The exposed slide debris consist mainly of quartz diorite belonging to the Spuzzum Pluton. A fault, possibly an extension of the northeast-trending Vedder Fault, passes through the headscarp area. A large graben, approximately 120 m wide and at least 35 to 45 m deep, has formed along the fault trend and appears to result from slope distress on the southeast-facing flank of an unnamed mountain overlooking the Fraser River valley. The failure surface appears to be an exfoliation plane.

Katz slide is believed to have occurred as at least two rock avalanches separated by a period of hundreds to thousands of years (Savigny, in press). The first extended across the Fraser Lowland (Fig. 12 and 13) probably blocking the Fraser River, forming a landslide dam and creating a small lake. No volume estimate has been made of the debris because a fan delta quickly prograded through the lake covering all but the largest blocks of the debris. At the time of the second rock avalanche, broad, shallow channels carried flow of the Fraser River along the northwest (right) and southeast (left) sides of the valley (Fig. 12). The second event extended about half way across the valley blocking the northwest channels and diverting all flow to the southeast side (Fig. 13). Debris from the second event covers an area of 1.1 km^2 and has a volume of 15 000 000 m^3. An organic sample from one of the abandoned northwest channel-fill sequences yielded a maximum radiocarbon age for the second rock avalanche of 3260 ± 70 BP (SFU W-02).

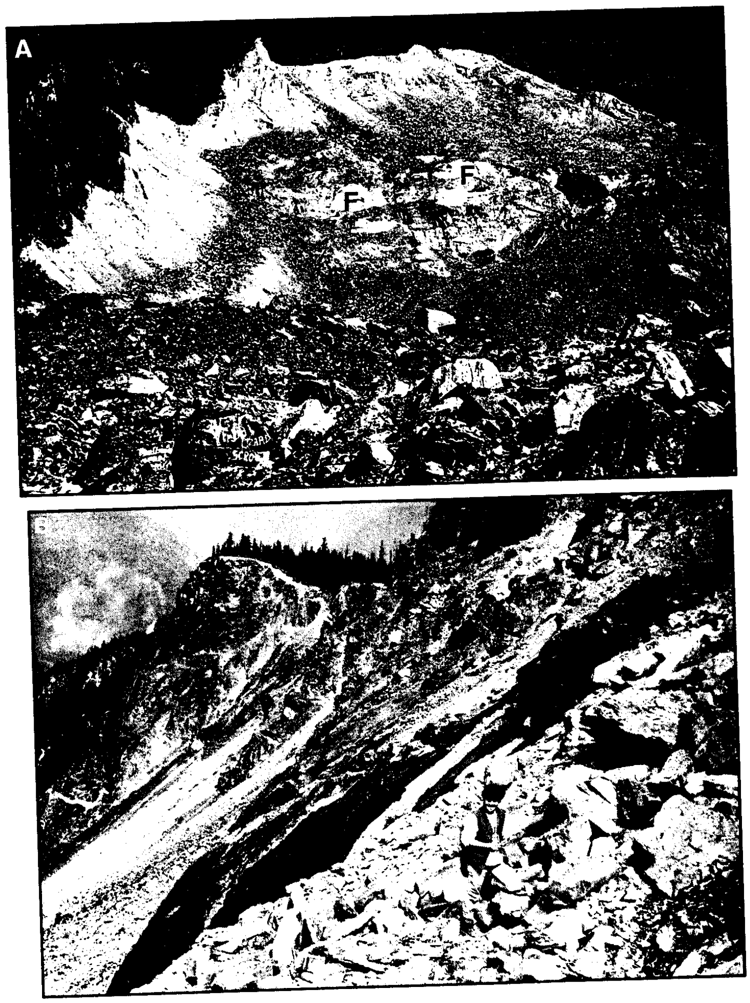

Figure 11. *A) 1965 Hope Slide sliding surface and debris; felsite sheets (F) in lower part of the slope. GSC 1994-738* ***B)*** *Sliding surface in upper part of the slope. Note steep irregular surfaces in greenstone. GSC 1992-114B*

Cheam slides

Cheam slide is a prehistoric rock avalanche complex located on the southeast side of the Fraser River valley 20 km east of Chilliwack (Fig. 1 and 14). The landslide debris forms a hummocky surface which contrasts sharply with the surrounding flat Fraser Lowlands and the adjacent steep slopes of the North Cascade Mountains. The landslide was first examined by Smith (1971); the debris was mapped by Armstrong (1980) as a slope deposit. Naumann (1990) undertook a detailed assessment of both the source and deposition areas and Naumann and Savigny (1992) reported a detailed numerical analysis.

