The most recent eruption in the Belt was at Plinth Peak, within the Mount Meager complex, at about 2350 BP (Read, 1990; Evans, 1992b) which deposited the so-called Bridge River Ash to the east (Nasmith et al., 1967).

The term "debris avalanche" is used here to describe the transformation of a volcano slope failure into what Schuster and Crandell (1984, p. 567) described as "a sudden and very rapid flowage of an incoherent, unsorted mixture of rock and soil material...Movement of the mass is characterized by flowage regardless of whether it is wet or dry..."

Debris avalanches in the Mount Garibaldi Complex

Large landslides have taken place in two types of settings within the Mount Garibaldi Complex; from the flanks of the volcanoes themselves (e.g., Mount Garibaldi) and from the high precipitous margins of lava flows at some distance from the source vent (e.g., Rubble Creek).

Major debris avalanche deposits have been documented in the Mount Garibaldi-Cheekye River area and Rubble Creek.

Mount Garibaldi-Cheekye River

Debris avalanche deposits were first described in the Mount Garibaldi-Cheekye River area by Mathews (1952a, 1958). They cover a large area of the Squamish valley (Fig. 24) and consist of large dacitic blocks set in a matrix of pulverized tuff/tuff breccia, typical of debris avalanche deposits described elsewhere (e.g., Crandell, 1971; Evans and Brooks, 1991).

Mathews (1952a) has argued that the Mount Garibaldi volcanic cone was partially built over Fraser Glaciation ice, the melting of which during deglaciation removed support from the volcanic edifice resulting in the collapse of its western flank.

The area of the debris (including the Cheekye Fan) is 25 km^2 (Evans, 1990b). Assuming a mean thickness of 100 m this yields a volume of approximately $2.5 \cdot 10^9$ m^3. This is identical to Mathews (1952a) estimate and compares favourably to his estimate of the missing volume from the western flank of Mount Garibaldi ($2.9 \cdot 10^9$ m^3).

The debris avalanche deposits originated in the dacitic lavas and tuff-breccias which make up the western flank of Mount Garibaldi. The amphitheatre-shaped headwater region of the Cheekye River (Fig. 25) is in effect a massive landslide scar created by multiple failure events. Successive failure events may have built up what Mathews (1952a) termed the 'terraced fanglomerates' at the mouth of the Cheekye valley. Unpublished radiocarbon dates obtained by S.G. Evans and Thurber Engineering/Golder Associates (1993) suggest that large landslides continued to occur on the western slopes of Mount Garibaldi and travelled down the Cheekye valley to the Cheekye Fan through prehistoric time. The occurrence of these events has had a major impact on recent land-use decisions regarding the fan (Hungr et al., 1993; Thurber Engineering/Golder Associates, 1993).

Debris flows have continued in historical times. As described by Jones (1959), following heavy rains in August 1958, a debris flow swept down the Cheekye River and formed a 5 m high temporary dam across the Cheakamus River at its mouth. Local residents reported that a similar debris flow occurred in the 1930s (Jones, 1959). Both flows were of the order of 100 000 m^3 (Thurber Engineering/Golder Associates, 1993).

Rubble Creek

The Rubble Creek basin has been the site of at least two large debris avalanches and several debris flows during the Holocene (Mathews, 1952b; Moore and Mathews, 1978; Hardy et al., 1978). The source of the landslides is The Barrier, a precipitous face forming the margin of a dacite lava flow that erupted from Clinker Peak in the late Pleistocene (Fig. 26; Mathews, 1952b). Much of the debris has accumulated in the

