cone. A debris flow of the same magnitude as that in 1958 probably would spill over the natural embankments and could seriously interfere with the highway and the Cheekye bridge.

In the past, parts of the Cheekye uplands have also been logged in large clear cuts and Brohm ridge has been the site of an aborted ski development. Most of the unstable volcanic bedrock slopes are inside Garibaldi Provincial Park and thus protected from major denudation by logging.

BROHM LAKE

North of the bridge across Cheekye River Highway 99 follows the western bank of Brohm River, climbing gradually above the Cheakamus canyon. At Brohm Lake the road approaches one of several NNW-trending fracture zones in quartz

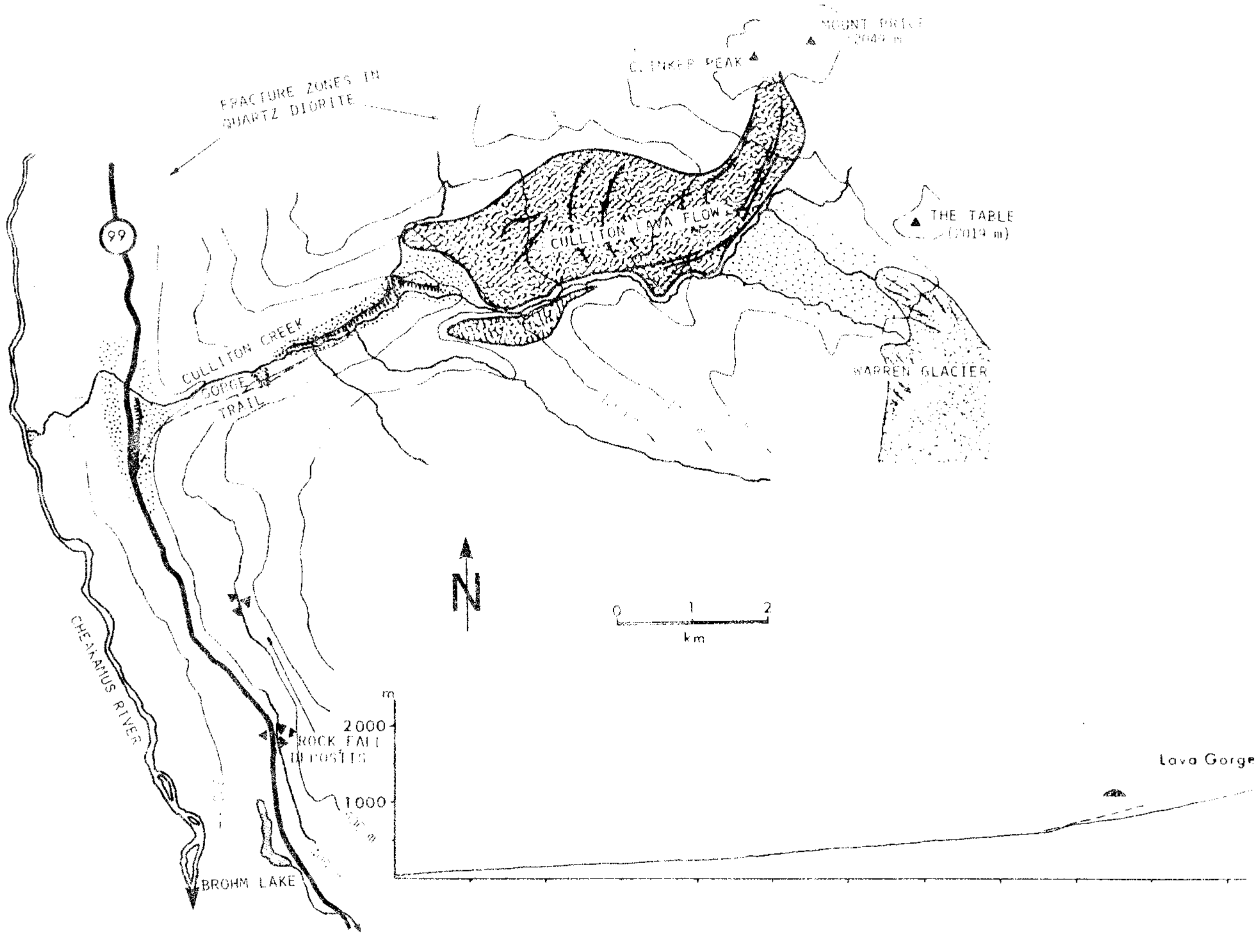


Figure 14 - Sketch map of Culliton Creek area and longitudinal profile of the torrent channel. Inverted-cup symbol and broken line on profile indicate the main debris source of the torrent below the lava cliff.

iorite which are parallel to Cheakamus Valley. Approximately 0.5 km north of rohm Lake the highway skirts a shattered cliff (on the east) and passes hrough rock fall deposits (on the west). Abundant talus east of the road is a roduct of recurrent rock fall activity from the broken ledges of bedrock that ake up the mountainside.

The highway also crosses an area which suffered extensively from forest ires in 1961 and 1963; the stark bedrock slopes above Cheakamus Canyon are now overed by a first succession of vegetation. To the west loom the spectacular ranitic peaks of the Tantalus Range (2600 m).

