CHEEKYE RIVER

TERRAIN HAZARD
and
LAND USE STUDY

Final Report – Volume 1

March, 1993

THURBER

Golder Associates

Prepared for B.C. Ministry of Environment Lands and Parks

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CHEEKYE RIVER TERRAIN HAZARD AND LAND USE STUDY

FINAL REPORT

VOLUME 1
MAIN TEXT

Submitted to:

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Lower Mainland Region
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DISTRIBUTION:

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March 1993

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CHEEKYE RIVER TERRAIN HAZARD AND LAND USE STUDY

1.0   INTRODUCTION

1.1   Terms of Reference

This report represents the work carried out for the Cheekye River Terrain Hazard Study. The Terms of Reference are included as Appendix I. The scope of work presented in the Thurber Engineering Ltd. (TEL)/Golder Associates (GAL) proposal dated May, 1991, responded to these Terms of Reference and are shown in Figures I-1 and I-2; at the request of the Working Group, further modifications to the Terms of Reference were made and these were addressed in letter from TEL to the Ministry of Lands and Parks dated September 9, 1991. This letter is also presented in Appendix I. Some additional modifications were made after the review of the Interim Report presented at the end of the first phase of the study.

1.2   The Study Team

The study team included G. Rawlings, P.Eng., P.Geo., (Project Manager), U. Hunger, P. Eng., (Project Geotechnical Engineer), R.F. Gerath, P.Geo., (Engineering Geologist) J. Wollenberg (Landuse Planning Consultant), K. Rood (Hydrologist), F. Baumann, P.Geo., M. Goldbach, P.Eng., and J. Psutka, P.Geo. as Field Geologists.

1.3   Format of Report

This Final Report is presented in two volumes. Volume I carries the text and accompanying figures; it provides the justification for the project, describes the work carried out, presents a description of the project and identifies the potential terrain hazards affecting the fan. Volume 2 contains appendices which include the results of specific aspects of the work carried out by the consultants or their specialist sub-consultants.

A summary report is presented separately from this Final Report for more general circulation.

1.4   Background to Study

The lower Cheekye Fan is an area of 7 km² of gently sloping ground immediately to the north of Brackendale within the District of Squamish and some 80 km north of Vancouver (Figure 1.1). In many respects, the area is very suitable for development and has been the subject of past interest for the expansion of the Brackendale area of Squamish. In 1974, the Tantalus subdivision was planned and a review for permitting purposes was undertaken by the Ministry of Transportation and Highways (Crook and de Boer, 1974). On the basis of previous experience of debris flows and floods on the fan from the Cheekye River (Jones, 1959), it was recommended that a geotechnical study should be undertaken to determine the risks to potential developments from natural hazards in the catchment. A contract was let to Crippen Consultants who carried out an investigation for this purpose (Crippen, 1974). It was followed by a further report which described recommended mitigative measures which would permit development within limited areas on the fan (Crippen, 1975). However, the cost of the recommended mitigation was too great to be borne by the subdivision alone. Moreover, there were residual concerns over the extent and frequency of the natural hazards even if the recommended designs were implemented. At this stage, the infrastructure for the subdivision had already been put into place but as the final permits were not granted, the development did not proceed.

During 1980, a large distressed area within the Cheekye Basin was recognized (Baumann, 1980) and it was felt by several investigators that this could be the source of future large landslides which could impact the fan below. At the same time, consideration was being given to a new hospital and long term care facility for the Brackendale/Squamish District. Possible sites identified included one on the Cheekye Fan as well as an extension of the existing hospital site in Squamish. After further geotechnical concerns over this latter site had been allayed, and because the concerns over the hazards to the fan remained unresolved, the Minister of the Environment ruled that a hospital development on the fan should not be permitted. A further report by Crippen (1980) re-examined their earlier work in the light of the new geotechnical evidence obtained by Baumann; it was concluded by Crippen that all major events affecting the fan were "a product of the geologic past" and probably could be dated as immediately post-glacial. However, a wood sample obtained and dated immediately

after that report in 1980 yielded C-14 date of 5890 ±100 years B. P. and thus cast doubt on these conclusions.

No further systematic geotechnical work on the fan was carried out until the Novacorp studies regarding future development of the airport in 1990 (Baumann, 1990).

The Ministry of the Environment commissioned Mr. Graham Morgan, P. Eng., to make recommendations to resolve the geotechnical issues. This report (Morgan, 1990) set out terms of reference for a definitive study and estimated the budget required. On the basis of the Morgan report, a joint steering committee drawn from various B. C. government ministries, the District of Squamish and B. C. Rail was established. A request for proposals was sent out to consultants on April 17, 1991 and a contract was awarded to an association of TEL and GAL on June 17, 1991.

TEL/GAL subcontracted the hydrological aspects of the study to Northwest Hydraulic Consultants Ltd.; the land use aspects to Coriolis Consulting Corporation; the geophysical survey to Geotronics; and the topographic mapping to McElhanney Geosurveys.

In advance of the call for proposals, interim studies recommended by Morgan were carried out. In addition, aerial photography was flown and ground survey completed for the preparation of topographic maps when a consultant was appointed.

These interim studies comprised literature searches on known and dated occurrences of rock avalanches and debris flows within the Garibaldi Complex by Dr. S. G. Evans (1991); on the physical characteristics of local debris flows by Dr. P. Jordan (1991); on analytical procedures for assessing runout potential of rock avalanches and fine grained debris flows by Dr. O. Hungr (1991); and a report on the Cheekye Fan Garbage Dump Debris Flow Deposit by F. Baumann (1991).

An Advisory Board was established to review the aims, progress and conclusions of the study.

1.5 Work Carried Out

1.5.1 Objectives

The project was designed to be carried out in two phases.

The particular intent of Phase I was to address the question of a potential catastrophic event which could endanger the entire fan without possibilities for mitigation. Because of several major differences of professional opinion on the possibility of such an event occurring, and its potential consequences should it be shown to be a possibility, it was concluded that a definitive study should be carried out to answer these questions before further studies proceed. The final objective in Phase II was to describe the full spectrum of potential hazards on the fan, to provide input to a land-use plan for the fan and to recommend concepts for remedial works.

A summary of the work carried out by TEL/GA and their subconsultants by identified task is described below.

1.5.2 Topographic Mapping

Initially topographic maps of the basin and fan were produced by McElhanney Geosurveys at scales of 1:10,000 and 1:5,000 respectively. In addition, an orthophoto of the complete project area was compiled. Use was made of the government photographs flown specifically for the project as well as existing government photographs on file in Victoria.

1.5.3 Review of Available Information

A collection was made of all relevant geological, hydrological and geotechnical reports and maps, unpublished geological data, in-house files and other information. The references obtained, and others referred to in the text, are presented at the end of the Main Text, Volume 1. The collected material was reviewed for use in the subsequent studies.

A map of the regional geology compiled from this review is presented as Figure 3.1.

1.5.4 Review of Volcanic, Seismic and Neotectonic Hazards

The regional seismic history was reviewed from existing reports. A detailed seismic assessment was provided by the Pacific Geoscience Centre (Appendix II).

Volcanic hazards were reviewed from data already published on the Garibaldi Volcanic Belt and related to the overall context of the Cascades Volcanoes. Ages and periodicity of volcanic activity were analyzed.

The results of the review are presented in Appendix III.

1.5.5 Airphoto Terrain Analysis/Airphoto Comparative Analysis

Detailed photo-interpretation was carried out as input to the terrain analysis of the basin and fan; field checks were made. Various generations of airphotos were interpreted in order to analyze changes in hazard activity with time.

1.5.6 Geological Mapping of Cheekye River Basin

An extensive program of geological mapping was undertaken in the Cheekye Basin. The study was focussed towards areas of known, or suspected, instability, in particular Cheekye Ridge and the western slopes of Mr. Garibaldi, Dalton Dome and Diamond Head. During the fieldwork, a further area of potential instability was located on Brohm Ridge and detailed mapping was carried out in that area also.

The progress of the work was governed to a large extent by accessibility and weather. A very wet August, 1991 resulted in the fieldwork being separated into two phases. The steepness of the terrain, and weakness of many of the exposed faces, prevented actual traversing of some slopes which had to be mapped remotely by binoculars and airphoto interpretation. Helicopter support was utilized wherever practicable.

A report on the geological mapping of the basin is presented as Appendix IV and the results are summarized in Figure 3.2. Regional photolineaments are shown on Figure 3.5.

1.5.7 Seismic Profiling of Cheekye Ridge

A geophysical survey across the linears previously identified on the Cheekye Ridge was carried out by Geotronics and is presented in Appendix V. Resistivity measurements were attempted but the results were ambiguous and further profiling was discontinued.

1.5.8 Trenching of Cheekye Linears

Limited trenching across the Cheekye Linears was carried out from the forest access roads.

1.5.9 Dendrochronology

There has been no requirement for dendrochronology during the study, as the age of significant hazard events exceeds the age of the forest cover.

1.5.10 Instrumentation

A monitoring system has been established on Cheekye Ridge. Targets for first-order survey have been installed and founded at a sufficient depth to avoid problems of frost heave or surficial instability. An initial survey has been carried out. A description of the installation and initial results is given in Appendix VI.

1.5.11 Analysis of Basin Slope Stability

On the basis of the fieldwork and review studies, various potential scenarios for catastrophic failure were identified. Analyses were carried out for each of these, assuming different magnitudes and probabilities of failure.

1.5.12 Surficial Geological Mapping of Cheekye Fan

A summary was made of Quaternary geological events in the region surrounding the study area (Figure 3.3). Detailed geological mapping was carried out on the fan (Figure 3.4) which then permitted a chronology of Quaternary events to be established in relation to the regional picture.

1.5.13 Test Pitting in Fan Area

Test pits were excavated across the fan to supplement information from existing natural exposures, current excavations (Garbage Dump, gravel pits etc.), well records and boreholes.   Pits excavated during Stage I were generally shallow and thus only investigated recent activity on the fan.   Logs of these test pits are presented in Appendix VII and locations are shown on Figures 3.2 and 3.4. Five deep test pits were excavated during Stage II to explore the stratigraphy of the fan deposits. Detailed logs of these test pits are provided on Figures 3.17 through 3.22.

1.5.14 Laboratory Testing

Testing has been carried out in the TEL and GAL laboratories on soil samples from the fan for classification, on rock material from Cheekye Ridge for identification and assessment of strength, and on organic samples from test pits for age dating. The results of grain size analyses are presented in Figures 3.26 and 3.27.   The rock and soil test results are presented in Appendix VIII, the age dating in Appendix IX and petrographic analysis in Appendix X. The age dates are also summarized on Table 6.1 of the report.

1.5.15 Analysis of Fan History

Data obtained from the preceding tasks on the fan was collated to achieve an understanding of the fan history. Stratigraphic correlations of debris flow deposits on the fan were established (Figure 3.24).

An analysis of precipitation events in the study area was carried out to correlate with known flood or debris flow events (Section 5). However this represents only the most recent period in the development of the fan deposits.

1.5.16 Probability of Occurrence of a Catastrophic Landslide

The results of the basin slope stability and the analysis of the fan history were jointly interpreted in order to consider past events and the probability of future catastrophic landslides which could have major consequences on the fan.

1.5.17 Runout Analysis

The runouts from various assumed failure scenarios were analyzed in order to consider whether the fan could be impacted and, if so, what the extent of the inundated areas could be. Analogies were used from comparable failure models in volcanic terrain elsewhere.

1.5.18 Debris Flow Probability

From the stratigraphic correlations, and considering the volume of sediments in the fan, it was possible to construct an approximate frequency-magnitude relationship for major debris flows in the Cheekye Basin.

1.5.19 Debris Flow Runout

The runout characteristics (distance, velocity and flow depth) were estimated for various classes of debris flow events, using empirical and analytical methods of analysis.

1.5.20 Risk Analysis and Zoning

Detailed risk assessment at various locations on the fan was carried out using two distinct approaches:

a) Hazard probability was estimated for several classes of events and compared with relevant acceptance criteria.

b) Probability of outcome of serious loss was estimated in terms of risk to an individual and to groups and again compared with acceptance criteria.

The fan and adjacent lands were divided into zones of approximately equal risk from the largest magnitude event.

1.5.21 Mitigation Concepts

Three alternative schemes for protection works were developed based on the two types of risk assessments. The basic dimensions of the works were outlined and residual risks were estimated.

1.5.22 Land Use Recommendations

Detailed descriptions of existing land use and development, existing land ownership, and mineral claims were made and are summarized on Figures 9.1 and 9.2. Implications for existing and future land use from the potential hazard scenarios have been assessed and recommendations made for land uses compatible with hazard probability levels both before and after mitigation. A summary was made of the legislative tools available for land use planning in geotechnically hazardous areas.

2.0 PHYSIOGRAPHY

2.1 Location

The project area lies within the Coast Mountains of British Columbia at the north end of Howe Sound, some 80 km north of Vancouver, at the confluence of the Squamish and Cheakamus Rivers (Figure 1.1). At this location, drainage flowing westwards off Mt. Garibaldi by means of the Cheekye River has created a large fan which has displaced the Squamish River to the west. The area is thus approximately bounded by the Cheakamus and Squamish Rivers to the west and north and the topographic limits of the fan to the south and east.

2.2 Topography

The topographic relief within the Cheekye catchment is extreme, varying from the Mt. Garibaldi summit above El. 2,670 m down to the Cheakamus River at El. 25 m. The steep western slopes of Mt. Garibaldi, Dalton Dome and Diamond Head between El. 1,200 m and El. 2,000 m are the dissected relicts of Quaternary volcanoes; the lower slopes of the headwaters are formed in altered, weathered or fresh basement rocks of Cretaceous or Jurassic age (Figure 3.1); and the much flatter lower slopes below El. 600 m are formed on Quaternary glacial, alluvial and slide materials. The instabilities in the upper slopes, and the transportation of the slide materials to lower elevations, together with complex glacial events, have been responsible for the development of the extensive fan below El. 600 m in Quaternary sediments.

The fan may be divided into three parts (Baumann, 1991; Figure 3.3) a relict Upper Fan forming a high terrace along the east wall of the valley and incised to depths up to 90 m

by the Cheekye River; a Middle Fan showing very irregular topography resulting from glacial wasting and glaciofluvial erosion, also incised by the Cheekye and the active Lower Fan showing very uniform slopes of 2 - 3° and truncated by the Cheakamus and Squamish Rivers. The Lower Fan has an area of 7.0 km² and the combined upper and Middle Fans an area of 8.0 km². The upper basin and the fan are separated by a bedrock gorge which provides a "throat" through which the river must pass en route to the fan.

2.3   Drainage

The project area is defined by the drainage basin of the Cheekye River and includes a major tributary, the Brohm River, which flows southwards to join the Cheekye at the eastern edge of the Lower Fan. The Cheekye River drains an area of approximately 50 km² on the west flank of the ridge connecting Mt. Garibaldi (El. 2,670 m) with Diamond Head (El. 2,100 m).

The Cheekye River is highly volatile and torrential flows are frequently experienced. It is apparent that in addition to the severe flood flows, the river experiences debris floods and debris flows and that these have occurred within the historic past (Jones, 1959). They have been instrumental in the formation of the fan.

2.4   Vegetation

The catchment shows varying degrees of vegetation coverage. The steep slopes of Dalton Dome and Atwell Peak where it is difficult for vegetation to become established on the steep, dry or ravelling slopes are largely bare. Elsewhere, the upper part of the catchment is densely forested although some areas have been clear-cut in recent years. The fan areas below El. 600 m have been widely logged and much of the area is covered by 80 year-old second growth timber.

3.0   GEOLOGY

3.1   Regional Setting

The regional geology of the area surrounding Mount Garibaldi was described by Mathews (1952 and 1958), Green (1977, 1990) and others. A geological map authored

by Green (1977) has been reproduced as Figure 3.1. A geological report by J. Psutka on mapping in the Cheekye Basin is presented in Appendix IV.

Of relevance to the present investigation are two formations of basement rocks and a series of volcanics of various ages ranging from the early Pleistocene to the end of the last episode of glaciation (Table 3.1).

3.1.1   Basement Rocks

The mapping by Green, which incorporates earlier information from Mathews, and Roddick and Woodsworth (1977) shows the basement rocks in the Cheekye valley as belonging entirely in the Cretaceous Cloudburst Pluton, consisting of foliated and non-foliated quartz diorite and diorite. However, the Cloudburst Pluton was recently dated as Late Jurassic (see Appendix X) and its rocks are generally absent from the upper Cheekye Basin, except as occasional dykes or migmatitic zones.

The dominant basement rocks encountered in the geological mapping of the upper basement are metavolcanics including dark green plagioclase porphyry, welded volcanic breccias with minor rhyolite flows or dykes, tuffaceous sediments and diabase dikes (Appendix IV). The metavolcanics are mainly massive but locally develop a weak to moderate foliation. Chloritization and epidotization are common. The siliceous (rhyolite) dykes are intensely sheared in certain locations and resemble siliceous phyllites.

Following Green's terminology, the metavolcanics would be grouped with roof pendants of Lower Cretaceous or Jurassic Gambier Group age. Read (Appendix X) presents arguments that these rocks may more properly be assigned to the Middle Jurassic Harrison Lake Formation.

The general character of the unaltered basement rocks in the Cheekye Basin is green to silvery green colour, fine-grained texture with variable degrees of foliation, consistently high to very high strength and generally massive structure with isolated zones of bedded or fissile rocks. Generally there are two or three well defined joint sets, although none is very dominant or persistent, except in the bedded or fissile zones. The discontinuities tend to be smooth or moderately rough, curved, not very consistently oriented, unfilled

and tight. A collection of discontinuity attitude measurements from a wide range of localities within the basin is given in Figure 3.6. The character of altered basement rocks is discussed in Section 3.3.

The regional structure of the area is not well documented. Mathews (1958a, Figure 1) indicates intense steep foliation striking north-west by north, consistent with the foliation data shown in Figure 3.6. Neither Mathews nor Green (1977) show any faults in the basin or west towards the Cheakamus River. Green (1977) and Roddick and Woodsworth (1977) show some large north-west or north trending structures to the north of the study area. The interpretation during airphoto study identified a predominance of lineaments averaging a due north trend (Figure 3.5). Some of these lineaments form prominent features in the morphology of the east wall of the Cheakamus Valley and must represent major unmapped structures.

3.1.2 Quaternary Volcanics

The area contains a variety of volcanic rocks of various ages. Of the 15 eruptive episodes identified in Table 3.1, the following relate to the Cheekye Valley:

> Rocks of the 0.4 to 0.7 Ma volcanic episode include dacitic lava flows and underlying moderately indurated pyroclastic breccias situated on Brohm Ridge.

> Rocks of the 0.2 - 0.3 Ma (Cheekye Stage) episode consisting of remnants of a dark grey plagioclase porphyry flow situated at the extreme western end of Cheekye Ridge and on the Middle Fan, east of Alice Lake.

> Lavas and pyroclastic breccias of the 11 - 26 ka Atwell Peak stage, forming extensive deposits at the head of the Cheekye Valley, including the core complex of Atwell Peak and a surrounding 1000 m thick conical sequence of pyroclastics of dacite composition. A small lava plug projects to the surface of Cheekye Ridge near Elevation 1800 m.

> Lavas and pyroclastic interbeds of the 11 ka Dalton Dome stage. This sequence, represented by a schematic stratigraphic column in Figure 3.9 contains three thick units of dacitic lavas and dense welded tuffs, separated by thinner layers of uncemented pyroclastic breccias.

3.1.3 Other Quaternary Deposits

A summary of the main Quaternary features of the Cheekye Basin is presented in Figure 3.3. Brohm Ridge is covered by a thin veneer of glacial drift up to at least El. 1850 m and this may represent the upper limit of Pleistocene ice in the area. In contrast, only the western part of Cheekye Ridge has glacial drift. The segment of the ridge above El. 1350 m, including the area of the Cheekye Linears, is covered by pyroclastic breccias generally with no signs of glaciation. An exception is found in the area immediately south of the linears, at El. 1350 m, where two large dioritic erratics have been observed, situated on top of the breccias.

A few altered and rounded basement (metavolcanic) clasts have also been observed in an exposure of the breccia within metres of the basement contact in the same area. This evidence indicates that some interaction between the pyroclastics and Pleistocene ice took place during their deposition and serves to fix the date of the Atwell stage near the height of Fraser Glaciation.

Both Brohm and Cheekye Ridge, as well as the smaller ridge descending west from Dalton Dome, are covered by a pervasive but generally thin veneer of silt. Well developed dunes on Brohm Ridge suggest that this material is of aeolian origin (Mathews, 1952).

A distinct terrace composed of stratified sands and gravels is found on the south wall of Brohm Ridge, at El. 1300 m. This is identified as a kame terrace of Late Pleistocene origin, as the quantity and character of the glacio-fluvial deposits are not consistent with a neo-glacial origin.

The Cheekye Gorge, at the outlet of the valley, is a narrow chasm cut in massive, unaltered basement rocks and locally only a few tens of metres wide (Plates 14 and 15).

The Upper Fan (Section 2.2) is a segment of a large fan of colluvial (debris flow) origin, the deposition of which was apparently truncated on the west by a barrier of Pleistocene ice. This interpretation is suggested by the gradual slope and somewhat irregular morphology of the western margin of the feature and its internal structure, which includes faint layering dipping 20° to the west.

The Middle Fan area further downstream exhibits chaotic, pitted topography typical of ablation terrain, with several well defined kettle lakes. Most, if not all, of the abrupt knolls and hummocks in this area are found to be bedrock cored. The material forming the ablation features is texturally similar to the debris flow diamictons of the Upper Fan, although it includes some basement clasts.

One well defined outwash channel passes north-south through Alice Lake (it is possible that the Cheekye itself at one time followed this channel to discharge along the present course of Hop Ranch Creek). A possible second outwash channel may have passed further east through the present Edith Lake, to join Mashiter Creek and thus access the extensive glacial outwash deposits of the Garibaldi Highlands.

The ablation terrain of the Middle Fan is bordered on the west, south and north by glacially rounded bedrock hills, some of which are covered by a thin veneer of drift.

The Cheekye passes through the Upper Fan deposits in a well-defined funnel-like erosional gap, floored by debris flow deposits. The upstream end of the gap is cut in bedrock. A belt of hummocky debris flow material with numerous relict channels follows the river through the Middle Fan. The river course is fixed by three bedrock "gates" shown on the detailed surficial geology map in Figure 3.4. Alice Lake appears to have been confined by the recent debris flow deposits.

After passing the last gate upstream of Highway 99, the Cheekye enters the wide, gently sloping expanse of the Lower Fan, prograded only slightly above the wide, braided floodplains of the Squamish and Cheakamus Rivers. The fan contains a few bedrock outliers but no indication of buried glacial or colluvial landforms.

Contemporary glaciers surround the Atwell, Garibaldi and Dalton summits on three sides (Figures 1.1, 3.2, 3.3 and Plate 3). Very small hanging glaciers extend into the Cheekye Basin from the col between Atwell and Dalton (Plate 1) and from the north side of the Dalton summit. Both produce continuing icefalls.

There is a strong possibility that Warren Glacier once extended a branch into the north arm of Cheekye valley at the location shown in Plate 4. However, no direct evidence of

this was found. The heads of gullies in all parts of the basin contain ice cored talus and abundant snow avalanche deposits.

3.2   Late Quaternary Geological History

An understanding of the geological history of the area is provided primarily by the work of Mathews (1952 and 1958).

The configuration of the early volcanic edifice is unknown, as the early volcanic rocks are represented only by fragmental remnants. It appears that the last (Fraser) glaciation encountered a mature, dissected topography somewhat similar to the present, although with a more subdued relief. The Cheekye Valley and adjacent valleys were already existing in some form. Fraser ice covered this landscape to at least El. 1850 m.

A series of Pelean eruptions formed the Atwell core complex and the surrounding cone of pyroclastic breccias. At least some of this activity took place at the height of the Fraser Glaciation.

Where the hot pyroclastics came into direct contact with the basement metavolcanics, more or less shallow alteration of the latter is considered to have occurred. An alternative hypothesis is that the alteration advanced from below, but this would make it difficult to explain its peculiar distribution following the complex geometry of the contact (Section 3.3.1).

It appears possible that a large portion of the pyroclastic sequence exposed in the headwall of the Cheekye Valley was deposited by eruptive activity preceding glaciation. This may be the finer grey breccia forming the lower part of the headwall below Elevation 1600 m, separated from the overlying coarse deposits by a near-horizontal unconformity (Plate 2, Figure 3.5).

Only such a sequence of events could sustain the notion of origin of the basement alteration by contact with the overlying pyroclastics, since the alteration exists at elevations as low as El. 800 m. Should all the breccias have been developed during the period of glacial expansion, the lower portions of the contact would be free of alteration as they would have been deposited on top of the ice sheet and not in direct contact with

the basement rock. The tongue of breccia extending into Mashiter Creek appears to have produced no alteration and thus may have been deposited onto the ice.

At some time during deglaciation, meltwater flowed west along the north margin of the waning ice tongue in the Cheekye Valley, to deposit a kame terrace on the wall of Brohm Ridge.

The Dalton Dome volcanic sequence was formed by a separate eruption, following retreat of ice from the head of Cheekye Valley and exposure of the sloping headwall. The eruption was completed before the end of the Pleistocene, allowing for deposition of aeolian silt on top of the volcanics on the lower Dalton ridge.

After retreat of Fraser Ice, 11,000 years B.P., much of the supra-glacial breccia deposits collapsed piecemeal into the Cheekye Valley and were transported through the gorge in the form of massive debris flows. This process took place fairly rapidly, while a wall of ice stood east of the present Alice Lake. On further retreat, ablation terrain was formed west of the Upper Fan margin and one or two major meltwater channels formed through the Middle Fan area.

The Cheekye rapidly cut through the Upper Fan deposits creating a funnel shaped gap.

With the end of deglaciation, the Cheekye found a gap through the bedrock hills and directed its steady supply of sediment towards the Cheakamus River, displacing its channel to the west and forming the Lower Fan. This process continues at present.

3.3   Geology of the Cheekye Basin

3.3.1   The Contact and the Altered Zone

The contact between the basement and the volcanic rocks forms a complex surface which in many places shadows the topography of the present valley walls (Figure 3.2). In particular, a distinct down-valley slope of the contact has been identified near both the Cheekye and Brohm Linears. At the Cheekye Linears, a thin tongue of pyroclastics descends almost the entire height of the valley wall and is presumably responsible for the active surficial instability in the bulging toe segment of the slope (see Figure 7.1).

In almost all locations where the contact is exposed, it is underlain by a thickness of altered basement rocks (Plate 6). In many places the thickness is definable, ranging from 10 to 30 m. In some locations, however, the thickness appears considerably greater and the base of the altered zone is not exposed. An interpretation of the geophysical profiles reported in Appendix V indicates that the altered zone is 40 to 50 m thick in the area examined.

The altered rock retains the bedded structure of the parent rock, where present. The alteration is manifested by discolouration (whitish with bright orange or rusty brown staining), weakening of the rock material to weak strength (20 MPa or less, see Appendix VIII), increased fissility, much reduced joint spacing (typically to a few cm) and the appearance of gouge-filled seams (Plate 7).

The latter are typically one to 5 cm thick, consisting of rock fragments in a loose matrix of slightly cohesive micaceous silt. Typical grain size distribution curves of the gouge are shown in Figure 3.7. The fine fraction of the matrix has a liquid limit of 20.2 and a plastic limit of 17.2. This gives an activity of approximately 0.6, corresponding to kaolinite. X-ray diffraction tests reported in Appendix X confirm the dominant clay mineral as kaolinite. This contrasts with tests carried out on behalf of Professor Mathews in 1952, which identified 30 to 50 percent of expanding lattice clays (smectites), in addition to illite and kaolinite. His sample originated from an exposure low in the Cheekye River valley.

Shear box tests carried out both on intact and remolded samples of the gouge indicated friction angles in the order of 28 to 30° (Appendix VIII). It is possible that the sampling did not encompass the weakest component of the altered zone, although one sample each was collected from both Cheekye and Brohm Ridge. Sampling of materials was constrained by the availability of exposure and access.

Despite the relatively high frictional strength of the gouge, the bulk strength of the altered zone under high normal stress levels may be quite low, as discussed further in Section 7.1.

3.3.2   The Pyroclastic Breccias

With the exception of some of the older breccias on Brohm Ridge, the pyroclastic material is totally unindurated and has the character of well graded, angular sand and gravel, with varying proportions of silt, cobbles and boulders. A collection of typical grain size distribution curves from various parts of the basin is given in Figure 3.8. Histograms of grain size distribution are shown in Figure 3.27. The breccias contain up to 28 percent of silt, but are non-plastic.

The lower half of the stratigraphic column exposed in the headwall below Diamond Head is a grey-coloured variety, distinguished by a lack of boulder and cobble particles, although the matrix is less silty than that of the upper Cheekye Ridge breccias. A similar fine-grained deposit is found at the head of Brohm Ridge (Plate 4).

The upper breccias contain at least 50% of coarse fragments ranging from gravel to large boulders. The clasts are sharply angular and often exhibit patterns of radial cooling cracks. The breccias are faintly stratified with dips of 10 to 12° away from the summit of Atwell Peak.   The fine-grained and coarser varieties are separated by a sharp near-horizontal contact, marked on Figure 3.2.

3.3.3   Dalton Dome Sequence

A generalized stratigraphic column through the Dalton Dome volcanic sequence is shown in Figure 3.9 and can also be recognized on Plate 5. The sequence consists of alternating massive lava units and thinner interbeds of pyroclastic breccias and sandy gouge. The finest non-indurated material observed in the column is a 1 m thick layer of sandy gouge whose grain size distribution is shown in Figure 3.10. The material is a well graded, angular silty sand.

Contacts between the various units are wavy, with a characteristic amplitude of one or two metres over several tens of metres. The average dip is 32° to the west, although local range of dips is between 20 and 35°.

The baked pyroclastic breccias are indurated and appear moderately strong. The thickest unindurated breccia unit resembles closely the coarse breccias of Cheekye Ridge.

3.3.4   Seepage Patterns

Seepage points identified in the course of field mapping are shown on Figure 3.2. Practically all seepage in the basin occurs at or directly below the pyroclastics/basement contact.

The pyroclastic breccias appear largely free-draining, with the exception of periodic aquicludes formed by silty horizons in the fine, basal breccia unit (Plate 2). These aquicludes produce multiple perched water tables with very minor discharge.

The Dalton Dome volcanic sequence appears dry. Minor seepage points in the vicinity of Dalton Dome can invariably be identified as resulting from melting of buried or surficial ice and snow.

3.3.5   Cheekye Linears

Cheekye Linears are a cluster of scarps situated along the northern crest of the ridge, above the tongue of pyroclastics mentioned above. An overall view of the linears is shown in Plate 8 and a detail in Plate 9. The distribution of the scarps and the scale of the largest among them is shown in Figure 3.11.

A series of surveyed cross-sections showing the detailed morphology of the linears is presented in Appendix XI. The linears are shown to consist of a mixture of normal scarps (resulting from downward movement on the valley side) and reverse scarps, resembling graben structures. The size of the scarps indicates local displacements of more than 10 m.

The log of a trench excavated at the toe of one of the largest normal scarp is shown in Figure 3.12 and Plates 12 and 13. The location of the trench is indicated as Test Pit 91-1 on Figure 3.2. The trench showed that the scarp, which is now sloping at less than 40°, originated as a near-vertical normal shear. The upper part of the steep scarp apparently collapsed, forming a colluvial wedge in front of the lower third. A sample of peat buried beneath the colluvial wedge was dated as 3220 B.P. (Sample 7 in Table 6.1).

An interpretation of the origin of the linears is given in Section 7.1.

3.3.6 Brohm Ridge Linears

Another swarm of linears was identified on Brohm Ridge, as shown in Figure 3.13 and on Plate 11. They are very similar to the Cheekye features in several aspects. The disturbed area is covered partly by a lava flow. In the lava, the linears assume the character of tension cracks and sharp-edged depressions, or vertical scarps with normal displacement.

3.3.7 Other Slope Disturbance Features

Small groups of cracks indicative of normal sagging movements appear at El. 1650 on Cheekye Ridge and El. 1800 m on Brohm Ridge. These show relative vertical displacement with the downslope side moving down. Plate 10 and surveyed Section E-E show the former feature.

There is also a tension crack, open less than 1 m, behind the lava plug at Elevation 1750 m on Cheekye Ridge.

Trees show no signs of active movements on any of the linears. The only exception is a tension crack 10 m behind the main slope crest at Elevation 1490 m on Cheekye Ridge, which exhibits stretched tree roots. Other open tension cracks have been noted by the geophysical crew during their work (Appendix V).

3.4 Geology of the Fan Area

3.4.1 Upper Fan

The Upper Fan is a large terrace situated on both sides of the Cheekye River, just downstream of the end of the gorge (Figure 3.3). The smooth gently sloping top surface of the unit, concentric on the mouth of the gorge, indicates an origin due to a series of debris flows of moderate discharge consisting of liquefied material. This is confirmed by the relatively fine-grained texture, small size of the maximum clast and the presence of faint stratification. All of the material is of volcanic origin.

The 20° westerly dip noted at the powerline exposure (Figure 3.14) indicates either that the deposits were placed on glacier ice and sunk after melting, or that the debris flows

deposited into water of a temporary proglacial lake. In either case, the Upper Fan deposits testify to an extremely active period of debris flow activity from the Cheekye Basin, which occurred during the last stage of retreat of Fraser glaciers, approximately 11,000 years ago.