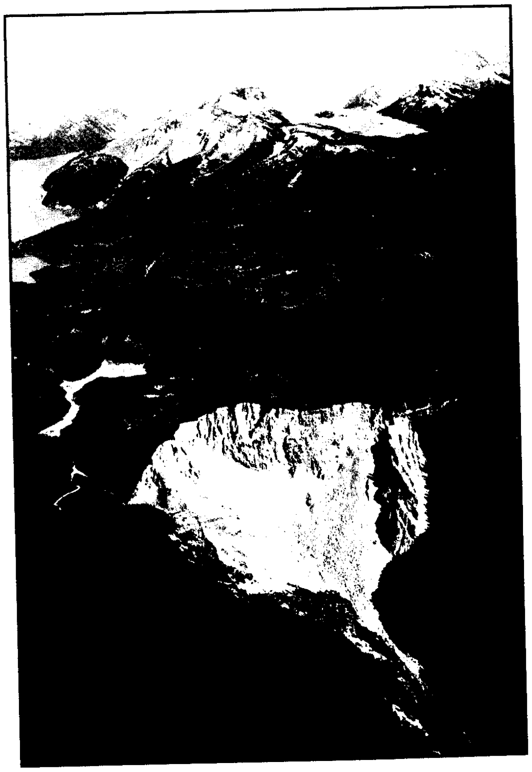

Figure 26. *Aerial view of The Barrier, a steep rock face formed by the successive failure of the margin of the Clinker Peak lava flow, the most recent failure being the 1855-56 rock avalanche. Clinker Peak is visible as the obvious source of the lava flow. Mount Garibaldi is visible in right background.* GSC 1991-300