CULLITON CREEK

On approaching Culliton Creek, Highway 99 hugs a bedrock ledge partly ntled with late Pleistocene ice margin deposits. Culliton Creek originates the snout of Warren Glacier (1600 m), which is fronted by bouldery Neo-acial moraines. From there the channel of the torrent drops into a twisting rge that follows the unstable southern edge of the Culliton lava flow (Fig.). The steep front of the flow below the gorge is an ice-contact face where va congealed against the late Pleistocene glacier in the Cheakamus Valley lathews, 1952b). Below the lava front the torrent is bordered by a terrace mposed of relict debris flow and rock fall deposits rising up to 50 m above e channel floor. The lava gorge and the terrace embankment supply abundant ocky debris to the channel of the torrent. Downstream from these debris urces the torrent descends into a second gorge carved in quartz diorite and bouches onto the bench crossed by Highway 99. Culliton Creek joins Cheakamus ver after flowing across a steep debris cone west of and below the highway.

During the intense rainstorm of December 26, 1980, (see Whistler Village) veral thousand cubic metres of debris and logs were pushed against the up-ream embankment of the highway by the swollen Culliton Creek. The culverts ross the road were completely blocked and overflow carved a wide gash into road bed. Judging from the stream gauge records of other torrents of sim-ar size in this region (e.g. Mashiter Creek) maximum flood discharge of lliton Creek during this storm amounted to about 30 times the mean rate of charge for the month of December.

The highway is being relocated from the mouth of the gorge onto a bridge eral tens of metres to the west.

RUBBLE CREEK

Approaching Rubble Creek from the south, Highway 99 descends from a bed-k ledge high above Cheakamus Canyon through a series of deep road cuts in ctured quartz diorite to the level of the Cheakamus River. Skirting the tern river bank and passing the former settlement of Garibaldi, the highway mbs for three kilometres along the southern sector of the Rubble Creek fan cone). It crosses Rubble Creek along the axis of the large debris accumu-ion filling the valley at this point.

Mass Movements along Rubble Creek

The Rubble Creek drainage basin has an area of 74 km^2. It extends from ice-covered mountain ridges at 2500 m a.s.l. to the Cheakamus River at Garibaldi (340 m). The uplands of this basin are underlain partly by quartz diorite and Mesozoic sedimentary rocks and partly by the Pleistocene lava flows and tephra cones of the Garibaldi volcanic complex (Fig. 15). The youngest units of the Garibaldi volcanic complex are two andesitic flows (Culliton and Rubble Creek flows) which erupted on Clinker Peak and whose fronts abutted against the late Pleistocene Cheakamus Valley glacier which at that stage reached an elevation of about 1350 metres (Mathews, 1952a). On its north side the Rubble Creek lobe is flanked by several subsidiary lobes, numbered I to IV in Figure 15. These subsidiary lobes have created the depressions now filled by three lakes: Garibaldi Lake (1468 m), Lesser Garibaldi Lake (1381 m), and Barrier Lake (1377 m). Downstream from the lakes retreat and downwasting of the valley glacier created a steep ice-contact face along the front of the lava lobes. In the uplands beyond Garibaldi Lake all but vestiges of mountain glaciers disappeared. However, following the postglacial Altithermal period mountain glaciers of the region experienced renewed growth. Sphinx and Sentinel glaciers overrode subalpine forests dated from 6170 to 5270 years B.P. (Mokievsky-Zubok, 1973). At their most advanced Neoglacial positions (1600 and 1860 AD) these two principal sources of Rubble Creek probably calved directly into Garibaldi Lake.

Today the ice-contact lava face below Barrier Lake is known as The Barrier. Barrier Lake drains mainly through, rather than over, the cliff because the lava flows and interbedded volcanic rubble are intensely fractured and highly permeable. Normally, the springs at the foot of the Barrier (950 m a.s.l.) flow at a rate between 2 and 7 m^3/sec (Moore and Mathews, 1978). Only during flood stage does Rubble Creek discharge over the Barrier at the lower outlet of Barrier Lake.

Because of its ice-contact origin, the initial Barrier slope must have been very unstable; north-northwest-trending fractures subparallel to prominent regional fracture zones and steeply inclined columnar joints probably opened and penetrated to the base of the volcanics behind the ice-contact face. Given the vagaries of its subterranean drainage, the cliff probably failed repeatedly spreading blocky debris towards the Cheakamus River. Although much of the material reaching the main valley may have been carried away by the Cheakamus River, some of it accumulated as a composite debris cone that interfingered with the alluvial and lacustrine deposits on the valley bottom. This cone has a volume in excess of 100 x 10^{6}m^2 and in the area of the lower Rubble Creek is about 40 m thick (Hardy et al., 1978, their Fig. 20). A weathered surface older than 600 years defines the main prehistoric debris cone (Hardy et al., 1978); this surface is still exposed locally near the mouth of Rubble Creek (Fig. 16).