The total volume of the Upper Fan Pleistocene debris flow deposits is estimated as 150 Mm³, based on a plan area of 3 km² (segments on both sides of the Cheekye River) and an average thickness of 50 m. This does not include similar Pleistocene diamicton material on the Middle Fan, which was reworked by glacial activity and which may amount to additional 10 Mm³.

The extent of the Upper Fan is shown on Figure 3.4. Only a few exposures of the fan material are available. The best exposure is on the right bank of the Cheekye at the power line crossing (Figure 3.14). The exposure shows sloping, faintly stratified layers of diamicton (unsorted debris), generally sandy and relatively fine-grained. They are formed entirely of volcanic clasts and appear to contain no organics.

A terrace (Unit E) of more recent diamicton is plastered against the exposure. It was eroded away by the river at the centre of the exposure, as shown. This terrace contains a small proportion of basement rocks and occasional tree trunks, some of which were brought from the bank slopes above it.

A schematic log of a bank exposure on the opposite side of the river is shown in Section G, Figure 3.15. This is typical of the Holocene debris flow sequence deposited on the floor of the erosional gap.

3.4.2   Middle Fan

The Middle Fan again contains few exposures, as the river flows between bedrock walls for most of its length (Figure 3.4). A high exposure located above and east of Alice Lake shows a diamicton closely resembling the texture of the Upper Fan deposits.

The debris deposits located in a wide band south of the Cheekye River channel between the mouth of the gorge and Highway 99 are interpreted as a result of intermittent debris flow activity of relatively recent date (Section G, Figure 3.15). The deposits consist of

diamictons of variable thickness and composition, interbedded with fluvial material. The individual layers are typically only 1 to 2 m thick. The surface is hummocky with a maximum amplitude of 1 to 3 m, except for bedrock-cored knolls.

No datable material was recovered from these deposits. It is considered that date Sample 2 (see Table 6.1) collected by S.G. Evans, may originate from Holocene debris flow material, emplaced at the foot of the Pleistocene Upper Fan deposits. The C_{14} age of this sample is 1550 years. It is probable that the Middle Fan debris deposits represent a large number of events occurring throughout the Holocene Period and that these deposits are coeval with the Lower Fan diamictons. Their total area is 1 km². The volume of a large single event in this segment of the deposition area is 2 Mm³, based on an average thickness of 2 m. However, it is not certain whether any single diamicton unit is continuous over the whole area.

3.4.3   Lower Fan

Approximately 50 shallow and 6 deep test pits were excavated in Lower Fan deposits, in addition to an examination of available soil exposures. The locations of all test pits are shown in Figure 3.4. The test pit logs for the shallower pits are in Appendix VII. Detailed graphical logs of the deep test pits and the most important natural exposures appear in Figures 3.17 through 3.23.

A schematic summary of the Lower Fan stratigraphy is presented in a three-dimensional isometric fence diagram, Figure 3.24. This diagram shows the fan as a planar surface. Test pits are shown at 40 times exaggerated vertical scale aligned at the ground surface elevation. Sections A to E are indicated, to facilitate reference to the plan view, Figure 3.4. The test pit stratigraphy is simplified to distinguish only diamicton (debris flow) units, shown in black, and stream flow units (white). The distinction between the two types of deposits was based on particle shape (angular vs. rounded), gradation (lack of fines in the stream flow deposits, (cf. Figure 3.27), maximum particle size and the character of unit boundaries.

Nine available radiocarbon dates are indicated at their appropriate sample locations.

The wealth of data recovered in the two phases of the test pit program permitted the establishment of certain correlations within the stratigraphy of the fan. Three major debris flow units have been recognized:

*   Surface Unit is the uppermost layer in most of the test pits (Plates 19 and 20). It represents one or several debris flow events which covered most of fan surface approximately 1,000 years ago. The greatest observed thickness of the Surface Unit is at the Garbage Pit (TP 92-1), where a homogeneous, unsorted deposit 5.1 m thick covers large logs and even a mature tree stump standing in an upright position and rooted in underlying river sand (Baumann, 1991 and Plates 16 and 17). From the numerous test pits penetrating the Surface Unit, it was possible to construct approximate isopachs (thickness contours), which appear in Figure 3.25. Based on these, the unit is calculated to contain nearly 7 Mm^3 of material and covers an area of 3.76 km^2. Its average thickness is thus 1.9 m.

    The distribution of the isopachs indicates that the bulk of the debris flow event passed through the fourth bedrock gate of the Cheekye River, downstream of Highway 99 bridge, before spilling onto the surface of the fan. Only minor overflow into the Highway 99 corridor south of the present river channel is indicated. This, together with our observations in the Cheekye Gorge (Section 6.4.3) shows that the peak discharge of the event was quite modest, relative to its magnitude.

    The gradation of the Surface Unit is presented by two grain size curves in Figure 3.26 and five histograms showing the full range of grain sizes (Figure 3.27). The gradation is somewhat variable but tends to be dominated by silty sand and gravel with only a trace of clay and relatively few large particles. The largest boulder recovered at the Garbage Pit was 8 m^3 in volume (21 tons). The clasts are sub-angular to angular, with over 90% of multi-coloured volcanic lithologies and a minor amount of fresh or altered basement metavolcanics.

    Radiocarbon dates recovered from the base of the unit are 1,010 to 1,390 years B.P. at the Garbage Pit and 1,215 B.P. at the Highways Pit, 1.5 km further downstream. A 305 years date recovered near the Highways Pit in Stage 1 appears to represent contaminated material (stumps of trees over 300 years old exist near the site).

    The limited dates available do not permit us to conclude whether the Surface Unit originates from a single event or a group of events.

- Squamish River Unit. This diamicton unit was recognized and dated at the Squamish River Exposure (Exposure H100), Plate 22, at the south-western margin of the fan, in the Highways Pit (TP 92-2) and at the Garbage Pit (TP 92-1). In the later two it is overlain by the Surface Unit and by fluvial material. Wherever exposed, it is less than 2 m thick. It apparently does not extend into the southern part of the fan, as indicated by two old dates there. The exposure dates range from 5,660 years to 6,595 years B.P. The unit has less fines than the Surface Unit (Figure 3.27). At the Squamish River, it is quite cobbly. There is no clay and the coarse clasts are sub-angular and predominantly of multi-coloured volcanic lithology.

- Intermediate Unit. An intermediate diamicton was found between the former two units at the Squamish River Exposure (Plate 22) and at the Highways Pit. It does not exist at the Garbage Pit and therefore appears to be limited only to the western part of the fan, where it is less than 2 m thick. It contains a very high proportion of gravel. At the Squamish River Exposure it consists of two distinct layers, the thin upper one being cobbly, while the lower one is almost clean, angular gravel. No datable material was found in the Intermediate Unit, but its age is bracketed by its position between the other two diamictons.

Minor uncorrelated diamicton layers have also been found in some of the test pits. The remainder of the test pit stratigraphy is made up of stream gravels and cobbly gravels, recognized primarily by high degree of clast roundness, lack of fines and boulder particles and tendency for exhibiting layers and channel structures (Plates 18, 19 and 21). The lithology of the stream deposits is also predominantly volcanic. A number of sand layers have been found, which may represent the more fluid phases of debris flow deposits, similar to the "runout flows" described by Scott (1988).

The Lower Fan has an area of 7 km². The total quantity of deposits in the fan is difficult to estimate, as it depends on the post glacial topography of the valley floor. It is probably in the order of 100 to 200 Mm³.

The deep test pits excavated in 1992 provide an indication of the rate of deposition in recent time. An estimate of the quantity of deposits over the period of approximately 6,000 years since the deposition of the Squamish River Unit was made. The estimate was based on the assumption that Test Pits 92-1, 92-2, 92-5 and the Squamish River Exposure are characteristic of the central, western, southern and south-western parts of

the fan respectively. The sediment column above the 6,000 year level in each location was multiplied by the area of the related part of the fan. The result is that the total volume of deposition over the given period is 34.4 Mm³, of which 17.4 Mm³ are diamictons (debris flow units) and 17.0 Mm³ are stream gravel and cobble units. Some additional quantity of debris was removed by the Squamish River and this is allowed for in Paragraph 7.1.3.

A comparison of typical grain size distributions of various materials from the fan is given in Figures 3.26 and 3.27. It is of interest to note that the diamictons are comparable in terms of texture with the volcanic breccias also shown in Figure 3.27. This indicates that the diamicton material is probably derived primarily from the pyroclastics.

All of the materials on the Lower Fan contain a small percentage of non-volcanic clasts, although it is generally less than 10 percent by particle count.

Organic material is absent in most of the fan deposits. Voids have been identified which indicate that wood was contained within the deposits but has been lost by decomposition under the oxidizing conditions above the water table (Baumann, 1991; Feagel, 1991).

4.0   SEISMICITY

4.1   Primary Effects

Seismic effects which could potentially affect the Cheekye Fan area are strong earthquake shaking and surface fault rupture. However, no documented moderate (> M = 5.0) or large (> M = 7.0) historic earthquakes appear to have affected the Cheekye Fan area and there are no records of active faults within the region. (Note: active faults for the purpose of this study are considered to be structures with a demonstrated history of movement within the last 10,000 years). A review of the airphotos of the fan for indications of surface rupture has not yielded any evidence.

A review of earthquake hazards has been undertaken based primarily on regional seismotectonic investigations and is included as Appendix III. A seismic risk assessment and earthquake epicentral maps have been provided by the Pacific Geoscience Centre;

they are included as Appendix II. The maps show no concentration of either large or small events in the vicinity of the Garibaldi Volcanic Complex.

During the review of seismicity for revised safety consideration of the Cheakamus Dam, (B. C. Hydro, 1985), parameters were ascribed to events occurring within two source zones. These have been modified to make them applicable to the Cheekye Fan.

- Crustal Sources

     Beaufort Range Fault, M = 8.5 at 100 km
     Volcanic Event, M = 6.0 at 10 km
     Random Event, M = 6.5 at 15 km

  Subduction Zone Sources

     Interplate Thrust Event, M = 8.5 at 145 km
     Interplate Normal Event, M = 7.5 at 40 km

Deterministic assessments of events from these sources using the Joyner and Boore (1988) attenuation relationships, give the following accelerations:

- Crustal Sources

Beaufort Range Fault	0.10 - 0.15 g
Volcanic Event	0.15 - 0.25 g
Random Event	0.15 - 0.25 g

  Subduction Zone Sources

Interplate Thrust Event	0.10 - 0.15 g
Interplate Normal Event	0.30 - 0.40 g

The recurrence intervals for these events is poorly known because of the shortness of the instrumented or felt records. Subduction zone events for nuclear power plants in Washington State have been estimated to have a recurrence of 500 years. The crustal events likely have a longer return period because of lower rates of strain in comparison with the subduction zone.

The probabilistic assessment carried out by the Pacific Geoscience Centre (Appendix II) is based on historic records; it gave the following results.

Probability of Exceedance in 50 year period	Acceleration
40%	0.062
22%	0.089
10%	0.136
5%	0.196

4.2   Secondary Effects

Soil liquefaction and earthquake-induced landsliding may also be the result of seismic shaking.

Liquefaction is much dependent on the soil gradation and density, groundwater conditions and level of shaking. No evidence of settlement or failures due to liquefaction have been obtained from the Cheekye Fan.

Earthquake-induced landsliding has been recorded from areas several hundreds of kilometres from the epicentres of large magnitude events. Mostly, they are small events. Some large landslides have been generated by seismic activity (e.g. Mt. Huascaran in Peru). However, many slides, although believed to have occurred concurrently with seismic events cannot be unequivocally related to that cause (e.g. Hope Slide). Keefer (1984) states that an $M = 4$ event could cause rockfalls, rock slides, soil falls and soil slides; an $M = 5$ event could cause rock slumps, rock block glides, slow earthflows, soil lateral spreads, rapid soil flows and subaqueous landslides; an $M = 6$ event could cause rock avalanches.

It is considered that the level of seismic activity anticipated at the Cheekye fan could result in numerous small slope failures over time. Seismic acceleration would be a contributory cause to any of the scenarios of large scale instability discussed in Sections 6 and 7.

There is no evidence to indicate that ground rupture and associated instability would be likely secondary hazards in the Cheekye Fan area.

5.0   HYDROLOGICAL ASPECTS

5.1   Climate Near the Cheekye Basin

5.1.1   Regional Climate

Two variants of the Pacific Coast climate have been described by Hare and Thomas (1979). One occurs on windward slopes and results from uplift of Pacific air masses over the west-facing mountain slopes which receive prolonged, and often heavy, precipitation whenever a Pacific cyclone approaches. The second occurs on eastern or lee slopes of the Coast Mountains which receive less precipitation, as air masses are descending, dispersing cloud and lessening rainfall.

There are effectively two seasons along the Pacific Coast. The first extends from late September or October until March and consists of a continual procession of Pacific westerlies onto the coast, occasionally broken by the formation of high pressure ridges. Winter storms are of large areal extent, and temperature variation in the air mass often produces rain at low elevations and snow at higher elevations. The second season occurs during the summer months when a high pressure zone dominates off the coast. Summer storms are usually small and intense; however, large storms occasionally disrupt the high pressure zone. These infrequent large storms often produce extreme flooding (Thurber Consultants Ltd., 1983; Ward and Skermer, 1992; Evans and Lister, 1984; Schaefer, 1983).

The Cheekye River basin lies north of Howe Sound in an area that is transitional between the Pacific coast and an interior or cordilleran climatic region. Howe Sound and the Cheakamus Valley are oriented to receive the predominantly southwesterlies that occur during the winter months, and winds associated with low pressure zones can transport moist air up the Sound and many kilometres inland. Precipitation depletion produces declining precipitation totals along the valley bottom leading inland from Howe Sound. In the colder inland climate, a greater portion of the precipitation falls as snow.

There is large local variation in precipitation inland from Howe Sound as a result of convergence and orographic enhancement. Total annual precipitation at higher elevations is considerably greater than recorded in valley bottoms, as indicated by snowcourse measurements and short-term precipitation stations. Higher elevation

stations also record a much greater portion of their annual precipitation as snowfall; in winter, snow often falls at higher elevations while rainfall occurs at valley bottom stations. Snow accumulates rapidly near the Cheekye basin in the fall, and more than a metre of snow may accumulate at high elevations by the end of November (B.C. Hydro 1983).

Elevation also enhances rainfall during the summer. Ward and Skermer (1992) report that summer rainfall on Whistler Mountain, at an elevation of 1800 m, is about 40% greater than at Alta Lake near Whistler Village.

B.C. Hydro (1983) have concluded that the critical meteorological conditions for generation of the probable maximum flood (PMF) in the Cheakamus River occur in December and consist of a long cool fall with a thick snowpack accumulation, a sequence of above-normal temperatures to ripen the snowpack and initiate runoff, and occurrence of the probable maximum precipitation (PMP) near the end of the temperature sequence.

5.1.2   Climate Records near the Cheekye Watershed

The Atmospheric Environment Service (AES) of Environment Canada operates long-term precipitation gauges at Britannia Beach, Tunnel Camp, Woodfibre, Squamish, Garibaldi, and Alta Lake (Figure 5.1). Table 5.1 describes the records of the various climate stations. At some key locations the station has moved several times and the records may not be homogeneous. Some stations, particularly Woodfibre, have a number of years with incomplete records that are not suitable for analysis.

Long-term climate records suggest that sea-level precipitation declines from the west side of Howe Sound (Woodfibre) to Squamish, declines along the east side of Howe Sound but continues to decrease up the Cheakamus Valley towards Whistler (Table 5.2). For example, the normal annual precipitation at Alta Lake, 55 km north of Squamish, is 37% less than at Squamish. The climate records also show an increase in normal annual precipitation with elevation; Tunnel Camp at El. 670 m receives 30% more precipitation than nearby Britannia Beach at El. 50 m.

The Cheekye Watershed lies between the Squamish and Garibaldi AES stations and these two stations provide the most suitable description of climate at low elevations in the

Cheekye Basin. Table 5.3 shows the normal distribution of precipitation at both Squamish and Garibaldi and also maximum recorded one-day precipitations (rain at these low elevation stations). Monthly precipitation can vary greatly from the normal: for instance, in November, 1990, 644 mm was recorded at the Squamish station, compared to a normal of 314 mm.

The fraction of mean annual precipitation that falls as snow is 4% at Britannia Beach, 19% at Tunnel Camp and 43% at Alta Lake, some 55 km northeast of Squamish. The percentage of precipitation falling as snow increases with distance inland from Squamish and also with elevation.

Snow is ephemeral at many of the valley bottom stations. However, at higher elevations near the Cheekye Basin, maximum snow accumulations ranging from 1,200 to 1,600 mm water equivalent have been recorded (B.C. Hydro 1983; Water Management Branch 1992). The water equivalent recorded in the snowpack is often less than the total precipitation that falls at higher elevations, as several cycles of snowfall and melt may occur in the fall and early winter.

5.1.3   Historic Storms Near the Cheekye Watershed

Tables 5.4 and 5.5 summarize the largest historic storms recorded at the Garibaldi and Squamish AES stations. The selected storms include the five largest one-day, two-day, three-day and four-day precipitation totals. Because maximum one-day and maximum multi-day precipitations often occur during the same storms only 8 separate events are required at Garibaldi and at Squamish to include all the maximum totals.

The storms are listed in date order at both stations and also ranked according to the size of the one-day total. There is little overlap on the dates of storms at the Squamish and Garibaldi stations because their records only partly overlap and because there are differences in the climate between the two stations. As well, the record at Squamish is based on two different station locations and does not include records for all years.

Maximum one-day totals at Garibaldi reach 115 mm, and maximum recorded four-day totals are twice as much, or about 230 mm. Similar maximum one- and four-day

precipitation totals are recorded at Squamish. The only anomalous event occurred in October 1981 when an extremely large one-day total was recorded.

5.1.4   Intensity-Duration-Frequency Analysis

Daily precipitation totals at various return periods are shown in Table 5.6 for the long-term stations near the Cheekye Basin. Other than at Woodfibre, a reasonably consistent series of daily precipitation intensities is obtained, with roughly 100 mm at a 10-year return period and roughly 130 mm at a 100-year return period. There is little indication in this data set of variation with elevation. Britannia Beach and Tunnel Camp are similar despite differences in elevation and the predicted rainfall intensities are reasonably constant leading north from Squamish. Multi-day intensity-duration-frequency curves for the Squamish and Garibaldi stations are shown on Figures 5.2 and 5.3.

The rainfall totals are much smaller than experienced in the Coast Mountains south of the Cheekye basin. Stations in North Vancouver and West Vancouver have 2-year and 200-year rainfall totals averaging in the order of 120 and 300 mm. At Coquitlam the corresponding values are 130 and 250 mm.

B.C. Hydro (1983) reports the ratios of extreme short-duration rainfall to 24-hour rainfall intensities for a number of stations in Vancouver and the surrounding region. One-hour rainfalls are a fairly consistent percentage of 24-hour totals maximum rainfalls but different for orographic and non-orographic rainfall, and range from 10% for orographic stations such as Coquitlam, to 20% at stations such as Vancouver Airport. Greater percentages are obtained in the mountains north of Squamish. At the Daisy Lake Dam station, extreme 1-hour precipitation is about 20% of the 24-hour total. A similar value occurs at Pemberton BCFS, but at the (composite) Whistler Station the recorded ratio is about 12%. Six hour totals are generally assumed to be about 30% of 24-hour totals at orographic stations and 50% of the 24-hour total at non-orographic stations (U.S. Weather Bureau 1966). However, the Daisy Lake Dam record has 6-hour extreme rainfall exceeding 50% of the 24-hour total.

We have estimated one-hour rainfall totals by assuming that these correspond to 20% of the daily precipitation at all the long-term stations without short-duration data

(Table 5.6). No adjustment was applied to daily precipitations to convert to maximum 24-hour values.

5.1.5   Probable Maximum Precipitation (PMP)

B.C. Hydro (1983) report probable maximum precipitation estimates for the Cheakamus River watershed upstream of the Daisy Lake Dam. Their estimates are derived from a climate model and represent the sum of maximized convergence and orographic components of precipitation. Table 5.7 quotes probable maximum precipitations at various durations and elevations.

An adjustment is required in order to compare the daily precipitation totals in Tables 5.4, 5.5 and 5.6 to the above 24-hour PMP's. Daily totals should be increased by 13% to account for the difference between fixed and floating periods; 4-day totals by 3%. After the adjustment, at the elevation of the Garibaldi station (366 m), the predicted 24-hour PMP's are about 30% greater than corresponding 100-year value (Table 5.6) and about 50% greater than the maximum recorded values (Tables 5.4 and 5.5).

The only historic storm in the Cheekye region that approached the above PMP values occurred in late October 1981, when the one-day total at Squamish reached 186 mm. Probable maximum precipitation at Squamish may be greater than that in the Cheakamus Basin; in that case, this event may not be as remarkable as it appears.

5.1.6   Summer Rainstorm Characteristics

As discussed, summer rainstorms may produce intense short-duration rainfall, but generally maximum daily precipitation is lower than observed during winter storms (Table 5.3). A review of records at the Squamish and Britannia Beach climate stations between July 1 to September 30 found average maximum daily precipitations of 40 mm at both stations. The largest daily values were 95 mm (1924) 87 mm (1921) and 79 mm (1972) at Britannia Beach; and 79 mm (1991), 75 mm (1961) and 71 mm (1972) at Squamish.

5.1.7   Precipitation Characteristics of Floods and Mudflows on Cheekye River

Major debris flows, debris floods or floods in the Cheekye River are thought to have occurred in 1921, 1940, 1958, 1984, 1990 (2 events), and 1991. Jones (1959), while discussing a mudflow that occurred in August 1958, also discusses a mudflow that occurred more than thirty years earlier. This event has been tentatively assigned to 1921 and is assumed to be associated with the largest winter storm in that year (F. Baumann, personal communication). However, there is little evidence for this conclusion and the mudflow may be associated with the large summer rainfall recorded in 1921. Little is known of the events in 1940 and 1984 and it is assumed that they were associated with the annual maximum storm. (In both 1940 and 1984 maximum daily summer rainfalls were near average.)

Table 5.8 summarizes precipitations associated with the flood and mudflow events. Selected storms are plotted on Figures 5.2 and 5.3. Detailed storm descriptions and data summaries are available from AES for the events of October 7-9, 1984, November 9-11, 1990, and November 21-24, 1990 (Schaefer, 1984; Thomas and Stobbe, 1984; Coatta, 1990, Anon., 1990).

Examination of annual maximum daily precipitation for nearby gauges indicates that most recorded mudflow or floods were not associated with severe daily precipitation (when compared to annual maximum storms), except for October 1921 and January 1991 when local return periods were near to, or exceeded, 50 years. However, local short-duration precipitation may have been more severe and in some instances flooding may have been augmented by snowmelt.

The various storms are briefly discussed below:

> **October 24 - 29, 1921.** Extreme daily precipitation was recorded at Britannia Beach but only a moderate event was recorded at Garibaldi. Extreme flooding was recorded in the Cheakamus Basin and the estimated discharge for the Cheakamus River (B.C. Hydro 1983) was the flood of record to 1983.

> **October 16 - 21, 1940.** A moderate intensity storm was reported at Garibaldi and Britannia Beach.

August 27 - 31, 1958. The storm at the end of August 1958 recorded minor rainfall totals at both Garibaldi and Britannia Beach. There was also a minor storm in early August and a more intense storm in mid-September.

October 6 - 11, 1984. Squamish recorded a moderate storm with return periods near 5 to 10 years at durations up to 5 days. The storm caused severe flooding in the area north of Squamish.

November 9-11, 1990. The storm caused severe flooding in the eastern Fraser Valley. Maximum 1-day precipitation at Squamish Airport was 164 mm but records are too short to estimate its return period. 5-day precipitation was 380 mm, greater than the normal monthly total at Squamish. Return periods for precipitation at Squamish range from 5 years for 1-day totals to 50 years for 5-day totals, suggesting long-duration but not particularly intense rainfall.

November 21 - 24, 1990. This storm was not as severe as that of November 9-11 but it brought monthly totals to record levels at Hope and Agassiz. Total rainfall recorded at Squamish Airport was nearly twice that recorded at Squamish, where return periods were less than 2 years.

August 26 - 31, 1991. Moderate precipitation totals were recorded at the Squamish STP station. Further up the Cheakamus Valley, at Alta Lake, the return period of the one-day precipitation was about 15 years. Despite the moderate precipitation, extreme flooding was reported at Fitzsimmons Creek (Ward and Skermer 1992) and peak inflows to the Daisy Lake Dam had an estimated return period of 40 years.

With reference to the return periods mentioned above, it should be noted that the Squamish record is confused by the existence of several gauge locations with generally short records, so that values for long return periods cannot be determined with any confidence. Reported daily precipitations for the same event also differ substantially between gauge locations.

5.2   Hydrology of the Cheekye River

5.2.1   Description of Watershed

The total drainage area of the Cheekye River is 64 km². Its largest tributary, the Brohm River, joins the Cheekye about 2.5 km upstream of the mouth, near the head of the lower fan, and has a drainage area of 26 km². Upstream of the Brohm River and the head of the lower fan, the Cheekye River has a drainage area of 36 km².

The river profile is shown on Figure 5.4. A detailed description of the Cheekye Drainage appears in Section 2 and 3.

5.2.2 Predicting Peak Discharges on the Cheekye River

a.   Gauging Records on the Cheekye River

The Water Survey of Canada operated a manual gauge on the Cheekye River from October 1954 to September 1956 ("Cheekye River near Brackendale", 08GA39). The gauge was located at the B.C. Railway Bridge, roughly 100 m upstream of the confluence with the Cheakamus River. The maximum recorded discharge in the 2-year period occurred on November 4, 1955 and was 29.7 m³/s.

b.   Gauging Stations near the Cheekye River

Water Survey of Canada stations near the Cheekye River are listed in Table 5.9. Nearby basins of similar size and relief include Culliton, Stawamus and Mashiter Creeks. The Rainy River is of similar size but drains the western side of Howe Sound.

c.   Previous Predictions of Flood Magnitude

Crippen Engineering (1974) estimated flood discharges in the Cheekye River from maximum recorded discharges for (1) Mashiter and (2) Culliton Creeks, assuming the peak flood discharge varied with the square root of the drainage area. Analogous maximum discharge estimates for Cheekye River were (1) 39.6 m³/s and (2) 124.6 m³/s. The report recommended that "...a flood well in excess of 5000 cfs (140 m³/s) in the lower reaches of the Cheekye River below its confluence with the Brohm River would have to be assumed in order to design for an adequate return frequency".

Crippen Engineering (1981) calculated the risk from flooding on the alluvial fan, for the Tantalus Project, using a method developed by Dawdy (1979). 100-year and 200-year flood flows used at the apex of the fan were 295 m³/s and 371 m³/s, based on transfer of the observed flood record from Mashiter Creek.

d.   200-Year Instantaneous Discharge

The 200-year peak discharge in Cheekye River was estimated by transferring 200-year instantaneous discharges from adjacent basins and adjusting for differences in drainage areas according to the trend of the Creager flood envelope (Appendix XII-A). The 200-year instantaneous discharge estimates for Mashiter Creek and Stawamus Creek are 251 m³/s and 174 m³/s (Table 5.9) which correspond to Creager C values of 23 and 16. Assuming that the 200-year flood in the Cheekye Basin has a C value of 20, then 200-year instantaneous discharges of 210 m³/s and 300 m³/s are estimated for above the Brohm River and at the mouth. Bland (1992; Appendix XII-B) used a similar procedure to estimate 200-year instantaneous discharges at the mouth. The estimate at the mouth assumes that hydrographs from the Brohm River and the upper Cheekye basin are coincident.

As well as transferring estimates from local gauges we have also used the following empirical rainfall-runoff approaches to confirm the estimated 200-year instantaneous discharge.

Watt and Chow synthetic hydrograph (Watt et al 1989) - The time to peak for Cheekye River above the Brohm River was estimated as 0.67 hours, based on empirical formula in the reference. Assuming a runoff of 25 mm during the 200-year flood, the peak instantaneous discharge is estimated as 280 m³/s.

Rational Method - The basin was assumed to be near-saturated, with a runoff coefficient of 0.9. The time of concentration, based on basin area and steepness, is in the order of 1 hour and a 200-year rainfall intensity of 30 mm/hr was adopted. The resulting peak instantaneous flow for a drainage area of 36 km² is approximately 270 m³/s.

Empirical Hydrograph - The total runoff during a 200-year storm is assumed to be 25 mm. The effective hydrograph timebase is assumed to be 2.7 hours (four times the time to peak), and the peak flow is assumed to be 3 times the average flow. For a drainage area of 36 km², the estimated peak instantaneous flow is 280 m³/s.

All estimates are summarized in Table 5.10.

The estimated 200-year instantaneous discharge, for the Cheekye River above Brohm River, ranges from 210 m³/s to 280 m³/s. For the purposes of estimating bedload transport in short critical floods, a peak discharge of 250 m³/s was assumed. This is considered to correspond to a return period in the range of 100 to 200 years. It is compared with a maximum recorded daily flood envelope and probable maximum daily flood estimates on Figure 5.5, adapted from B.C. Hydro (1983). Our instantaneous value plots near the envelope for Coastal Zone maximum recorded daily flows and local PMFs. 200-year daily discharges on the Cheekye River are considerably less than the instantaneous peak and below the envelope curve.

5.2.3   200-Year Flood Hydrograph

The adopted hydrograph is based on the SCS dimensionless hydrograph with a time to peak of 0.67 hours and a peak discharge of 250 m³/s (Figure 5.6). The total volume under the adopted hydrograph is 850,000 m³ over the four hour time base.

For small basins, critical short-duration rainfall intensities, which determine peak instantaneous flows, are normally contained within rainstorms of longer duration, or occur in summer thunderstorms. This hydrograph could be scaled to represent different rainfall intensities and then combined to form a storm hydrograph.

5.3   **Bedload Transport on Cheekye Fan**

5.3.1   The Cheekye River

Studies were carried out to predict the quantity of bedload which would be transported on the Cheekye Fan during a short-duration, intense flood.

Cheekye River was inspected on March 12, 1992 at various points between the head of the lower fan and its mouth at the Cheakamus River. The head of the lower fan is located where the river emerges from bedrock approximately 600 m upstream of Highway 99. At Highway 99 the channel cuts through a bedrock ridge. Downstream of the highway, it is partly bedrock-controlled for a further 700 m. Beyond this bedrock outcrop, to the mouth, the river is entirely alluvial.

The slope of the river on its lower fan appears to be fairly constant at about 4 to 5 percent. The bed material consists mainly of gravel, cobble, boulder sizes in the range of 20 to 500 mm, with a matrix of sand and erratic inclusions of very large boulders up to 1.5 to 2 m in size. The D_{50} size, estimated from inspection of the bed material, lies between 200 and 300 mm, discounting the erratic larger boulders.

The cross-section of the channel is variable and has been affected by recent bulldozing for channel maintenance and flood protection. The natural flood channel in unrestricted reaches seems to be roughly 20 to 30 m wide, and maximum depths of flow are expected to be in the order of 1 to 2 m.

5.3.2 Hydraulic Characteristics

Manning's n was estimated as 0.05. For the given channel slope and roughness, a flow of 100 m³/s would have a depth in the range of 1 to 1.5 m, a velocity in the range of 4 to 5 m/s, and a Froude Number in the range of 1.3 to 1.5. Flow is supercritical at all significant discharges. A depth of 2 m would probably be reached during the 200-year instantaneous discharge of 250 m³/s.

5.3.3 Regime Considerations and Bed-Material Stability

Assuming a dominant discharge of 100 m³/s, a regime width would be in the order of 30 m. For the same dominant discharge and a slope of 4.5%, a D_{50} grainsize of around 500 mm or more appears to be required for stability.

Applying the Shields criterion to the estimated D_{50} size of 250 mm and a slope of 0.045, bed movement begins at a depth of around 0.4 m, probably corresponding to a flow near 20 m³/s, far below typical flood flows. The bed is expected to be mobile even during very small floods.

5.3.4 Bedload Transport in Short Critical Flood Events

Bed-material transport rates were calculated by the procedures of Meyer-Peter and Muller (1948) and Ackers and White (1973). The flood hydrograph on Figure 5.6 and an assumed bed material D_{50} of 200 mm were used in the calculations. As discussed earlier, the return period of this flood event is estimated to be between 100 to 200 years.

Table 5.11 summarizes the results of the bedload calculations. The threshold for significant transport is approximately 50 m³/s, and total transport during the flood event amounts to 8,000 t or 5,000 m³. This volume of sediment is sufficient to aggrade 200 m of 20 m wide channel to a depth of 1.25 m.

5.4   The Cheekye and Cheakamus River Interaction

5.4.1   Changes in the Cheekye River

Major flood or debris flow events in Cheekye River have been observed, or are assumed to have occurred, in 1921, 1940, 1958, 1984, November 1990 (2 events), and August 1991. Aerial photographs of the Cheekye Fan are available for various years between 1946 and 1990. Table 5.13 summarizes the observed changes of the Cheekye River on its lower fan between successive dates of photography. In many instances the photographs were at small scales and possible subtle changes to the channel could not be detected.

Aerial photographs were taken the year before and the year after the 1958 mudflow (Figure 5.7). The photographs suggest only minor modification to the Cheekye River. Following the event the channel was slightly larger and some additional secondary channels had been cut into the surrounding fan.