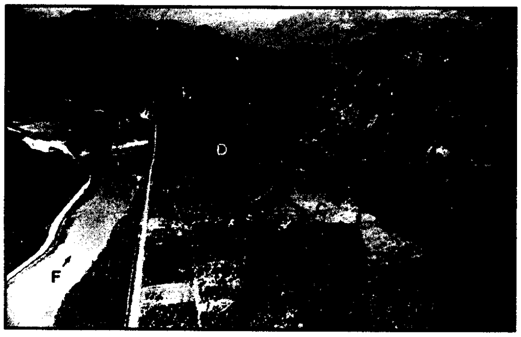

Figure 12. Oblique aerial view of Katz rock avalanche(s) looking southwest in the downstream direction of the Fraser River (F). The source area of the rock avalanche(s) is indicated with a vertical arrow. The debris in the Fraser Valley (D) blocked a channel of the Fraser River (C) and results in a constriction of the present Fraser River channel at point "N". (Photo by K.W. Savigny)

The rock avalanche is believed to have begun as a large asymmetric wedge on an unnamed mountain immediately southwest of Mt. Cheam; a northeast-dipping thrust fault and a steeper, southeast-trending, southwest-dipping joint set may constitute the two slide surfaces in Devonian to Permian Chilliwack Group rocks which consist of volcanic arenites, argillites, and cherty or argillaceous limestones (Naumann, 1990; Naumann and Savigny, 1992). The intersection of these surfaces outcrops in the slope approximately 400 m above the Fraser Lowlands. The source area volume is estimated to be 150 000 000 m^3 (Naumann, 1990). The volume of debris is barely one-third of this, a discrepancy which remains unexplained. The debris shows evidence of multiple events, possibly involving failure onto Late Wisconsinan ice. The debris contains fragments of trees; radiocarbon ages from these wood fragments range between 4350 ± 70 BP (SFU-W-04) and 5010 ± 70 BP (GSC-4004, collected by J.J. Clague) indicating a mid-Holocene age for the events.

Mystery Creek

The Mystery Creek rock avalanche (Fig. 1, 15; estimated volume 40 000 000 m^3) is located 20 km north of Whistler and involved the failure of a portion of the east side of the Green River valley. The debris covers an area of 1.2 km^2 in the bottom of the Green River valley, and is traversed by a B.C. Hydro main transmission line and B.C. Highway 99. The landslide was first reported by Eisbacher (1983), and described briefly by Clague et al. (1987) and Evans (1992a). The rock avalanche involved the failure of a mountain slope consisting of foliated, hard intrusive rock of the Pemberton Dioritic Complex. Slopes adjacent to the scar of the rock avalanche show indications of mountain slope deformation (Fig. 15).