During the winter of 1855/56, a major section of the Barrier failed along a near-vertical composite fracture zone, causing a stream of broken rock, 30 x 10^{6}m^3 in volume, to hurtle down Rubble Creek (Moore and Mathews, 1978; Hardy et al., 1978). The climatic and hydrological conditions, seismicity, and precursary slope movements at the time of the Barrier collapse are unknown. Its results were obvious to the explorer Major Downie two years after the event; he had to cross a vast expanse of blocky and barren debris fanning all the way

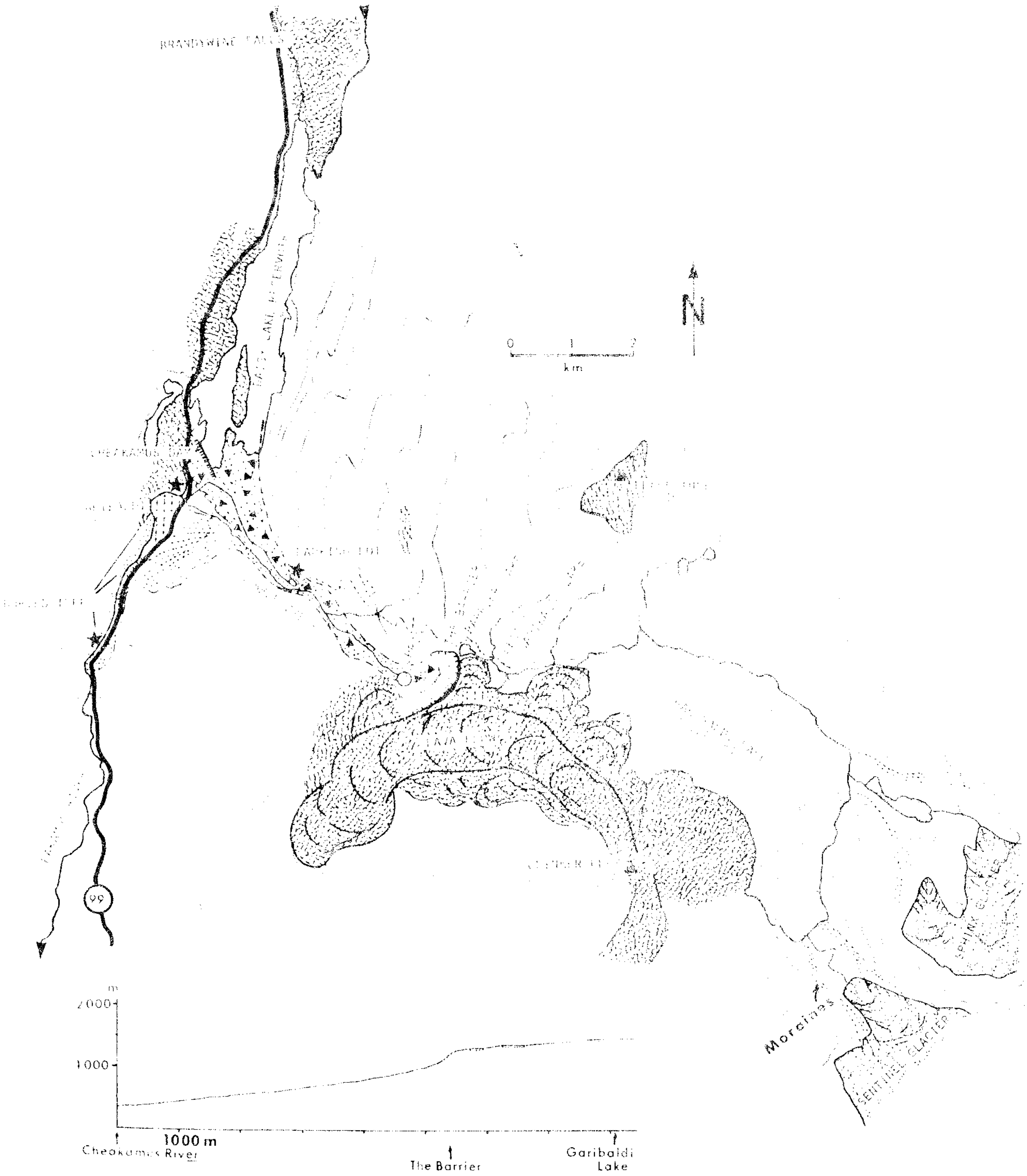


Figure 15 - The Rubble Creek basin and longitudinal profile of the torrent; note the debris lobe of 1855-56 (triangles) which originated by failure of The Barrier (see text).