Discussions with individuals from the Water Management Branch indicated that there have been several periods of gravel removal from the Cheekye River. Small quantities of gravel were removed between the mouth and the B.C. Rail bridge in 1981, 1983 and 1985: total removal amounted to a few thousand cubic metres. Gravels were also removed upstream of the B.C. Rail Bridge: in February 1985, roughly 35,000 m³ was bulldozed into a linear stockpile along the left bank of the river (Appendix XII-C). Following the November 1990 storm, gravel excavation was begun in the vicinity of Fernwood Road. Roughly 4,000 m³ was removed prior to the August 1991 storm which deposited about a 2.5 m depth of gravel along the reach. A further 18,000 m³ was removed in September 1991 (Bland 1992; Appendix XII-B).

In August 1991, the Cheekye River overflowed its left bank upstream of the Highway 99 bridge apparently as the result of channel blockage following deposition from a debris

flow (Appendix XII-D). A dyke was constructed along the left side of the Cheekye River as shown in Appendix XII-C.

5.4.2   Changes in the Cheakamus River

As well as several other tributaries, the Cheekye River contributes sediment to the Cheakamus River, and affects bed-levels and flood-levels in the vicinity of the confluence.

The Cheakamus River is gauged by the Water Survey of Canada at the station "Cheakamus River near Brackendale, 08GA043" which has operated continuously since 1958. The gauge site is two kilometres upstream of the mouth of the Cheekye River and upstream of a small rapid.

The rating curves compiled for this gauge were used to estimate the time-wise variation of water surface elevations associated with discharges of 45 and 300 m³/s (Figures 5.8 and 5.9). The total shift in water level over the period of record, for a discharge of 45 m³/s, amounts to about 0.8 m, but recent shifts have only amounted to 0.3 m. The specific gauge curve shows declining gauge levels representing downstream degradation, until the mid-1970s, followed by fluctuating levels. The pattern of shifting is not well correlated with flooding on the Cheakamus or Cheekye Rivers.

The higher stages in the late 1950s and early 1960s may have resulted from deposition of sediment from the 1958 "mudflow" in the Cheakamus River. Bed-levels were apparently higher at the Paradise Valley Bridge in 1958 than during surveys in the late-1970s (Bland 1992, Appendix XII-B). Declining stages over the next 15 years may result from re-working and removal of this material by the Cheakamus River.

A review of surveys along the alignment of the Paradise Valley Bridge indicates high bed elevations in 1926 and 1958 and declining bed levels until September 1989 (Bland 1992). Gravel build-up was reported in the Cheakamus River following the August 1991 flood. Surveys in October 1991 indicated accumulations of roughly 2 to 3 m in the vicinity of the bridge which returned the bed to its 1958 elevation and a total deposition of roughly 17,000 m³. The October 1991 surveys also indicated scour of about 2.8 m at 600 m downstream of the bridge.

Additional deposition was observed following the August 1991 flood, amounting to additional 0.6 m by February 1992 (Bland 1992). It is reported that bed-levels declined following the 1992 snowmelt freshet on the Cheakamus River (Baumann, personal communication).

5.4.3   Gravel Removal and Training Structures

The Water Management Branch indicates only limited removal of gravel from the Cheakamus River. Small quantities were removed along the left bank during Provincial Emergency Program construction in 1990 and 1991. These were spoiled on site.

6.0   POTENTIAL TERRAIN HAZARDS AFFECTING CHEEKYE FAN

6.1   Eruption Hazards

6.1.1   Processes

Potential volcanic hazards deriving from eruptions from silicic volcanic centres are fully described in Appendix III. They may include tephra fall, pyroclastic flow, explosion phenomena, ground deformation, lava flow/dome building, volcanic earthquakes, flooding, erosion and sedimentation (secondary effects).

Experience shows that most of these processes occur within 10 - 15 km of the volcanic centre except for those that are dependent on topography (pyroclastic/lava flows, and floods), wind direction and velocity (tephra). Green (1990) and Green et al (1988) have developed a chronology for volcanic events within the Garibaldi Complex; these events have also been correlated with glacial events and are shown on Table 3.1. Four main eruptive stages are described.

The processes operative in the past in the Garibaldi Complex as deciphered from the material exposures are pyroclastic flows (hot debris flows and lahars) and lava flows. No tephra falls have been identified. However, future activity might include most of the above processes.

> Pyroclastic flows as evidenced by the geological record around Mt. Garibaldi may be misleading since travel distance may have been impeded by the ice. Evidence from elsewhere in the Cascades show that hot pyroclastic flows have travelled

between about 6 and 25 km from an individual volcano. However, the maximum extent from Garibaldi appears to be 10 km.

Dacitic lava flows have extended up to 18 km from Mt. Garibaldi with an average of 7 km. This is comparable to Mt. St. Helens and Mt. Shasta where the maximum extent and average extent are 12 km and 7 km respectively.

Volcanic earthquakes up to magnitude 6.0 have been recorded accompanying volcanic eruptions and are focussed at shallow depth (1 to 5 km). These effects are considered in conjunction with other seismic activity.

Ground deformation can also occur most commonly within 20 km of the volcanic centre and takes the form of uplift, subsidence and faulting concurrently with magma intrusion. The maximum deformation is usually 1 - 2 m and decreases to less than 20% of this within a 10 km radius.

Explosion phenomena occur in some cases and are of concern within 10 km of the volcanic centre.

If volcanic activity were to occur, the most likely processes would be pyroclastic flows and lava flows with their secondary effects of debris flows, mudflows and floods. In the absence of glacial ice, these effects could impact areas up to 10 - 15 km downstream which could include the Cheekye Fan.

6.2   Non-eruption Terrain Hazards

Review of specialized literature concerned with the physical geology of volcanic terrain identifies several types of terrain hazards which could potentially be encountered at Mount Garibaldi as described below.

6.2.1   Rock and Debris Avalanches

Large sliding failures of volcanic deposits, including lavas, pyroclastics or basement rocks, may accelerate on steep slopes to develop rapid flow-like motion referred to as a rock avalanche (simplified from rock slide-debris avalanche, Varnes, 1978) or sturzstrom (Hsu, 1975). Events involving a predominance of pyroclastic materials should be referred to as debris avalanches.

Rock avalanches may be connected with earthquakes. For example, the 1984 Mount Ontake event in Japan was the largest of a cluster of major slope failures triggered by the M 6.8 Nagaoken-seibu earthquake (Tanaka et al., 1985; Moriwaki et al., 1985). A mass of 36 Mm³ of lavas and pyroclastics slid from a ridge near the summit of the volcano within seconds of the main earthquake tremor. The sliding surface followed a thin layer of weak pumice containing swelling clays and oriented in the downslope direction (Figure 6.1a). Such an orientation of planar weakness surfaces is a common consequence of the conical structure of stratovolcanoes. The Ontake rock avalanche flowed down a system of valleys, branching and re-connecting several times, to reach a distance of 11.5 km from the foot of the source area (Figure 6.1b). The maximum flow velocities were estimated at 114 km/hour (Oyagi, 1987). Flow depths were locally more than 100 m. The duration of the event may have been as short as 6 minutes (Kobayashi and Kagawa, 1987). The flow was essentially dry, but incorporated large quantities of loose valley infills and residual soils, which were saturated by a period of heavy rains preceding the earthquake. The entire path of the avalanche was confined in relatively narrow valleys.

The 1855 rock avalanche at Rubble Creek, 15 km north of the Cheekye Fan, originated from the collapse of 25 Mm³ of dacitic lava from the Barrier, a 400 m high, near vertical cliff forming the head of the Rubble Creek valley (Figure 6.2). The apparently dry masses of broken rock flowed down the valley for more than 6 km reaching velocities of 140 km/hour and flow depths of over 70 m (Hardy et al., 1978). The front of the avalanche ran out onto the surface of the Rubble Creek Fan. Deposits of several metres to more than 20 m deep were left along the entire length of the valley and were later re-worked by massive debris flows or debris floods. An earthquake trigger is possible, but uncertain.

A similar collapse, involving approximately 13 Mm³ of lava and 2.5 Mm³ of glacier ice, occurred in 1975 at Devastation Glacier, in the Mount Meager volcanic complex (S.G. Evans, pers. comm., Mokievsky-Zubok, 1977, Hardy et al., 1978). This slide had no apparent seismic or climatic trigger. The slide masses flowed for 6 km over a valley base underlain by recent morainal deposits (Figure 6.3). A part of the Devastation Glacier was also overridden by the debris (S.G. Evans, pers. comm.).

The 1963 Dusty Creek rock avalanche on Mount Cayley began by the sliding failure of approximately 5 Mm^3 of tuff breccia and dacite (Clague and Souther, 1982). The basal failure surface followed in part the contact between the volcanic rocks and altered basement rocks. The slide masses flowed down a steep valley system reaching flow depths of 40 to 70 m and velocities of over 60 km/h. Thick debris deposits accumulated within 2 km of the source area (Figure 6.4). Triggering of this rock avalanche by minor earthquakes is considered possible, but not firmly established.

The common factors of rock avalanches include:

- Large volume (over several Mm^3).

- Steep source slope and a failure mechanism conducive to the onset of very rapid motion.

- Lack of water, resulting in minimal saturation of the moving masses.

Rock avalanches can be very mobile and more so, the greater their volume. This is illustrated in Figure 6.5. The "fahrboschung" or travel angle (Heim, 1932) is defined as the vertical angle between the highest point of the source scar and the distal margin of the deposit, measured along the flow path. As shown in the plot, the angle decreases with increasing volume of the event. The "apparent friction coefficient" is defined as the tangent of the travel angle.

Ui (1983) noted that volcanic rock and debris avalanches tend to have lower equivalent friction coefficients, i.e. higher mobility, than other rock avalanches (Figure 6.6). Reasons for this include the closely jointed nature of lavas, presence of fragmental pyroclastics and other abundant fine-grained materials and the long gradual slopes of volcanic terrain.

6.2.2 Rock Avalanches - Debris Flows

Some rock or debris avalanches are able to entrain sufficient quantities of water to change into large flows of fully saturated material. The mobility of these events is significantly greater than that of "dry" rock avalanches, which may contain only a small proportion of saturated material, concentrated in a liquefied basal zone.

The rainfall-triggered June 1984 event in the headwaters of Turbid Creek on Mount Cayley began with the detachment of approximately 500,000 m³ of pyroclastic breccia from a steep headwall 0.7 km north of the 1963 Dusty Creek rock avalanche (Evans and Jordan, 1991, in prep.). The failure exploited a weak layer near the contact between the breccia and an underlying hydrothermally altered sequence of older volcanic rocks (Plate 23). The debris avalanche (Plate 24) descended a vertical distance of 600 m following a steep gully, then flowed for 2.5 km on a slope of 15°. The peak flow depths were of the order of 30 to 40 m and velocities over 110 km/h. The landslide left only deposits generally thinner than 1 m, completely evacuating the flow path and thinly coating the massive deposits left by the 1963 rock avalanche. Some of the fluid debris converted into a series of mudflows which continued flowing for another 3 km at a slope angle as low as 5°, to deliver some hundreds of thousands of m³ of liquid debris into the channel of the Squamish River. The first debris flow took place shortly after the debris avalanche. It may have been either a direct continuation of the initial movement, or a delayed flow following the breach of a short-lived debris dam on Dusty or Turbid Creek. The second debris flow occurred three months after the debris avalanche, following another major rainstorm. The debris flows had flow depths of only 10 to 14 m and velocities of less than 40 km/h, yet they succeeded in evacuating hundreds of thousands of m³ completely from the Turbid Creek basin.

The reason for the exceptional mobility of the 1984 debris avalanche, given its small size, has not been clarified. However, Cruden and Lu (1992) note that the gully downstream of the source area contained approximately 450,000 m³ of snow resulting from the accumulation of snow avalanche deposits. Melting and incorporation of this snow may have provided the water required to saturate the debris.

A major debris flow occurred in the Devastation Glacier basin in 1931 (Jordan, 1991). The source of the flow was in the same general area as that of the 1975 rock avalanche. The extent of glacier ice was reportedly greater in 1931 than in 1975 (see Figure 6.3). The debris flow is said to have resulted from the breach of a landslide dam on the glacier, although no detailed information is available. Jordan (1991) estimates that the debris flow had a volume of 5 Mm³ and moved 20 km down Meager Creek valley on slope angles of 2° to 5°, reaching velocities of 80 to 130 km/h and flow depths of 12 m. This mobility is in a striking contrast to the behaviour of the 1975 rock avalanche.

The above two examples illustrate the importance of water in the mobility of rock and debris avalanches. Where water is incorporated by melting of snow or ice, or through the process of temporary damming of drainage channels, the mobility of the events can be greatly increased.

6.2.3   Volcanic Debris Flows

Debris flows of smaller magnitude can also originate spontaneously, without a specific mechanism for incorporation of water, other than entrainment of surface flows and of saturated loose surficial soils.

The December 1980 Polallie Creek debris flow on Mount Hood began with a 4,000 m^3 debris slide in a headwall cut in pyroclastic and lahar deposits (Gallino and Pierson, 1984). A debris flow started, incorporating loose material from the channel of Polallie Creek. The flow reached a total magnitude of 70,000 m^3 in 7 km of flow on an average slope of about 8° and deposited on the creek fan and in the channel of East Fork Hood River. The debris flow reached flow depths of 8 m and velocities of up to 90 km/h. The breach of the 10 m high debris dam caused extensive flooding on the East Fork Hood River downstream of the dam. The maximum flood discharge was estimated as 850 to 1400 m^3/s.

An August 1958 debris flow event on Cheekye River was described by Jones (1959). The report describes only a single surge, 3 m deep and moving at 8 km/h near the mouth of the Cheekye. The flow depth and velocity must have been very moderate, as the event failed to overflow the sharp right hand bend of the existing channel downstream of Highway 99, where the existing channel freeboard is only about 1.5 m. Jones describes a 5 m thick dam of boulders and logs across the Cheakamus River in front of the Cheekye. The Cheekye channel itself is said to have been both scoured and aggraded by the event in different sectors. Eisbacher's (1983) estimate of a 100,000 m^3 volume for the event is based on the above mentioned flow velocity and depth and an assumed surge duration. Such a volume would be sufficient to aggrade the entire length of the river on the lower Fan by more than 1 m. A comparative study of airphotos dating from 1957 and 1959 shows that deposition in the Cheekye River Channel was quite moderate, not more than 1 - 2 m. No information exists concerning the source of the debris flow. Jones (1959)

speculates that it was triggered by a small debris avalanche in the headwaters, but was unable to find a corresponding slide scar.

A similar debris flow was reported to have occurred in Cheekye River in the 1920's.

6.2.4 Flooding

The study area could be affected by various types of flooding as follows:

- "Avulsion" flooding, due to an overflow of the present Cheekye River channel during a normal flood. (See Section 4). An avulsion would most likely be associated with the occurrence of a debris flow, possibly even a very minor debris flow event caused by bed instability, log jam or a minor bank failure upstream, which could cause channel plugging and overflow at one of the several existing weak points.

- Flooding associated with the occurrence of a debris flow event. Usually, sediment-laden water flow reaches beyond the point of deposition of the debris flow surges, causing lesser but still significant damage. This flooding hazard is transitional from the actual debris flow hazard and is termed a debris flood. Both types of hazard have been considered together in the risk analyses. The peak discharge of a debris flow event at the head of the fan has been estimated as 1,700 m^3/s, or nearly seven times the peak discharge of a 200-year flood. The peak discharge would occur during the passage of debris surges and their characteristics would reduce sharply with distance from the fan apex as shown in Tables 7.1 and 7.2. The more water-dominated intersurge flows would have considerably lower discharges, perhaps comparable to the 200-year flood.

- Flooding originating from the Cheakamus and Squamish Rivers. This normally only affects the recognized floodplains of the rivers, and areas at risk have been mapped by B.C. Ministry of Environment. A special case of flooding can occur as a result of constriction of the Cheakamus River channel by deposition of debris from the Cheekye. The most likely site of the constriction is at the mouth of the present Cheekye Channel. However, during the larger debris flow events, or if there were avulsions in the existing channel during smaller events, the constrictions could occur at any point on the fan perimeter depending on where the main tongues of debris flow deposition were located. As shown by the severity of recent flooding events, the consequences are also dependent on the flood stages of the Cheakamus and Cheekye Rivers at the time of the debris flow from the Cheekye Basin.

6.3   Frequency of Occurrence of Terrain Hazards

As a first step towards estimating the probability of occurrence of volcanic hazards, it is necessary to review the frequency with which such phenomena appear in general.

Volcanic eruptions have repose times ("return periods") of 0 to over 10,000 years. Sixty-five percent of the world's active volcanoes have repose times of less than 10 years. 30% erupt every 10 to 100 years, less than 10% 100 to 1000 years and 3% 1,000 to 10,000 years (Siebert, 1984). Frequency of eruptions is thus unique and widely different for any volcano. Eruptions also typically do not occur at regular intervals, but tend to concentrate in clusters of activity separated by longer quiescent periods. In the Cascade Volcanic Belt, Mount St. Helens shows the most frequent present activity, with two major clusters of events occurring over the last 200 years.

The eruptive history of Mount Garibaldi, based partly on potassium-argon dating and partly on correlation with glacial history of the area, has been reviewed by Green (1990) and is summarized in Table 3.1. Unfortunately, the record is not sufficiently continuous to establish a regular periodicity. It may be said, however, that a repose period of over 25,000 years may have preceded the latest cluster of eruptions, which coincided with the Fraser Glaciation. Given the complete absence of geothermal or seismic activity in the Mount Garibaldi region at present, it is concluded that the most recent cluster of activity is probably completed. This contrasts with the situation at Mount Meager, where the latest eruption was dated at 2400 years ago and geothermal activity exists to the present (Souther, 1980).

Major volcanic rock or debris avalanches occur either in association with eruptions or following an earthquake or other trigger. Caldera-forming major eruption rock avalanches similar to the 1980 Mount St. Helens event occur at a rate of about 4 per century worldwide (Siebert, 1984).

Following an extensive review of historic and geological data, Inokuchi (1989) estimated that major rock avalanches have occurred on Japanese volcanoes every 100 to 200 years. Given the total area of 24,000 km² covered by Quaternary volcanoes on the Japanese Islands, and assuming that a typical volcanic centre covers an area of about 400 km², this translates to a frequency of 1:12,000 to 1:24,000 per centre per year. Using such numbers, each volcanic centre would be expected to have about one post-glacial event of this type on average. The Garibaldi Volcanic Complex has had at least one or two such events, in the 36 Mm³ Rubble Creek rock avalanche of 1855 and one major event preceding it (Hardy et al., 1978).

A summary of landslide events reported from the main volcanoes of the Cascade Volcanic Belt in the U.S.A. and the Garibaldi Belt in Canada is presented in Appendix III, Table III-2. Post-glacial debris avalanches are reported from Mount Rainier (8 events), Mount St. Helens (1 event - 1980), Mount Meager (2 small events), Mount Cayley (3 events) and Mount Garibaldi (at least 2 events). The numbers may be somewhat distorted due to the uncertain origin of prehistoric deposits. For example, the large lahars of Mount Rainier, such as the Osceola event of 5700 B.C. which travelled over 100 km, belie non-eruption origin by their great mobility.

A summary of this imperfect record indicates that the frequency for significant rock avalanches at a volcanic centre such as Mount Garibaldi ranges characteristically from 1:10,000 to 1:1,000 per year.

Debris Flows. The largest debris flows are triggered by volcanic eruptions, either through landsliding or by means of rapid melting of snow and ice by geothermal heat (e.g. the 1985 Nevado del Ruiz event, or the 1982 lahar on Mount St. Helens). Their frequency is thus related to that of eruptions as reflected in Table 3.1. Major non-eruption debris flows are, on the other hand, connected with the occurrence of debris avalanches as already reviewed. Exceptions are debris flows triggered by glacier outbursts or breaching of lakes, whose frequency is significant only under specific circumstances.

Smaller debris flows are very frequent in volcanic terrain. Their frequency is probably inversely proportional to magnitude, following some form of Poisson's Distribution. Unfortunately, no reasonably complete chronology of such events exists, as it is very difficult to reconstruct the magnitudes and circumstances of occurrence beyond recent historical period.

The most recent record from Mount Cayley and Mount Meager, summarized in Table III-2, Appendix III, indicates that debris avalanche-debris flow events of the order of 1.0 Mm^3 in magnitude appear at least once every 100 years at each centre. Small events (less than 10^5 m^3) occur every few years.

7.0 ANALYSIS OF TERRAIN HAZARDS

7.1 Evidence of Past Landslide Activity in the Cheekye Valley

7.1.1 General

Section 6 considered the range of potential natural hazards that could affect the Cheekye Fan. It is apparent that the major processes are rock avalanche and debris flow activity.

Consequently, the study has concentrated on collecting evidence of such activity both in the basin and on the fan itself to provide some indication of past events and assist in prediction of future events.

7.1.2   Rock Avalanche Activity

It is considered that none of the deposits identified in the study area correspond to major rock or debris avalanche deposits such as described by Ui (1983) or Siebert (1984). Evidence for this includes:

- Lack of characteristic hummocky topography and large lobate features. Hummocks on the Middle Fan are invariably bedrock-cored, or could be designated as glacial ablation features.

- Shortage of large clasts (over 1m diameter) in all parts of the fan.

- Lack of thick unstratified units.

- Lack of a major scar in the basin.

The evidence of mass wasting collected from the fieldwork only indicates debris flow activity and not rock avalanche activity. However, such debris flows could have resulted from debris avalanches of moderate magnitude in the headwaters of which there is little remaining evidence, consequently this aspect was analyzed further.

7.1.3   Debris Flow Activity

There is much evidence of past debris flow activity in the basin as recorded in the diamicton deposits of the Cheekye fan. This has been described in Section 3.4. The stratigraphy of the upper, middle and lower fans has allowed a chronology to be built up and a sequence of depositional activity to be established. This can be summarized as follows:

- A period of very intense debris flow activity occurred at the end of glaciation, forming the Upper Fan Terrace. Some 150 Mm^3 of debris flow deposits were brought out of the Cheekye Valley during a relatively short period of time, while stagnant ice covered most of the Squamish Valley.

- Little is known about mass movements and transport during the first half of the Holocene Period (12,000 to 6,000 B.P.). Presumably, the erosional

gap in the Upper Fan terrace formed during this time, and some 30 Mm³ of reworked debris moved from the Upper Fan downstream, in addition to an unknown quantity of debris brought out of the Cheekye Valley.

- During the last 6,000 years, a total of approximately 34.4 Mm³ of material was deposited on the Lower Fan. Of this, at least 17.4 Mm³ was transported as debris flow. Probably, the total quantity of debris flow material was even greater, to allow for misidentification of some of the finer "runout facies", for material originally deposited as diamicton but later reworked by streamflow activity and for debris eroded by the Squamish River. To allow for such factors, the total estimated debris flow material quantity has been adjusted to 20 to 28 Mm³, or 60 to 80% of the total deposition volume.

- Identifiable debris flow events during the last 6,000 years include:

  - One or several events containing up to 7 Mm³, which occurred approximately 1,000 years ago (the Surface Unit). There is a possibility that the Surface Unit does not represent a single event of 7Mm³ but may be the result of a cluster of several events at least one of which was larger than about 3Mm³.

  - One event of a magnitude of several million m³, but smaller than the Surface Unit, occurring approximately 6,000 years ago (termed the Squamish River Unit).

  - One or two events of an approximate magnitude of 1 Mm³, occurring between 6,000 and 1,000 years ago (termed the Intermediate Unit).

  - A large number of events smaller than 1 Mm³. Of these, two are historic events documented by Jones (1959), which occurred in the 1920's and in 1958. Both were small enough to avoid spilling out of the present channel of the Cheekye River and had volumes of less than 100,000 m³.

Little is known concerning the specific source areas of the recognized debris flow events. In many parts of the upper basin of the Cheekye River there is abundant evidence of continuing instability in the form of rockfall, shallow debris sliding and erosion. However, no evidence has been found of a single major detachment which could testify to a rock or debris avalanche of more than 1.0 Mm³ volume. There is also no remnant of a major debris dam from such an event in the valleys in the basin (although this may have been removed by erosion). The lower canyon of the Cheekye (Plates 14 and 15) was traversed with the purpose of observing flow terraces, trimlines or deposit remnants of a

major debris flow discharge such as observed in the recent examples described in Sections 6.2 and 6.3, but no such features were found. It appears that no debris discharge deeper than approximately 5 m above the present channel passed through the gorge in the recent past and probably for several centuries.

In spite of the lack of direct evidence of triggering mechanisms for large debris flows in the upper basin, such debris flows unquestionably occurred in the past. It must be assumed, therefore, that the evidence of trigger events was removed by the continuing erosion in the basin, or at least rendered difficult to identify.

7.1.4   Landslide Hazards Analyzed

Subsequent phases of the work were directed towards analysis of the potential for rock or debris avalanches, their possible magnitude and runout distance, and the potential for debris flows either connected with, or separate from, a rock or debris avalanche. Although the field evidence at the fan indicated that avalanches have not reached that area in post-glacial times, it was considered necessary to model this conclusion analytically. The results of all these analyses have formed the basis of the risk assessment and zoning.

7.2   Potential Sources of Rock or Debris Avalanches

7.2.1   Location of Instability

The extreme topographic relief of the Cheekye Basin provides many opportunities for the development of slope instability. For example, the headwall below Diamond Head, formed of uncemented pyroclastic breccia, is a continuous slope 800 m high with an average slope of 33°, the upper segment of which reaches 43°. The south face of Atwell Peak rises 1,000 m at an average slope of 45°. There are two small hanging glaciers in the basin, producing ceaseless falls of rock and ice fragments.

Although the above attributes of the basin are spectacular, they are not uncommon in the context of volcanic terrain and cannot be translated into a prognosis of specific hazards, except for the general acknowledgement of continuing and abundant debris production. Small and medium detachments of rock or debris (up to several hundreds of thousands of

m^3, in magnitude) are certainly possible from many parts of the basin and cannot be reasonably predicted.

The following assessment of major catastrophic landslide potential is based on the analysis of three specific source areas, selected either because they showed signs of distress or because of structural conditions which indicated the potential for large scale failure. These areas are the Cheekye Linears, the Brohm Ridge Linears and Dalton Dome.

7.2.2 Cheekye Linears

The linears have been described in Section 3.4. There are three alternative explanations of their origin:

- Deep seated rotational slumping (see Baumann, 1980).

- Shallower translational sliding, exploiting the weak altered rocks beneath the contact.

- Deep seated spreading movements characteristic of mountain top spreading.

Deep-seated slumping is illustrated in Figure 7.1. There is no evidence of structural features (e.g. schistosity, major joint sets or faults) oriented so as to contribute to a sliding failure of this type. Consequently, the circular failure must pass through the rock mass. The assumed stratigraphy is shown in Figures 7.1 and 7.2 and is based on observation of exposures and an interpretation of the seismic profiles. A layer of pyroclastics averaging about 50 m in thickness overlies weak altered basement rock 30 to 40 m thick. The underlying unaltered basement rock is considerably stronger.

The unaltered metamorphic basement rock is considered to be very strong and relatively massive, with clean and tight discontinuities at moderate to wide spacings. The general classification of the rock mass is "good quality". A characteristic shear strength envelope for such rock mass was suggested by Hoek and Brown (1980, page 176), as indicated in Figure 7.3c. In the typical range of stresses for a deep seated failure, this envelope corresponds approximately to a cohesion of 2,000 kPa and a friction angle of 43°.

The deep seated slump mechanism was analyzed using the program CLARA based on the Bishop Simplified Method, which can utilize directly the non-linear strength envelopes shown in Figure 7.3. The geometries assumed are shown in Figure 7.1. A piezometric surface was assumed at the contact of the pyroclastics with the basement. Circle A was chosen so as to pass through the main scarp of the linears and defines a failure of 300 Mm^3 volume. Its Factor of Safety is 2.03 and the "critical acceleration", i.e. earthquake horizontal acceleration sufficient to reduce the Factor of Safety to unity, is 0.42.

A search for the sliding circle with the minimum Factor of Safety was carried out, resulting in Circle B which is considerably more shallow. The location of this circle is not consistent with the distribution of the linears. Other searches were conducted using lower rock strength properties (based on "fair rock", Envelope b in Figure 7.3 and a lower uniaxial compressive strength). These searches produced yet shallower critical circles (C and D).

Based on these results, a deep seated slumping mechanism does not appear to be probable. This is in agreement with the morphology of the linears, as discussed below.

The alternative sliding mechanism considers that an approximately planar segment of the sliding surface follows the weak altered zone beneath the pyroclastics (Figure 7.4). The pyroclastic material is assumed cohesionless, with a friction angle of 40° (based on the steep angle of repose observed in the headwall). A piezometric surface is again placed at the contact. The altered rock is classified as "poor quality" metamorphic rock mass, with a Uniaxial Compressive Strength of 20 MPa, consistent with the results of several Point Load strength tests carried out on typical samples of altered rock collected from exposures. The parabolic strength envelope shown in Figure 7.3 corresponds to a cohesion of 100 kPa and a friction angle of 17° over the range of normal stresses considered.

The four trial surfaces shown in Figure 7.4 correspond to failure volumes of 20 to 50 Mm^3 based on a slide width of 1,000 m^3 and have Factors of Safety ranging from 1.09 to 1.77. Critical earthquake accelerations, required to produce displacements, range from 0.03 g to 0.20 g, which is within the range of accelerations expected at this location

(Section 4). It should be noted in this context, that experience in the 1990 Loma Prieta earthquake in California indicated a magnification of horizontal accelerations near the crests of steep slopes (Shedlock and Weaver, 1991).

Also during the same earthquake, a series of cracks opened near ridge crests of the Santa Cruz Mountains (Harp et al., 1991). The ground cracks observed in California may not, however, represent a clear precedent for the origin of the Cheekye Linears, as they may be connected with tectonic movements along structures such as are not present at Mt. Garibaldi.

Another possible destabilizing factor would be an increase in pore-pressure along the potential sliding surface. Assuming the strength properties described above, analyses show that it would be necessary for the slope to become nearly fully saturated in order to trigger failure. Should the rock strength be less, lower pore pressures could be required.

Both the Factor of Safety and Critical Acceleration are seen to increase with the distance of the back scarp behind the slope crest as shown in Figure 7.4, the increase becoming especially strong behind the main scarp.

It is considered that the origin of the Cheekye Linears is due to displacements caused by an increase in pore pressure or by earthquake shaking, producing permanent displacements along the shallow surfaces as indicated, increasing gradually towards the valley. The date of 3220 years B.P., obtained from peat considered possibly to have formed shortly after the origin of the linears, may be the date of a triggering event (i.e. precipitation or earthquake) which initiated the process.

The shallow translational sliding mechanism appears plausible also on morphological grounds. Figure 7.5 is an extract from a classification of slope deformations proposed by Hutchinson (1988). Sagging controlled by rotational, deep-seated deformations, called R-sagging (a in Figure 7.5), is characterized by relatively few normal scarps concentrated near the head of the unstable area. Compound listric ("CL") sagging, on the other hand, is controlled by flat non-circular surfaces and produces widely distributed reverse scarps and grabens similar to those of the Cheekye Linears. A typical example of a slope profile

showing a system of cracks formed by sliding along a shallow planar weak surface in Cretaceous shales is shown in Figure 7.6.

The few individual scarps which cut obliquely across the trend of the others indicate a lateral component in the displacements, which may be related to the local shape of the contact.

The final alternative mechanism involves shear displacements along a series of near-vertical planes striking parallel with the lineament scarps and perpendicular with the downslope directions. Such displacements are characteristic of ridge top spreading or mass toppling mechanisms such as described by Tabor (1971), Radbruch-Hall et al. (1976), and Thurber Engineering Ltd. (1990). We do not consider this interpretation as likely, because neither regional, nor local review of structure in the basement rocks identified discontinuities of suitable orientation. Also, the Brohm Ridge linears, which share many of the attributes of those at Cheekye, would require controlling discontinuities of a different orientation.

The most probable future development of the slope disturbance is not expected to involve a full scale catastrophic detachment of the entire mass. In our estimate, the most likely process is continued increase in deformations due to creep, fluctuations in groundwater levels or earthquake shaking. A frontal mass of relatively limited volume (up to a maximum 20 Mm³, but probably considerably smaller) could eventually detach catastrophically and descend into the valley of the Cheekye River. This detachment was considered in the runout analysis reported in Section 7.3 and also in connection with debris flow sources, Section 7.4..

7.2.3   Brohm Ridge Linears

The group of linears identified at elevation 1400 m on Brohm Ridge share many similarities with the Cheekye Linears. This includes factors such as the situation relative to the slope crest, existence of an adjacent gully which removes lateral restraint, similarity of depth of the contact, valleyward dip of the contact and the presence of deep alteration in the basement rocks beneath the contact. The distribution and general morphology of the linears is also similar, except where it is affected by the presence of surficial lava. The mean trend of the linears is due north, i.e. 40° counterclockwise from

the Cheekye Linears. It has, however, exactly the same relationship to the orientation of the slope surfaces, both downhill from the linears and to their side.

No detailed analysis of the stability of the Brohm Linears was carried out, although it may be expected to yield very similar results to those reported in Section 7.2.2.

A terrain model of the disturbed area was assembled and a single surface of the shallow non-circular type was analyzed using the three-dimensional version of the program CLARA (Figure 7.7). The assumed failure surface consists of a shallowly inclined plane located below the estimated contact. Planar head and side scarps are imposed corresponding to the limits of the disturbed area. The volume of the potential maximum slide is 26 Mm^3 and a Factor of Safety only slightly above unity is indicated.

The Brohm Ridge linears are thus shown to have a potential approximately equal to the Cheekye Linears, to produce a failure in the order of 20 Mm^3 maximum which could serve as a trigger for a major debris flow..