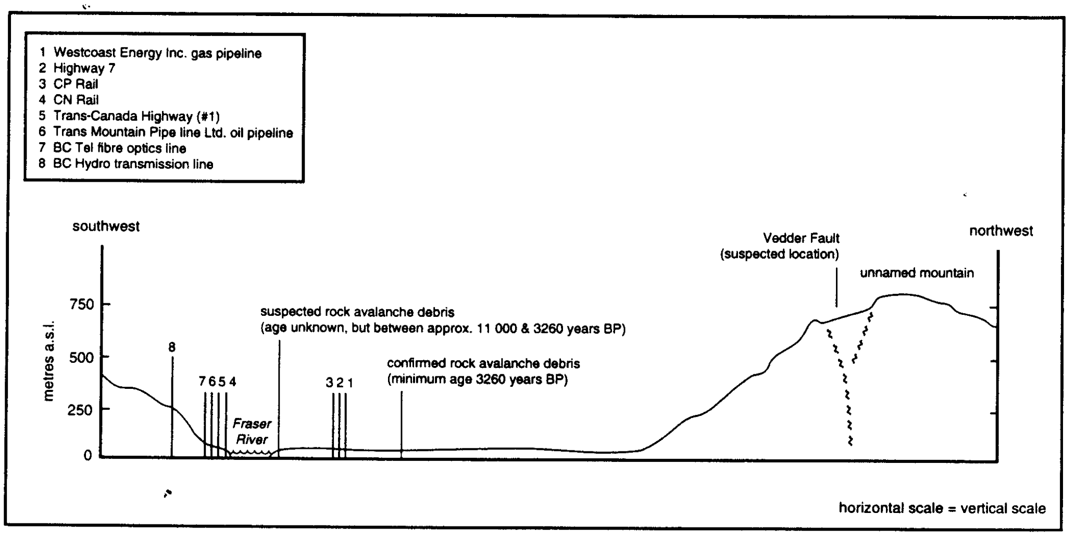

Figure 13. Profile of Katz rock avalanches in relation to linear infrasructural elements and the Fraser River.

A radiocarbon date from charcoal dug out from beneath a large boulder in the debris yielded a radiocarbon age of 880 ± 100 BP (GSC-4237) and is thought to represent a minimum age for the landslide.

Detachment on a low angle (18°) joint surface dipping out of the slope appears to have been preceded by toppling toward the Green River valley involving flexural slip on steep foliation surfaces dipping into the slope (Evans, 1992a). Antislope scarps formed by toppling are present in displaced rock masses along the southern margin of the scar (Fig. 16). The characterization of the process by which this type of slope deformation terminates in catastrophic detachment remains a current research problem in géotechnique.

Other features related to rock avalanches

Some rock avalanches, which have occurred in similar terrain in other parts of the Coast Mountains, exhibit dramatic mobility (e.g., spectacular run-ups, marked changes in direction, and superelevation of debris in curves) and travel long

Figure 14. Airphoto of Cheam slide(s), Fraser Valley. Both source area (S) and extent of debris (D) have yet to be defined in detail. The debris is crossed both by the Canadian National Railway and the Trans-Canada Highway. Radiocarbon dates quoted in text were obtained from wood in debris in pit marked P. Fraser River (F) and flow direction are indicated. NAPL A27109-40

Figure 15. Oblique aerial view to the east of the prehistoric Mystery Creek rock avalanche, 20 km northeast of Whistler. Toppling shown in Figure 16 occurs on right hand (southern) margin of scar. GSC 204107G

Figure 16. Antislope scarp formed by toppling on southern margin of Mystery Creek rock avalanche. Downslope is to the left. GSC 1994-709E

distances from their source, an example being the Pandemonium Creek event (Evans et al., 1989) which occurred in 1959, 360 km northwest of Vancouver, in Tweedsmuir Provincial Park. The debris travelled up to 9 km from its source over a vertical distance of 2 km; an analysis of the event indicated that the velocity of the debris may have reached 100 m•s^{-1} (Evans et al., 1989). Although this type of highly mobile rock avalanche has not been documented so far in the nonvolcanic rocks of the Vancouver region, in view of the similarity in geology and terrain, the potential for such an occurrence is thought to exist.

Rock avalanches may produce important secondary effects, including the damming of rivers and streams to form landslide dammed lakes and landslide-generated waves.

Figure 17. Landslide dammed lake in the Nahatlatch River watershed. The rock avalanche occurred in plutonic rocks. GSC 1992-0815

There are several lakes in the Vancouver region which are dammed by rock avalanche debris (Fig. 17; Evans, 1986; Clague and Shilts, 1993; Clague and Evans, 1994b). They include Dickson Lake, Lake of the Woods (also known as Schkam Lake), Silver Lake, and Foley Lake (Fig. 1).

Landslide-generated waves, which extend the zone of potential damage well beyond the limits of the rock avalanche debris, have not been documented in the Vancouver region but have been reported from nearby Vancouver Island (Evans, 1989b).

Rockslides and mountain slope deformation

Numerous rockslides involving noncatastrophic movement of rock masses on defined shear surfaces, and in which the debris largely remains on the sliding surface, have been mapped in the Vancouver region (e.g., Armstrong, 1984; Savigny, in press). On the north slope of Mount Burnaby for example, (Fig. 1, 18) small rockslides have developed in southerly dipping Tertiary sediments (Armstrong, 1984).