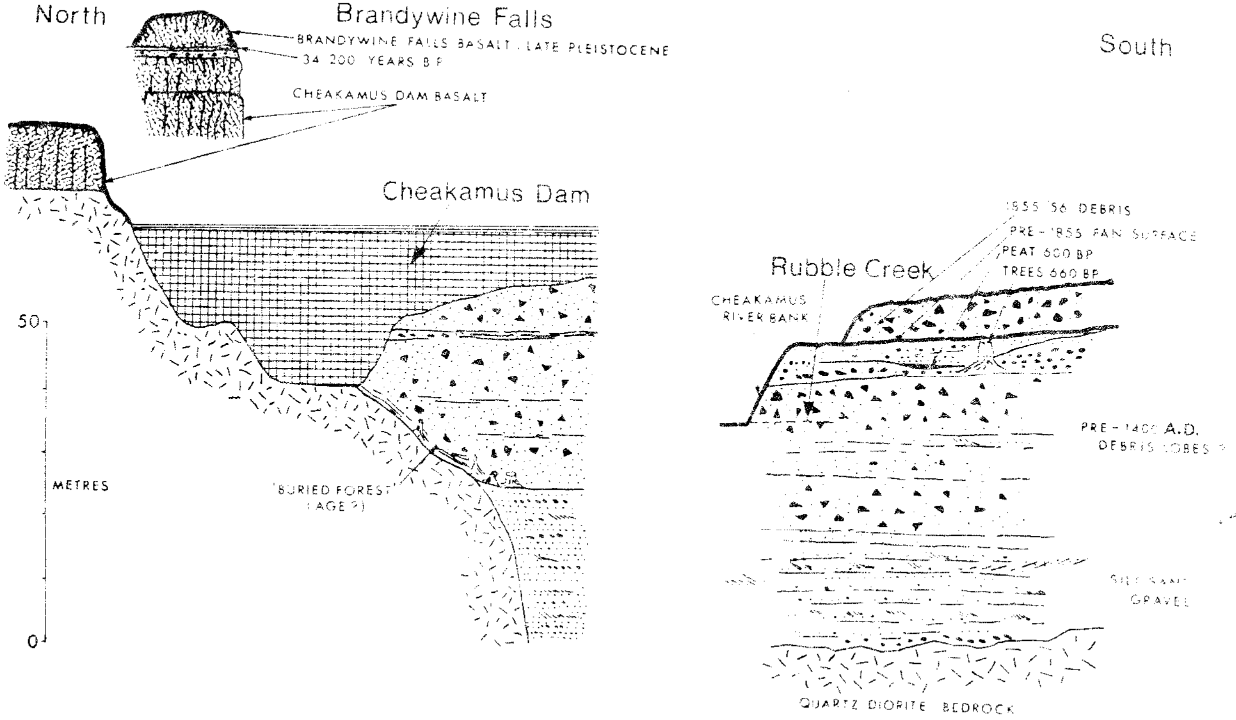


Figure 16 - Schematic stratigraphic relationships of the Rubble Creek fan with other deposits of the Cheakamus Valley(Terzaghi, 1960; Green, 1977; Hardy et al, 1978). Only the surfaces marked by bold lines are exposed. Other information is derived from the references cited above.

across the valley. Traces of debris along the fringes of the debris track and superelevation at bends of the Rubble Creek valley suggest that the front of the mobile mass descended at high velocity, locally in excess of 20 m/sec and lapping some 80 m onto the valley walls (Moore and Mathews, 1978). The main debris stream, carrying slabs of volcanic rock several metres in diameter, spread over the northern half of the fan and blocked the Cheakamus River. Subsequent bouldery flows, composed of reworked slide material and rock fall talus from the toe of the Barrier, covered the southern sector of the fan. Debris floods, launched by the overtopping of slide debris by the impounded Cheakamus River buried tracts of forest on the flood-plain of the Cheakamus River immediately below its junction with Rubble Creek; numerous rooted stumps of trees killed by these floods are still visible in the banks of Cheakamus River.

In the 130 years that followed this landslide forest gradually reconquered the Rubble Creek fan. However, some of the aggradational terraces along the shifting torrent channel have remained barren to this day. Rubble Creek has eroded as much as 10 m into the apex of the debris accumulation. Occasional rock falls from the Barrier have spread a blanket of talus across the lower half of the imposing cliff. For example, on December 24, 1977, approximately 00,000 m^3 of rock fell from the near-vertical upper cliff face, covering most of the springs at the foot of the talus (Moore and Mathews, 1978). At present the 200-metre lava cliff rises above a 300-metre talus slope.

Development

Between 1955 and 1957 British Columbia's hydro authority built an earth-nd-rockfill dam across the Cheakamus River (Cheakamus Dam). Karl Terzaghi 1960) was deeply involved in the design and construction phase of this project hich used the Rubble Creek slide not only as a substratum for the southeast butment of the dam but also incorporated fine grained matrix material of the lide into the impervious section of the dam. Adjacent to the northeast abutment of the dam which is founded in quartz diorite are outcrops of a lava flow hich is older than 34,000 C_{14} years (Green, 1977). During construction of the am a zone of 'buried forest' (Fig. 16) encountered below 'Rubble Creek wash' osed several challenges to the dam builders. The completed Daisy Lake reser-oir was connected by a tunnel to a powerhouse in the Squamish River valley, 10 m to the west of and 343 m lower than the level of the reservoir.

In the mid-1960s, when Highway 99 was built into the area a considerable umber of weekend retreats and permanent residential buildings sprang up in the ommunity of Garibaldi along the banks of the Cheakamus River west of the high-ay. In February 1972, the British Columbia Department of Highways, which is esponsible for land use regulations in unincorporated areas of the province, pproved the first stage of a new subdivision for 126 housing lots on the Rubble reek fan east of Highway 99. However, having been alerted by private citizens o the potential slide hazard on the Rubble Creek fan, the Department of High-ays refused to approve the second stage of development for the planned subdivision. The reasons given by the Senior Approving Officer were danger of flood-g and the possibility of another catastrophic slide from the Barrier. This cision was appealed in court by the developer (Cleveland Holdings), but the peal was dismissed by Justice T. Berger of the Supreme Court of British lumbia. The principal reason for rejecting the appeal was 'that there is