7.2.4   Dalton Dome

As shown in Section 3.3, the late volcanic sequence of Dalton Dome exhibits structure which should be considered as conducive to potential sliding failure. The slide would presumably exploit a weak surface between the lava flows. Such surfaces are seen to dip at an average angle of about 32° to the west and are apparently continuous for as much as 1 km of slope distance.

There is no question that a mechanism for large scale instability of a peak so structured exists. The terrain model shown in Figures 7.8 and 7.9 shows two potential detachments formed by planar sliding surfaces of the requisite orientation. The "small" detachment is formed by a separation beneath the uppermost massive lava unit of the volcanic sequence (see Figure 3.9 and Plate 5). Its volume is 23 Mm^3. The "large" detachment, involving 46 Mm^3, would include both of the uppermost lava units and the intervening pyroclastic layers. Both detachments have static Factors of Safety of about 1.12, assuming a friction angle of 35°, no cohesion and no pore-pressure.

A simple pseudo-static sliding frictional block analysis, assuming simultaneous application of a vertical acceleration equal to 50% of the horizontal acceleration, a slope angle of 32° and no cohesion or pore-pressure, yields the following values of critical earthquake acceleration required to initiate movement:

$$\text{Friction angle} \quad \phi = 35°; \ a_c = 0.05 \ g$$
$$\phi = 40°; \ a_c = 0.13 \ g$$
$$\phi = 45°; \ a_c = 0.21 \ g$$

The stability of Dalton Dome depends entirely on the average strength of the contact layers between the units. The following aspects should be considered:

- No unit with significant clay component has been noted in the stratigraphic column. The finest non-indurated material found is the sandy gouge graded as shown in Figure 3.10, which is well-graded, angular and non-plastic.

- Judging from the typical angle of repose of the uncemented pyroclastic breccias in the Cheekye Basin, their friction angle is typically in excess of 42°, even under high levels of normal stress.

- The contacts are characteristically wavy, potentially adding several degrees to the bulk frictional strength.

- The ridge is very well drained and no seepage is observed along its base (except for perched flows in talus deposits).

- There is some likelihood of a lava core interrupting the sloping contacts in the upper part of the ridge, but invisible in the walls. Such a core would add a significant component of cohesion to the bulk strength of the contacts.

Given the above considerations, all of which are difficult to quantify, we consider that a large scale failure of Dalton Dome is not probable, although it cannot be ruled out as impossible. It is concluded that there is no cause for the stability condition of the peak to be deteriorating either at present or during the recent past. The probability of failure is thus considered no greater now than it was during much of the Holocene Period (10,000 years).

Small scale failures, involving up to several hundreds of thousands of cubic metres of lava from the vertical cliffs of Dalton Dome are, of course, very probable and could again serve as debris flow triggers.

7.3   Rock Avalanche Runout Analysis

Runout of a potential rock or debris avalanche from the source areas considered above was estimated using empirical means and a dynamic model.

Figure 7.10 shows a correlation between the deposit volume and deposit area of a number of rock avalanches from a data base established by Thurber Engineering Ltd. (Hungr and Evans, 1991).   The cases are identified on the figure and include examples from sedimentary and other (circled) rocks. The correlation is reasonably consistent, except for four cases (5, 6, 8 and 9) which involved travel over glacier ice and whose deposits are abnormally thin.

The correlation was entered using the volume of the largest potential catastrophic detachment from Cheekye Basin (46 Mm^3 from Dalton Dome), multiplied by a bulking factor of 1.25. The resulting volume is 57 Mm^3 of debris and a maximum deposit area of 5.3 km^2. This area was distributed over the available gently sloping surface downstream of the Cheekye Gorge, resulting in the deposit shown in Figure 7.11. The predicted runout reaches approximately to Highway 99. The analysis is conservative in neglecting deposition on the floor of the Cheekye Gorge, but it also does not allow for possible entrainment of material on the upper path.

The smaller rock avalanche scenario from Dalton Dome (Figure 7.17) or the Cheekye Ridge (Figure 7.18) would not, according to this analysis, reach the apex of the Lower Fan.

The predicted reach of the large Dalton Dome avalanche is checked against other empirical correlations in Figures 7.12, 6.5 and 6.6. In Figure 7.12, "Excess Travel Distance" is the runout length beyond a line drawn at 32° from the crest of the source area as defined by Hsu (1975).

All three correlations indicate that the predicted runout distance places the potential rock avalanche among the most mobile of the documented events. The runout also compares well with typical examples of volcanic rock avalanches such as Rubble Creek in Canada and Mount Ontake and Tombi in Japan.

Another means of checking the predicted runout is by using the lumped mass dynamic model developed by Koerner (1976) and used by Hardy et al. (1978) in their analysis of the Rubble Creek slide. The model is based on the assumption that the front of the slide mass moves as an isolated block, driven by gravity and resisted by a drag force dependent on a constant friction coefficient and a turbulent resistance factor dependent on the square of velocity and the inverse of flow depth. In our implementation, the model begins at the centre of the source area and extends to the distal end of runout. The flow depth in various segments of the path must be estimated beforehand. The model was implemented by a computer program, solving the one-dimensional equations of motion at short intervals of the path.

The calibration of the model is carried out in Figures 7.13, 7.14 and 7.15, using the examples of Rubble Creek, Mount Ontake and Dusty Creek discussed in Section 6.1. Actual flow depths and velocities estimated from the superelevation of the flow in bends are used.

The velocity comparisons indicate that the turbulent parameter, ksi, should have a value of 200 to 300 m/s^2, consistent with the findings of Koerner (1976). The friction parameter, mu, shows a minimum value of 0.0338 for the Rubble Creek avalanche. The Ontake event requires greater friction because it is better channelized. The Dusty Creek event is even more frictional, a result which is not surprising given its small volume. It is felt that this selection of case histories provides a good representation of the possible range of applicable circumstances. The lowest values of the mobility factors were applied to three cases of potential rock avalanches from the Cheekye Basin as shown in Figures 7.16 through 7.18.

The flow depths were estimated by assuming modifications of the shape of the moving mass in passing through the typical cross-sections of the path, as indicated in Figure 7.11.

(The flow depth was reduced somewhat in the Cheekye Gorge, to account for added resistance due to the extreme degree of confinement).

The analyses in general confirmed the validity of the runout estimate shown in Figure 7.11.

Marginal phenomena, i.e. mudflow or splash of debris, could extend some distance west of Highway 99, although the rock hills bounding a large part of the runout margin will provide considerable protection.

7.4   Potential Sources of Debris Flows

Debris flows can originate in the Cheekye Basin by one of the following mechanisms:

- Spontaneous transformation of a "dry" landslide in the headwaters into a debris flow, by incorporating water. Possible sources of water include snow and ice accumulated in the avalanche gullies of the upper drainage and water flowing in the upper channel system which could be overtaken and incorporated by debris surges. The two sources are estimated to provide a maximum of 200,000 and 230,000 m^3 respectively, the former quantity assuming 50% melting.

  Assuming a typical solid volume concentration of liquefied debris of 70% (Jordan, 1989), the given quantity of water is sufficient to produce about 1.5 Mm^2 of debris from material that was originally dry. We therefore conclude that the magnitude of debris flow triggered spontaneously is limited to 1 to 2 Mm^3. This corresponds to the experience at Devastation Glacier and Turbid Creek (Section 6.2.2), where smaller events liquefied but larger ones did not.

- A dry landslide could trigger a debris flow indirectly, by damming a stream channel in the headwaters. The debris flow would result from the sudden breach of the landslide dam, once it was overtopped by impounded water. A detailed quantitative analysis of this scenario was carried out using numerical models developed by the U.S. Weather Service (Appendix XII - F). The result indicates that a detachment of several millions of m^3 from the location of the Cheekye Linears could form a dam over 100 m high. The resulting reservoir would have a volume of 4 - 8 Mm^3 and could fill over a period of 1 to 3 days under extreme flooding conditions. The dam failure would take place over about 2 hours,

producing 1 to 2 Mm³ of sediment in addition to several millions of m³ of water. Much further sediment could be incorporated from the stream channel further downstream. The analysis predicts peak debris flow discharges in the order of 1,700 m³/sec. and flow depths of 7 - 10 m at the apex of the Lower Fan, prior to lateral spreading of the debris flow surges.

The quantities obtained from the model are consistent with the estimated character of the Surface Unit debris flow as reconstructed in Section 7.4. It is therefore concluded that a similar dam breach scenario was probably responsible for the 1,000 years old event, although no remnant of the landslide dam has been found.

- A final possibility for the formation of debris flow is as a result of glacier outburst or collapse, similar to a number of events on the Cascade volcanoes in the U.S. (e.g. Grater, 1948). The present glaciation of the Cheekye Valley is too sparse to have the potential for such events. It is possible, however, that more extensive glaciation in former times provided the trigger for some of the prehistoric flows. The period around 1,000 years B.P. is not recognized as a period of glacial advance in the region (Ryder and Thomson, 1986). The glacier trigger mechanism must therefore be considered as speculative and has not been used to modify our assessment of event probability.

7.5   Debris Flow Runout Analysis

Volcanic debris flows are highly fluid and can move long distances on flat angles (Jordan, 1991a). There is no maximum runout distance for debris flows on the Cheekye Fan; any significant event reaching the fan apex can travel as far as the fan toe, while leaving decreasing quantities of deposits along the way.

The extent of areas covered by debris is, however, determined by the magnitude (volume) of the event. Figure 7.19 was derived by plotting the volume and area of the best documented deposit (the Surface Unit). Lines were extended from this point, corresponding to alternative assumptions of geometrical similarity of deposit and constant thickness. A line situated between the two limits was chosen for analysis and design purposes and can be used to estimate the deposition area of an event of given magnitude.

The results of dynamic analyses of debris flow movement are shown in Figures 7.20 and 7.21. The first was derived with the use of a computer program modelling unsteady flow of Bingham materials (Jeyapalan, 1980). The calculation parameters include Bingham viscosity, selected as 1 kPa/sec. based on the work of Jordan (1989), and dynamic shear strength, selected so as to provide a correspondence with the distribution of deposit thickness in the Surficial Unit (5 kPa). The lower part of the figure gives the corresponding velocity of the debris flow front during its progress down the fan. This analysis is in good agreement with the dam break mudflow model (Appendix XII - E).

The velocity of smaller events was derived approximately from normal depth - velocity relationships for ideally viscous (Newtonian) material, plotted in Figure 7.21.

The results of the debris flow runout analyses are presented in Tables 7.1 and 7.2, which give quantitative and qualitative descriptions of the expected characteristics of events of various magnitude classes in different parts of the fan. Zones designated on this basis are shown on Figure 8.1.

The above runout analysis is based on an interpretation of the postulated 3 to 7Mm^3 extreme event, which could have been the source of the surface unit. The other two debris flow units (Intermediate and Squamish River Units) have deposits near the outer margin of fan, indicating a runout reach greater than that of the surface unit. We do not, however, know the configuration of the fan at the time when these deposits were created. Their mobility may have been increased by channelization. For this reason, it was considered more realistic to base the runout estimates on the behaviour of the surface unit, which was deposited was on a fan surface similar to the present.

The flow characteristics given in Tables 7.1 and 7.2 are influenced by the magnitude of the event, but not too strongly. For example, a more confined flow in a 3Mm^3 event might be as destructive as a wider flow in a 7Mm^3 event.

7.6   Hazard Scenarios and Probabilities of Occurrence

7.6.1   Rock and Debris Avalanche Occurrence

It may be concluded from the previous sections that the following hazard scenarios are possible.

Any major rock avalanche (of estimated magnitude between 45-57Mm^3) would most likely originate from Dalton Dome with runout limits at Highway 99, as shown in Figure 7.11. Marginal phenomena such as flooding and debris flow due to displaced fan deposits could extend further, but are considered to have effects comparable to those of a large debris flow.   One potential effect of a rock avalanche would be sudden displacement of water contained in Alice and Stump Lakes and resulting flooding on the Cheekye Fan and in Hop Ranch Creek.

However, there is no precedent for a major rock or debris avalanche in the Cheekye Valley, on the basis of the fieldwork carried out during this study. Moreover, it cannot be considered any more probable in the foreseeable future than it has been during post-glacial times. This major catastrophic event could be considered to be a unique event and not subject to recurrence; it is not considered further in the risk analysis.

7.6.2   Debris Flow Occurrence

By comparison, debris flows are periodic events, have a history of activity on the fan and their occurrence can be explained by demonstrated causative mechanisms. However, it has not proven to be possible to explain indisputably the origin of the largest of the postulated debris flows (7Mm^3); this may in fact represent a cluster of smaller closely spaced events.

Instability from the Cheekye or Brohm Ridges could be as great as 20 Mm^3 in magnitude. Although such catastrophic detachments would not pose a direct threat to the fan by means of an avalanche or debris flow, they could create temporary damming of either branch of the Cheekye River and, on breaching, result in the formation of a major debris flow involving saturated material, or catastrophic flooding. Smaller debris flows (up to approximately 2 Mm^3) could occur spontaneously as a direct propagation of a slope failure in the headwaters.

7.6.3   Debris Flow Probability

The basis for a determination of debris flow probability is an assumption that future activity will continue at the same rate as during the period of the investigated stratigraphic record (6,000 years). As described in Section 7.1.3, diamicton deposition during this period is considered to have resulted from 3 or more large events with a combined volume of 10 to 12 Mm^3 which, together with smaller events, have resulted in a total volume of 20 to 28 Mm^3. Two small events have also been recorded in historical time.

Using this data and the method developed by Morgan et al. (1992) given in Appendix XIII, an estimated magnitude-frequency relationship has been developed for the spectrum of debris flows which have affected the fan. The results are shown in Figure 7.22. For the purpose of further analysis, the spectrum of events has been divided into three main classes:

- Class A - major events with magnitudes of 3 to 7 Mm^3
- Class B - intermediate events of 1 - 3 Mm^3
- Class C - small events of 100,000 to 1 Mm^3.

Each of these three classes is considered to have well defined characteristics which are described in Tables 7.1 and 7.2.

Thus risk analysis and zoning has been carried out for debris flows affecting the Cheekye fan on the basis that large catastrophic rock or debris avalanches would be very unlikely to occur and, if they did, their runout would not extend onto the lower fan and would terminate at the Highway 99 bridge.

7.6.4   Flooding from Avulsion of the Cheekye River

Past occurrences of flooding on the Cheekye Fan are summarized in paragraph 5.1.7. Predictions of maximum flood discharge and associated sediment transport are given in Paragraphs 5.2.2 and 5.3.4.

Small debris flows are assumed to have return periods of as little as 50 years. Review of climate records indicates that a flood event of comparable return period is often associated with the debris flow.

To be conservative, it has been assumed that the "dominant discharge" occurs during or immediately after the debris flow. Under these circumstances, the discharge in the main existing channel would be 100 m^3/s, flowing with a depth of about 1 to 1.5 m and a velocity near 4 m/s and this could extend as far as the confluence.

The Cheekye River flowed overbank upstream of Highway 97 in August 1991 and this upper reach is one potential avulsion site. The Cheekye River has also experienced overbank flow on both the left and right banks in the reach upstream of the B.C. Rail bridge to the downstream end of the canyon (Appendix XII-D).

Avulsion at the "major bend" on the Cheekye River some 800 m downstream of Highway 99 has the potential to affect the largest area of the fan. The existing flood overflow area at this site is filled with gravel which might increase the probability of an avulsion.

The following scenarios could result from overbank diversion of a substantial portion of the flow in the main channel:

- the flow could form a new channel (approximately 20 to 30 m wide) across the fan, entering the Cheakamus or Squamish rivers at a new location;

- the flow could enter existing channels and depressions along the main channel, returning to the main channel further downstream; or

- the flow could diffuse over the fan surface, without forming a new channel, causing local flooding behind obstructions and erosion and deposition along flow pathways oriented down the fan, such as ditches, depressions, etc.

Table 7.3 summarizes estimated depths of flooding, maximum velocities and the damage corridor widths for various zones on the Cheekye Fan. In preparing this table it has been assumed that 1) within Zone 1 there is a potential for a new channel to be formed which would have hydraulic characteristics similar to the existing channel, and 2) within Zones 2, 3 and 4, flows from the Cheekye River would not form a new channel but would follow existing ditches, paths, depressions or drainage channels. It is within these

channels, where velocities are appreciable, that damage from scour, erosion and deposition occurs. In certain areas, scour of up to 1 m might be expected, such as downstream of obstructions or constrictions. However, the total quantity of coarse sediment eroded and deposited is expected to be moderately small.

Outside these channels, velocities are low and damage is expected to result mostly from local backwater flooding behind obstructions. The depth of flooding depends on the height and orientation of obstacles such as road crowns, driveways, etc and must be determined separately for individual situations. One value cannot be easily applied to the fan or the various zones. The flow characteristics should be re-assessed by a site-specific analysis if used for design.

Probability of avulsion flooding is difficult to assign. It is true that historic debris floods, although of considerable size, remained within the existing channel. It is considered, however, that even the smallest events in the debris flow/flood spectrum have the ability to leave the established channel at several of its weak points under existing conditions. Consequently, avulsion flooding has been assigned a probability equal to that of the historic debris flood events, i.e., $1/50$. This probability could be dramatically reduced by even modest channel improvement and training works.

7.6.5   Cheakamus River Flooding

Flooding along the right bank of the Cheakamus River can occur as the result of sediment or debris deposition at the north of the Cheekye (Section 5.4). It is estimated that significant flooding due to this course of events can be expected at approximately 50 year intervals. For detailed flood hazard estimates it is recommended that a total blockage of the Cheakamus channel should be assumed to occur during such an event, diverting the Cheakamus discharge onto the right (north) bank.

7.6.6   Flooding on the North Bank of the Cheakamus River

It is not expected that the direct impact of debris flow or debris flood surges would extend as far as the right bank of the Cheakamus at the confluence. However, as described in Section 5.4.2, the periodic injections of coarse debris from the Cheekye to the Cheakamus would cause fluctuations in the channel depth of the larger river and,

occasionally, cause overflows onto the right (north) bank both upstream and downstream of the Paradise Valley bridge. We understand that serious flooding resulting from such overflows took place both in 1958 and in August 1991.

Based on records of the channel cross-section at the bridge, each of the above events led to channel bed aggradation of about 3 metres and this is suggested as the basis for the design of flood control dyking based on the 50 year debris flow and flood. Larger debris flows can cause a greater amount of aggradation. The actual degree of potential blockage of the Cheakamus channel by debris flows in the Cheekye is extremely difficult to predict, as it would depend on the relative timing of floods in the two rivers, as well as on pre-event configuration of the channel bed. Movement and concentration of floating debris (logs) is also difficult to predict. A judgement-based subjective estimate of the degree of blockage at the bridge as a function of probability of occurrence is given as follows:

Mean Depth of Aggradation (m)	Return Period
3	50
4	100
5	200
6 (full blockage of channel)	500

The probability of an avulsion downstream of the bridge, on the fan of the Cheakamus is considerably higher, as the river may re-occupy some of its former channels on the fan without much influence from the Cheekye. We understand that an assessment of the consequences of channel blockage and avulsion of the Cheakamus are being studied by others and that a double dyking system is being considered to protect the lands in Hazard Zone 6.

7.6.7   Potential Catastrophic Drainage of Cat Lake

Cat Lake is situated approximately 30 m above the Cheekye channel. The edge of the lake is separated from the river by a 160 m wide band of land, underlain by deposits of the sandy "upper fan" diamictons (Section 3.4.1). There is active ongoing erosion along the river bank just downstream of the power line crossing. The eroding bank is approximately 10 m high at the point closest to Cat Lake and shows signs of minor seepage, possibly from a water table connected to the lake. The Upper Fan terrace rises

immediately upstream from this point, increasing the height of the eroding bank to over 30 m at the powerline (Figure 3.14).

Given the above characteristics of the site, it is expected that the lateral erosion of the Cheekye towards Cat Lake would progress at a very slow and diminishing rate. Also, in view of the considerable distance between the lake and the river, and the graded nature of the soils, it is not expected that seepage erosion would occur rapidly. Consequently, the risk of a catastrophic outburst of Cat Lake into the Cheekye is considered negligible under the present conditions. However, further progress of lateral erosion at this point should be monitored by geotechnical specialists at intervals of very two years, along with inspections recommended for the upper basin.

8.0   RISK ANALYSIS AND ZONING

8.1   General Approach

The purpose of risk analysis is to provide suitable criteria to determine whether certain land uses in an area are acceptable to the regulators or not. According to the Terms of Reference, the risk analysis was approached in two ways:

    a)   **Hazard probability approach**. In this approach, the probability of occurrence of various types of hazard affecting the specific zones was determined and compared to acceptability criteria used for similar situations elsewhere. For example, "debris flow hazard in Zone 1" is the possibility of debris flow surges occurring in some part of the zone. Both the nature and probability of that hazard will vary from one zone to another.

    b)   **Risk to life approach**. In this approach, the risk to life of an individual, or of a group, situated in each specific zone was estimated and compared to general criteria of risk acceptance by society. This approach considers not only the probability of any type of hazard occurring but also severity criteria which include exposure and the probability of death occurring given that exposure. For example, an individual living in Zone 1 may face a certain probability of loosing life in an accident resulting from the range of debris flow hazards affecting that zone.

Both methods have been applied to the same distribution of hazard zones, shown on Figure 8.1. The two approaches give somewhat different conclusions in terms of management strategy, as discussed below.

8.2 Hazard Zoning

Figure 8.1 shows the distribution of 6 hazard zones on and adjacent to the fan based on the physical characteristics of the hazard which change with distance from the source as described in Table 8.1 (facing Figure 8.1). Detailed descriptions of the effects of various hazards in the zones are given in Tables 7.1 and 7.2. The impacts from the hazards change continuously over the area as the nature of the hazard changes and the zone boundaries therefore had to be assigned somewhat arbitrarily. The intent has been to outline zones within which the severity of the hazards would be approximately constant irrespective of the exposure of groups or individuals.

Zone 1 is on the Upper Fan, where the highest velocities and discharges and the thickest debris deposits can be expected.

Zone 2 is an intermediate transition between 1 and 3.

Zone 3 is the estimated distal limit of true debris flows. In this zone, relatively moderate velocities and thin deposits are expected and the coverage is discontinuous due to "fingering", due to local topographic variations even during the largest events.

Zone 4 is considered subject to relatively low velocities and discharges with less severe potential for impact on structures and inhabitants.

Zone 5 is the floodplain of the Cheakamus and Squamish Rivers, where the main hazard is river flooding.

Zone 6 is an area on the right bank of the Cheakamus, which may be impacted by flooding due to the displacement of the Cheakamus by accumulating debris from the Cheekye.

8.3   Acceptability Criteria for Hazard and Risk Analyses

A search was undertaken for quantitative criteria used to determine the acceptability of natural and man-made hazards and their associated risks either to the public or to regulators. The effort involved a literature search as well as interviews with experts locally and abroad. The results of this search are summarized in Table 8.2, and suggested criteria for the various types of hazard and risk analyses are given in the following subsections.

8.3.1   Hazard Analyses

Criteria for acceptable hazard probabilities are given in Table 8.2 and Figure 8.2 (a). A large number of authors consider the value of 1/10,000 per annum to be an important limit. In one case (Cave, 1991), this value has been chosen simply as the representation of the limit of the post-glacial record, and more accurately stated requires that there has been no debris flow occurrence under consideration in post-glacial times.

It should be noted that Oosthuizen (1988) is the only source that explicitly has considered a variation of acceptable hazard level with the number of lives endangered. This is an important consideration, because from a planning perspective it places some limits on population density in the exposed areas. Unfortunately, the criteria given by Oosthuizen is based on very limited data and thus also has limited application.

8.3.2   PDI Risk Analyses

Criteria for acceptable PDI ("Probability of Death of an Individual") risk are given in Tables 8.2 and 8.3, and Figure 8.2(b). While there is some variation in acceptable risk dependent upon the specific exposure, it appears that a value of 1/10,000 per annum (representing the boundary between voluntary and involuntary risk) provides a suitable criteria for application to the Cheekye fan analyses.

8.3.3   PDG Risk Analyses

References have been located which discuss acceptability criteria for PDG ("Probability of Death of Groups of Individuals"), (Kinchin, 1978; Whitman, 1984; Dutch Environmental Policy Plan, 1989). The latter reference is concerned with environmental

hazards and this may not be directly applicable to natural hazards such as debris flows and rock falls.

A proposed PDG risk acceptability criterion was developed as part of this study. The criterion was derived from actual data on the frequency of multiple deaths due to landslides, over a long historic period in the European Alps as compiled by Eisbacher and Clague (1984) and Schuster and Fleming (1986). It is based on the premise that if, over a long period of time, society has comfortably (knowingly?) lived with a particular risk in a certain number of exposed locations, then frequency of death data for that risk constitutes an acceptability criteria.

The acceptability criteria developed on this basis are given in Figure 8.3, and further details of their derivation are provided in Appendix XIII.

It should be noted that the upper limit of acceptability as suggested in the Dutch Environmental Policy Plan corresponds to the boundary between low and moderate risks in the criteria for debris flows and landslides proposed in Figure 8.3.

The above hazard and risk acceptability considerations are offered here as quantitative guidelines. Actual decisions concerning acceptability, however, must be made by the public and its government representatives, based on their preferences and interests.

The risk acceptability criteria presented consider only life-threatening risks. Risks of material losses are additional. These risks should be evaluated by means of detailed cost-benefit analysis carried out in connection with the design of developments or mitigation measures.

8.3.4   Acceptable Risk and Public Perception

It must be kept in mind that there are limitations to the risk analysis approach, and nowhere is this more evident than when considering the effect of public perception on planning decisions.

The public is often shocked by the occurrence of a catastrophe. Morgan (1991) discusses some of the factors that affect this reaction, including familiarity with a risk,

controllability (including ability to withdraw from the risk), and perceived benefits. He gives an example of a campground situated on a floodplain, and how PDG values could be decreased to "acceptable" values by downgrading the campground to a picnic or rest area. However, after considering the likely affect of public perception, he concludes that "a wise planner would still search for alternatives with even less risk".

It is not within the scope of this report to consider public perception factors in depth. However, it is felt that there are situations in which any exposure to risk to life will provoke public response, and for which public perception should play a more dominant role in a planner's decision-making process than risk analyses. Such situations would include existing or proposed schools, hospitals, etc. where the specific population at risk is less conscious of the risk, is less able to withdraw from it, and for which there are questionable benefits.

8.4   Hazard Probability Assessment

The field investigations have shown that events of debris flow Magnitude Class A (2M-7Mm^3) have affected various parts of the whole of the Lower Fan in the past. The maximum probabilities of the hazards of varying magnitudes affecting the six zones on the Lower Fan, according to the severity of the event (rock avalanche/debris flow/debris flood) are presented in Table 8.4 and are based on the results of analyses described in the preceding sections.

Acceptability criteria for natural hazards developed recently in the Regional District of Fraser Cheam in South-western B.C. (Cave, 1991) and Table 8.5 can be used to evaluate the hazards. The table is explained in detail in Section 9.3.3. The literature search described in Section 8.3 indicates that these criteria are generally consistent with hazard-policies developed elsewhere.

The Fraser Cheam criteria distinguish various types of hazards, recognizing that the severity (the potential to impact developments and inhabitants) varies significantly among different types of natural phenomena. Of relevance to this project are three types of hazard: 1) Debris flow, understood as a high velocity, high discharge flow of liquefied soil, capable of demolishing structures by impact or burial and causing death or serious injuries to inhabitants. 2) Debris flood, a process transitional between debris flow and

stream flooding, characterized by large quantities of transported sediment, but with moderate velocities and discharges. Debris flood causes moderate damage to structures and poses less danger to the lives of the inhabitants. These are also detailed on Tables 7.1 and 7.2. 3) Avulsion flooding, caused by uncontrolled flow of the Cheekye River flood outside its regular channel. (Table 7.3). We consider that there is a smooth transition between the smaller debris flows and the larger floods. Consequently avulsion flooding has been assigned the same probability as Debris Flow C in Zones 1 to 3. Its reduced probability in Zone 4 reflects our belief that radial dissipation will reduce the flooding effects during most events.

In the present case, the effects of even the largest debris flow events varies with location on the fan. It is considered that the true debris flow effects as recognized in the Fraser-Cheam criteria apply only where the predicted velocity of the debris front is 3 m/sec. or more (Table 7.1). Where it is less, the hazard should be evaluated using the debris flood criteria.

The result of the above assessment is that Zones 1 to 3 cannot be zoned for housing development without mitigation. Zone 4 alone could be used with some drainage works such as channellization or diversion to reduce the hazard of flooding (see Section 8.6.7). Zones 1 to 3 require mitigation of the major (but infrequent) hazards (Types A and B). This is considered further in Section 9.4.

8.5   Risk to Life Assessment

8.5.1   Risk to Life of An Individual

Risk to life of any specific individual resident on the fan is a product of several factors. The probability of death of an individual (PDI) due to a given type of hazard can be calculated as:

PDI   = $P(H) \cdot P(S{:}H) \cdot P(T{:}S) \cdot P(L{:}T)$, where

P(H)   =   Probability of the hazard occurring

P(S:H) =   Probability of spatial impact, i.e. of a house being in the path of the debris flow, given that the debris flow occurs. Generally speaking, for PDI this equals the hazard corridor width divided by the zone

width, although this value also depends upon the depth of flow (i.e. can it be diverted by structures such as small berms or roads in the outer zones of the fan) and the existence of mitigation works.

P(T:S) = Probability of temporal impact, i.e. of a house being occupied, given that the debris flow occurs and that the house is in its path. The value calculated for, or assigned to, this probability depends upon the type of development, work and recreation habits of the community, seasonality of usage, etc. In general, it relates to the average percentage of time that an individual spends in his home.

The value assigned to P(T:S) also depends upon what type of warning systems are in place. If, without any warning system the value of P(T:S) is P#, then with a warning system, the value would be:

P(T:S) = $P^{\#} \cdot W$

where W, the "Warning Factor", represents the effectiveness of the warning system. An ineffective warning system is assigned a value of 1 but as the warning system becomes more effective, W decreases towards zero.

P(L:T) = Probability that there would be a loss, (i.e. that a specific individual would die), given the occurrence of all previous events on the event path. The value of this probability depends mostly on the nature of the debris flow, specifically, its depth and velocity.

The total PDI values given in Table 8.6 result from estimating the above factors for each type of debris flow in each zone and summing the results to obtain the total probability resulting from the full spectrum of hazards. The detailed calculations are presented in Appendix XIII. The "no warning" temporal impact probability P#(T:S) was taken as 1.0 in all cases, assuming each inhabitant is present in the hazard zones 100% of the time. The resulting PDI values are therefore very conservative for those residents who leave the area periodically to work or study, or who do not reside in the area. Revised PDI values for a part-time resident can be calculated by multiplying the values in Table 8.6 by the appropriate temporal factor.

Flooding hazards have not been considered in the risk analyses, as the life-threatening aspects of flooding damage are included in the factors describing Class C debris flows.

The values of Table 8.6 include warning factors W. It was assumed that only a modest system of identifying precedent conditions would be implemented and thus the warning factors were assigned as follows:

W = 0.5 for debris flow Type A.

As discussed earlier, the largest debris flows would need to be initiated by the formation of a landslide dam in the reservoir and the filling of a temporary lake, estimated to require a <u>minimum</u> of 1 to 3 days. In our subjective estimate, there is a 50% probability that a sequence of such events would be recognized and that evacuation of the residents could occur.

W = 0.75 for debris flow Type B.

In our estimate, the probability that an effective warning would be issued for a debris flow in the intermediate class is only 25%.

W = 1.0 for debris flow Type C.

No warning was assumed for debris flows of type C, with magnitudes less than 1 Mm^3.

The warning levels assigned above do not presuppose any systematic warning systems or programs to be in place. The given factors assume merely chance warnings.

If an acceptability criterion of 1:10,000 is used, the numbers provided in Table 8.6 would indicate that <u>housing and non-residential developments are possible in most of Zones 3 and Zone 4</u>. This contrasts with the results of the bazard-based approach which permits housing only in Zone 4. Non-residential uses with lower temporal factors could be acceptable in other higher risk zones as well. The PDI approach also shows that the most effective mitigation policy would be to prevent the smallest, most probable events, because these constitute a large proportion of the total risk to the individual. The assumptions behind application of the PDI approach are:

- that it ignores personal injury and property damage,

- that is assumes that there will be sufficient warning of the largest debris flows that evacuation can take place, and

- that it assumes that some limited loss of life may occur under extreme conditions but that the probability is minimized for any given individual because there is a statistical chance that he might not be home at the time and/or that the debris flow might impact a neighbour's land instead of his own.

8.5.2   Risk to Life of Groups of People

Society reacts with shock to the news of accidents involving large groups of people (Morgan, 1991).   The intensity of feeling may vary, depending upon how well-recognized the risks are and whether those exposed to them consciously assumed the risks. For example, the reaction to news of people killed in a rock avalanche might be more intense than news of the same number of people killed over a holiday weekend in traffic accidents.   This intolerance of "catastrophic" accidents is natural, and should govern to a large extent decisions made by government agencies on whether or not to allow development in an area exposed to such risks.

A method of calculating risks to groups of people has been derived specifically for this study. It is based upon a key assumption that the population density in any particular risk zone is approximately uniform (such as might be achieved in a normal residential development).   In practical terms, this means that the risk to groups of people in a particular risk zone is set by the area of highest population density, which is conservatively assumed to apply to the entire zone. Note however that the method at present has not been applied to account for points of extreme population concentration, such as a school, hospital or high rise apartment.