The deformation of steep mountain slopes is a common slope movement process in the Vancouver region. It is manifested in topographic features such as cracks, fissures, trenches, antislope scarps at mid- or upper slope locations, collectively known as linears, and, in some cases, bulging at lower slope locations. Frequently, these features occur without well defined headscarps, or lateral scarp or lateral shear zones suggesting that slope movement is occurring without well defined shear surfaces having been formed, unlike rockslides described above. These characteristics often lead to problems in the identification and interpretation of mountain slope deformation as the following examples illustrate.

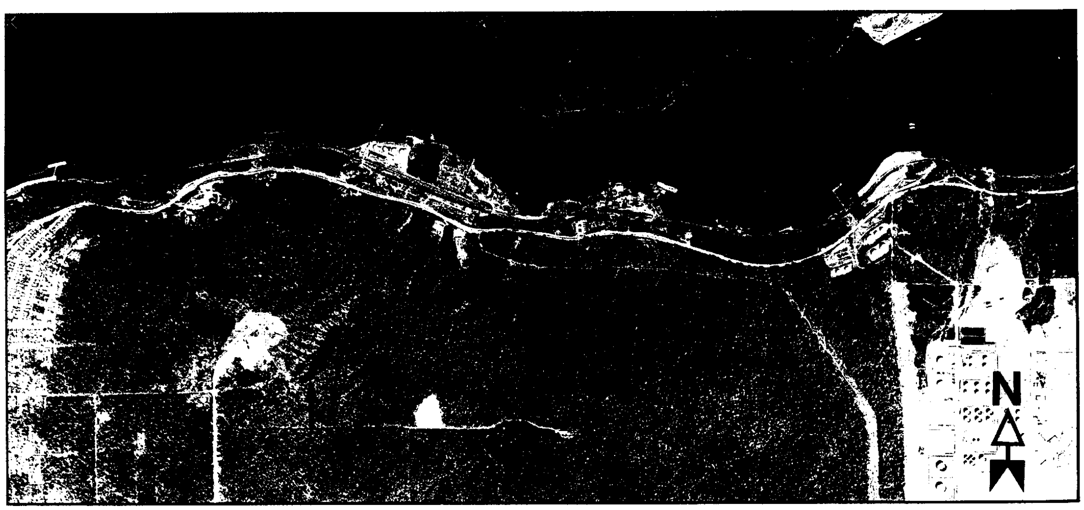

Figure 18. Airphoto taken in 1959 of rockslides on north slope of Mount Burnaby. The scarps of the rockslides are indicated with arrows. NAPL A16830; 121

Wahleach

The best documented example of mountain slope deformation in the Vancouver region is that at B.C. Hydro's Wahleach Power Station in the Fraser Valley (Moore et al., 1992; Savigny and Rinne, 1991). The Wahleach power station generates electricity by water flows from a reservoir at Wahleach Lake through a complex conduit system (Fig. 19) which consists of a 3 m diameter, 3500 m long upper tunnel, a 600 m shaft inclined at 48°, a 300 m lower tunnel, and a 485 m surface penstock to the power house located adjacent to the Trans Canada Highway. A total of 620 m of head is developed. In 1989 the steel lining of the upper tunnel was ruptured by slope movement (Fig. 19) and water was released into the slope.

The slope at Wahleach consists of hard, strong granodiorite cut by minor dykes and has total relief of approximately 920 m and an average slope of 25° (Fig. 19). The rock mass is characterized by closely spaced fractures and shear zones. There is a gradual increase in rock quality with depth (Moore et al., 1992). Throughgoing discontinuities with downslope dips of less than 45° are absent. According to Moore et al. (1992), the Wahleach slope has undergone prehistoric movement down to average depths of 150-200 m as indicated by loosened rock down to this elevation, and the linear troughs and scarps in the upper part of the slope (For location, see D in Fig. 34); the current movement involves rock to depths of 60-120 m (Fig. 19). Between 1990 and 1992 the movements have resulted in surface displacements of 4-40 mm•a^{-1} and, on the basis of their distribution and timing are concluded by Moore et al. (1992) to be consistent with gravitational creep which may also involve elements of sliding and block rotation. Moore et al. (1992, p. 106) concluded that, "lack of throughgoing adversely oriented discontinuities, the long history of diffuse, slow movements and the insensitivity of these movements to groundwater, indicate that the present movements will continue for considerable time and that a large rockslide is not imminent".