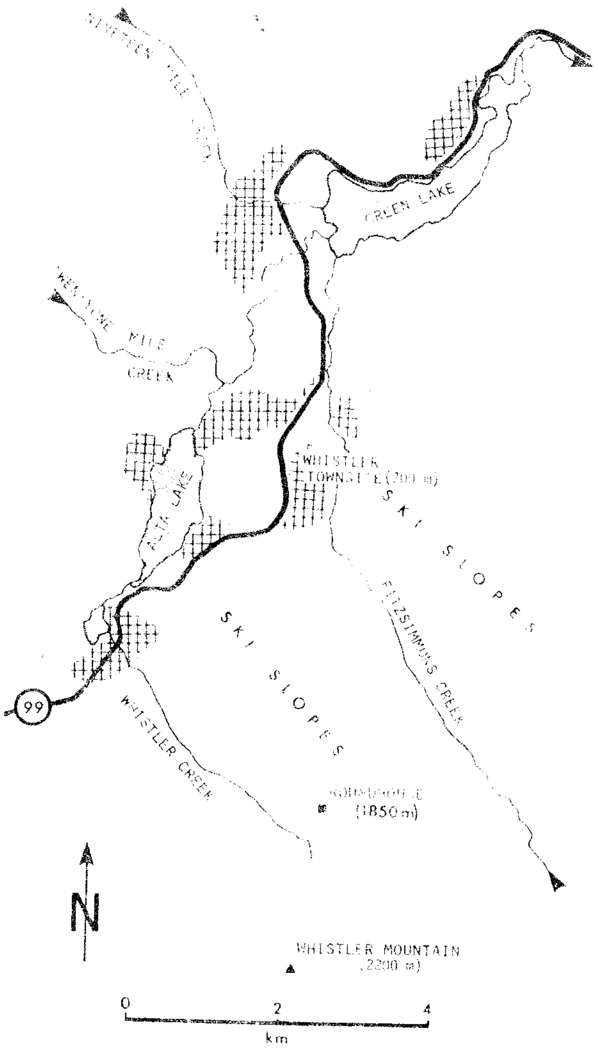


Figure 17 - Sketch map of the Whistler area showing urbanized zones (criss-cross pattern).

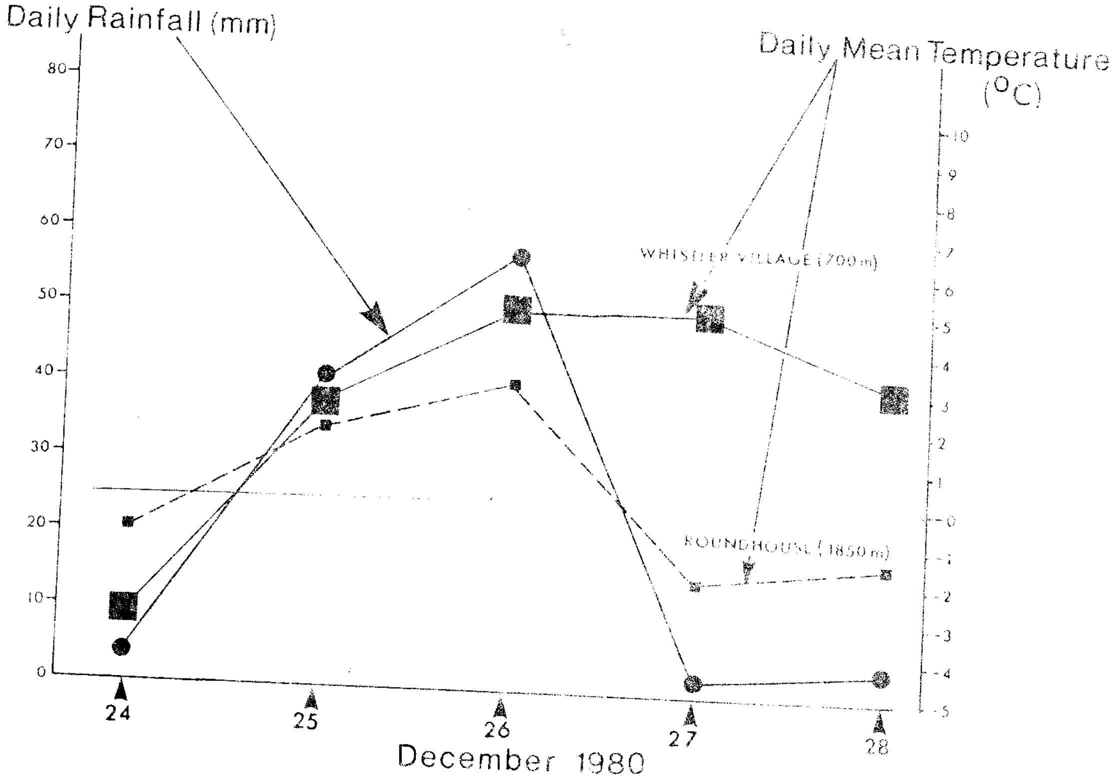


Figure 18 - Rainfall and temperature pattern responsible for development of extensive mass transport along torrents of the Cheakamus River-Green River valley on December 26, 1980.

sufficient possibility of a catastrophic slide during the life of the community' (Berger, 1973). The judgment establishes an important precedent relating to the planning and development of permanent settlements in the mountainous region of western Canada. In 1978 the Garibaldi Advisory Panel (Hardy et al., 1978) recommended that concentrated development in the Rubble Creek Valley and the adjacent Cheakamus River-Daisy Lake Reservoir area be severely limited. In 1981 a provincial Order in Council under the Emergency Program Act designated the Rubble Creek area as being too hazardous for human habitation and set aside 14,000,000 dollars to buy out and/or relocate the property owners in Garibaldi. Warning signs pointing out the potential slide hazard have been posted recently along Highway 99 and on adjacent tracts of land. In addition, the Daisy Lake reservoir has been lowered by 2 metres.