PDG values have been calculated in a manner similar to PDI, as discussed in the previous section.   The basic terms of the risk equation are the same, but since the exposed population is spread out over the entire fan, the calculation method is quite complex. Details of the method are provided in Appendix XIII, and are summarized as follows:

(1)   Consider a real or assumed distribution of population in the hazard zones.

(2)   Take groups of various sizes, ranging from a few individuals to the entire population. Determine the probability of a disaster affecting each given group size, resulting from each type of hazard event. This requires estimation of the probability distribution of group sizes involved in any event type. For example, a debris flow of a given magnitude will have a certain most likely affected group

size. Smaller or larger groups can also be impacted by the same event type, but with a reduced probability. This probability distribution was estimated for each event type based on the most likely range of damage corridor widths.

(3)   For any given group size, accumulate the probabilities resulting from all event types, to determine the overall PDG as plotted in Figure 8.4.

(4)   Acceptability is determined by the position of the PDG curves relative to the acceptability limits in Figure 8.3. The PDG curves should not cross the acceptability line at any point.

Figure 8.4 shows the results of two example calculations, based on an assumed population density of 1,500 per sq. km in Zone 4. Other populations would be distributed as shown in Table 8.7. The results shown by the full line (no mitigation) show that a narrow range of groups are exposed to moderate to high risk. This peak is a consequence of our expectation that practically any size of a debris flow event can impact a narrow "corridor" in the populated Zone 4. The low severity factors $P(T:S)$ and $P(L:T)$ do not appear to affect the risk to groups as favourably as they do the risk to an individual. Furthermore, there is no benefit of "spreading" of risk due to the assumption of uniform density.

The dashed line result shows that the PDG result could be brought into the acceptable range by mitigation of the smaller events.

The sample PDG calculations in Appendix XIII and Figure 8.4 are intended only to illustrate the potential of the method. More appropriate use of the PDG approach is to analyze an actual distribution of population resulting from specific development proposals. Such detailed analyses should, in our opinion, be required in connection with future development plans and also to assess the effectiveness of proposed mitigations schemes. They should be supplemented by cost-benefit analyses which take into account property risks.

The PDG approach differs from both the probability of hazard and PDI approaches in that it is the only risk assessment method that is sensitive to the density of population in the risk zones. The probability of hazard approach may recognize typical population densities in an indirect manner, but does not specify allowable values, and the PDI approach does not deal with population density at all. The ability to assess allowable

population densities is a very important aspect of the PDG approach, and one of the reasons why risk analyses should ideally proceed on the basis of several complementary techniques rather than one technique alone. Thus the most useful applications of each approach can be combined to address different planning issues - such as land use, density, mitigation strategy, etc.

8.6   Mitigation Concepts

8.6.1   Options Considered

Defenses protecting populated areas against debris flow damage include passive and active measures (Hungr et al., 1985). Passive measures aim at keeping populations or structures away from the hazard areas in space (through zoning) or in time (by means of warning and evacuation programs). Active measures modify the hazard phenomenon itself, by means of engineered remedial works such as diversion dykes, storage basins and barriers, or stabilization works in the headwaters.

Of the range of measures available, the three considered to have possible application to the situation on the Cheekye Fan include the implementation of a warning system, development control by zoning, and the use of diversion dykes in the deposition area. Combination of these may also be considered.

The most important mitigation approach is land use zoning and this is covered comprehensively in Section 9.

8.6.2   Warning Systems

In theory, prior warning is an excellent highly cost effective means of reducing risk to life from low probability hazards. In the present case, there are two main possibilities.

a.   Monitoring in the Upper Basin

Monitoring in the upper basin could provide advance notice of precursory signs which might herald a significant landslide. A displacement monitoring system was installed in 1991 on the Cheekye Ridge (Appendix VI). A systematically executed program of periodic monitoring could reduce the risk of unexpected occurrence of a major slope failure and consequent debris flow but it would not

eliminate the risk completely, as instability could develop within a few days, or during an earthquake. A remote monitoring system is not considered feasible in the upper basin, except if and when an active localized instability develops.

Thus, monitoring in the upper basin cannot be recommended as a reliable method of mitigation at present.

The system currently put in place on the Cheekye Ridge may prove to be useful in improving the future understanding of the mechanism which caused the origin of the Cheekye linears and therefore allow for a more reliable prognosis of future developments.

Based on the observation of trees in the area of the linears, it appears likely that measurable displacements will not occur for several decades, unless some change in the stability condition of the ridge takes place as a result of changed ground water conditions, or a seismic event. Periodic readings of the displacements at intervals not exceeding two years are recommended once exposed parts of the fan are developed in order to ensure that possible gradual stability changes do not go unnoticed. While periodic readings are taken, aerial inspections of the basin by an experienced engineering geologist should also be carried out to take note of major changes (e.g. cracking, development of scarps, increased small scale instability, erosion etc.).

b.   Monitoring of the Cheekye River

The expected scenario for large scale debris flow involves temporary damming of the Cheekye River in mid-basin by landslide deposits. Perhaps the most effective means of monitoring the river for precursory signs of such an event is by visual inspection at the Highway 99 bridge, which would be carried out by specially briefed personnel during and following major rainstorms. A checklist of observations, an inspection program and a contingency plan should be developed with specialist advice beforehand. This program could be maintained by the Municipal or Provincial authorities.

The possibility of advance warning would also be increased by installing a remotely operated weather gauge in the upper basin (e.g. on the Cheekye Ridge) which would serve to improve flood and debris flows forecasting in the wider region. It is understood that the Ministry of Transportation and Highways already monitors several remote gauges on Highway 99 close to Vancouver. Parallel monitoring of weather gauges and river discharges might provide a basis for a warning system in the future.

It should be stressed that monitoring can reduce but not eliminate the risks at this site.

8.6.3 Mitigation by Dyking

The areal extent of the various hazard zones could be modified by the use of dyking. At this conceptual stage, homogeneous earthfill dykes constructed of local materials with 2H in 1V upstream and 1.5H in 1V downstream slopes and a crest width in the order of 6 m have been considered. The dykes would be covered by topsoil and planted with forest. Some degree of erosion protection would be required in specific locations.

The preliminary sizing of the dykes considered in the study was based on the capacity necessary to store sufficient quantity of debris, and on dynamic analysis of the runup of rapidly moving debris surges. The dynamic analysis is an extension of the theory developed by Hungr et al. (1984) and produces the design chart shown in Figure 8.5.

Two alternative design approaches were followed, the hazard based approach and the risk-based approach corresponding to the two types of risk analysis discussed in Sections 8.4 and 8.5. In addition, for the hazard-based alternative, two scenarios (Sections 8.6.4. a and b) have been considered for mitigation. These scenarios are not considered to be unique but present two typical options which would be further studied during subsequent stages of development.

The first approach, based on the hazard probability assessment of Section 8.4 dictates that, in order to permit any development in Zones 1 to 3, it is necessary to mitigate against the largest magnitude hazards (Types A and B) to meet the criteria shown in Table 8.5. This can be achieved by major dyking works, such as those shown in the two typical scenarios on Figures 8.6 and 8.7. These dykes change the extent of the hazard zones as shown on the figures but they do not significantly modify the probabilities as listed in Tables 8.4 and 8.7 for various types of event in each zone.

The second approach, based on the risk to life assessment described in Section 8.5, utilizes the finding that the largest reduction in risk to life (PDI) results from mitigation of the smallest, but more probable hazards. The conceptual dyke layout shown in Figure 8.8 is designed to resist debris flows of Type C only. The extent of the zones changes only slightly, because they are determined by the large events. Descriptions of the mitigated fan zones are given on Table 8.10 (facing Figure 8.8). The risks assigned to each zone, however, are reduced to residual values, as listed in Tables 8.8 and 8.9.

8.6.4   Large Dyke Layouts

a.   Scenario 1

Scenario 1, shown in Figure 8.6, provides a string of large dykes situated to cut off potential run-out paths leading to the southern one-third of the fan. Dykes A and B, approximately 7m high, prevent spillage to the south into the Highway 99 corridor. With these measures in place, the future debris flows should pass through the established channel as far as the fourth bedrock gate, downstream of Highway 99.

Dykes C and D, ranging from 4 to 7m in height, constrain the potential deposition area to the north side of Alice Lake Road as far west as Government Road. Another dyke, Dyke E, could be used optionally to prevent debris flow runout from extending into the north-east corner of the fan. Construction materials could be obtained from borrow pits on the fan.

As a result of this dyke layout, the deposition areas for debris flows of all magnitudes as well as all potential flooding paths would be confined to the central segment of the fan, freeing the southern and north-eastern extremities for development. The confined area is, however, sufficiently wide to preclude excessive accumulation of debris. Even in the event of the maximum debris flow magnitude ($7Mm^3$), there would be sufficient area available between the dykes so that the flow and deposition behaviour of the event would not be excessively modified by increased lateral confinement.

The boundaries of the hazard zones are changed from the existing conditions as the result of the dykes (compare Figure 8.1 and 8.6.) The hazard characteristics within each zone would remain approximately as defined in Tables 8.5 and 8.7.

Although the flow characteristics are not expected to change very much within the dyked-off area, the boundaries between Zones 1 and 4 have been shifted downstream by subjectively estimated distances, to allow for a possible increase in runout distance of the largest events as a result of the dyking. This downstream shift of hazard zone boundaries must be regarded as a form of risk transfer, increasing the expanse of the hazard areas on the central fan in order to reduce the same in the protected marginal segments. The quantitative impact of this risk transfer on existing developments (especially the Cheekye

substation and the airport) must be addressed in greater detail during the design stage of the dyking system.

Residual risks in the undesignated ("Minimal Hazard") zones of Figure 8.6 relate to the probability of failure, or insufficient capacity, of the remedial dykes and again need to be assessed in detail as part of design work for the dykes. A Zone 3 and 4 buffer has been allowed at the downstream toe of the dykes, to reflect reduced probability (residual) risks close to the dykes.

b.   Scenario 2

The second scenario shown in Figure 8.7, is another system of large dykes, laid out so that the Highway 99 corridor between Alice Lake Road and Brackendale is sacrificed and remains a part of the debris flow depositional area. A wedge shaped parcel of land north-east of Brackendale is opened to development. Dyke B is again used to protect the north-east corner of the fan.

The main Dyke A is estimated to be 4 to 6 m high. A narrow "gate" with strong erosion protection and elevation control needs to be designed to allow Highway 99 to pass through the dyke, without opening a significant corridor for debris and flooding.

Comments made regarding transfer of risk and residual risk in connection with the first scenario also apply to this alternative.

8.6.5   Small Dykes Layouts

Dykes A and B, approximately 5m high, are designed to restrain the smaller debris flow events from moving into the Highway 99 corridor. Dyke A is similar to the avulsion flood control structure existing at present and will fullfil the same function. Its construction would involve upgrading of the existing dyke. Dyke B is intended to control flows which might spill out of the channel at the highway bridge.

Dyke C, approximately 4m high and 600m long, directs flows into a designated deposition area located west of the present Cheekye channel downstream of the main bend. A wide shallow basin excavation in this area could provide borrow material for

Fig 8-8

construction of the dykes and increase the storage capacity of the deposition area. Dyke C is purposely removed a certain distance from the existing channel, in order to provide the required deposition area and to prevent channelization of the debris flows towards the Cheekye/Cheakamus confluence. We consider that, with the provision of the excavated basin, the design of this scheme could ensure that there would be no significant increase in risk of damming the Cheakamus at the confluence. For the same purpose, Dyke C should be sufficiently low to permit overflow by the larger, less frequent, debris flow events.

The residual values of hazard probability and PDI given in Tables 8.8 and 8.9 facilitate placing new developments on the Cheekye Fan. If and when development proposals based on the protection by the smaller dykes are made, the acceptability of the residual risks downstream should be re-assessed using the PDG approach.

8.6.6   Localized Protection Structures

The estimated debris flow velocities and flow depths for Zones 3 and 4 are relatively moderate (Table 7.1) and this gives an opportunity for localized protection dykes to be used in these zones to reduce the risk of damage to certain sensitive facilities, such as the schools. The dykes would have a form similar to the existing dyking surrounding the Cheekye Substation. Provided the protected areas are of limited extent (i.e. approximately 200 m maximum width), we expect no significant increase in risk to neighbouring areas, although this should be assessed. Areas downslope from the protection works would have their risks reduced. Each localized protection structure must be evaluated from the point of view of debris flow dynamics, flood erosion potential and risk assessment (including residual risk and possible risk transfer) in a separate site-specific study.

Localized protection structures could be used in conjunction with the small dyke system to provide additional risk reduction for sensitive facilities.

8.6.7   Other Remedial Measures

a.   Forest Cover

Protective forest cover should be maintained and cultivated on the Middle Fan and in the apex area of the Lower Fan (Zones 1 and 2). Recreational projects (such as golf courses) or roads, located in these areas should be planned so as to minimize clearing of the forest and especially to prevent the creation of open downslope - oriented corridors which could encourage channelization of debris flows and floods. Newly cleared areas (e.g. after construction of protective dykes) should be promptly re-forested.

These requirements will place certain restrictions on developments such as golf courses in Zones 1 and 2, but are not expected to affect the feasibility of such developments.

b.   Flood Protection

All new construction in the study area must incorporate avulsion flood control measures such as dyking, ditching and floodproofing of houses, to be designed on a project specific basis in accordance with the flood parameters provided in this study (Table 7.3). Such measures can be relaxed only if dyking protection according to one of the above schemes is implemented.

c.   Avulsion Protection

A dyke controlling the Cheekye channel upstream of Highway 99 has been constructed recently. Additional dyking is recommended to prevent avulsion of the Cheekye at the highway bridge. This could be accomplished using a dyke similar to "B" shown on Figure 8.8. Further avulsion dyking is recommended for the main bend of the Cheekye. These structures could be designed so as to serve as pilot dykes, to be incorporated into the larger ultimate works.

9.0   LAND USE PLANNING CONSIDERATIONS

9.1   Introduction

The purpose of this section is to assess the implications for land use planning arising from the Cheekye River geotechnical study. The objectives of this planning component are:

- to describe existing and proposed land use, existing land ownership, mineral claims, and existing planning and zoning designations in the study area.

- to assess the general implications of the geotechnical study for existing and possible future land uses in the study.

- to assist in the evaluation of mitigation measures.

- to outline an appropriate approach to land use and development regulation in the area subject to the hazard.

9.2   Existing Situation

9.2.1   Existing Land Use

Existing land uses (as of 1991) in the study area are shown on Figure 9.1. The study area includes five main areas plus major corridors.

A.   Lands within the District of Squamish located west of Highway 99 and on the Brackendale side of Ross Road.

This sub-area is the most intensively developed part of the study area. It takes in the Brackendale community, which is developed for urban residential uses. Brackendale contains a mix of older single family housing, newer single family and townhouse developments, and a small amount of commercial land uses. There are some undeveloped parcels of land in Brackendale, including the unoccupied subdivision on Crown land along Ross Road. There are also two schools in Brackendale: Brackendale Elementary (kindergarten to grade 7) with 465 students and Brackendale Secondary (grades 8 to 10) with 337 students. A church is located on Ross Road near the schools.

B.   Lands within the District of Squamish located west of Highway 99 and north of Brackendale.

This sub-area is sparsely developed and has the following land uses:

- The Municipal Airport on the west side of Government Road which is owned by the District of Squamish and leased to a flying club. The airport facilities include a 2400 ft. paved runway, offices and hangars for the flying club and commercial operators, and an inactive weather station.

- A privately operated wood waste dump site south of the airport.

- The Mt. Garibaldi Cemetery on the east side of Government Road. This Municipal cemetery presently occupies about 10 acres of a 50 acre site owned by the District of Squamish.

- The Municipal Sanitary Landfill on the north side of Alice Lake Road. The landfill has about 10 years capacity remaining based on anticipated population growth.

- The Municipal Reservoir on the south side of Alice Lake Road. This one million gallon water tank serves the Brackendale area.

- The BC Hydro Cheekye Sub-station on Government Road. Power is supplied to the Cheekye sub-station by three lines from northern BC and then transferred from the sub-station to Vancouver, the Sunshine Coast, and Vancouver Island.

- A small lumber mill north of the BC Hydro sub-station.

- A small pocket of mainly single family houses along Government Road near the confluence of the Cheakamus and Cheekye Rivers.

- The Cheekye Stables, a commercial stable operation which uses riding trails in the area.

C. Lands within the District of Squamish located east of Highway 99

The major land uses on the east side of Highway 99 are recreational, including:

- Dryden Creek Resort across from Depot Road, which is a small commercial campsite along Dryden Creek.

- Alice Lake Provincial Park, which is a 978 acre park that contains four lakes and offers camping (95 campsites), picnicking, swimming, fishing, and hiking. The park also contains the Parks Branch regional headquarters office.

The District of Squamish operates a rock quarry for dyking material on leased Crown land between Highway 99 and Alice Lake Provincial Park, south of Alice Lake Road.

D.   <u>Lands outside of the District of Squamish in the eastern part of the study area</u>

This sub-area has forested, rugged terrain with no urban development. A Ministry of Forest recreation area and trail are located around Cat Lake.

According to the Squamish Forest District, timber in the upper Cheekye drainage was harvested between 1986 and 1990[1]. Harvesting operations are now complete and no additional harvesting is proposed in the headwaters area. Most of the harvested blocks have fully regenerated with natural vegetation. Road rehabilitation, slash disposal, fill planting to supplement natural regeneration, ongoing stocking surveys, and possible stand-tending treatments are the only forestry related activities planned for this area.

E.   <u>Cheakamus Reserve</u>

The study area includes a small part of the Cheakamus Indian Reserve (Reserve No. 11) of the Squamish Nation west of the Cheakamus River. There are a few houses on this reserve near the confluence of the Cheakamus and Cheekye Rivers.

F.   <u>Corridors</u>

The study area contains corridors for Highway 99 (the Sea to Sky Highway connecting Vancouver to the Whistler resort), the BC Rail line (North Vancouver to northeastern BC), and BC Hydro power lines (supplying power from northern BC to the Cheekye sub-station and from Cheekye to Vancouver, the Sunshine Coast, and Vancouver Island).

9.2.2   <u>Proposed Land Uses and Development Potential</u>

The Provincial Government has received expressions of interest in the acquisition of Crown land for golf course, resort, and residential development on lands in and adjacent to the study area.

Other specific development proposals include:

- the Howe Sound School District is considering replacement of the Brackendale Elementary School with a new facility, although the location of the new school depends on the findings of the geotechnical study.

- a small tourist cabin development is proposed at the confluence of the Cheekye and Cheakamus Rivers.

- an extension to the Dryden Creek Resort has been proposed.

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1   Letter dated December 3, 1991.

9.2.3   Land Status

Figure 9.2 shows available information (as of 1991) on land ownership and status in the study area. This information was compiled from Provincial Government Crown land status maps and BC Assessment Authority data.

The major land owner in the study area is the Provincial Government. Major tenures and reserves on this Crown land include:

- the 978 acre Alice Lake Provincial Park on the east side of Highway 99.

- an 820 acre Woodlot License between Highway 99 and Government Road.

Other major public sector bodies with land holdings in the study area are BC Hydro, the Howe Sound School District and the District of Squamish.

The study area includes lands in Indian Reserves 11, 13 and 14 of the Squamish Nation.

Most of the lands in the southern portion of the study area (in Brackendale) are privately owned.

A review by the Mineral Policy Branch, Ministry of Energy, Mines and Petroleum Resources indicates that, as of late 1991, there were no subsurface tenures in the study area.[2] The District of Squamish has a license for a rock quarry on Crown land east of Highway 99.

9.2.4   Existing Community Plan and Zoning Designations

Lands within the District of Squamish

The District of Squamish's Official Community Plan (OCP) designates lands in the northern part of Squamish (north of Brackendale and Alice Lake Park) as "Limited Use" in part because, when Squamish's OCP was adopted in 1989, there appeared to be no imminent development prospects for the North Squamish area and because of factors such as the threat of flooding and mud flows, steep terrain,

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2   Letter dated November 13, 1991.

and the high cost of providing services to the area. For development to occur in the North Squamish area, an amendment to the OCP would be required.

North Squamish is currently zoned for Resource use in the District of Squamish's Zoning Bylaw. Permitted uses in this zone include: extractive industries, agriculture, small scale manufacturing, silviculture, forestry, and logging, non-profit campsites and picnic grounds, parks and playgrounds, aquaculture or mariculture, dog kennels and veterinary hospitals, municipal, police, fire, or school district operations, auction and liquidation sales, nurseries, and recreation uses with the approval of the Municipal Council.

The southern portion of the study area takes in the northern part of the Brackendale community. Brackendale is designated as a Residential Neighbourhood in Squamish's OCP. Residential Neighbourhoods are intended to accommodate all forms of housing, schools, churches, local parks and local commercial outlets. The major zoning designations in Brackendale are Residential 1 (single family dwelling) and Residential 2 (single and two family dwellings).

Indian Reserve Lands

The study area takes in some lands in Indian Reserves 11, 13 and 14. Municipal land use policies and regulations do not apply to Indian Reserves.

A development plan is being prepared for Reserve No. 11 by the Squamish Nation.

9.3   Land Use Implications in the Absence of Mitigation

This section reviews the broad land use implications for the study area based on the findings of the geotechnical study, assuming no construction of mitigation works.

9.3.1   Acceptability of Risk

An extensive review of the acceptability to society of the probabilities of various natural hazards and man-made risks was undertaken as part of the geotechnical study

(Section 8.3). It was determined that a probability of 1:10,000 was an important limit based on other hazards that people live with and risks that they take. Therefore, the Steering Committee for this study has directed the consultants to use the 1:10,000 probability as the basis for defining land use guidelines, meaning that areas subject to a probability of 1:10,000 or higher of the occurrence of a natural hazard event should be given special consideration in land use planning and development regulation. The Class A debris flow hazard (with a probability of 1:2,450 to 1:10,000) is, therefore, used as the basis for assessing land use and development implications.

9.3.2   Evaluation Approaches

As described in more detail in Section 8.1, there are two approaches which can be used to evaluate a natural hazard:

- **hazard probability approach,** in which the probability of the occurrence of various types of hazards is determined and compared to the limit of acceptability used for similar situations elsewhere.

- **risk to life approach,** in which the risk to life of an individual (probability of death of an individual) or group (probability of death of a group) is compared to general limits of risk acceptance. This approach considers not only the probability of any type of hazard occurring, but also considers severity, suddenness, likelihood of warning, actual patterns of human use and other variables which determine the probability that an individual or group of specified size would be killed during a hazard event.

These two approaches can yield different conclusions in terms of the acceptability of risk and, therefore, lead to different land use recommendations.

The Steering Committee has directed the consultants to look primarily at the hazard probability approach, but to also consider the risk to life approach in assessing land use implications of the Cheekye fan hazard. Therefore, sections 9.3.3 and 9.3.4 of this report review the land use implications arising from the hazard probability approach and the risk to life approach respectively, in the absence of any mitigation works.

9.3.3   General Land Use Implications Based On The Hazard
         Probability Approach

The hazard probability approach tends to be used most often in defining appropriate land
uses in areas exposed to natural hazards. Generally, this approach has been applied to
land uses which involve significant improvements where people spend all or a
considerable part of the day for most of the year, as distinct from occasional or brief uses
and activities. This group of land uses (i.e. habitable uses) would include all forms of
housing, schools, hospitals, hotels, community recreation facilities (e.g., ice rinks,
swimming pools, theatres), offices, stores, and industrial facilities.

The Regional District of Fraser-Cheam in the eastern Fraser Valley of southwestern BC
has done considerable work on the regulation of land use in areas prone to natural
hazards. Because the Regional District of Fraser-Cheam is located in the same climatic
zone and has a similar geological environment to the Squamish area, and because the
Regional District is also dealing with the same legislative powers and responsibilities,
Fraser-Cheam's hazard probability approach to evaluating land uses in natural hazard
areas was used as a guide for this study.

The Regional District of Fraser-Cheam has developed hazard acceptability thresholds for
several types of natural hazards (Cave, 1991). These thresholds can be used to evaluate
applications for improvements to existing buildings and applications for proposed
developments. The Regional District of Fraser-Cheam has developed acceptability
thresholds for various types of hazard because each has the potential to cause different
types and severity of impact.

The geotechnical study has determined that the Debris Flow and Debris Flood hazards
used by Fraser-Cheam (Table 8.5) are relevant to the potential hazards on the Cheekye
Fan. Because the predicted consequences of the occurrence of the hazard vary by
location on the fan, it is the opinion of the geotechnical consultants that the hazard should
be evaluated as a Debris Flow in Zones 1, 2, and 3 and as a Debris Flood in Zones 4, 5,
and 6 (see Section 8.4 and Table 8.4 for more detail). All six zones are also subject to
flooding.

The Fraser-Cheam approach to evaluating applications in hazardous areas takes the form of a matrix with seven types of development approvals and five potential regulatory responses.

The seven types of development approval situations are:

A.   Minor repair to existing structure   -   cost of repair is not greater than 25% of the value of the building before repair.

B.   Major repair to structure   -   cost of repair exceeds 25% of the existing assessed value of the structure before repair.

C.   Reconstruction   -   replacement of an existing building.

D.   Extension   -   increase the size of an existing building.

E.   New building   -   on an existing, subdivided vacant lot.

F.   Subdivision   -   infill or extension of existing development.

G.   Major rezoning & Community Plan Amendment   -   development which involves community plan creating new neighbourhoods or amendment communities in previously unsubdivided or undeveloped areas.

Cave (1991) provides a more detailed discussion of the issues involved in considering each of these types of development.

The five different possible regulatory responses to a development application are:

1.   Approval without conditions relating to hazards.

2.   Approval, without siting conditions or protective works conditions, but with a covenant including "save harmless" conditions.

3.   Approval, but with siting requirements to avoid the hazard, or with requirements for protective works to mitigate the hazard.

4.   Approval as (3) above, but with a covenant including "save harmless" conditions as well as siting conditions, protective works or both.

5.   Not approvable.

The Fraser-Cheam Regional District has developed matrices which indicate the preferred regulatory response to each type of development application in an area subject to a

particular hazard (see Table 8.5). Based on the Fraser-Cheam hazard acceptability thresholds and evaluation approach and the predicted impacts of the hazard by zone (Table 7.2), the following subsections discuss the broad implications for land use[3] for each of the hazard zones in the absence of mitigation. Table 9.1 provides more detailed guidelines for land use planning and development approvals.

Zone 1

There are no existing habitable structures in this zone and, based on the estimated effects of the Class A event in this zone, no habitable structures should be developed in this zone under existing conditions.

Zone 2

The only existing habitable uses in this zone are a few houses at the confluence of the Cheakamus and Cheekye Rivers. Most of Zone 2 near the confluence of the rivers is in the floodplain and so is also subject to flooding.

Because of the dual hazard exposure in this area, no additional habitable structures should be developed in Zone 2.

Zone 3

In Zone 3, the estimated effect of the Class A Debris Flow is described as "forest and structures surrounded but not destroyed" (Table 7.2). Zone 3 is also subject to possible debris flooding and to flooding.

The major habitable land uses in Zone 3 are the high school and church on Ross Road. There a few houses north of the Cheekye River. Also, a small part of the Tantalus subdivision on Ross Road is in Zone 3. (This subdivision was serviced, but the lots were not sold and houses were not built because of concern about natural hazards).

The Fraser-Cheam approach would require that repairs, building extension, reconstruction, the construction of new buildings on existing lots, and infill subdivision would all need conditions intended to avoid

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3   The Fraser-Cheam Regional District only applies its approach to residential uses, because the lands subject to hazard are generally only considered for residential use.

    Because the Cheekye Fan study area includes existing non-residential uses and could be subject to applications for further non-residential urban development, the approach must be broadened in scope.

    The purpose of adopting regulatory approaches for the hazard area is to minimize or avoid damage to structures and injury or death. Residential, commercial, industrial, and institutional uses (i.e. the habitable uses) are similar in that they include substantial improvements and they are occupied by people much of the time.

    Therefore, it is proposed that the Fraser-Cheam approach can be applied to this whole group of habitable uses, without addressing the minor differences in the intensity, frequency, or patterns of human occupancy.

liability on the part of the Municipality and siting controls and flood protection as required for specific sites or the entire area.

Under the Fraser-Cheam approach, the portion of the Tantalus subdivision which is located in Zone 3 could be approved for housing development with mitigation and an effective method of protecting approving authorities from liability. In the current situation (i.e. no mitigation), and given that the land is Crown land, housing should not be developed in the Zone 3 portion of the Tantalus subdivision.

Based on the Fraser-Cheam approach, Zone 3 would not be appropriate for new major residential and commercial developments at present, nor for new significant public facilities.

Zone 4

Zone 4 contains the major existing residential area in the study area, taking in the northern part of Brackendale. Zone 4 also includes the elementary school and the majority of the Tantalus subdivision.

The types of applications most likely to occur in a developed residential area like Brackendale include repairs and extension to existing older houses, construction of new houses on existing vacant lots or to replace older houses, infill subdivisions on larger vacant parcels, and extensions to existing subdivisions (e.g. Tantalus subdivision).

Zone 4 is subject to non-destructive debris floods and to floods. While the severity of impact is not great, the annual probability is relatively high, requiring a regulatory response.

Almost all repairs, new permits, and infill subdivision would require some mechanisms to limit Municipal liability and siting or works to reduce risk. Rezoning for new residential neighbourhoods and major residential subdivisions and developments could only be approved if buildings are sited, or works are constructed, to eliminate exposure to the hazard.

Zone 5

There is little development in Zone 5 because most of this zone is in the Cheakamus and Squamish River channels. However, there are a few houses at the confluence of the Cheakamus and Cheekye Rivers. Presumably, most of this zone is in the floodplain and, therefore, subject to floodproofing regulations.

Zone 6

Zone 6 takes in part of Indian Reserve No. 10 on the west side of the Cheakamus River. There are a few houses located on this part of the Reserve.

Zone 6 is subject to a potential debris flood. Repairs, extension, reconstruction, and new buildings could be allowed without conditions relating to the hazard. The question of how new development on this land should be dealt with should be reviewed in the context of options available to the Squamish Nation. This type of examination is beyond the scope of this study.

The Fraser-Cheam hazard probability approach to land use regulation in natural hazard areas emphasizes the avoidance of human death and injury and severe damage to large scale improvements. However, there is a range of land uses in which individuals spend relatively little time and/or which involve a lower intensity of investment (i.e. value of improvements over the total affected area). These uses may not require as restrictive regulations as, for example, housing or schools. These types of land uses include:

- facilities such as the District of Squamish's landfill, water reservoir, cemetery, and quarry, and BC Hydro's sub-station.

- transportation infrastructure (e.g. Highway 99 and secondary roads, BC Rail line, and Squamish Airport).

- outdoor recreation uses (e.g. golf course[4] and riding trails).

The strict application of the hazard probability approach to these types of land uses would not be significantly different than for habitable types of land uses. With the hazard probability approach it would likely be concluded, for example, that new golf courses and highways would not be appropriate in Zones 1 and 2. However, the hazard approach is oriented to the dual objectives of preventing damage to property and preventing death and injury to an area's occupants assuming a high intensity of human use. Where land uses involve a much lower intensity of human use, the hazard probability approach may result in land use regulations which are too restrictive in many people's minds. For these types of land uses, the risk to life approach may be more appropriate for determining the acceptability of locating in an area exposed to a natural hazard.

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4   Golf course means literally the golf course only. Any hotel or condominium development should be considered habitable use. This means, quite reasonably, that a golf course, on which individuals spend a small amount of time, could be approved in a location, provided there was not a hotel or residential component exposed to the hazard.

9.3.4   General Land Use Implications Based on the Probability of Death Approach

The geotechnical study presents an alternative to the hazard probability approach as the means of evaluating the risks of hazard exposure.

The alternative is to use probability of death, as distinct from the probability the occurrence of a hazard event.

The rationale for this alternative approach is that there may be circumstances in which the probability of an event occurring could be high, but the actual risk of injury or death is very low; this situation could call for a different regulatory or decision-making response in comparison with a situation in which the probability of the event both unacceptable.

The probability of death approach acknowledges that many variables affect the chance of death once the hazard event occurs. The rapidity, severity, actual physical character of the event, degree of warning, actual land use, and actual pattern of human occupancy could combine to create a very low likelihood of death even if the hazard event occurs.

The geotechnical analysis notes the distinction between Probability of Death of an Individual (PDI) and Probability of Death of a Group (PDG). For various technical reasons, PDG may be the most appropriate measure but it is also the less-developed methodology of the two. Therefore, this section applies the PDI approach to the study area to illustrate the potential differences between this approach and the probability of hazard approach in terms of land use implications.

The probability of a hazard or risk of 1:10,000 is being used in this study as the basis for identifying acceptable land uses on the fan. As shown in Table 8.6, the PDI for full time residents for the range of potential hazards for Zones 1 to 4 is as follows:

Zone 1 -   1:500 to 1:160

Zone 2 -   1:2,000 to 1:900

Zone 3 -   1:19,000 to 1:9,000

Zone 4 -   0 to 1:20,000

Based on the 1:10,000 probability threshold and the calculated PDI values, following is a discussion of the broad implications of the PDI approach for land use in hazard zones 1 to 4.