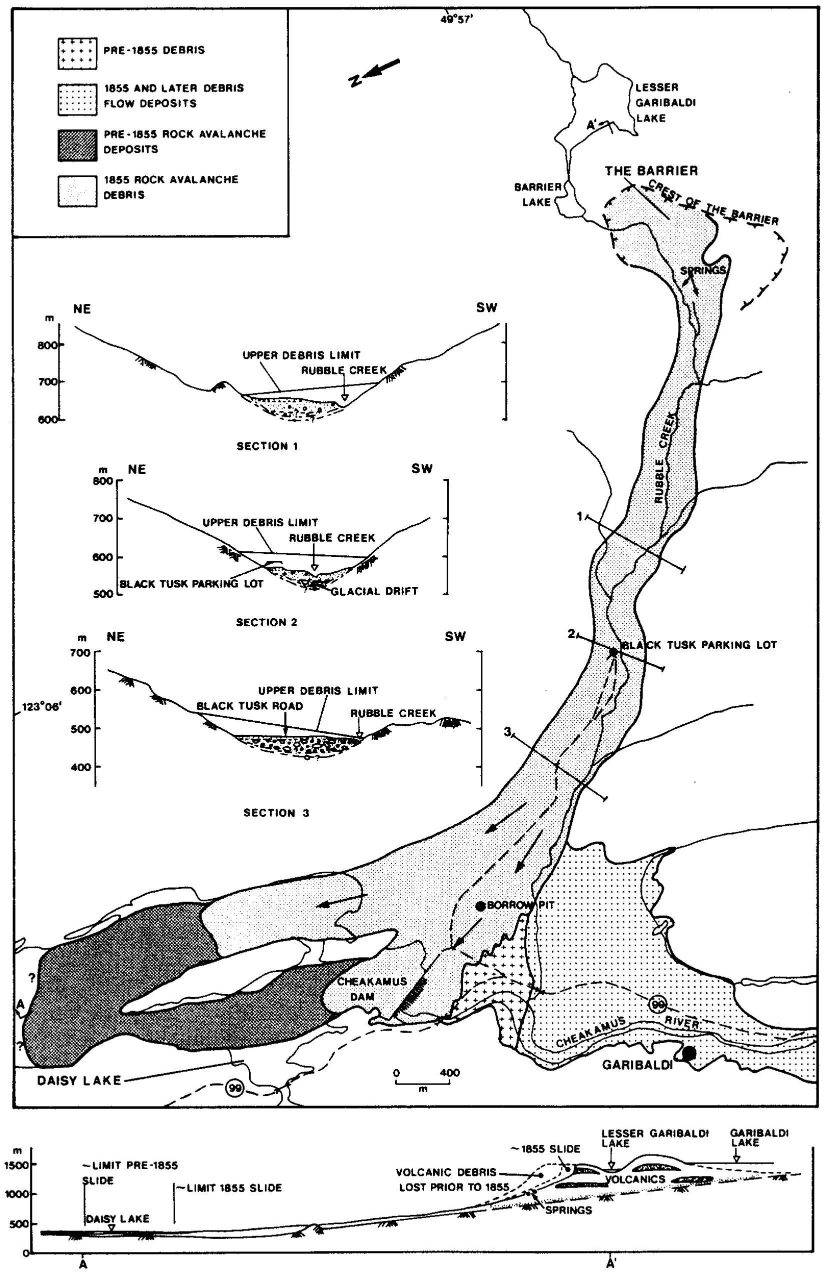

Figure 27. Landslides in Rubble Creek, Mount Garibaldi volcanic complex; map, longitudinal profile, and cross-sections showing upper limit of debris of 1855-56 rock avalanche (reproduced from Clague et al., 1987 which was redrawn from Hardy et al., 1978).

Cheakamus valley in a large fan at the mouth of Rubble Creek. Subsurface investigations indicate that the volume of the fan is between 156-186•10^6 m^3 and contains between 5-10 separate landslide units averaging 5-10 m in thickness (Hardy et al., 1978). A weathered surface exposed near the mouth of Rubble Creek separates historic landslide debris from similar materials which are older than about 600 calendar years (Hardy et al., 1978).

The most recent major failure occurred during the winter of 1855-56, when a major part of The Barrier failed along vertical fractures producing a large debris avalanche (estimated volume 30-36•10^6 m^3; this volume estimate is from Hardy et al. (1978)). Earlier estimates ranged from 15-25•10^6 m^3 (Mathews, 1952b; Moore and Mathews, 1978)). The debris travelled 6 km down Rubble Creek to the Cheakamus valley on an average gradient of 7° (Fig. 27; Moore and Mathews, 1978; Hardy et al., 1978). Based on superelevation data (Fig. 27) the debris reached velocities in excess of 20-25 m•s^{-1} (Moore and Mathews, 1978). A more complex analysis of the movement in Hardy et al. (1978) suggested that velocities may have reached 60 m•s^{-1} in the upper part of the path and that the landslide decelerated down the valley emerging from it onto the fan at about 25-40 m•s^{-1}.

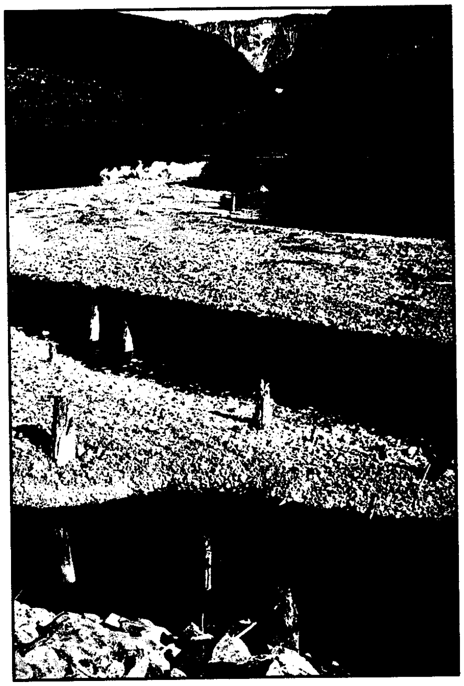

Figure 28. View across Cheakamus River up Rubble Creek to the Barrier showing trees killed in growing position by the 1855-56 debris avalanche and/or subsequent debris flows. GSC 1994-7091