WHISTLER VILLAGE

The community of Whistler (700 m) is a growing ski resort and summer recreation centre. Development extends along a series of lakes (Alta Lake, Green Lake, etc.) that dot the divide between the south-flowing Cheakamus River and the north-flowing Green River (Fig. 17). Torrents entering the main valley in this area flow from presently glaciated upland basins through gorges flanked by bedrock and late Pleistocene surficial deposits onto well-entrenched relict debris fans at the valley bottom. During extreme rainstorms and/or periods of rapid snowmelt embankment failures and debris avalanches contribute abnormal bedload to the channels of the torrents.

On December 26, 1980, a two-day rainstorm (and rising air temperature) along the snow-covered mountains was the trigger event for extensive debris floods in the southern Coast Mountains. Near Whistler Village the freezing level rose to about 2000 metres and snowmelt combined with more than 100 mm of rain (Fig. 18) to create sudden runoff which mobilized logs from clogged channel reaches along many torrents (e.g. Nineteen Mile, Twentyone Mile, and Fitzsimmons creeks). Although the impact of most of the debris washed down by the swollen torrents was neutralized by dikes or deposited in natural or artificial depressions along the lower reaches, some damage was done to roadworks and bridges.

GREEN RIVER VALLEY (WHISTLER VILLAGE-PEMBERTON)

The valley of the Green River changes its orientation at Green Lake (610 m a.s.l.) and winds north-northeasterly down to its junction with the Lillooet Valley near Pemberton (200 m a.s.l.). Bedrock slopes adjacent to the Green River valley rise to elevations above 2000 metres; the lowermost portions of these slopes are mantled by highly varied late Pleistocene surficial deposits and relict alluvial fans.

The most interesting features in the area with respect to slope stability are: a) rock avalanche and rock fall deposits mantling bedrock slopes on both sides of the valley (Mystery Creek rock avalanche, stepped rock fall aprons); b) bedrock scarps on Mt. Currie; c) debris movement and erosion along the torrential Rutherford Creek; and d) stability of road and railroad cuts in blocky rock fall moraine near Nairn Falls (Fig. 19).