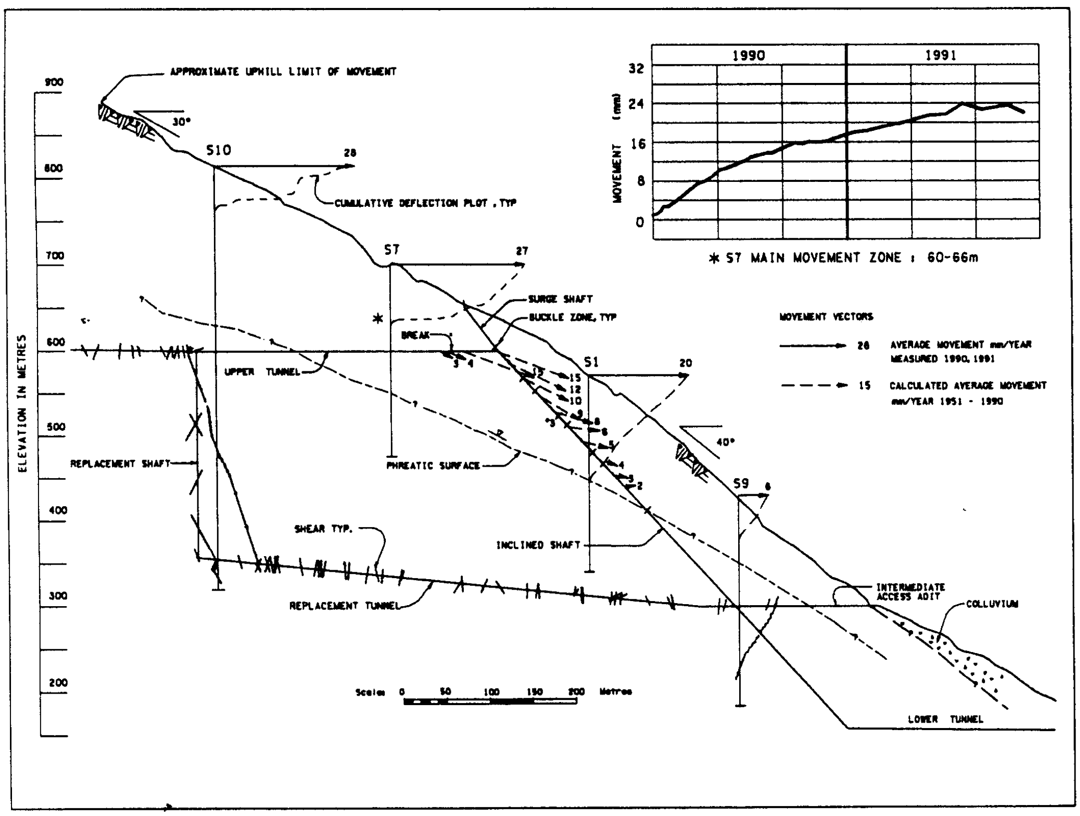

Figure 19. Mountain slope deformation at B.C. Hydro's Wahleach Power station in the Fraser Valley. Section showing movement and geology (after Moore et al., 1992).

Figure 20. View of mountain slope deformation at Mt. Breakenridge, Harrison Lake. GSC 1994-709F

Figure 21. Displaced rock masses resulting from mountain slope deformation, Mt. Breakenridge, Harrison Lake. GSC 1994-709G