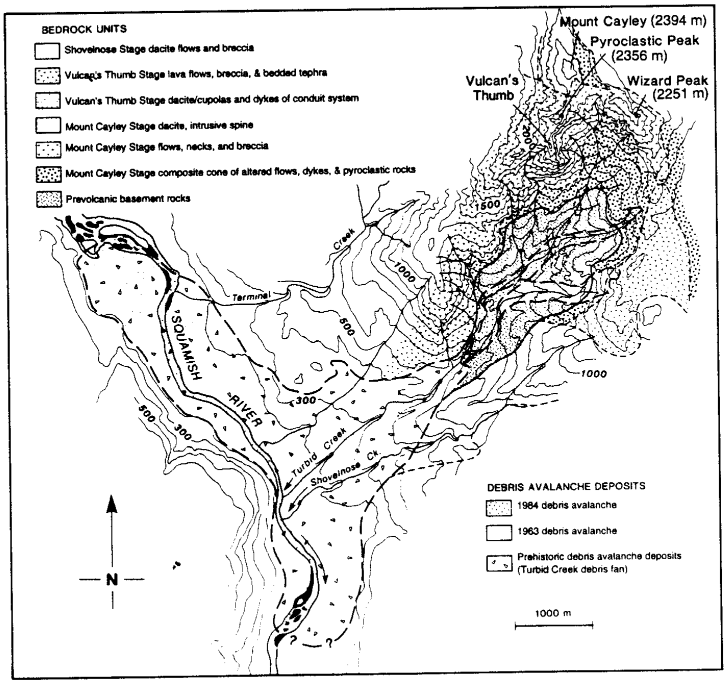

Figure 29.

Map of the Mount Cayley area showing the geology of Turbid Creek basin (after Souther, 1980), limit of prehistoric debris avalanche accumulation and historic debris avalanche paths (after Evans and Brooks, 1991).

The main debris stream spread over the northern half of the Rubble Creek fan and blocked the Cheakamus River (Evans, 1986). Debris flows associated with and following the rock avalanche covered the southern sector of the fan (Hardy et al., 1978). Debris floods, initiated when the Cheakamus River overtopped the landslide dam, buried tracts of forest on the floor of the Cheakamus valley up to 3.5 km below Rubble Creek; numerous rooted stumps of trees killed by these floods are still visible in the channel of the Cheakamus River (Fig. 28).

Between 1955 and 1957, B.C. Hydro constructed an earth and rockfill dam (Cheakamus Dam) across the Cheakamus River less than 1 km north of Rubble Creek (Fig. 27). The southeast abutment is located on the 1855-56 rock avalanche debris. Material obtained from a borrow pit in the 1855-56 debris was incorporated into the core of the dam (Terzaghi, 1960a, b).

A ban on the development of a housing subdivision on the fan was upheld by the B.C. Supreme Court in 1973 (Berger, 1973) because of the risk of another catastrophic landslide from The Barrier and adjacent steep slopes at the margin of the Clinker Peak lava flow. In 1980, Provincial Order in Council 1185 under the Emergency Program Act, designated the Rubble Creek area too hazardous for human habitation. Property owners in the area were bought out, or relocated, at a cost of $17.4 million (Morgan, 1992).

Debris avalanches from Mount Cayley Volcano and the damming of the Squamish River

Investigation of diamicton units exposed in an extensive accumulation of volcanic debris in the Squamish valley, west of Mount Cayley volcano (Fig. 29), has yielded evidence for the occurrence of at least three major debris avalanches, initiated by the collapse of its western flank in the mid-Holocene (Evans and Brooks, 1991, 1992; Brooks, 1992).

Radiocarbon dates obtained from tree fragments (Fig. 30) contained in the deposits indicate that the events took place at approximately 4800, 1100, and 500 BP. All three events dammed the Squamish River and formed temporary lakes upstream of the debris (Brooks, 1992; Brooks and Hickin, 1991) in which fine grained sediments accumulated (Fig. 31).