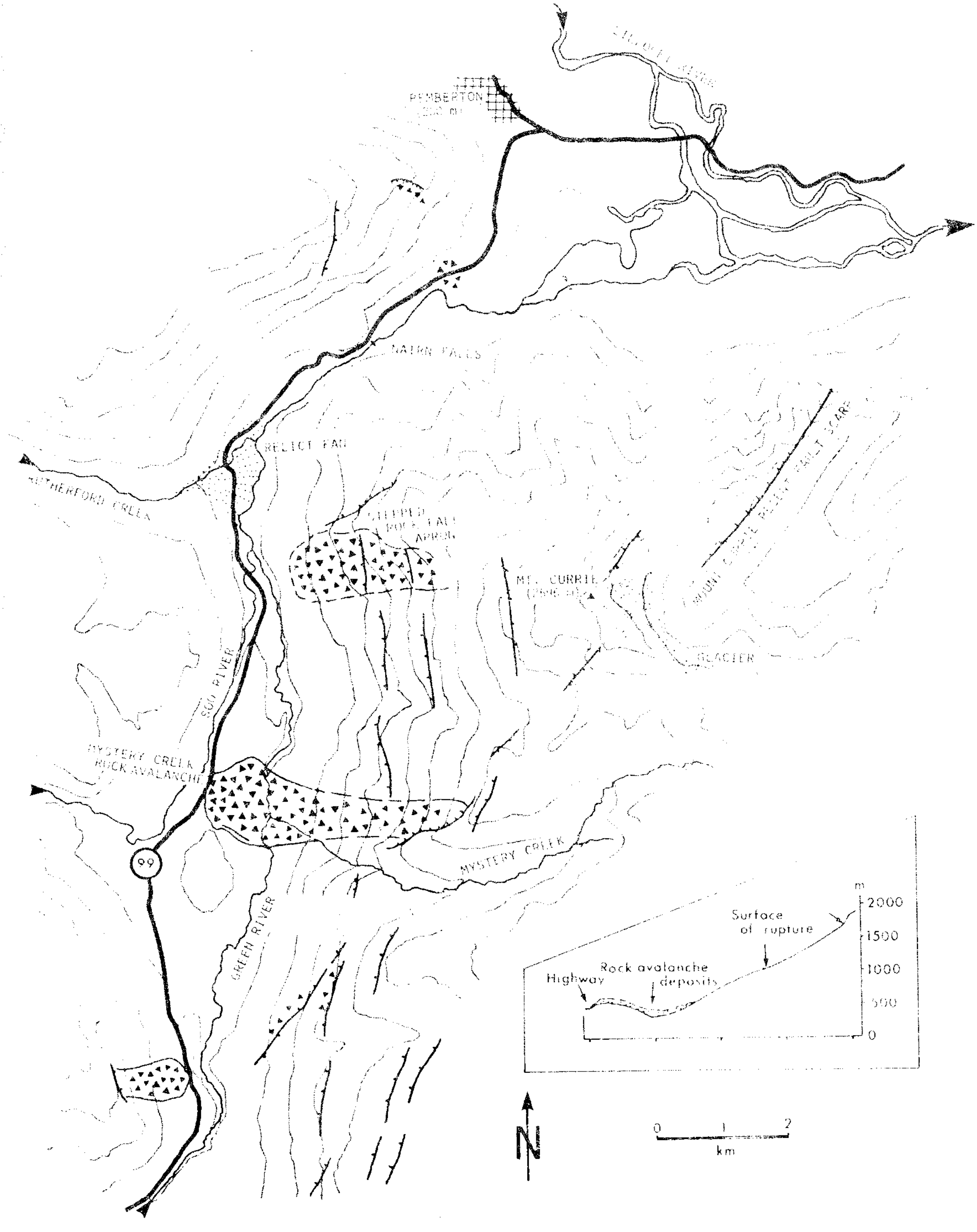


Figure 19 - Index map of the Green River valley and Mt. Currie showing the location of the Mystery Creek rock avalanche, stepped rock fall apron, and Mt. Currie fault scarp. Triangular symbols indicate blocky debris.

Mystery Creek Rock Avalanche

The prehistoric Mystery Creek rock avalanche is the largest landslide in the Green River valley. Its deposits rest at the foot of the distinctly scarped west slope of Mt. Currie (2596 m), east of Green River. The surface of detachment of the prehistoric rock avalanche is a fracture in diorite extending from 1200 m a.s.l. to 1600 m a.s.l. The main basal rupture plane dips about 23° to 30° to the west, a few degrees less than the inclination of the mountainside immediately south of the breakaway zone. The composite crown fracture of the detachment zone behind the basal rupture surface forms a jagged back wall. After failure, the disintegrating slab of diorite descended about 1000 metres to the foot of the slope and crossed the channel of the Green River (approximately 400 m a.s.l.). The front of the block stream climbed about 140 metres up a bedrock ridge in the centre of the valley, overtopped its crest, and swept down to the present location of Highway 99. During its ascent of this ridge, the stream of angular blocks left a 30-metre levee along its southern border. Blocks up to 15 m in diameter are found in this levee and on the surface of the main slide mass. The roadcut at the front of the lobe suggests that block size in the basal zone is possibly smaller due to grinding of the moving avalanche along its track. From energy considerations it can be calculated that the rock avalanche attained a velocity of at least 50 to 60 m/sec at the foot of the mountain before climbing the ridge in the centre of the valley. The lateral block levee suggests that the inner part of the lobe was propelled forward relative to the southern flank of the avalanche after the latter had come to a halt during its ascent of the bedrock ridge in the valley. Assuming an average thickness of about 20 to 30 metres for the landslide debris its approximate volume is estimated at 30 to $40 \times 10^6 m^3$.

The age of the rock avalanche is unknown; the presence of very large Douglas firs and cedars on the floodplain aggraded upstream from the rock avalanche suggests that failure of the cliff and blockage of the Green River channel occurred at least 400 years ago.

The crown fracture of the Mystery Creek slide is on trend with a Holocene fault scarp that runs along the northeastern summit ridge of Mt. Currie (Figs. 19 and 20). The detachment zone is also intersected by slope-parallel north-trending scarps and cracks associated with rock fall detritus. It is suggested tentatively that the Mystery Creek rock slide was triggered by the earthquake that also created the Mt. Currie fault scarp and whose epicentre must have been in the vicinity of Pemberton. The fault scarp on Mt. Currie shows a normal displacement of up to 3m; according to recent investigations of fault scarps showing normal displacement (Swan et al., 1980) this amount of offset would be caused by an earthquake of an approximate Richter magnitude of 7.

Stepped Rock Fall Aprons and Scarps

North of Mystery Creek the dioritic bedrock slope of Mt. Currie shows numerous uphill- and downhill-facing stepped scarps which are associated with bands or lobes of blocky rock fall deposits (Fig. 19). Locally, the entire mountainside seems to be littered with discontinuous talus related to these sharp breaks of the generally smooth bedrock surface. It is possible that the

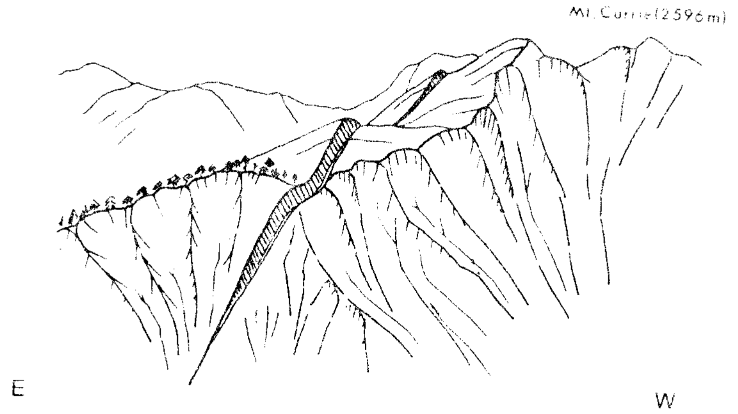


Figure 20 - View of the Holocene fault scarp northeast of Mt. Currie as seen from an aircraft looking south.