Zones 1 and 2

The PDI values for a full time resident in Zones 1 and 2 are much greater than the 1:10,000 threshold and, therefore, residential uses should not be approved. Other types of habitable land uses are also likely to have PDI values greater than the 1:10,000 threshold even though they may not be occupied all day, every day of the year. For example, the PDI for a hypothetical full-time employee in Zone 2 can be calculated as 1:3,494 (resident PDI of 1:900 multiplied by 50/52, allowing for two weeks holiday, multiplied by 5/7, allowing for weekday occupancy, multiplied by 8/24, allowing for an 8 hour shift plus 1 hour for lunch). The likelihood of death of an individual is significantly lower than the likelihood of a hazard event occurring, but it is still greater than 1:10,000.

For Zones 1 and 2, the PDI approach results in essentially the same implications for habitable land uses as does the hazard probability approach. The PDI approach, however, may support the acceptability of some uses (e.g. outdoor recreation, even if major facilities are involved).

Zone 3

The estimated PDI values for a full time resident in Zone 3 (1:19,000 to 1:9,000) are within the range of the 1:10,000 probability threshold. The difference is likely too small (particularly given the uncertainties in the analysis) to conclude that PDI has less restrictive implications regarding residential use. However, for uses which do not involve a full time human presence on the fan, PDI values would be even lower. For example, the PDI for a hypothetical employee, calculated as for Zones 1 and 2 above, would be 1:34,944, which is well beyond the threshold of 1:10,000.

If these PDI values are correct, and if the 1:10,000 probability threshold is acceptable, then the PDI approach suggests that land use regulations in Zone 3 could be less restrictive than implied by the hazard probability approach, for non-residential habitable uses, such as commercial, industrial, and some institutional uses.

Zone 4

The estimated PDI for full time residents in Zone 4 (1:20,000) is already lower than the 1:10,000 probability threshold, so for an individual who is on the fan less than full time the PDI would be even lower than 1:20,000.

The land use constraints suggested for Zone 4 by the hazard probability approach are not highly restrictive. With the PDI approach, land use

restrictions in Zone 4 could be even more lenient, at least for those sites exposed to debris flows but not to flooding.

As discussed in the previous section, there are some types of land uses which are more appropriately considered with the PDI approach. These types of land uses include:

- facilities such as the District of Squamish's landfill, water reservoir, cemetery, and quarry and B.C. Hydro's sub-station.

- transportation infrastructure (eg. Highway 99 and secondary roads, B.C. Rail line, and Squamish Airport).

- outdoor recreation uses (e.g. golf courses, not including associated hotel or residential development, hiking trails and riding trails).

For these types of uses or activities where individuals are only occasionally or briefly in a location exposed to a potential hazard, the risk to life approach could be more useful. The main advantages for using the PDI approach for these non-habitable uses are:

- it provides a better indication of the true risk to individuals using different types of facilities or involved in different types of activities.

- it addresses uses that have no other choice than to locate in the affected area (e.g. Highway 99).

- it may be particularly applicable to uses with low-value improvements, where concern about injury or death is valid but concern about damage to improvements is minimal.

There are many possible circumstances in which non-habitable land uses should not be as restricted as uses such as housing or schools. Three examples are as follows:

- **Highway and rail corridors.** These transportation routes really have no alternative but to go through the fan area. It is widely recognized that Highway 99 is subject to a variety of hazards, but people continue to use this route. Presumably, people perceive the risk of death or injury as low because they do not spend very much time using the highway. Because the probability of an individual being on a road in the fan area when the debris flow strikes is likely very low, it should be acceptable to allow transportation corridors throughout the fan area.

- **BC Hydro Cheekye sub-station.** This facility is used by a small workforce which is not located on-site most of the day. Therefore, the probability that these workers will be at the sub-station when the debris flow occurs is likely very low. The sub-station is an important, expensive facility in BC Hydro's system and it could be argued that it is up to BC

Hydro to determine if the risk of loss or damage to the sub-station in Zone 2 outweighs the cost of relocation.

- **Outdoor recreation (not including any hotel or residential development).** Crown land in the fan area is the subject of development interest for golf course use and there could be other outdoor recreation potential as well. A golf course involves a significant capital investment usually by a single corporate entity, which is presumably sophisticated in making land investment decisions. From the point of view of golfers or other outdoor recreationists, an individual is likely to spend a relatively small amount of time in the area only occasionally, thereby reducing the probability that an individual person would be in the area when the debris flow occurs.

    In Zone 1, using the PDI of 1:160 for a full time resident and assuming a golfer is in Zone 1 twenty days in one year for eight hours per day, the PDI for a golfer would be 1:8,760. This value, if it is correct, suggests that golf course development in parts of Zone 1 would not be appropriate. In Zone 2, using the same assumptions and the full time resident PDI of 1:900; PDI is 1:49,275 for a golfer. This value suggests that a golf course (but not necessarily associated hotel or residential use) would be an acceptable use in Zone 2.

For these types of land uses, municipal land use regulations need not be as restrictive because the probability of death to an individual is likely very low. Also, these types of uses involve investment decisions made by relatively large organizations, (e.g. Ministry of Highways, BC Hydro, golf course developer) which are presumably able to evaluate the costs and benefits of the alternatives available to them.

9.3.5   Conclusions Regarding the Two Approaches

The review of the two approaches supports these conclusions:

1. The Fraser-Cheam approach, which relies on probability of hazard, is well-thought out, tested, internally consistent and readily applicable to residential uses in other areas with similar potential exposure to hazard.

2. The Fraser-Cheam approach could reasonably be applied to other urban uses that combine relatively intensive improvements and continuous human occupancy by the same group of people (e.g. employees, students, patients), such as commercial, industrial, and some institutional uses.

    If the objective of land use regulation is to minimize the likelihood of significant property damage and to minimize the likelihood that some people would be hurt

or killed, the Fraser-Cheam approach can be applied, with few modifications, for all habitable uses.

3.   The probability of hazard approach may not be particularly well-suited to the following kinds of circumstances:

- uses which have no alternative locations and, in any case, are occupied infrequently or only short-times by individuals (e.g. a highway corridor).

- uses which, while valuable, have limited human occupancy and are owned by knowledgeable, sophisticated owners who must balance the risks of locating in (or remaining in) a hazard area against the costs of choosing an alternative site (or cost of relocating). The Hydro substation is a good example.

- location in which the probability of hazard may be high but (due to factors such as severity, rapidity, and physical features) the risks of significant property damage or injury or death are much lower.

- uses which involve infrequent, brief occupancy by specific individuals, such as outdoor recreation and some facilities (e.g. landfill).

4.   Using either approach, there are clear general implications for land use in the study area:

- new habitable uses should not be approved in Zones 1 and 2.

- Zone 3 should have some restrictions on new habitable uses, but maintenance of existing uses and some new uses are acceptable provided the appropriate measures are taken.

- Zone 4 is acceptable for existing and new uses, provided appropriate measures are taken.

9.5   The Effects of Mitigation Works on Land Use

The comments on land uses in the Cheekye Fan in the previous section were made in the absence of a mitigation program. The geotechnical study has looked at three mitigation scenarios (see Section 8.6)[5]. The mitigation scenarios, as shown in Figures 8.6, 8.7, and 8.8, appear to limit the risk of the natural hazard on portions of the fan which are particularly sensitive from a land use planning perspective (i.e. existing developed areas). However, this reduction of risk for some parts of the fan is achieved at the cost of

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5   It is important to note that there are many alternative approaches to mitigation, which could be categorized as cautionary, regulatory, or physical. Cautionary mitigation involves full disclosure of information and provision of warning systems. Regulatory mitigation involves limiting future concern via restrictive or conditional approvals. Physical mitigation involves

elevating the risk for other parts of the fan because a substantial dyking program could alter the geographic distribution of hazard zones. It is essential, therefore, that there be a cost/benefit analysis of mitigation alternatives before one mitigation approach is selected.

It is clear from the analysis that several mitigation approaches are possible on the Cheekye Fan and that so far it is not possible to state which approach is best. All realistic mitigation approaches need to be identified and then evaluated on the basis of:

- the actual cost of works and land acquisition and who pays these costs.

- the costs to properties which have their exposure to the hazard increased.

- the benefits to properties which have their exposure to the hazard decreased.

A mitigation approach which reduces the impacts to existing developed areas in Brackendale and vacant lands in the southern part of the Cheekye fan area and increases impacts on some lands in the northern part of the fan where there are few existing uses and less potential for development, is probably preferable from the perspective of the community.

9.6   Key Planning Issues

Up to this point, Section 9 has examined existing land use and ownership in the study area, employed two different approaches to broadly describe the land use implications of the geotechnical analysis, and touched on the complexities of the dyking approach to mitigation.

The work carried out in the current study is sufficient to identify six critical planning issues that the District of Squamish and the Provincial Government are facing on the Cheekye Fan. These issues are summarized below and are addressed in Sections 9.7, 9.8 and 9.9.

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dyking or relocation. The geotechnical anlaysis has focused on warning and dyking. There are potentially many different dyking scenarios and the geotechnical anlaysis has selected three to illustrate the range of possibilities.

Issue 1

As shown in Figure 9.3, the Cheekye Fan can be roughly divided into five areas, based on the probability of hazard and the impacts of the dyking alternatives considered:

Area A: This area appears to be a high risk location for any habitable uses, even if mitigation works are constructed. Development and land use in this area should clearly be extremely limited.

Area B: This is a relatively large area of mostly Crown Land that appears to be, in all cases, not suitable for habitable uses but potentially suitable for outdoor recreation, such as golf, horse-riding, or tennis, based on the PDI approach. Some of the land in Area B is in hazard Zone 1, but could be appropriate for recreation developments such as golf because of low PDI and because Area B is at the "outer edge" of Zone 1, within which there is a gradation of risk.

Area C: This is a large portion of Brackendale which is in Zone 4. In this zone land use controls do not have to be overly restrictive but mechanisms are necessary to limit liability and reduce exposure to hazards in the absence of any mitigation works. This is likely to be the key area to be protected by any significant mitigation program. Thus, development in this area can proceed provided that appropriate measures have been taken to minimize liability and reduce exposure (e.g., siting, protective works, flood protection or floodproofing).

Area D: This is a large part of the study area which is heavily constrained by the hazard in the absence of mitigation works. Depending on the design and siting of mitigation works, some portions of this area are made better off and some portions are made worse off. As a result, land use planning in this area (other than on an interim basis) is not really possible until a mitigation strategy is adopted. For this reason, the boundary between Area B and Area D is only approximately defined at this stage.

Area E: This area is affected at least as much by floodplain considerations as by the Cheekye Fan hazard.

Issue 2

It is clear that some portions of the study will require zoning that is highly restrictive and allows no habitable uses. This raises legal questions about zoning private lands for extremely limited use. These questions are addressed in Section 9.9.

Issue 3

Portions of the study area (if the Fraser-Cheam approach is used), depending on the siting/design of mitigation works, will be appropriate for the continuation of existing uses and the approval of new habitable uses, provided that appropriate measures are taken to limit the liability of approving authorities and of any public sector vendors of land. These measures must be well-thought out and based on consideration of the legal ramifications.

Issue 4

The selection of the hazard probability approach versus the probability of death approach will depend on many factors, including the specific uses, the reliability of the analysis, public perception, and law. For some uses, the probability of hazard approach is probably most appropriate, given that it measures the likelihood that some property or some people within the zone will be exposed to the hazard. For other uses it may be more appropriate to regulate based on the actual likelihood of death of specific individuals or groups, as this is consistent with how people relate to other risks they face in daily life.

Issue 5

Many approaches are possible to reduce exposure and to mitigate the impacts of a debris flow on the Cheekye Fan. All realistic mitigation approaches need to be identified and then evaluated on the basis of:

- the authority of the Municipality or Province to construct the works in the required locations.

- the actual cost of works (and land acquisition) and who pays these costs.

- the costs to properties which have their exposure to the hazard increased.

- the benefits to properties which have their exposure to the hazard decreased.

A preferred mitigation approach needs to be selected, designed, and an implementation program developed. A mitigation approach which broadens the portion of Brackendale which could be developed may be preferable, but this type of mitigation approach would probably increase the exposure of some areas farther north.

Issue 6

There are some existing buildings and facilities in parts of the Cheekye Fan that require decisions about how best to respond to the hazard:

- B.C. Hydro will have to consider if the risk of loss or damage to its facilities and staff at its Cheekye sub-station outweighs the cost of relocation.

- the Howe Sound School District will have to examine the issue of the Brackendale Secondary School's lifespan, the need for expansion, and the availability and costs of alternatives to house the students. This situation also applies to the nearby church.

- the District of Squamish may want to consider the costs and benefits of retaining its facilities on the fan (i.e. landfill, reservoir, airport).

9.7   The Regulatory and Mitigation Response

Having identified the key planning and land use issues arising from what has been learned about the Cheekye Fan hazard, the next step is to outline the possible and appropriate responses by the agencies with the main responsibility for regulating land use and development.

This section draws on three main sources in order to outline the regulatory and mitigation response that is warranted by the situation. The sources are:

- the work of the geotechnical and planning team.

- the regulatory framework used by the Fraser-Cheam Regional District.

- a legal review[6].

This section provides guidelines for the Municipality and the provincial government regarding land use regulation, mitigation, and land sales.

The following subsections address these points:

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6   The legal review was commissioned by the land use planning subconsultants, Coriolis Consulting Corp., who identified the specific issues to be addressed. The review was prepared by Lidstone, Young, Anderson (Barristers and Solicitors), who specialize in municipal law and is appended as Section 9.9.

- use of the hazard probability versus the probability of death approach.

- the extent of the obligation to do anything.

- issues associated with adopting a mitigation strategy.

- tools and approaches available to the Municipality to regulate land use and development and to limit liability, before and after completion of a mitigation program.

- dealing with existing uses with significant hazard exposure.

- selling municipal or provincial land with hazard exposure.

9.7.1   Probability of Hazard versus Probability of Death

The legal review concludes that the essential test is the reasonableness of the policy and regulatory response.

There are no laws or precedents which define a probability threshold at which regulatory or mitigation responses are required, or laws which dictate how a risk to property or life should be measured.

The lawyers note that the probability of death approach could be justified if it produces a more reasonable (based on factors such as cost-effectiveness or best interest of the community) policy or regulatory framework in some circumstances.

It may be that the best approach is to start with a "base" of hazard probability (because it is more conservative) and use probability of death to fine-tune the regulatory response for specific uses or specific sites. Insofar as this would be using defensible engineering analysis to make reasonable decisions about land use, it should be a supportable approach, especially for non-habitable land uses such as outdoor recreation, airport, substations, and transportation corridors.

9.7.2   The Obligation to Act

The legal review indicates that the regulatory agencies at a minimum have an obligation to warn those potentially at risk. There also appears to be an obligation to seriously

consider the implications and the policy alternatives before adopting a policy to either do something (e.g. mitigate) or do nothing (other than issue warning).

The lawyers suggest that a good-faith policy decision to not proceed with mitigation (say for reasons such as comparatively low risk, high cost, or imprecise knowledge) could withstand a charge of negligence, whereas inaction resulting from a failure to consider the available options could result in liability.

9.7.3   Issues Associated with Adopting a Mitigation Strategy

The work to date indicates that there is not a single mitigation solution. There are several alternatives, which differ in terms of cost, effectiveness and distribution of positive and negative impacts.

Selecting the preferred approach will clearly require a cost-benefit analysis which analyzes the benefits conferred on properties that have reduced exposure, the cost of the works, and the costs imposed on properties that have increased exposure. (It appears that there is not a mitigation solution which leaves all properties with the same or lower exposure; some properties necessarily have higher exposure or greater severity of hazard after mitigation works are in place).

The implementation of mitigation works raises several issues:

- who has the authority to construct the works? The legal review indicates that there are several mechanisms by which the Province or local government could have the authority to construct works.

- who pays? This depends on the mechanism that is used. The creation of a local dyking authority would use property taxes on benefitting properties to pay for land acquisition and dyke construction. A provincial dyking authority could charge the municipality for the works (in the form of a debt). Alternatively, the Province could absorb the costs.

- what liabilities would be involved? If the dyking system (intentionally but reasonably) makes some properties suffer an increased exposure to hazard, there may be an obligation (legally or from a sense of fairness) to compensate. There could also be a risk of liability if the siting or design of mitigation works result in

inadvertent, unanticipated damage to properties (for example, through incorrect design or location).

9.7.4   The Municipal Regulation of Land Use and Development

Municipal land use policy and regulations in the study area will have to evolve: <u>there is a need for an immediate response to regulate land use and development prior to any mitigation works and then subsequent adaptation if mitigation works are constructed</u>.

The principal tools the Municipality can use to regulate land use and development in the study area are:

- Official Community Plan

- Zoning Bylaw

- Development Permits

- Development Approval Processes and Procedures and Other Regulations

Official Community Plan

Section 945 (2)(d) of the <u>Municipal Act</u> states that a community plan must include statements respecting "restrictions on the use of land that is subject to hazardous conditions or that is environmentally sensitive to development". An OCP should contain general policy statements on the use of land in areas with natural hazards and should state how the Municipality intends to control land use in these areas (e.g. through zoning regulations, development permits, flood-proofing requirements). Specifically, the OCP can designate areas subject to hazard for uses that are appropriate to the hazard and the OCP can designate Development Permit Areas where land is at risk.

Zoning Bylaw

Zoning is viewed as more of a supplementary tool for regulating land uses in areas exposed to natural hazards because zoning is not very amendable to site-specific regulation. However, zoning designates permitted land uses and densities and should "... reflect the geotechnical realities of the land" (Cave, 1992).

Section 969 of the Municipal Act provides for the designation of floodplains and for the specification of construction levels and setbacks (by order of the Minister of Environment, Lands and Parks or by local government bylaw).

The municipality can also use its zoning power to zone land for only those uses which do not present a significant risk of property loss, injury or death due to the natural hazard. Zoning can exclude any habitable development but, in order to avoid a claim for compensation, some economic use must be allowable on the land. The legal review notes that lands severely affected by the hazard could possibly be designated for only silviculture or limited outdoor recreation use, although the legal implications of highly restrictive zoning will have to be considered when specific zoning proposals are developed.

Development Permit Areas

Section 945 (4)(b) of the Municipal Act provides for the use of development permits in OCPs to "... designate areas for the protection of development from hazardous conditions". Section 976(1) requires a development permit before subdivision, building alteration or addition, or alteration of land is allowed (although some exemptions may be allowed).

The OCP must "... describe the special conditions or objectives that justify the designation" (Section 945(4)(f)) and specify guidelines stating how these conditions will be alleviated (Section 945(4)(g)).

Development permits are a very useful tool in dealing with natural hazards because they allow the varying of land uses and densities (as they relate to health, safety or protection of property from damage), the maintenance and enhancement of natural drainage, and the planting or retention of trees and vegetation.

Before issuing a development permit, the Municipality may require a geotechnical report paid for by the applicant to assist in determining what conditions or requirements will be imposed in the permit related to land use and density (Section 976(8)).

Development Approval Processes and Procedures and Other Regulations

The OCP, zoning bylaw, and development permit are legislative tools which can be used by local government to designate policies for the use of land in areas of potential natural hazards. Once this policy framework is in place, the process of development approval is essentially a technical process. According to Cave (1992):

> "The aim is to implement the regulations so as to ensure that new development is "safe" (i.e. exposed to lower levels of risk than the acceptable thresholds) and to ensure, so far as possible, that the local government will not be held liable in negligence or for inadequate duty of care in the event of damage, injury or loss of life" (p. 10).

There are five approval instruments and the process of approving most new developments will usually involve most of these instruments (Cave, 1992) namely:

- rezoning bylaws

- subdivision approvals

- development permits

- building permits

- covenants

In the case of rezoning, subdivision, and development permit applications, the municipality should ensure that all applications are considered in the light of adopted policy about the hazard and the body of knowledge that has been assembled about the hazard. It would be reasonable to require that any proposal for use or development that differs significantly from adopted policy must be accompanied by geotechnical analysis that confirms the safety of the use and identifies any necessary conditions.

The Land Title Act gives the Approving Officer the authority to refuse to approve a subdivision plan if the land is subject to natural hazard and also requires the approval of the Minister of Environment in certain instances. A standard Ministry requirement for alluvial fan flood hazard areas is that mitigative works to protect against a 1:200 year flood hazard plus a maintenance agreement with a local authority must be in place before subdivisions can be approved. In hazard areas, the officer can require geotechnical

analysis and can impose conditions that must be met prior to approval of a subdivision. Conditions can be imposed in the form of covenants registered on a title.

The Municipal Act enables the Building Inspector to require that, on sites subject to natural hazards, the owner of the land must provide a report certified by a geotechnical engineer that the land is safe for the proposed development. If the use is safe, the Inspector can then issue a permit on the condition that the owner enter into a covenant that obligates adherence to the engineer's requirements for siting, design, or fill.

The Municipality also has some ability to regulate tree cutting, but this may not be of much concern in the lower portions of the Cheekye Fan. There may be advantages to regulating tree cutting in upper areas, if limitations on tree cutting can be shown to reduce the probability or severity of flooding or debris flows. Site specific analysis would be required to identify locations where regulation of tree cutting would have a positive effect.

9.7.5   Dealing With Existing Uses

The study area contains many publicly and privately owned improved properties. These existing uses are, to varying degrees, exposed to the risk of the hazard and so each requires a response.

As already stated, there appears to be an obligation to advise all affected parties of the knowledge now available about the hazard.

Existing private uses can remain in the study area, provided that the Municipality acts appropriately with regard to all future applications for approval to repair, renovate, or expand existing structures. As already discussed, some of these applications must be denied and some can be approved if the municipality is adequately insulated from liability. As indicated in the legal review (Section 9.9), covenants provide a potential method of limiting municipal liability, although Section 9.9 also indicates that this approach is not without pitfalls.

The public uses require a different kind of response. Once informed about the hazard, people can make their own choice about continuing to live in the area but they have less choice in matters such as sending children to school or using transportation facilities.

Each public use will require a careful analysis of alternatives. In the case of an existing school, for example, the alternatives may be to immediately close the existing school and build a new one, to maintain the existing school without making improvements that extend its life and then build a new one in the future, or accept the risk.

The factors to be considered in evaluating these alternatives include:

- the remaining usable life of the facility.

- the degree of risk (considering both the potential damage to the facility and the risk of injury or death).

- the potential for site-specific or area-wide mitigation.

- the availability of funds for new construction.

- the attitude of the community.

- the availability and acceptability of alternative sites.

In the case of a school, presumably the School District must conduct this type of assessment. In the case of a municipal facility (e.g. airport, landfill, reservoir, cemetery), Squamish must conduct a similar assessment. BC Hydro, BC Rail, and the Ministry of Transportation and Highways are other agencies with substantial investments in the study area; each of these agencies must identify and evaluate its alternatives and act accordingly. For most of these, the Municipality is only directly involved if an application is made to renovate or expand an existing use.

9.7.6   Selling Publicly Owned Lands

The Provincial Government and the Municipality own lands in the study area that they may wish to sell. The legal review suggests that the owner should make full disclosure of the nature of the hazard before entering into a contract of sale and thereby absolve itself of liability.

9.8   Outline of a Municipal Regulatory Approach for the Cheekye Fan.

Figure 9.3 suggests that the study area can be divided into 5 broad areas based on the exposure to hazard before and after mitigation. The figure shows that some portions of the study will not be appropriate for habitable use under any circumstances, some are appropriate (with conditions) at present and (with fewer conditions) after mitigation, and some cannot be considered for habitable use now, but could be after mitigation works are constructed.

This final section on planning is intended to <u>outline</u> a municipal regulatory approach that appears reasonable based on the nature and extent of the hazard, the legal review, and the characteristics of the study area. Because mitigation works will alter exposure to risk, this outline of a regulatory approach is keyed to the hazard zones, not to specific sites. For example, the outline suggests an approach for lands in Zone 3. If a site is in Zone 3, it should be regulated accordingly. If mitigation improves the site's hazard rating to Zone 4, the site should be regulated in accordance with Zone 4.

The outline is presented in Table 9.1. Note that Zone 5 is not included because this Zone is influenced more by floodplain considerations than by the geotechnical hazard.

This outline is intended to suggest the general approach to land use planning and development regulation that is warranted based on the analysis of hazards in the study area. The outline makes it clear that significant effort is required to draft new OCP policies and zoning regulations, to draft sound covenants that will maximize the Municipality's protection from liability, to draft Development Permit guidelines, and to adopt new development approval procedures.

9.9   Legal Review by Lidstone, Young, Anderson

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PRIVILEGED AND CONFIDENTIAL

By Courier

January 29, 1993

Mr. Jay Wollenberg
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Dear Mr. Wollenberg:

Re: Province of British Columbia ("Province") - District of Squamish ("District") -
Cheekeye River Hazards
Our File No. 13,356

1.   Your Request And Scope Of This Letter

You have asked us to discuss in general terms a variety of legal issues relating to hazardous conditions potentially affecting the Cheekeye River fan. This letter is not a legal opinion. It merely addresses in necessarily general terms some of the legal questions which may arise out of possible geotechnical hazards in the Cheekeye River fan, the details of which we are not aware. It will be necessary for the District and the Province, on whose behalf you have engaged us, to seek legal advice regarding any proposed actions. Further, this letter may not be relied upon in even general background terms by anyone other than the Province or the District. It is the responsibility of other persons to obtain legal advice as well.

2.   Background

We understand that a steering committee comprised of representatives from the Province and the District has commissioned a geotechnical study of certain potentially hazardous conditions around the District. At our meeting of January 15, 1993 - which was attended by you, Donald Lidstone and the writer - you outlined for us in general terms the nature

of the risks which the geotechnical report indicates are involved. We understand there is a risk that part of a mountainside around the District may collapse into the Cheekeye River, causing mechanical damage to land and structures and (possibly) flooding and debris-torrents.

3. Discussion

This section discusses generally the various issues you have raised at our meeting and in our subsequent telephone conversations.

3.1 What are the legal consequences of using the District's official community plan ("OCP"), development permit regulations and zoning restrictions in order to protect life and property?

The District may use its powers under Part 29 of the *Municipal Act*, R.S.B.C. 1979, c. 290, to adopt appropriate protective measures through its OCP and its zoning bylaws. These land use regulatory powers can be used selectively. According to the degree of risk, the District may choose to control development through development permits, or to use its zoning powers to ensure that only appropriate land uses are undertaken in areas at risk. The District's building inspector also has useful powers under s. 734 of the *Municipal Act*. The District's approving officer also has an independent power under the *Land Title Act*, R.S.B.C. 1979, c. 219, to refuse subdivision approval in hazard areas.

(a) OCP And Other Designations

Section 945(2)(d) of the *Municipal Act* clearly *requires* local governments to include in their OCP "statements and map designations" regarding "restrictions on the use of land that is subject to hazardous conditions or that is environmentally sensitive to development". Section 945(4) in turn provides that an OCP *may*, for the purposes of the development permit powers under s. 976, "designate areas for the protection of development from hazardous conditions". The District could therefore use its OCP to designate development permit areas where land is at risk. This would in turn permit the District to impose development permit conditions designed to protect development from hazards.

We should note that there may be an argument that s. 945 of the *Municipal Act*, which requires OCP designation of areas that are subject to hazardous conditions - and the setting out of "restrictions" on land use in those areas - in turn imposes a duty to adopt development permit guidelines under s. 945(4). This is despite the fact that the latter subsection says that a local government "may" adopt such designations. A court might find that despite the use of the word "may", the intent of ss. 945(2) and (4) was to impose a *duty* to adopt such conditions. It is noteworthy in this regard that s. 945(2) *requires* the District to designate "restrictions on the use of land" subject to hazards. A court might find that s. 945(4) should be read as mandatory, since it can be said that OCP "restrictions" under s. 945(2) have, of themselves, little if any practical effect. Only through s. 945(4) and the other development permit powers can the protection supposedly contemplated by s. 945(2)

be achieved. We believe this argument is likely to fail, so that there is not, in fact an obligation to adopt development permit regulations under s. 945(2). However, this is an argument which could be made. Even if we are correct, of course, the District still must comply with s. 945(2) in respect of its OCP and impose restrictions on use of land which the District's Council considers is subject to hazardous conditions.

Even if the District adopted development permit guidelines and conditions under s. 945(4), we think a court would likely not hold the District liable for loss if those development conditions were wrong or inadequate. Adoption of such measures is arguably a policy choice and a legislative act, a factor which could protect the District from liability. See *Just* v. *British Columbia*, [1990] 1 W.W.R. 385 (S.C.C.); *Welbridge Holdings Ltd.* v. *Metro. Corp. of Winnipeg*, [1972] 3 W.W.R. 433 (S.C.C.); and *Bowen* v. *City of Edmonton (No. 2)* (1978), 3 M.P.L.R. 129 (Alta. S.C.).

To the extent it has not already been done in the risk areas, the District could also designate areas as flood plain under s. 969 of the *Municipal Act*, with the cooperation of the Minister of Environment, Land and Parks ("MOE"). This would allow the District to specify construction setbacks and minimum elevations. These approaches would be useful only where there is some assurance that sufficient protection can be obtained through permit conditions.

(b)   Zoning

Where the risk is considered to be too great to permit development for residential or intensive commercial uses, for example, the District may wish to use its zoning powers to zone land for uses which do not present as great a risk of property loss or loss of life. To do that validly, the District would have to be certain that it did not sterilize the rezoned land from any economic use, or limit it to a use for a public purpose. Either of those results could expose the District to liability to compensate and would almost certainly be an invalid rezoning. Liability to compensate in such cases is contemplated by s. 972 of the *Municipal Act*, which reads as follows:

> (1)   Compensation is not payable to any person for any reduction in the value of that person's interest in land, or for any loss or damages that result from the adoption of an official community plan, a rural land use bylaw or a bylaw under this Division or the issue of a permit under Division (5).

> (2)   Subsection (1) does not apply where the rural land use bylaw or bylaw under this Division restricts the use of land to a public use.

If a court found that the protective rezoning was intended to protect against loss to the public generally, it might find that this fell under subsection (2).

Accordingly, in order to avoid any claim for compensation, the District would have to ensure that some economic use could be still be made of the land. For example, the land could be zoned for certain types of agriculture or for silviculture. (There is, however, some

doubt that agriculture involving the growing of crops - as opposed to feed lots and so on - is a land use which may be regulated by zoning. The same may be said of silviculture. See *Twp. of Pickering* v. *Godfrey*, [1958] O.R. 429 (Ont. C.A.).) Land could also be zoned for recreational use (including golf courses), bulk storage of goods (*e.g.*, logs) or allotment gardens.

The particular uses which may be available will have to be examined later in the process. At present we note simply that certain rezoning options may be available to enable adoption of protective zoning. It will also be necessary later in the process to assess whether a particular use entails a degree of human presence or investment which is unacceptable given the risk in that area. In other words, zoning would have to be applied to permit uses compatible with the risks at hand, which may vary. As always, of course, the duty to warn alluded to below will always have to be discharged; quiet re-zoning alone cannot protect the District.

(c)   Building Permit Powers

Section 734(2) of the *Municipal Act* gives the District certain powers during the building permit process, provided the District has a building bylaw in force at the relevant time. Section 734(2) reads as follows:

> Where a building inspector considers that construction would be on land that is subject to or is likely to be subject to flooding, mud flows, debris flows, debris torrents, erosion, land slip, rockfalls, subsidence or avalanche, he may require the owner of the land to provide him with a report certified by a professional engineer with experience in geotechnical engineering that the land may be used safely for the use intended.

Section 734(2.1) defines "construction" in s. 734(2) as meaning "new construction of a building or structure, or the structural alteration of or addition to an existing building or structure", but as excluding "repair of an existing building or structure". This gives the District considerable scope to deal with existing buildings and structures, *i.e.*, in all but repair cases.

If a geotechnical engineer determines that land may not be used safely for the purpose intended, the building inspector must refuse to issue a building permit. There is no discretion to do otherwise. On the other hand, if the engineer determines and certifies that the land may be used safely for the intended purpose, the building inspector may issue a building permit on the condition that the landowner enters into a covenant with the District that the engineer's conditions relating to siting, design, fill and so on will be implemented.

Such a covenant must also contain conditions for reimbursement of the District for expenses incurred by it through breach of the covenant conditions. Such a covenant may include a release and indemnity in favour of the District. The indemnity may - although it is not absolutely certain - bind successor landowners under s. 215 of the *Land Title Act*. The covenant must be registered against title to the land, which is a considerable advantage to the District.

The District's Council may, under s. 734(6), override the building inspector and direct him or her to issue a building permit if it is refused, but only on the condition that a covenant as described above be entered into and registered.

(d)   Other Cases Where Covenants May Be Useful

Land use covenants under s. 215 of the *Land Title Act* - which are sometimes referred to as "save harmless covenants" - may be useful in a variety of circumstances to regulate land use in order to minimize exposure or protect against hazards. They may also in certain circumstances be useful to hold harmless the District or the Province.

For example, a covenant under s. 734 of the *Municipal Act*, discussed above, can be used only in cases where there is new construction, an addition to or structural alteration of a building or structure. Where, for example, a home owner simply wishes to obtain a building permit in order to repair his or her home, a s. 734 covenant requirement will not be available. Further, there may be cases where s. 734 is technically applicable, but the expense and delay involved in obtaining a geotechnical report - much less in carrying out protective works - may in the District's view be too onerous. In such circumstances, the building inspector may decide not to require a geotechnical report under s. 734(2). This raises the question of what protections may be available to the District in the alternative.

It may be possible for the District to protect itself to some degree in such cases by requiring the landowner to grant a s. 215 covenant to the District. Strictly speaking, the District could not force the landowner to grant such a covenant as a condition of issuing the building permit unless the formal procedure of s. 734 were available or enforced. Nonetheless, if a landowner is willing to grant such a covenant, the District could require the landowner to use the land only in accordance with the covenant and to release the District from any loss the landowner might suffer because he or she has chosen to continue using or occupying land which is acknowledged to be at risk.