Figure 30. Broken trees in debris avalanche deposits in Turbid Creek. Tree above person's head gave radiocarbon date of 950 ± 80 (GSC-5195). GSC 1994-709J

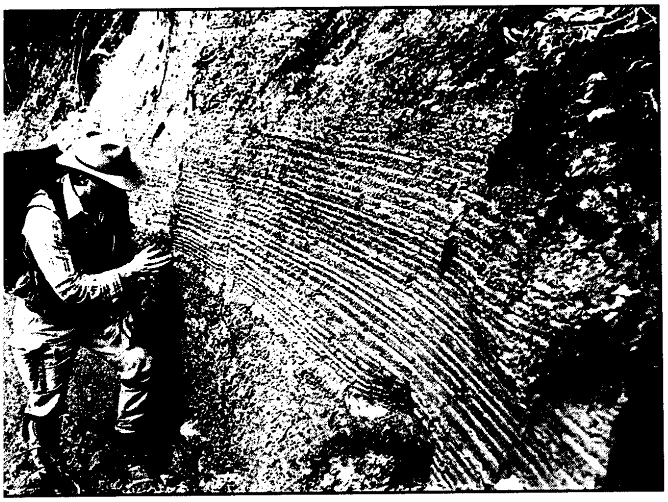

Figure 31.

Varved lacustrine sediments deposited in Squamish valley in lake formed by the blockage of Squamish River by mid-Holocene collapse of Mount Cayley. GSC 1994-709L

As described by Evans and Brooks (1991), failure of the cone took place after considerable dissection of the original edifice had exposed weak pyroclastic materials at the base of the steep upper slope of the volcano. No evidence of older debris avalanches from Mount Cayley has been discovered.

Smaller scale debris avalanches involving mechanically weak pyroclastic materials continue to occur from Mount Cayley's western flank in historic time. A 1963 event (Fig. 32; estimated volume $5{\cdot}10^6$ m^3) has been described by Souther (1980) and Clague and Souther (1982). The fahrböschung[1] of the landslide was 22° and velocities, calculated from superelevation data, reached 15-20 $m{\cdot}s^{-1}$.

In 1984 a similar debris avalanche took place from Mount Cayley's western flank (Fig. 32) and resulted in a debris flow which temporarily dammed the Squamish River (Evans, 1986; Jordan, 1987; Cruden and Lu, 1989). Two different interpretations have been made of the event. According to Cruden and Lu (1992) approximately 3.2 million cubic metres of material travelled down into Turbid Creek and blocked it. The breaking of the dam then caused an extremely fast debris flow in Turbid Creek which produced wind gusts up to 34 $m{\cdot}s^{-1}$ and travelled down to the Squamish River. By contrast, Evans (1993) suggested that the 1984 event, contrary to an initial estimate of (Evans and Gardner, 1989), was an order of magnitude smaller (estimated volume $0.5{\cdot}10^6$ m^3). He did not find evidence to suggest that the debris stopped in Turbid Creek to form a dam. Instead, he proposed that the movement was continuous over a vertical distance of 1.18 km, to 3.46 km from its source. Below this point a debris flow was then initiated which travelled down the lower reaches of Turbid Creek and blocked the Squamish River as described by Cruden and Lu (1992). Evans (1993) concluded that the 1984 event showed hyper-mobile characteristics, i.e. the distance of travel of the debris was typical of a debris avalanche an

Figure 32. Aerial view of historic debris avalanches in Turbid Creek on the western slopes of Mount Cayley volcano; "A" is the source of the 1963 debris avalanche and "B" is the source of the 1984 event. Both landslides involved initial failure in Pleistocene pyroclastic rocks. This photograph, taken in 1985, shows the swath cut through the tree cover by the 1984 debris avalanche. GSC 204857-F

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[1] The Fahrböschung of a landslide is the angle of the line joining the top of the headscarp and the distal limit of the debris.

order of magnitude greater. The fahrböschung for the 1984 landslide was 19° and based on superelevation measurements, velocities reached at least 31 $m{\cdot}s^{-1}$.

Debris avalanches from Mount Cayley and the effects of a possible damming of the Squamish River are major geomorphic hazards to public safety and economic development in the Squamish valley.