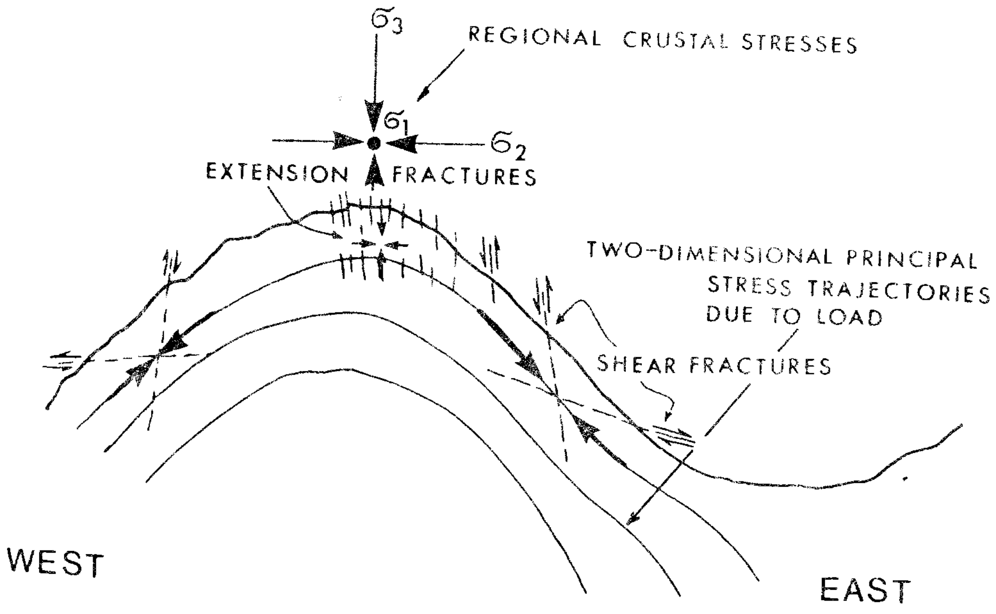


Figure 21 - Diagram of trajectories of maximum compressive stresses due to gravitational load of mountain (after Kohlbeck et al., 1979), the possible superimposed regional crustal stresses (see Fig. 2), and failures resulting from the composite rock stresses.

steps formed in response to earthquakes.

Opening of slope-parallel cracks in highly competent diorite might be the response to combined regional and local stress fields activated during earthquake shaking. Although speculative, the following lines of reasoning might be useful in understanding these and possibly other slope-parallel cracks in the southern Coast Mountains.

Kohlbeck et al. (1979) have produced a general two-dimensional finite element model for the self-generated gravitational stresses in a mountain massif. According to their model the trajectories that define the orientation of the maximum compressive stress tend to mimic broadly the shape of the mountain's surface. The largest stresses are encountered along the lower mountainsides, while ridge zones are almost stress free. Under such conditions and without considering throughgoing anisotropies weight-generated stresses would favour failure as indicated in Figure 21: uphill-facing scarps and downhill-facing toe failures. In areas where a regional stress field is superimposed onto the self-generated gravitational stresses one might expect that the tendency for 'spalling' of mountainsides is enhanced or restrained depending on the orientation of the slopes relative to the regional stress field.

In the southern Coast Mountains, where a regional stress pattern from studies of first motions of earthquakes suggests north-south compression (see Fig. 2), the regional stress field would enhance 'spalling' along north-trending bedrock valleys. In addition, isostatic rebound might have aided in the general expansion of mountain ridges. The opening of north-trending extension fractures along ridges under regional and topographic stresses could also explain the location of young volcanic vents on north-trending mountain ridges of the southern Coast Mountains. North-trending 'antislope' scarps of very recent origin have also been described by Bovis (1982) from an area 70 km west of Pemberton, although a different explanation - toppling in the near-surface zone - was proposed by him.

Rutherford Creek

Rutherford Creek is a major western tributary of the Green River. Above its junction with the Green River it is incised into a large relict alluvial fan whose surface is strewn with large blocks. Its channel is flanked by near-vertical 10-m embankments composed of very coarse unconsolidated fan deposits. During floods these embankments are undercut locally and blocky-bouldery debris collapses into the raging torrent, creating dramatic shifts of the channel and setting the stage for further undercutting. Like many other basins in the area, the Rutherford Creek basin has recently been opened to logging operations. Bedload in the torrent has increased markedly below a major embankment failure of late Pleistocene ice-contact deposits approximately 4 km upstream from the mouth of Rutherford Creek.

During the rainstorm of December 26, 1980, one abutment of the railroad bridge across Rutherford Creek was washed out, necessitating replacement of the whole structure. During the same storm there was a major shift of the braided Rutherford Creek channel between the bridge and Green River.

Nairn Falls

Nairn Falls is the site of a Provincial Park and campground located on a
lder-strewn terrace on the west side of the Green River. The falls them-
/es are carved into dioritic bedrock south of the campsite and can be
:hed by a trail from there. Directly above the falls the highway and rail
have been excavated from a large transverse ridge of crudely stratified
Pleistocene surficial deposits (moraine composed of rock fall material?).
le granitic-dioritic blocks are suspended loosely in a finer grained matrix.
ng rain storms and snowmelt blocks have tumbled from the cuts onto rail and
beds creating considerable maintenance problems. Recently, large segments
he cut have been covered with shotcrete.

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