Section 215 of the *Land Title Act* permits covenants under that section to include indemnities in favour of the local government receiving the covenant. We should note that there is some question as to whether a covenant of this kind - are designed only to get an indemnity on title is truly a covenant governing *land use* under s. 215. It may therefore be invalid in the first place. We should also note that there is a further question as to whether a release by the landowner in favour of the local government is truly an indemnity

which runs with title to the land under s. 215. These are issues that will have to be examined in the particular circumstances of each case, since it may be possible to draft a s. 215 covenant so as to meet these concerns, depending on the facts. It is clear at this stage that such covenants cannot be regarded as a panacea.

Section 215 covenants may also be useful as a backstop to development permits issued under the *Municipal Act*. We should note, however, that the *Municipal Act* provides for registration of notice of a development permit on title to land subject to the permit. The Land Title Office has in the past taken the position that a s. 215 covenant which essentially duplicates a development permit is not to be registered against title to the land. This is something that will also have to be revisited in more concrete circumstances, since we think there are good arguments that, regardless of the attitude of the Land Title Office, s. 215 contemplates registration of such covenants. Indeed, we think that a s. 215 covenant could be a useful adjunct to a development permit and is worth serious consideration in each case.

3.2   What authority is there for the Province or the District to undertake dyking and other works and how would such works be paid for?

There are several means by which flood and debris-torrent control works could be undertaken. The Province could undertake such works through the MOE, using the authority provided in the *Environment Management Act*, S.B.C. 1981, c. 14. Protective works could also be undertaken through the *Drainage, Ditch and Dyke Act*, R.S.B.C. 1979, c. 98, the *Dyking Authority Act*, R.S.B.C. 1979, c. 100, or under Part 13 of the *Municipal Act*.

The MOE has the authority under the *Environment Management Act* to manage, protect and enhance the environment through, among other things, the "planning, design, construction, operation and maintenance works and undertakings for the management, protection or enhancement of the environment." The Province could therefore use its powers under the *Environment Management Act* to build suitable works to protect against or mitigate the risks at hand.

In addition, the *Drainage, Ditch and Dyke Act* could be used to create a new dyking district, which could construct a dyke and levy property taxes on land in the dyking district for that purpose. (We should note that the repeal of Part 2 of that Act, which is the relevant part, is pending). The *Dyking Authority Act* would allow the British Columbia Dyking Authority to construct such works for any municipality, or for the Province by agreement with it.

The District has certain limited powers under Part 13 of the *Municipal Act* in relation to construction of dykes and related works which may be of use in some cases.

To summarize, the above-noted statutes offer a variety of avenues for construction of the appropriate protective works. The various tools available differ as to which level of government assumes the responsibility for and control over construction of such works. They also differ as regards which level of government must pay for those works.

If protective works are undertaken on Crown land or District land, direct land acquisition costs are not an issue (apart from the cost inherent in the loss of those lands to the Crown or the District and apart from compensation which may be payable to any forest or other resource tenure holders). If private land is required for construction of the control works, it will be necessary to purchase it at fair market value or expropriate it at that value. Moreover, if private land adjacent to such works, but not expropriated for them, is injuriously affected by the works themselves, compensation may be payable to those landowners under s. 40 of the *Expropriation Act*. S.B.C. 1987, c. 23, s. 544 of the *Municipal Act* or, in some cases, the law of public nuisance. This leads us to the next issue.

3.3 What liability is there toward landowners whose properties may be worse off as a result of construction of flood protection works?

We understand that construction of flood protection works may expose some land to greater loss, while affording greater protection for the area in the aggregate. You have asked what can be done about this. Is compensation payable to landowners in such a position?

(a) No Liability Without A Loss

Compensation will not be payable to landowners whose land is deleteriously affected in this way unless they can prove, on the balance of probabilities, that (a) they have suffered a loss (caused by the protection works and not as an inevitable consequence of the flood), and (b) the District or the Province are liable for that loss based on some recognized principle of legal liability. It may be possible to establish that such a loss has occurred because of construction of the works, *i.e.*, because the present market value of the land has thereby been diminished by the perceived increase in risk resulting from that work being done. Conversely, there may be no such present loss, but a loss might be suffered if the predicted event occurs.

The first element - the need to prove a loss - is relevant because there is no liability to compensate anyone until they have actually suffered a loss. The fact that studies predict that some properties may be exposed to greater risk than before does not of itself cause that loss to the owners. It may be that the properties will not suffer actual loss in any flood and, until the predicted loss is actually suffered, there can be no liability in law. It may be, however, that a landowner will assert a claim now, on the ground that the market has discounted his or her property's value because of the property's predicted exposure to loss. This loss could be characterized as "injurious affection". If this alleged loss of value can be substantiated, the landowner is not necessarily any closer to imposing liability for that loss on government.

This is because infliction of a loss does not of itself render a person liable to pay damages. In addition to the fact of the loss, the second element noted above must be present; *i.e.*, there must be a legal principle which imposes liability to pay for the loss. We turn to this issue now.

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(b)   Possible Grounds Of Liability

The fact that we are at present necessarily operating in a factual vacuum means that we express any opinion on the actual exposure to liability of the District or the Province for such losses. We can, however, make the following general observations about principles of legal liability. The principles of negligence, nuisance, the doctrine in the case of *Rylands* v. *Fletcher* and expropriation law are relevant here.

Negligence

We assume from your question that it is not technically or economically feasible (or both) to protect all properties equally, or at all. In undertaking the planning, design and construction of protection works, we assume, government would seek to maximize the aggregate benefits to be achieved within the technical and economic constraints. Canadian law does not as yet counsel perfection from our governments. Our courts will not impose liability on government where the loss complained of was suffered as a result of a good faith policy decision. If a policy decision is taken and loss is suffered, the government will not be liable.

There are two important observations which flow from this. First, immunity from negligence liability depends on the court accepting that the decision in question is truly a policy choice. If the court concludes that the loss was suffered because of government negligence at the operational level, and not as a result of a policy choice, liability will follow. Operational matters are those which involve implementation of policy, *i.e.*, the putting into operation of government programmes and activities. It is not possible to catalogue all policy decisions, but they are generally characterized as high level decisions in which budgetary and social issues are accounted for. In *Just*, above, Cory J. quoted with approval the following passage from the decision of Mason J., of the High Court of Australia, in *Sutherland Shire Council* v. *Heyman* (1985), 60 A.L.R. 1, at pp. 34 -35:

> The distinction between policy and operational factors is not easy to formulate, but the dividing line between them will be observed if we recognize that *a public authority is under no duty of care in relation to decisions which involve or are dictated by financial, economic, social or political factors or constraints.* Thus budgetary allocations and the constraints which they entail in terms of allocation of resources cannot be made the subject of a duty of care. *But it may be otherwise when the courts are called upon to apply a standard of care to action or inaction that is merely the product of administrative direction, expert or professional opinion, technical standards or general standards of reasonableness.* [emphasis added by Cory J.]

At p. 402 of *Just*, Cory J. noted that "[t]he dividing line between 'policy' and 'operation' is difficult to draw". At p. 406 of *Just*, Cory J. said the following:

> In determining what constitutes such a policy decision, it should be borne in mind that such decisions are generally made by persons of a high level of authority in the agency, but may also properly be made by persons of a lower level of authority. The characterization of such a decision rests on the nature of the decision and not on the identity of the actors. As a general rule, decisions concerning budgetary allotments for departments or government agencies will be classified as policy decisions.

Our second observation here stems from statements in *Just* and in other decisions - such as *Laurentide Motels Ltd.* v. *Ville de Beauport* (1989), 45 M.P.L.R. (S.C.C.) - which leave some scope for court review of policy decisions. It has been intimated that if a court concludes that a policy decision was not *bona fide*, or reasonable, the decision may be open to review and form the basis for government liability. See Cory J. in *Just*, above, at p. 406. There are also indications in the judgement of Wilson J. in *Kamloops* v. *Nielsen* (1984), 26 M.P.L.R. 81 (S.C.C.), at p. 104, that "inaction for no reason or inaction for an improper reason cannot be a policy decision taken in the *bona fide* exercise of discretion". These comments may be used to impose liability here if a government failed to do anything if for no reason *i.e.*, without at least considering action or inaction as a policy choice.

In this case, a government's decision not to construct flood works - or to construct them in a particular way knowing that the possible or likely result would be greater exposure of some properties - could well be characterized as a policy decision and therefore not a source of liability in negligence. Bearing in mind what Cory J. said in *Just*, above, about the nature of such decisions, this characterization would be more likely if the decision were taken at a very high, political level (*e.g.*, by District Council or the Provincial Cabinet) and if it were expressly (and truly) based on budgetary and other public interest considerations. This is an issue which must be re-visited further, when the options are, so to speak, more concrete.

Again, the decision not to undertake protective works - or to undertake works knowing they will increase the risk for some properties - *may* be an immune policy decision. However, if the design and construction of the works is done *negligently* and causes loss to someone, that operational failure is likely to render the government responsible liable, depending on the facts. Only the policy decision to do the work or not, based on *bona fide* policy reasons, is likely to be protected from judicial interference.

Liability For Nuisance And Similar Defaults

There are other liability principles which may apply in addition to the principles of negligence. Canadian law may impose liability in damages for nuisance or, perhaps, based on the rule in the case of *Rylands* v. *Fletcher*.

The former principle imposes liability where a person uses his or her land unreasonably and causes damage to a neighbour, *e.g.*, by allowing water to flow off his or her land and flood a neighbour's land. The principle in *Rylands* v. *Fletcher* is in many respects similar, since it imposes liability where a landowner allows an inherently dangerous substance to accumulate, with the result that it escapes and injures another person.

Accumulation of water and its escape through flood control works may trigger this rule in appropriate cases, although considerable doubt has been case on this in the case of statutorily authorized public works by the decision of the Supreme Court of Canada in *Tock et al* v. *St. John's Metropolitan Area Board* (1989), 47 M.P.L.R. 113.

In either case, the courts may impose strict liability, *i.e.*, they may impose liability even though there is no negligence or other knowing default on the part of the defendant. This principle has caused many problems in the past for Canadian municipalities, since they are exposed to liability when sewer or water systems malfunction.

The courts used to excuse municipalities from liability where the malfunctioning work was statutorily authorized. However, in *Tock*, above, a plurality of the Supreme Court of Canada limited the defence to those cases where the damage was an inevitable consequence of undertaking a work which was required, not merely permitted, by statute.

The *Municipal Act*, however, contains a statutory protection which may assist the District here. Section 755.3 of the *Municipal Act* provides that a municipality "is not liable in any action based on nuisance or the rule in *Rylands* v. *Fletcher* where the damages arise, directly or indirectly, out of the breakdown or malfunction of ... a water or drainage facility or system, or ... a dyke". It is important to note that the protection offered by this section may not cover all kinds of flood protection works. If a court believes that compensation should be paid to an injured landowner, it may well hold that the work in question is not a "dyke", so that s. 755.3 does not apply. At present, however, we note that there is some prospect of protection, at least, through this express statutory exemption from liability. This protection would, of course, extend to the District only and not the Province.

Liability To Compensate For Injurious Affection

As was noted above, in some cases the District or the Province, as the case may be, may be under a duty to compensate landowners for injurious affection. For example, if a landowner can establish that the value of his or her property has been diminished because construction of protective works is predicted to cause greater loss to that property than would otherwise have been the case, governmental liability to compensate for that reduction in property value may be triggered. This may be the case even if that property is nowhere near the protective works and there has been no interference with access to the property or some other property right.

In the case of the District, the potential for liability stems from s. 544 of the *Municipal Act*, which reads as follows:

> The council shall make to owners, occupiers or other persons interested in real property entered on, taken, expropriated or used by the municipality in the exercise of any of its powers, *or injuriously affected by the exercise of any of its powers*, due compensation for any damages necessarily resulting from the exercise of those powers beyond any advantage which the claimant may derive from the contemplated work [emphasis added].

Before a property owner can claim compensation, he or she must satisfy each of the following conditions, which were set out by the Supreme Court of Canada in *The Queen* v. *Loiselle*, [1962] S.C.R. 624:

1.   the damage must result from an act which is made lawful by statute,

2.   the damage must be of a kind which would have given the property owner a cause of action to sue for damages at common law but for the fact that the statute allowed the act in question to be performed,

3.   the damage must injure the land itself and not be a personal injury or a loss caused to a business, and

4.   the damage must have been caused by construction of the public work in question, not by its use.

The British Columbia Expropriation Compensation Board has observed that "[e]ach case involving injurious affection where no land is taken must be critically examined on its own peculiar set of facts": *Jesperson's Brake & Muffler Ltd. and District of Chilliwack* (E.C.B. 43/90/034, July 7, 1992; now on appeal to the British Columbia Court of Appeal). The Board noted that in *St. Pierre* v. *Minister of Transportation and Communications*, [1987] 1 S.C.R. 906 (S.C.C.) the Supreme Court of Canada confirmed the four conditions laid down by *Loiselle*, above, and also confirmed that injurious affection where no land is taken leads to compensation only where the loss would have been actionable at common law.

In the kind of situations which are likely to be involved here, it is questionable whether a property owner whose property may be more exposed to risk would have had a cause of action at common law, as is required by the second criterion in *Loiselle*, above. It may be that such a property owner could, at common law, sue the District or the Province on the grounds that construction of the works in a way which exposed his or her property to greater risk of flooding or debris-torrents in itself constituted a nuisance. The common law recognizes the right to obtain an injunction to restrain an anticipated nuisance, but it is not clear to us that a court would entertain such a claim unless it was abundantly clear that construction of works in such a manner did in fact constitute a present nuisance. Until loss was actually suffered through such a nuisance, the court might well conclude that there was

no present nuisance. See *Halsbury's Laws of England* (3rd ed.), vol. 28. Further, if the District were the authority constructing the works, the court might advert to the fact that s. 755.3 of the *Municipal Act* confers protection on the District for nuisances, as was noted above.

Again, while we cannot express any firm views on this subject, it may be that compensation for injurious affection will *not* be payable to landowners unless there is some interference with or damage to their property rights which would otherwise be actionable at common law, but for the statutorily authorized nature of the works. This is an issue that will have to be revisited by the District and the Province when more concrete proposals are in hand.

We should also note that it is not by any means certain that pure economic loss because of a reduction in property value due to a perceived risk of physical damage is actionable at common law as a nuisance. See *Wirth* v. *City of Vancouver* (1990), 47 B.C.L.R. (2d) 340 (B.C.S.C.).

3.4 Assuming no protective works are undertaken, what liability might governments have in relation to properties at risk?

We have already outlined the situation regarding government liability in respect of policy choices and operational actions.

One of the policy decisions open to government may be the choice not to build any flood works or take any other steps at all, although there can be no absolute guarantee that the courts would not in fact impose liability for such a choice. We have already noted that statements in *Laurentide* and *Just*, for example, leave the door ajar for the courts to characterize a policy choice as unreasonable and therefore a source of liability. Nonetheless, if a cost-benefit analysis persuaded the government not to act, a policy choice of that nature might well survive review. There is, therefore, some scope for government to decide to do nothing to prevent or protect against the predicted event. In addition to *Just*, above, see *Hunt* v. *Westbank Irrigation District*, [1991] 6 W.W.R. 549 (B.C.S.C.); and *Riverscourt Farms Ltd.* v. *Niagara-on-the-Lake* (1992), C.C.C.L.T. (2d) 231 (Ont. C.J., Gen. Div.).

Having said that, we think that the courts would require the governments at least to warn those potentially at risk of the possibility of harm. Informing citizens of the risk gives them the choice to accept that risk and remain, or to reject it and move away. Failure to warn would likely expose the governments to liability.

To summarize, government may be in a position to choose to do nothing - there being no guarantee this will not expose it to legal liability - but there is, we think, a minimal duty to warn which must be discharged by the release of as much accurate information as is practicable. This has practical ramifications, of course, but that is not a legal issue.

Access To Information

In passing, we note that in addition to the above-noted duty to warn, the *Freedom of Information and Protection of Privacy Act*, S.B.C. 1992, c. 61, has provisions which may well apply in this case. That Act is scheduled to be proclaimed this coming Autumn, at least as regards the Province. (The District will be subject to comparable legislation at a later date.)

When it is proclaimed, s. 25(1) may require the MOE and the District to disclose information about the risk involved here. Section 25(1) reads as follows:

> Whether or not a request for access is made, the head of a public body must, without delay, disclose to the public, to an affected group of people or to an applicant, information
>
> (a)   about a risk of significant harm to the environment or to the health or safety of the public or a group of people, or
>
> (b)   the disclosure of which is, for any other reason, clearly in the public interest.

This section - especially paragraph (a) - could well apply to the circumstances at hand.

3.5   Should any development already existing in hazard areas be allowed to expand or not?

You asked whether existing land uses in hazard areas should be allowed to expand or change, even though new development will not be possible in such areas. For example, should it be possible to withhold a building permit for the new wing of a school in such an area? Or what of the homeowner who simply wishes to add a carport? We think the District could effectively use its development permit powers and other *Municipal Act* powers to deal with such situations.

Specifically, as noted above the OCP could be amended to designate areas at risk as development permit areas and could include guidelines for alleviating conditions hazardous to development. In turn, the development permit powers under s. 976 of the *Municipal Act* would allow the District to specify areas of each parcel of land which are subject to harm and require that they remain free of development, or be developed in compliance with permit conditions. The other tools discussed above in part 3.1, should also be useful in this context, especially s. 215 covenants.

We cannot, of course, offer any guidance as to the merits of permitting expansion of development already existing in hazard areas. It will be necessary for the District to consider the circumstances of each case in determining what protective measures it should (and can legitimately) require the landowner to take. The development permit powers given to the District can, of course, be used to lay down general guidelines in this regard,

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which can then be applied in the circumstances of each case. However, the risk and costs of each situation will have to be weighed in determining what measures, if any, should be imposed as a condition of permission to proceed with expansion of existing development.

3.6   What can be done to protect the Province or the District when either of them sells their land?

The traditional legal rule of buyer beware still holds true in Canadian law, but it has some exceptions. The law has always required disclosure of hidden defects which are dangerous. Moreover, Canadian law appears to be moving toward a rule which requires a seller of land to disclose all hidden defects which substantially affect the value of the land, not just hidden defects which are dangerous. The law has not moved that far with absolute certainty, but seems to be heading in that direction. See *Harnett* v. *Wailea Construction Ltd.* (1987), 43 M.P.L.R. (B.C.S.C.) and *Sevidal* v. *Chopra* (1987), 64 O.R. (2d) 169 (Ont. H.C.).

It could be argued that the risk of loss due to landslide, flood or debris torrent is not a defect of the land itself and need not be disclosed. It could be said that such a risk is simply the risk inherent in many areas, *i.e.*, of loss due to natural phenomena; it is not a risk specific to any one parcel of land. On balance, we think it safest to assume that a court might hold that such a risk was in fact a defect in the land, since it is something which fundamentally affects the safety and value of the land, even though the forces constituting the risk are forces of nature operating from outside the land's boundaries.

Accordingly, the more cautious approach for the Province or the District to follow would be to disclose the risk before a contract of sale's entered and absolve itself of any liability. Advertisements for sale, invitations for tender and all contract documents should make the risk known and the purchaser should be given access to information disclosing the nature of the risk. The contract of sale should include a clause disclosing the risk and disclaiming any responsibility for loss, contractually or otherwise.

Since Canadian law is apparently moving toward a requirement of greater disclosure of risk in the land sale context, the District and the Provincial Government should consider the above recommendation even though it raises the possibility of loss of value, since a purchaser may claim a reduction in price because of the risk. This may be the consequence of disclosure, but failure to disclose could lead to costly litigation and further expense.

3.7   Are there any precedents setting quantitative triggers as to when the duty to take action is triggered?

This question is in a sense dealt with by the discussion in parts 3.3 and 3.4, above. To the extent a policy decision is legitimately taken to do nothing other than warn the public, it is probable the courts will not intervene and impose liability. But we have already noted the possibility that our courts will intervene in certain cases, a legal development which may come about after this letter has been considered and acted upon. So what do the cases

say about the degree of risk which will trigger a duty to act, assuming even a policy decision will not shield the Province or the District?

The blunt answer is that there is little guidance from the courts on this issue. Scientific precision is not found in the law. The courts apply the imprecise standard of what is reasonably foreseeable as the touchstone of legal liability. They will ask what a reasonable person would have done to prevent a harm which was reasonably foreseeable. Some argue that this inevitably leads to 20:20 judicial hindsight; that is an observation which has some truth to it.

This means we cannot say whether a 1 in 100 or 1 in 10,000 chance of loss will trigger a duty to act. We can only offer the rough and ready guide that the greater the anticipated loss, or the greater the likelihood of a large loss occurring, the more likely it is the courts will find that there was a duty to act.

During our discussions, you drew the distinction between the *probability of an event occurring* and the *probability of a loss being caused to a particular property* or persons within the area subject to the probable event. As you put it, there may be a 1 in 10,000 chance that a land-slip will occur, but the probability of loss to a house located in the area potentially covered by the event may only be 1 in 100,000. You asked whether the courts will distinguish between the probability of the event occurring and the probability of harm to the particular property in determining whether the standard of care has been met by a government.

In our view, the courts will not be interested in the probability of an event occurring. They are concerned with protecting against loss, be it personal injury or property damage. We think, therefore, that a court would look at the probability of loss or injury - and not the probability of a causative event -in determining whether or not the government had acted · appropriately in the circumstances. Of course, this brings us back to the observation we made above, *i.e.*, that the only guide we can offer is the observation that the greater the anticipated *loss*, or the greater the likelihood of a large *loss* occurring, the more likely it is the courts will find that there was a duty to act. So long as the courts are able to determine that there was a risk of loss, they will review the government's actions to determine whether the degree of risk or loss required them to act other than as they did.

We should emphasize that the discussion of *Just*, above, makes it quite clear that if a government takes a *bona fide* policy decision not to act in a face of a risk of loss, the courts will not (at present, at least) interfere and impose liability for negligence. It is only if the operational implementation of a policy is negligently performed that the courts will impose liability.

In this regard, we should add that we see nothing in the *Municipal Act* which specifically imposes a duty on the District to spend public funds to prevent loss to properties which may be subject to a particular natural event. As was noted above, the District is under a duty at least to consider acting or not. If it knows of the risk and acts for no reason, it may be liable. But if it makes a *bona fide* policy decision not to build protective works - or to do so in a particular manner - it will not be liable for that policy choice.

However, as was noted in part 3.1, above, there are certain provisions of the *Municipal Act* which require the District to adopt OCP designations placing restrictions on the use of land "that is subject to hazardous conditions". In turn, the District is given the power by s. 945 to designate areas of land for the "protection of development from hazardous conditions". The duty of the District to impose such restrictions through the OCP - and its power to impose development permit guidelines and conditions on lands in those areas - does not mean that it is required to construct protective works. It just means, at a minimum, that the District must take minimal planning and land use designation steps to protect land from hazardous conditions as far as is practicable.

4. Conclusion

As we noted above, the views expressed in this letter are necessarily general and it will be necessary for the governments involved to obtain legal advice on the implications of each particular proposed course of action. Moreover, this letter may not be relied upon by anyone other than the Province or the District for any purpose, it being the responsibility of others to obtain their own legal advice.

Yours very truly,

LIDSTONE, YOUNG, ANDERSON

David Loukidelis

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10.0   SUMMARY OF CONCLUSIONS

This report documents a comprehensive assessment of terrain hazards involving the drainage basin and depositional fan of the Cheekye River.   The impacts for land utilization on the fan resulting from the hazard study are considered.

The following main conclusions have been reached:

Hazard Assessment

- Mt. Garibaldi is a dormant volcano, whose latest period of activity was completed several thousands of years ago.   There is presently no indication of renewed volcanism and a repose period of many thousands of years is possible.

- A major non-eruption rock avalanche from the rim of the Cheekye Basin is possible, but is considered to have a very low probability of occurrence, i.e., its annual probability is in the order of one in several thousands.   Such an event probably would not impact the Lower Fan (west of Highway 99) directly and has therefore been discounted in further analysis.

- Debris flows involving granular volcanic material with magnitudes of individual events, or groups of events, ranging possibly as high as 3 to 7Mm³ have occurred on the Lower Fan in the past and could occur again.

- Lesser magnitude debris flows (say 1.0 Mm³ maximum) are likely generated by existing instability on the slopes within the Cheekye basin.

- Based on past events, and current evidence, the most likely trigger for a major debris flow event would be the breach of a landslide dam in the headwaters, releasing large quantities of water and liquefied sediment.

- The peak discharge of a major debris flow could reach as much as 1,700 m³/sec, or nearly seven times the estimated peak discharge for a 200 year flood.

Risk Evaluation

- An approximate magnitude-frequency relationship for a range of debris flows has been established from the historic stratigraphic evidence of the fan deposits.

- The consequences of the major events could be experienced at any point on the fan but the severity would be progressively reduced from the Cheekye Gorge towards the lower slopes as the character of the event changes from debris flow to debris flood.

- Maximum hazard probabilities have been estimated for each zone for debris flow, debris flood and water flood.

- Three approaches to risk assessment have been evaluated, they include the use of hazard probabilities, risk to life of individuals (PDI) and risk to life of groups (PDG). Risk acceptability criteria used by others have been explored. Hazard and PDI probabilities of 1:10,000 appears to be accepted criteria for safe habitable land uses although there are no laws or precedents which define a probability threshold at which regulatory or mitigation responses are required.

- It has been concluded that for the evaluation of land use for habitable purposes where there is a fairly high density of use, zoning by hazard probability is appropriate. Where there is a lower intensity of use, zoning by hazard probability appears to be restrictive and a PDI approach may be more useful. The full potential of the PDG approach can be utilized in consideration of population densities and is thus available as a planning tool for proposed developments.

- Some types of land use such as recreational developments, transportation corridors, airports, and municipal facilities where usage might be intermittent, are best analyzed using PDI. Regulations can be less restrictive in these cases.

Land Use Considerations

- For the existing (unmitigated) situation the hazard probability approach based on guidelines proposed by Cave (1992), and utilized in the Fraser Cheam Regional District, indicates that new construction on existing lots would only be permitted in Zone 4 (Figure 8.1). Approval of subdivisions would require prior mitigation of the flood hazard. For non-habitable land uses, the conclusions are similar but are considered to be conservative.

- For the existing (unmitigated) situation, use of the PDI approach also results in the conclusions that habitable land use is not permissible in Zone 1 and 2 but suggests that in Zone 3, habitable uses could be permitted, especially if they do not require a full-time presence on the fan.

Land use regulations in Zone 4 would be more lenient than determined by the hazard probability zonation.

- Areas have been identified (Figure 9.3) in which various planning strategies can operate. These largely correspond to the existing fan hazard zones but of course the zoning will change within these areas if, and when, mitigative measures are emplaced.

- Area A: Development and land use extremely restricted.
  Area B: Unsuitable for habitable development, but suitable for some types of recreational development.
  Area C: Development possible with some land use restrictions and mechanisms to reduce liability and exposure if there is no physical mitigation. Subdivisions would require flood mitigation.
  Area D: Development dependent on hazard mitigation hence a land use strategy is required. Risk transfer possible.
  Area E: Land use dominated by flood considerations.

Mitigation Options

- Mitigation comprises cautionary approaches (disclosure of information, provision of warning systems); regulatory approaches (limitations by restrictive or conditional approvals); and physical approaches (dyking or relocation).

- Of the various scenarios considered to reduce the risk to the population from the natural hazards on the fan, the most appropriate are considered to be land use zoning, diversion dykes and warning systems.

- Diversion dykes could increase the extent of Zones 3 and 4 thus permitting greater development on the fan. Two approaches have been explored: the hazard probability assessment indicates that dykes should be designed with respect to the largest but least probable event (several millions m³) to minimize the residual risk. The PDI and PDG risk assessments indicate that the greatest reduction in risk to the lives of both individuals and groups would result from controlling the smallest, most probable events, providing that some degree of warning could be established against the very rare, but highly damaging, events.

- Mitigation strategies need to be evaluated on the basis of cost: benefits for the alternatives. Some options will result in the transfer of risk from one part of the fan to another.

Public Perception

- Public perception is an issue which requires more attention. The study has produced evidence which indicates that in spite of the risk assessments, public perception does not look favourably on sensitive developments such as schools or hospitals in areas which are subject to even low risks of impact from natural hazards. New developments of this nature might best be located off the fan providing the decisions are supported by cost:benefit analyses for comparative purposes.

Regulatory Response

- Regulatory agencies have an obligation to warn those potentially at risk.

- Regulatory agencies have an obligation to consider policy alternatives and implications which may also include the decision not to proceed with any mitigation.

- As the studies have shown that as there is not a single unique mitigative solution to the threat from natural hazards on the fan, cost:benefit analyses will be required to weigh the cost of the engineered works, and the benefits to properties with reduced exposure, against the costs imposed on properties with increased exposure.

- Mitigative solutions can legally be implemented, and paid for, by either the Province or local government; liability could result.

- Existing private properties can remain although all future development applications will require a considered response from the Municipality; all affected parties must be informed of their exposure to the hazards.

- Existing public properties (e.g., schools, churches, airport, landfill, reservoir) will require careful consideration of the various available options which can range from acceptance of the existing risk. relocation, or construction of site-specific mitigative measures. These options must be considered in the context of possible area-wide mitigation plans by the Municipality.

- Full disclosure of the hazard situation must be required in the sale of Provincial or Municipal Land.

Recommended Process

- There is a need for an immediate policy response to regulate land use and development using the existing tools - OCP, Zoning, Bylaws and Development Permits.

- The regulations can then be implemented to ensure safe new development or extensions to existing developments by means of the existing approval instruments - rezoning bylaws, subdivision approvals, development permits, building permits and covenants.

We thank you for the opportunity of working on this challenging assignment and should be pleased to assist in answering any queries which arise from it.

Yours very truly,

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GLOSSARY OF SELECTED TERMS

Debris Avalanche   -   An unchannelized high velocity mass movement of debris which advances with a flow-like motion.

Debris Flood   -   A highly water-charged mass movement of debris with low discharge and moderate velocity. Intermediate between a flood and a debris flow.

Debris Flow	-	A high velocity channelized mass movement of debris containing a low content of fines (<10% silt and clay) and possibly a high organic content.
Diamicton	-	A non-genetic term for an unsorted or poorly sorted, non-calcareous terrigenious sedimentary deposit containing a wide range of particle sizes.
Group Risk	-	Probability that a group of people will suffer the consequences of a single hazard event at one and the same time.
Hazard	-	Physical event which can potentially cause loss of life, injury or economic loss (consequences).
Individual Risk	-	Probability that a person will suffer the consequences of a single hazard event.
Lahar	-	A mudflow composed mainly of pyroclastic materials on the flank of a volcano.
Linear	-	An alignment of geomorphological features considered to be representative of geological structures within the crust.
Mitigation	-	Measures taken to reduce the probability of a hazard occurring or to reduce the probability of a house, structure or area being impacted.
Pyroclastics	-	Rock material formed by volcanic explosion or aerial expulsion from a volcanic vent.
Risks	-	Probability of occurrence of the consequences.
Severity (PDI)	-	Probability of a site being impacted ($P(S:H)$) multiplied by the probability of a site being occupied ($P(T:S)$) multiplied by the probability of loss of life given the occupancy of the site by an individual ($P(L:T)$).
Warning Factor (W)	-	Probability of failure of an evacuation effort.

TABLE 3.1
SUMMARY OF KNOWN ERUPTIVE EVENTS IN THE MOUNT GARIBALDI AND GARIBALDI LAKE VOLCANIC FIELDS (after Green, 1990)

Age (ka)	Source Location	Deposit Location	Composition	Deposit Type	Other Features
Pre 1,000	Black Tusk and Mount Price	-	andesite	lava, pyroclastics	post-date an early glaciation
700 - 400	Vicinity of Mount Garibaldi	Round Mountain	andesite	pyroclastics, lahars	paleovalleys fill
440 - 550	Vicinity of Mount Garibaldi	Brohm Ridge	andesite, dacite	lava, pyroclastics	paleovalleys fill
300 - 200 Erosional dissection					
300	Mount Price	-	andesite, dacite		
260 - 220	Vicinity of Mount Garibaldi	-	dacite	lava	composite cone (Cheekye Stage)
210	Black Tusk	-	andesite	lava	plug dome
Glacial Retreat					
100	Cinder Cone & Sphinx Moraine	-	basaltic andesite	lava, tuff	Sphinx moraine deposit
Pre-50	-	Cheakamus Valley	basalt	lava	-
Cordilleran Ice Advance					
50 - 26 Olympia Interstade					
34	-	Cheakamus Valley	basalt	lava	B.C. Rail Quarry
26 - 11 Fraser Glaciation					
26 - 11	Atwell Peak	Cheekye Ridge	dacite	lava, tuff breccia	plug dome (Atwell), Supraglacial cone
26 - 11	The Table	-	andesite	lava	lava pit in ice
26 - 11	Eenostuck	-	basaltic andesite	lava	subglacial extrusion
11 Glacial retreat, collapse of Atwell cone					
11	Dalton Dome	-	dacite	lava	filled landslide scar, not long after ice withdrawal
11	Clinker Peak	Barrier, Culliton Creek	andesite	lava	two flows, deposited against ice at lower elevations
11	Cinder Cone	-	basalt	lava, pyroclastics	lava flow to the north (date uncertain)
11 - 7	Opal Cone	Round Mountain	dacite	lava	Ring Creek lava flow

TABLE 5.1
CLIMATE STATIONS NEAR THE CHEEKYE BASIN

Station	Latitude	Longitude	Elevation (m)	Period of Record
Alta Lake 2	50.09	122.59	640	1931-69
Alta Lake	50.09	122.57	668	1968-76
Alta Lake Northair Mine	50.07	122.57	1006	1975-87
Britannia Beach	49.37	123.12	49 9 49	1913-64 1964-65 1965-74
Daisy Lake Dam	49.56	123.08	381	1968-83
Garibaldi	49.59	123.08	366 366 381	1921-42 1942-66 1966-80
Squamish	49.42	123.09	2	1959-70 1983-92
Squamish FMC Chemicals	49.41	123.09	3	1968-83
Squamish A	49.47	123.10	59	1982-92
Squamish Upper	49.54	123.17	46	1979-87 1988-92
Tunnel Camp	49.37	123.08	671	1924-58 1959-64 1965-74
Woodfibre	49.40 49.39 49.40	123.16 123.16 123.15	6 6 3	1960-68 1968-81 1983-92

1. Station descriptions are from "Atmospheric Environment Service. 1989.
   Climatological Station Catalogue: British Columbia. Environment Canada.
   57 pp."