DEBRIS FLOWS

Channellized debris flows (also known as debris torrents) occurring in steep mountain watersheds and triggered by heavy, intense rains have been responsible for much damage in the Vancouver region (Evans and Clague, unpublished data; Evans, 1982; VanDine, 1985). They are defined by VanDine (1985, p. 44) as "a mass movement that involves water-charged, predominantly coarse grained inorganic and organic material flowing rapidly down a steep, confined, pre-existing channel". They are relatively frequent and are generally less than 100 000 m^3 in magnitude; many are less than 50 000 m^3.

Figure 33. Debris avalanche (or open slope debris flow) which occurred in August 1991 as a result of heavy rains on north side of Britannia Creek, 4 km upstream of Britannia Beach. The landslide overran part of the abandoned townsite of Tunnel Camp. GSC 1994-492B

Debris flows are initiated by shallow slides in thin mantles of colluvium or till on slopes above a creek channel bed into which they travel and where they become transformed into debris flows by undrained impulse loading of saturated channel materials (Bovis and Dagg, 1992). Rockfall may also provide a debris flow trigger by undrained impulse loading of channel materials. In other cases, debris flows become mobilized by a large increase in creek discharge (e.g., by the bursting of a debris dam), to a critical stream discharge, which causes the destabilization of channelled bed materials (VanDine, 1985; Bovis et al., 1985; Boris and Dagg, 1988).

Shallow failures occurring on steep, open slopes do not necessarily become channellized, but may still develop into what are termed debris avalanches or open slope debris flows (Evans, 1982). Figure 33 shows an example from the northern side of Britannia Creek which occurred as a result of heavy rains in September 1991. The landslide overrode part of the abandoned townsite of Tunnel Camp.

Figure 34. Aerial photograph showing 1983 debris flows in vicinity of Wahleach Power Station (circled) in the Fraser Valley. Multiple starting points of debris flows are arrowed. Note at least three sources for the debris flow in Ted Creek (A) discussed in text. Point "D", located just south of Ted Creek, is an area of topographic linears associated with rock slope deformation illustrated in Figure 19. (BC 83020-104)

Lower Fraser valley/Hope-Chilliwack

Debris flows triggered by intense rains have occurred frequently in the lower Fraser valley in this century (Miles and Kellerhals, 1981; Evans and Clague, unpublished data) resulting in numerous deaths and extensive property damage. In July 1983, for example, a series of debris flows triggered by a severe local rainfall blocked the Trans-Canada Highway and the Canadian National Railway mainline for three days at a number of locations between Chilliwack and Hope (Evans and Lister, 1984) triggered by a locally intense rainfall (Slaymaker et al., 1987). The debris flows originated as shallow failures on steep mountain slopes covered with a thin veneer of colluvial and/or till materials that had been logged in the recent past. Some debris flows had multiple initiating point slides (Fig. 34). At least 14 debris flows reached the Trans-Canada Highway. No loss of life was associated with the debris flow activity although one house was partially engulfed. The cost of repairs to road and railway was estimated to be $300 000. The debris flow in Ted Creek (Fig. 34) had a volume of about 60 000 m^3, one of the largest debris torrent events to be documented in the Vancouver region (Slaymaker et al., 1987), and the velocity of the debris flow, estimated from superelevation data, reached at least 9.4 m•s^{-1} (Hungr et al., 1984).

Howe Sound-Whistler area

Debris flows, triggered by heavy rains, have occurred in the steep watersheds along the east side of Howe Sound fiord (Fig. 1). These have impacted on communities along the fiord as well as on the British Columbia railway and the Squamish Highway which run along its east side (Thurber Consultants, 1983; Jackson et al., 1985). In the 25 years between the completion of construction of both the railway and the highway in 1958, and 1983, 14 debris torrents occurred on six creeks resulting in 12 deaths, the destruction of 11 bridges, four houses, and other property damage (Lister et al., 1984). Four debris flows were described by Lister et al. (1984) (Fig. 35). They involved volumes in the range of 10 000 to 20 000 m^3; velocities were in the order of 3-6 m•s^{-1} and discharges were in the range 100-350 m^3•s^{-1}.