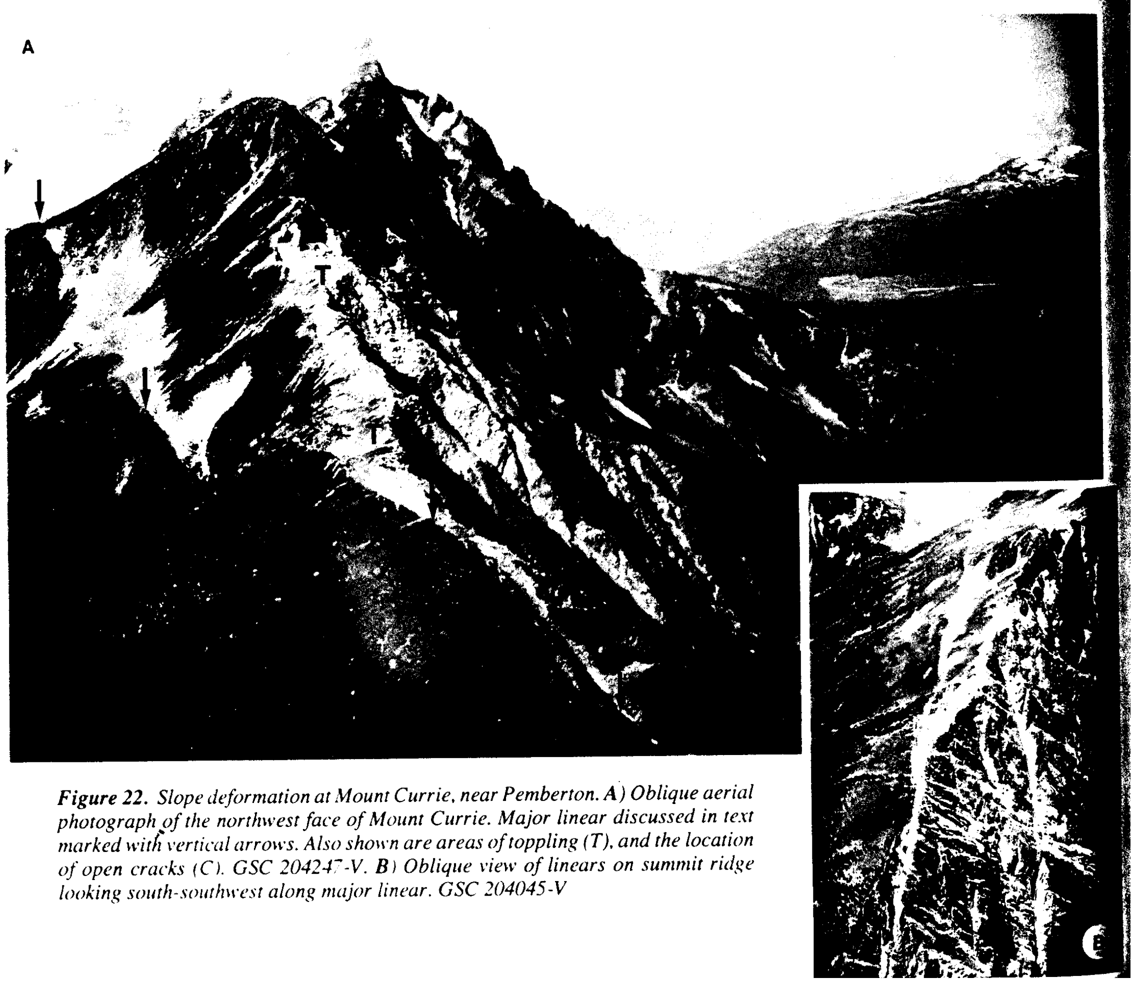

***Figure 22.** Slope deformation at Mount Currie, near Pemberton. **A**) Oblique aerial photograph of the northwest face of Mount Currie. Major linear discussed in text marked with vertical arrows. Also shown are areas of toppling (T), and the location of open cracks (C). GSC 204247-V. **B**) Oblique view of linears on summit ridge looking south-southwest along major linear. GSC 204045-V*

Mount Breakenridge, Harrison Lake

The geotechnical interpretation of mountain slope deformation features, particularly with respect to movement mechanism and catastrophic potential, is sometimes problematical. At Mount Breakenridge, for example, on the eastern shore of Harrison Lake (Fig. 20), a steep mountain slope has undergone considerable deformation (Fig. 21). The slope consists of metamorphic rocks of the Mesozoic Slollicum Schist; it extends from lake level to an elevation of 1445 m and runs beneath Harrison Lake to elevation -200 m, resulting in a total relief of 1645 m. The broken ground on the summit ridge of the slope consists of toppled blocks, scarps, and cracks and extends for 2.5 km along the ridge. The attitude of the foliation in displaced rock masses suggests that slope deformation has resulted from toppling. Concern was raised about the possibility of catastrophic failure at the site which could generate a displacement wave in Harrison Lake (Vancouver Sun, June 30, 1989), which in turn would impact on the tourist resort of Harrison Hot Springs at the southern end of the lake, 48 km from the site, and on the Port Douglas Indian Reserve at the head of the lake, 15 km from the site. Subsequent investigations by provincial authorities indicated that the likelihood of this scenario occurring was low. An acoustic survey of Harrison Lake by Desloges and Gilbert (1991) found no evidence of any disturbances of the lake floor sediments that could have resulted from a previous catastrophic failure of the Mount Breakenridge slope.

Mount Currie

In some parts of the Coast Mountains, mountain linears have previously been interpreted as tectonic features rather than the result of gravitational processes (e.g., Clague and Evans, 1994a). In the Vancouver region, a problematical example of slope deformation is that which exists on the northeast ridge of Mount Currie, overlooking the town of Pemberton (Fig. 1). A 1.75 km long southwest-trending linear, obvious from the air and on aerial photographs (Fig. 22), was first described by Eisbacher (1983) who ascribed a tectonic origin to the feature. A maximum of 20-30 m vertical displacement has taken place along the linear. The northeast ridge is made up of hard gneissic rocks of the Pemberton Dioritic Complex, the structural fabric of which is dominated by a near vertical foliation (Evans, 1987). Rock mass disruption and gaping tension cracks indicate that at least some of the vertical displacement is due to gradual large scale slope movement of the summit ridge. Toppling of the gneissic foliation is also present (Evans, 1987).

Hell's Gate

Slope deformation may also be triggered by large scale construction. During excavation of a 65 m high rock cut at Hell's Gate Bluffs during the construction of the Trans-Canada Highway in the Fraser Canyon, cracks exceeding 1 m wide in places, were discovered in hard granodiorite containing steeply dipping discontinuities. Construction was halted but movement continued. As described by Piteau et al. (1979), the cracks developed along a set of steeply dipping faults and analysis showed that the movements consisted of the outward overturning, or toppling, of fault defined blocks (Kalkani and Piteau, 1976). Movement was found to be a direct function of precipitation. The movement was stabilized by excavation of the head of the slope and the implementation of measures to prevent infiltration.

DEBRIS AVALANCHES IN QUATERNARY VOLCANIC ROCKS, GARIBALDI VOLCANIC BELT

Garibaldi Volcanic Belt

The Garibaldi Volcanic Belt is the northward extension of the Cascade Volcanic Belt. Quaternary volcanic rocks of the Garibaldi Group occur in three major centres, viz. Mt. Garibaldi, Mount Cayley, and Mount Meager (Fig. 23).

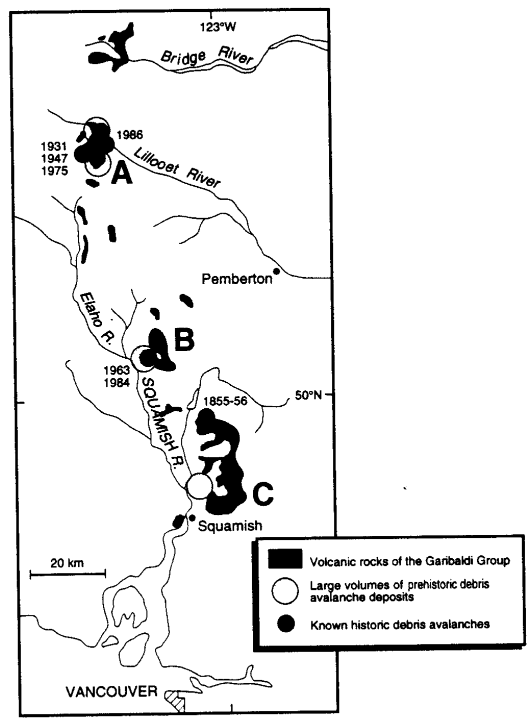

Figure 23. *Map of Garibaldi Volcanic Belt, southwestern British Columbia showing main volcanic centres (A = Mount Meager, B = Mount Cayley; C = Mount Garibaldi), location of large volumes of prehistoric debris avalanche deposits, and the location and dates of known historic debris avalanches (modified from Evans and Brooks, 1991).*