On October 31, 1981, a debris flow of about 20 000 m^3 in M Creek (Fig. 35, 36) swept down the steep mountain watershed over a distance of 2.2 km and destroyed the highway bridge crossing the creek. Nine people were killed when several vehicles drove into the chasm spanned by the destroyed bridge.

A similar debris flow occurred in Alberta Creek on February 11, 1983 and had a disastrous impact on the community of Lions Bay (Fig. 35, 37). The debris flow consisted of six surges during a period of approximately two and one-half hours in the early hours of the morning (Lister et al., 1984). In addition to substantial damage to transportation facilities, three houses in Lions Bay were destroyed and a house trailer crushed; two people in the trailer were killed.

In an earlier disaster, a debris flood in Britannia Creek in 1921, caused by the collapse of a blocked culverted, fill during heavy rains, devastated Britannia Beach destroying 60 houses and causing 37 deaths (Hungr and Skermer, 1992; Evans and Clague, unpublished data).

Triggers

Although debris flows are usually associated with heavy rainfall, attempts to specify weather conditions (e.g., total rainfall or intensity thresholds) which trigger debris flows have not been successful (e.g., Church and Miles, 1987). Factors that complicate such attempts include the role of snowmelt, antecedent moisture conditions, the availability of debris, and the fact that rain gauges are generally spaced too widely to detect localized high intensity rainfall cells which may trigger debris flows (e.g., the 1983 Wahleach events described above).

A second complex causative relationship is that between debris flow initiation and change in land use in the source watershed either by deforestation or forest fire. Studies by O'Loughlin (1972) and Howes (1987) for example, found that clearcut logging and logging road construction increased the occurrence of initial shallow landslides of the type that could be transformed into debris flows. In contrast, many major historical debris flows have been initiated on slopes that have not been logged (e.g., the M Creek event described above) and slopes with natural vegetation can undergo significant landslide activity (Howes, 1987).

Defensive structures

As described by Hungr et al. (1987), Slaymaker et al. (1987), and Kellerhals and Church (1990) a variety of debris flow defensive structures have been constructed at numerous locations in the Vancouver region in recent years, following the construction of debris flow defensive works to protect the Vancouver Island community of Port Alice (Nasmith and Mercer, 1979). They include debris retention structures that stop and dewater debris in containment basins upstream, channellization works that confine the debris in its passage over a fan surface, and deflection berms that either divert the flow away from potential impacts on infrastructural facilities into a predetermined deposition area, or create open containment areas (Hungr et al., 1987).

The most sophisticated structures in the region have been constructed at several locations along Howe Sound in the vicinity of Lions Bay (Fig. 1) for a total cost of about $20 million (Evans and Clague, unpublished data). At Charles Creek, (Fig. 35) a large debris retention basin (Fig. 38) was constructed in the mid-1980s at the head of the bay, to protect transportation routes and expensive homes below on the fan. A similar structure was constructed on Harvey Creek at the head of the fan which has a debris retention capacity of 70 000 m^3. At Alberta Creek, scene of the 1983 fatal accident, channellization of the creek (Fig. 39) was carried out to confine flood or debris flow discharges in its passage over the Alberta Creek fan within a gently curving concrete-lined channel (Hungr et al., 1987).

Less sophisticated debris retention structures have been built or have been planned in the region. Hungr (1993), for example, described proposed debris retention structures to protect part of Whistler (Fig. 1) from possible debris flows in Whistler Creek. They consist of two 11 m high debris flow barriers consisting of a series of triangular buttresses of tubular steel, connected by massive steel grating (Fig. 40) which would create a total retention capacity of about 24 000 m^3.

Since the introduction of deflection berms as debris flow defensive structures at Port Alice, Vancouver Island in the 1970s, a number have been built in the Vancouver region. Deflection berms have been constructed at several locations in the vicinity of Wahleach to protect the Trans-Canada Highway from debris flows (Fig. 1, 41). At Ted Creek, for example (see location in Fig. 34) a gravel borrow pit on the Ted Creek fan was shaped to act as a retention basin and a

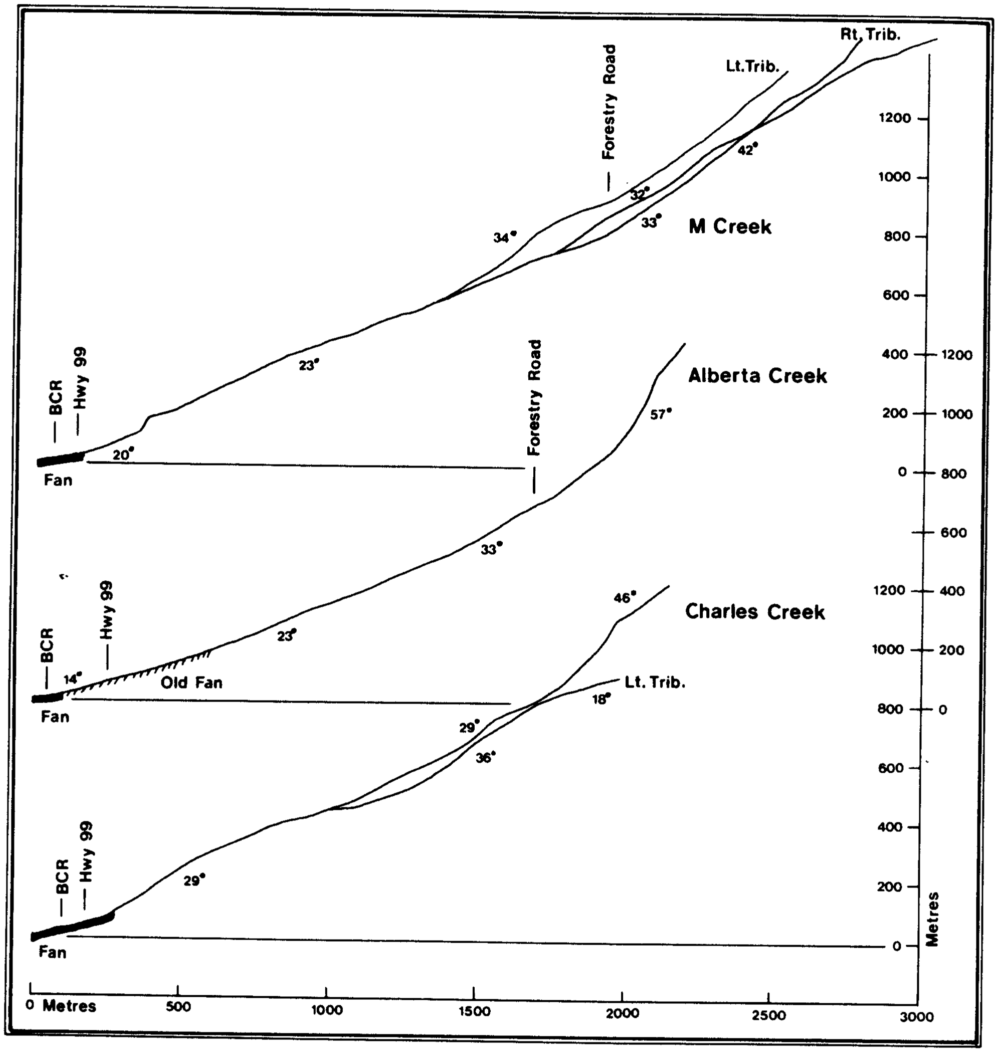

Figure 35. Profiles of creeks on east side of Howe Sound in which debris flows occurred between 1981 and 1983 (after Lister et al., 1984).