TABLE 5.2
CLIMATE NORMALS AT STATIONS NEAR THE CHEEKYE BASIN

Station	Elevation (m)	Period of Record	Climate Normals (mm)			
			Total Rainfall	Total Snowfall	Total Precip.	Maximum 24-hour Precip.
Britannia Beach	49	1914 - 74	2073.0	92.0	2164.3	121.9
Tunnel Camp	671	1924 - 74	2297.7	552.0	2849.7	129.8
Woodfibre	6	1961 - 91	2901.9	131.5	3071.3	197.1
Squamish	2	1960 - 91	2109.5	177.1	2247.0	111.8
Garibaldi	375	1922 - 80	1367.7	478.0	1845.8	115.1
Daisy Lake Dam	381	1969 - 83	1460.3	383.0	2054.2	95.6
Alta Lake	668	1931 - 76	800.6	657.4	1415.4	79.8

1. Data are from "Atmospheric Environment Service. 1982. Canadian
   Climate Normals: 1951-1980. Temperature and Precipitation: British Columbia.
   Environment Canada. 268 pp.

1/LOTUS/TAB-93/MAR/T52-1525.wk1

TABLE 5-3
DISTRIBUTION OF PRECIPITATION AT SQUAMISH AND GARIBALDI

Climate Normal	Unit	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec
Monthly Precipitation													
Squamish	mm	313.2	234.3	188.9	149.1	77.2	68.5	52.3	73.0	127.0	301.3	314.4	347.8
	%	13.9	10.4	8.4	6.6	3.4	3.0	2.3	3.2	5.7	13.4	14.0	15.5
Garibaldi	mm	266.1	199	172.8	103.3	72.4	64.2	47	58	108.6	217.2	250.5	286.7
	%	14.4	10.8	9.4	5.6	3.9	3.5	2.5	3.1	5.9	11.8	13.6	15.5
Greatest Daily Precipitation													
Squamish	mm	100.3	70.6	56.1	53.3	39.4	43.4	35.8	75.4	69.6	80.8	81.3	118.8
Garibaldi	mm	111.0	88.8	115.1	59.7	54.6	44.7	48.0	45.2	67.6	100.8	88.9	100.3

1. Data are from "Atmospheric Environment Service. 1982. Canadian Climate Normals: 1951-1980. Temperature and Precipitation. British Columbia. Environment Canada. 268 pp.

1/LOTUS/TAB-93/MAR/T53-1525.wk1

TABLE 5.4
LARGEST RECORDED STORMS AT GARIBALDI

Storm No.	Start Date of Storm	Precipitation (mm) on Day #			
		1	2	3	4
1	October 26, 1921	33.0	42.2	25.1	82.3
2	January 29, 1924	105.4	16.3	73.9	34.5
3	December 9, 1925	-	93.5	71.1	-
4	January 20, 1935	101.6	53.3	30.5	30.5
5	January 12, 1973	19.1	30.7	111.0	46.0
6	January 12, 1974	37.6	65.8	48.3	55.6
7	March 8, 1974	31.5	115.1	25.4	15.2
8	October 15, 1975	8.6	100.8	28.7	40.4

	Ranked Storms	Accumulated Precipitation (mm)			
		1-Day	2-Day	3-Day	4-Day
7	March 8, 1974	115.1	146.6	172.0	187.2
5	January 12, 1973	111.0	157.0	187.7	206.8
2	January 29, 1924	105.4	121.7	195.6	230.1
4	January 20, 1935	101.6	154.9	185.4	215.9
8	October 15, 1975	100.8	129.5	169.8	178.4
3	December 9, 1925	93.5	164.6	164.6	164.6
1	October 26, 1921	82.3	107.4	149.6	182.6
6	January 12, 1974	65.8	114.1	169.7	207.3

1/LOTUS/TAB-93/MAR/T54-1525.wk1

TABLE 5.5
LARGEST RECORDED STORMS AT SQUAMISH

Storm No.	Start Date of Storm	Precipitation (mm) on Day #			
		1	2	3	4
1	December 22, 1963	111.8	55.6	38.4	-
2	January 17, 1968	55.9	100.3	50.5	16.5
3	October 16, 1975	93.5	-	-	-
4	October 27, 1981	43.0	13.6	15.6	186.0
5	October 6, 1984	27.3	85.0	35.4	59.8
6	February 22, 1986	23.4	72.0	83.8	2.6
7	November 8, 1990	51.6	59.6	87.2	33.0
8	January 31, 1991	39.9	121.0	4.4	24.8

	Ranked Storms	Accumulated Precipitation (mm)			
		1-Day	2-Day	3-Day	4-Day
4	October 27, 1981	186.0	201.6	215.2	258.2
8	January 31, 1991	121.0	160.9	165.3	190.1
1	December 22, 1963	111.8	167.4	205.8	205.8
2	January 17, 1968	100.3	156.2	206.7	223.2
3	October 16, 1975	93.5	93.5	93.5	93.5
7	November 8, 1990	87.2	146.8	198.4	231.4
5	October 6, 1984	85.0	120.4	180.2	207.5
6	February 22, 1986	83.8	155.8	179.2	181.8

1/LOTUS/TAB-93/MAR/T55-1525.wk1

TABLE 5.6
DAILY AND 1-HOUR PRECIPITATION AT VARIOUS RETURN PERIODS

Climate Station	Daily Precipitation (mm)				1-Hour Precipitation (mm)			
	2 Yr	10 Yr	50 Yr	100 Yr	2 Yr	10 Yr	50 Yr	100 Yr
Britannia Beach	73	100	124	134	15	20	25	27
Tunnel Camp	85	110	130	-	17	22	26	
Woodfibre	103	150	189	209	21	30	38	42
Squamish	76	98	117	125	15	20	23	25
Garibaldi	66	94	118	129	13	19	24	26
Daisy Lake Dam	60	85	107	117	10	17	23	25
Alta Lake (combined)	52	73	92	100	10	15	18	20

1. Estimates of daily precipitation at various return periods provided by the Atmospheric Environment Service. Daily precipitations may be adjusted to floating 24-hour precipitations by multiplying by 1.13.

2. One-hour precipitations calculated as 20% of the daily precipitation except at Daisy Lake where data are from an Intensity-Duration-Frequency curve supplied by the Atmospheric Environment Service.

1/LOTUS/TAB-93/MAR/T56-1525.wk1

TABLE 5.7

PROBABLE MAXIMUM PRECIPITATIONS (PMP)

Elevation (m)	PMP (mm) 1-hr duration	PMP (mm) 24-hr duration	PMP (mm) 96-hr duration
200	32	188	358
400	37	221	445
600	41	256	538
1000	51	322	719
1400	60	392	907
1800	70	460	1093

TABLE 5.8
PRECIPITATION DURING DEBRIS FLOWS, DEBRIS FLOODS AND FLOODS

Year	Start Date of Storm	Station	Antecedent Precip. (mm)	Precipitation (mm) on Day #						Return Period (yr) f		
				1	2	3	4	5	6	1-Day	3-Day	5-Day
1921	October 24	Garibaldi	-	-	-	33.0	42.2	25.1	82.3	5	5	-
		Britannia	-	16.0	58.2	13.0	34.8	121.9	0.5	40	5	20
1940	October 16	Garibaldi	106	-	45.7	68.6	35.6	8.6	20.3	2	5	5
		Britannia	121	0.3	86.4	81.5	17.3	28.4	-	5	10	5
1958	August 27	Garibaldi	42	-	10.4	1.5	3.3	11.2	T	1	1	1
		Britannia	25	2.0	0.3	24.4	2.5	18.3	-	1	1	1
1984	October 6	Squamish	127	27.3	85.0	35.4	59.8	21.4	16.0	5	8	10
		Woodfibre	-	-	-	-	-	-	-	-	<2	-
1990	November 7	Squamish	260	3.5	51.6	59.6	87.2	33.0	47.2	5	20	50
		Squamish A	-	-	50.4	26.0	164.4	68.8	71.0	-	-	-
		Woodfibre	-	-	-	-	-	-	-	-	-	-
1990	November 21	Squamish	557	31.4	52.6	54.6	3.8	0.4	7.6	<2	<2	<2
		Squamish A	-	47.2	123.8	101.6	2.8	-	-	-	-	-
		Woodfibre	-	-	-	-	-	-	-	-	-	-
1991	August 26	Squamish STP	70	37.8	14.8	41.8	79.2	31.8	0.6	2	<5	5?
		Squamish Upper	92	31.2	13.5	42.4	128.6	41.2	2.3	-	-	-
		Woodfibre	80	25.0	25.0	58.2	87.6	C	25.0	<2	<2	<2

1. Antecedent precipitation is the total precipitation in previous 30 days.
2. Return periods for "Squamish STP" calculated from "Squamish" station record.

TABLE 5.9
WATER SURVEY OF CANADA GAUGES NEAR CHEEKYE BASIN

Station	Number	Period of Record	Drainage Area (km2)	Mean Runoff (mm)	Extreme Peak Flow (m3/s/km2)	Instantaneous Discharge at Return Periods of		
						2-yrs	10-yrs	200-yrs
Cheakamus R at Garibaldi	08GA017	1916-69	813	1734	1.01			
Cheakamus R near Brackendale	08GA043	1957-92	1,010	985	0.85			
Cheakamus R above Millar Creek	08GA072	1982-92	275	1979	0.98			
Culliton Creek near Brackendale	08GA040	1954-57	74	-	1.84			
Elaho R near the mouth	08GA071	1981-92	1,250	2528	0.91			
Mamquam R. above Mashiter Ck.	08GA054	1966-86	334	2413	1.10			
Mashiter Ck near Squamish	08GA057	1967-81	39	2103	3.10	33	88	251
Rainy River at the mouth	08GA020	1951-70	69	3986	6.20			
Squamish R near Brackendale	08GA022	1955-92	2,330	3223	1.12			
Stawamus R below Ray Creek	08GA064	1972-92	40	2875	2.83	58	97	174

1. Extreme peak flows are the maximum recorded instantaneous peak, or the
   maximum recorded daily discharge at manual gauges.

TABLE 5.10

ESTIMATED INSTANTANEOUS DISCHARGES

Technique	200-yr Inst. Discharge above Brohm River 36 km²	200-yr Inst. Discharge above Cheakamus River 62 km²
Creager's C	210	300
Synthetic Hydrograph	280	
Rational Method	270	
Empirical Hydrograph	280	
ADOPTED VALUE	250	

TABLE 5.11

ESTIMATED CHEEKYE RIVER BEDLOAD

Duration (hrs)	Discharge (m³/s)	Concentration (ppm)	Tonnes/hour (t/hr)	Total Tonnes (t)
0.4	30	negligible	negligible	negligible
0.4	160	7500	4320	1730
0.4	240	8700	7520	3010
0.4	190	8000	5470	2190
0.4	110	5800	2300	920
0.4	60	3000	650	260
0.4	20	negligible	negligible	negligible
			EVENT TOTAL	8,000 t 5000 m³

TABLE 5.12
CHANGES OBSERVED IN THE CHEEKYE AND CHEAKAMUS RIVERS FROM AIR PHOTOS

Year	Channel Width (m)	Development	Channel Changes
1947	42	- cut for powerlines crosses Cheekye 300 m from mouth.	- no changes observed in Cheekye River. Vegetation well-established on banks and channel islands.
1957	69	- B.C. Hydro power-station construction.	- Cheekye channel widened and shifted, particularly the upper and lower reaches on the fan. - Vegetated islands were removed and new channels cut through the fan/floodplain, forming new islands. - increased braiding on the Cheakamus.
1959	76	- power-station enlarged; new powerline crosses the Cheekye near the head of the fan.	- mudflow discussed by Jones (1959) occurred prior to date. - channel widened to limit of permanent vegetation. - additional small channels cut through trees. - large trees and rock left in main channel. - no observed changes to Cheakamus River.
1969	-		- Cheekye re-established into single channel. - vegetation encroached from overbank into channel.
1973	-	- Highway bridge construction.	- no changes observed in Cheekye River.
1978	44		- further encroachment of vegetation. - channel shifting d/s of highway bridge.
1980	-		- increase in channel width, particularly at downstream powerline crossing.
1982	67	- powerline crossing about 1 km above mouth of Cheekye.	- visible sediment accumulation downstream of the new powerlines.
1990	65	- construction along Cheekye River.	- some vegetation encroachment.

1. Channel width calculated from measured channel area and channel length.

TABLE 6.1
RESULTS OF C-14 AGE DATING

Sample Location	Sample Taken	Investigator(s)	Material	Age (years B.P.)	Comments
1. Toe of Cheekye Fan	'80	J. Clague/ F. Baumann	Charcoal sample from silt overlying diamicton	5890 ±100*	Charcoal from silty layer at the base of 13 m cut bank on Squamish River.
2. Upper Fan/Cheekye River Terrace between Cheekye Gorge and Highway 99	'90	S. Evans	Within diamicton	1550	Some doubt exists as to whether this sample came from Upper Fan deposits or from recent debris flow material within channel.
3. Garbage Dump/ Cheekye Fan	Feb., '91	F. Baumann	Wood samples within diamicton	1190 ±60	Log sample (17 cm diameter, 4.0 m below surface)
4. Garbage Dump/ Cheekye Fan	Feb., '91	F. Baumann	Wood samples within diamicton	1010 ±70	Log sample (51 cm diameter, 3.5 m below surface)
5. Garbage Dump/ Cheekye Fan	Aug., '91	F. Baumann	Wood samples within diamicton	1340±65	Tree sample.
6. Garbage Dump/ Cheekye Fan	Aug., '91	F. Baumann	Wood samples within diamicton	1390 ±65	Tree sample from Garbage Dump tree.
7. Test pit #TP2 on Cheekye Ridge	Sep., '91	O. Hungr	Peat layer within colluvium	3220 ±70	Peat sample interbedded with pyroclastic colluvium.
8. Sand and gravel pit west of airport	Sep., '91	F. Baumann/ G. Rawlings/ O. Hungr	Diamicton 1 m thick overlying fluvial sands and gravel	305 ±60	Bark sample. Trees estimated to be up to this age are growing within presumed outcrop of this diamicton.
9. Test Pit #TP64 on Ross Road near Brackendale	Oct., '91	F. Baumann/ G. Rawlings	Charcoal sample from diamicton overlying fluvial sand and gravel	7820 ±95	Diamicton has a bouldery top and surface expression. Charcoal most likely reworked.

Notes:
- All samples C-13 corrected
- Ages referenced to A.D. 1950
* ± 1 standard deviation. All other ranges are ± 2 standard deviations.

TABLE 6.1 (cont'd)
RESULTS OF C-14 AGE DATING

Sample Location	Sample Taken	Investigator(s)	Material	Age (years B.P.)	Comments
10. Test Pit #TP92-1 in Garbage Dump/ Cheekye Fan	Mar., '92	M. Goldbach	Charcoal sample from diamicton	5660 ±175	Sample taken from top 10 cm of diamicton, 8.6 m below ground surface.
11. Test Pit #TP92-5 on B.C. Hydro right-of-way/ Cheekye Fan	Mar., '92	M. Goldbach	Charcoal sample from sandy silt seam in fluvial sand and gravel	8715 ±100	Sample taken from 4.5 m below ground surface.
12. Test Pit #TP92-6/ Cheekye Fan	Mar., '92	M. Goldbach	Charcoal sample from contact between diamicton and underlying fluvial cobbly gravel	1665 ±65	Sample taken from 3.1 m below ground surface.
13. Exposure G3 in MOTH sand and gravel pit west of airport/Cheekye Fan	Mar., '92	M. Goldbach	Charcoal sample from buried soil horizon along base of diamicton	1215 ±120	Sample taken from 0.8 m below ground surface
14. Exposure G3 in MOTH sand and gravel pit west of airport/Cheekye Fan	Mar., '92	O. Hungr	Charcoal sample from silt seam in sand unit overlying and underlying diamictons	5975 ±180	Sample taken from 6.2 m below ground surface
15. Exposure on bank of Squamish River/ Cheekye Fan	Apr., '92	O. Hungr/ M. Goldbach/ R. Gerath	Charcoal sample from top 0.3 m of diamicton	6595 ±90	Sample taken from 14.5 m below ground surface at top of cliff.

Notes:
- All samples C-13 corrected
- Ages referenced to A.D. 1950

TABLE 7.1 - ESTIMATED PHYSICAL PARAMETERS OF POTENTIAL DEBRIS FLOW HAZARDS

Debris Flow	DEBRIS FLOW MAGNITUDE CLASS											
	A				B				C			
Return Period (years)	2,450 - 10,000				930 - 2,450				52 - 930			
Magnitude (m^3)	3M - 7M				1M - 3M				100,000 - 1M			
Area of Deposits (ha)	180 - 380				80 - 180				10 - 80			
Fan Zone	1	2	3	4	1	2	3	4	1	2	3	4
Damage Corridor Width[1] (km)	1.0 -1.5	0.7 -1.5	0.5 -1.0	0.4	0.7 -1.0	0.5 -0.7	0.2 -0.5	0.2	0.2 -0.7	0.2 -0.5	0.2	0.2
Maximum Flow Velocity (m/s)	7	4	3	2	4	3	2	1	3	2	1	1
Maximum Deposit thickness[2] (m)	5	· 3.5	2	1	4	2.5	1	0.5	3	2	0.5	0.2

1   Measured along fan contours, perpendicular to flow direction.

2   Greater thickness possible in existing depressions or channels.

TABLE 7.2 - ESTIMATED EFFECTS OF POTENTIAL DEBRIS FLOW AND FLOODING HAZARDS

Fan Zone	Debris Flow			Flood (Avulsion of The Cheekye River)
	A (3M - 7Mm³)	B (1M - 3Mm³)	C (100,000 - 1Mm³)	
1	Extremely rapid movement of massive debris trains, deep deposition, forest cover and all structures destroyed, topography changed.	Destructive debris flow, thick deposits, complete destruction possible in a part of corridor, complete change of drainage pattern.	Destructive debris flow surges in and close to the existing Cheekye river channel. Partial destruction elsewhere, especially along open corridors.	Destructive currents. Severe deposition of sediment (gravel) and erosion due to flood flow in new channels.
2	Less rapid but still very destructive debris flow, deposits of variable thickness, preferential flow along open corridors, some forest stands and structures will remain standing.	Moderate speed and depth, most forest stands and structures not destroyed some concentrated destruction, preferential flow along open corridors.	Moderately destructive debris surge movement in existing river channel or other open corridors. Forest and structures near corridors surrounded by debris.	Destructive currents in flood corridor. Diffuse flooding, deposition of gravel in low areas, plugging of channels and ditches.
3	Moderate speed and depth, most forest and structures surrounded but not destroyed, some deposits reworked by water. Very nonuniform damage.	Slow movements, thin discontinuous deposits controlled by topographic details and obstructions. Structural damage minor, erosion by water flow in new channels.	Flooding damage, sediment deposition (gravel), erosion by flow in new channels.	Moderately strong currents in main channel, branching, diffusion, deposition of gravel, erosion.
4	Slow movements, thin discontinuous deposits strongly controlled by topographic details and obstructions. Structural damage minor, erosion by water flow in new channels.	Most damage due to water flow, deposition of sediment (gravel), erosion due to flow in new channels. Water and sediment ponding in low areas.	Flooding damage (gravel deposition, erosion). Water and sediment ponding in low areas.	Moderately strong current in main channel, minor flooding damage outside (gravel deposition, erosion). Water and sediment ponding in low areas.
5	Debris filling the flood plain in some locations, possible temporary landslide dam several metres high, complete change of flow patterns in river, possible small outburst wave, erosion of fan margin scarp.	Possible temporary dam at the location of present Cheekye River mouth. Change of flow patterns in Cheakamus/Squamish due to sediment overload.	Possible temporary dam at the mouth of the Cheekye River. Moderate flow pattern changes downstream. Erosion of fan margin scarp.	Erosion of fan margin scarp.
6	No direct impact of debris. River flooding possible due to landslide dam, rapid erosion of the right river bank due to displaced current.	Possible flooding due to landslide dam at Cheekye mouth. Possible erosion elsewhere.	Possible flooding due to landslide dam at Cheekye mouth.	No effect.

TABLE 7.3

PARAMETERS FOR FLOODING ON FAN

Fan Zone	Damage Corridor	Max. Velocity	Max. Depth
1	20 to 50m (channel width)	about 4 to 5 m/s	about 1 to 1.5 m; locally deeper
2	up to 100 to 200 m; sporadic within the corridor.	up to 3 m/s in channels running down the fan; otherwise less than 1 m/s.	up to 1 to 1.5 m in channels; 1 to 2 m outside, depending on on obstruction heights.
3	up to 200 m; sporadic within the corridor.	up to 2 m/s in channels running down the fan; otherwise less than 1 m/s.	up to 1 m in channels; 0.5 to 1m outside, depending on obstruction heights.
4	200 to 300 m; very sporadic within the corridor.	up to 2 m/s in channels channels running down the fan; otherwise less than 1 m/s.	up to 1 m in channels; 0.5 to 1 m outside, depending on obstruction heights.

TABLE 8.1

EXPLANATION OF ZONING ON FIGURES 8.1, 8.6, 8.7, 9.1, 9.2 AND 9.3: ESTIMATED EFFECTS OF POTENTIAL DEBRIS FLOW HAZARDS

DEBRIS FLOW			
Magnitude Class	A(3M-7Mm³)	B(1M-3Mm³)	C(100,000 - 1Mm³)
Return Period **Fan Zone**	2,450 - 10,000	930 - 2,450	52 - 930
1	Forest cover and all structures destroyed, topography changed. V=7m/s T=5m W=1-1.5m	Complete destruction possible in a part of corridor; complete change of drainage pattern. V=4m/s T=4m W=-.7-1.0m	Destructive debris flow surges along and close in the existing Cheekye river channel. Partial destruction elsewhere. V=3m/s T=3m W=0.2-0.7m
2	Less rapid but still very destructive debris flow; deposits of variable thickness; preferential flow along open corridors. V=4m/s T=3.5m W=0.7-1.5m	Most forest stands and structures not destroyed, some concentrated destruction V=3m/s T=2.5m W=0.5-0.07m	Forest and structures near open corridors surrounded by debris. V=2m/s T=2m W=0.2-0.5m
3	Forest and structures surrounded but not destroyed. Very non-uniform damage. Damage minor, erosion by water flow in new channels. V=3m/s T=2m W=0.5-1.0m	Deposits controlled by topographic details and obstructions. Structural damage minor. Erosion by water flow in new channels. V=2m/s T=1m W=0.2-0.5m	Flooding damage, sediment deposition (gravel) erosion by flow in new channels. V=1m/s T=0.5m W=0.2m
4	Deposits strongly controlled by topographic details and obstructions. Structural damage minor, erosion by water flow in new channels. V=2m/s T=1m W=0.4m	Most damage due to water flow, deposition of sediment (gravel), erosion and sediment ponding V=1m/s T=0.5m W=0.2m	Minor flooding damage (gravel deposition, erosion). Water and sediment ponding in low areas. V=1m/s T=0.2m W=0.2m
5	Debris filling the plain in some locations, possible temporary landslide dam several metres high, erosion of fan margin scarp.	Possible temporary dam at the location of present Cheekye River mouth. Change of flow patterns in Cheakamus/ Squamish.	Possible temporary dam at the mouth of the Cheekye River. Moderate flow pattern changes downstream.
6	No direct impact of debris. River flooding possible due to landslide dam, rapid erosion of the right river bank.	Possible flooding due to landslide dam at Cheekye mouth. Possible erosion else- where.	Possible flooding due to dam at Cheekye mouth.

Maximum Parameters: V=Velocity in m/s, T=Thickness of deposits in m, W=Width of damage corridor in kilometres.

Note: 1) Hazard zone boundaries are transitional. Any site located within approximately 200m of a boundary could have some of the characteristics of the adjacent zone. Such sites should be reassessed by means of a site specific investigation, if the distinction is important.

TABLE 8.2
RISK ACCEPTABILITY CRITERIA QUOTED IN LITERATURE

No.	Source	Hazard	Country	Year	Acceptable Risk Limits			Notes
					P.D.I.	P_D	Acc. Hazard Probability	
1	Cave (1991)	Rapid landslide snow avalanches	Canada	1991			1/10,000	For establishment of new communities.
2	Puget Sound Council of Governments (1975)	Natural hazards	U.S.A.	1975	1/1,000,000 1/100			Including injuries (10 x deaths). Applicable for location independent development. Applicable for locating dependent (industrial) development.
3	Royal Society (1983)	Any hazards	U.K.	1983	1/1,000 to 1/1,000,000			Risk management required within the given range.
4	National Building Code (1990)	Structural failure	Canada	1990			1/10,000	Probability of damage to key structural components.
5	Swiss Standards	Snow avalanche	Switz.	1990			1/300	Probability of an event with any impact pressure.
6	Oosthuizen (1988)	Dam failure	S. Africa	1988	1/2000 to 1/200	1/100,000 - 1/10,000		Low to high risk range for 100 lives endangered. Low to high risk range for one person.
7	ICOSD, Coimbra (1984)	Dam failure		1984			1/10,000	
8	Dutch Environmental Policy Plan (1989)	Environmental hazards	Holland	1989		$1/10^{-7}$ to $1/10^{-5}$ $1/10^{-10}$ to $1/10^{-7}$		Major accident involving 10 casualties. Major accident involving 100 casualties.
9	T. Berger (1976) (Rubble Creek)	Rock avalanche	Canada				1/10,000	For establishment of a new community.
10	B.C. Ministry of Transportation & Highways	Various landslides	Canada				1/500	For subdivision approvals.
11	CSA LNG Standard (1991)	Seismic damage to LNG facilities	Canada	1991			1/10,000	"Safe shutdown limit"
12	B.C Hydro (1985)	Seismic damage to dams	Canada	1985			1/2,000	"Maximum credible earthquake".
13	Hestnes and Lied (1980)	Snow avalanche	Norway	1980	1/1660 to 1/3330			Assuming 5 - 10 accidents per fatality.
14	Morgan (1981)	Any hazards	Canada	1981	1/10,000			Boundary between commonly accepted "voluntary" and "involuntary" risks.

Notes: P.D.I. = probability of death of an individual
P_D = probability of a disaster involving a number of casualties

TABLE 8.3
ANNUAL PROBABILITY OF DEATH (PDI) OF AN INDIVIDUAL
INVOLVED IN VOLUNTARY OCCUPATIONAL RISKS
VERSUS INVOLUNTARY RISKS
(After Morgan, 1991)

ACTIVITY	ANNUAL PROBABILITY DEATH[1] (PDI)
VOLUNTARY INDIVIDUAL RISKS:	
National Leader	1:50
Rock Climbing	1:250[3]
Commercial Diving	1:350
Deep Sea Fishing	1:350
Offshore Oil & Gas	1:600
Air Travel (Crew)	1:1000
Agriculture	1:2000
Car Travel (B.C. 1984)	1:3500[2]
Motorcycle Racing	1:5000
Construction	1:1500 - 1:6000
Air Travel (passenger)	1:9000
Agriculture	1:9000[3]
Skiiing	1:10000
Child Bearing (UK)	1:10000
INVOLUNTARY INDIVIDUAL RISKS (including low risk occupations):	
Manufacturing (building materials)	1:15,000
Fire (UK average)	1:50,000
Household electrocution	1:65,000
Drowning (UK average)	1:100,000
Manufacturing (clothing/footwear)	1:200,000
Natural Hazards (Norway)	1:350,000
Lightning	1:5,000,000
Structural Failure	1:10,000,000

Notes:

(1) Relative to the population employed in, or exposed to, the activity.
(2) For an individual travelling 10,000 km/year.
(3) Participating 100 hours/year.

Sources:

Kinchin (1978); Rodin (1978); Cohen et al. (1978);
Hestness et al. (1980); Royal Society (1983); Ministry of Transportation and
Highways (1984); Pack and Morgan (1988); B.C. Hydro (1989)

TABLE 8.4

HAZARD PROBABILITY UNDER EXISTING CONDITIONS

Zone	Hazard Probability (annual)			
	Rock Avalanche	Debris Flow	Non-destructive Debris Flow (debris flood)	Flooding [1]
1	negligible	1/50	1/50	1/50
2	"	1/1,000	1/50	1/50
3	"	1/2,500	1/50	1/50
4	"	negligible	1/2,500	1/200
5	"	negligible	negligible	1/10
6	"	negligible	negligible	1/50 [2]

[1] See Table 7.3 for description of flooding parameters.

[2] Flooding as a direct result of interaction between the Cheekye and Cheakamus only.

Note: the distinction between debris flow and non-destructive debris flow was drawn at a flow velocity of 3m/sec.

TABLE 8.5

HAZARD ACCEPTABILITY CRITERIA DEVELOPED BY THE REGIONAL DISTRICT OF FRASER CHEAM (from Cave, 1991)*

Debris Flood	>1:50	1:50 - 1:200	1:200 - 1:500	1:500 - 1:10,000
Minor Repair (< 25%)	2	2	1	1
Major Repair (> 25%)	4	4	1	1
Reconstruction	4	4	3	1
Extension	4	4	3	1
New Building	4	4	3	1
Subdivision (infill/extend)	5	5	4	2
Rezoning (for new community)	5	5	5	3

Debris Flow/Debris Torrent	>1:50	1:50 - 1:200	1:200 - 1:500	1:500 - 1:10,000	< 1:10,000
Minor Repair (< 25%)	5	2	2	1	1
Major Repair (> 25%)	5	4	2	1	1
Reconstruction	5	5	4	3	1
Extension	5	5	4	2	1
New Building	5	5	4	3	1
Subdivision (infill/extend)	5	5	5	4	1
Rezoning (for new community)	5	5	5	5	1

Mountain Stream Erosion or Avulsion	>1:50	1:50 - 1:200	1:200 - 1:500	1:500 - 1:10,000
Minor Repair (< 25%)	4	2	1	1
Major Repair (> 25%)	4	4	1	1
Reconstruction	5	4	3	1
Extension	5	4	3	1
New Building	5	4	3	1
Subdivision (infill/extend)	5	5	4	1
Rezoning (for new community)	5	5	5	1

* Note that there is a erratum sheet attached to this reference and the above tables incorporate the amendments.

TABLE 8.6

ESTIMATED ANNUAL RISK TO LIFE OF A SPECIFIC INDIVIDUAL, ASSUMED TO BE RESIDENT ON THE CHEEKYE FAN 100% OF THE TIME

Zone	PDI * for a Specific Full-time Resident from the range of Hazards Listed in Table 7.2
1	1/500 - 1/160
2	1/2,000 - 1/900
3	1/19,000 - 1/9,000
4	0 - 1/20,000

* "Probability of death of a specific individual" (annual).
For a part-time resident, multiply by the percentage of time spent on the fan.

TABLE 8.7

ASSUMPTIONS REGARDING LAND USE AND
POPULATION DENSITY FOR THE PDG ANALYSIS

Zone	Development and Land Use	Population Density (D)
1	No development; no land use.	0
2	No residences or work places; temporary recreational use only.	$0.05 \cdot D$
3	Light commercial/industrial use; no concentrated populations; no residences.	$0.5 \cdot D$
4	No restrictions on development, except no concentrated populations, such as schools, hospitals.	D

TABLE 8.8

ESTIMATED RESIDUAL HAZARD PROBABILITY, AFTER CONSTRUCTION OF SMALL DYKES (SCENARIO 3)[1]

Mitigated Zone[2]	Rock Avalanche	Debris Flow	Non-destructive Debris Flow (Debris Flood)	Flooding
A	negligible	1/1,000	negligible to 1/50	1/50
B	negligible	1/1,000	1/1,000	negligible
C	negligible	1/2,500	1/1,000	negligible
D	negligible	negligible	1/1,000	negligible
5	no effect of dykes			
6	no effect of dykes			

1   See Figure 8.8.
2   Resulting from partial mitigation by "small" dykes.

TABLE 8.9

ESTIMATED RESIDUAL RISK TO LIFE, AFTER CONSTRUCTION OF SMALL DYKES (SCENARIO 3)[1]

Mitigated Zone[2]	Residual PDI for a Specific Full-time Resident, from Debris Flow Types A and B
1	1/3,000 - 1/2,000
2	1/12,000 - 1/7,000
3	1/100,000 - 1/50,000
4	1/300,000

[1]   See Figure 8.8.
[2].   Resulting from partial mitigation by "small" dykes.

TABLE 8.10
EXPLANATION OF ZONING ON FIGURE 8.8:
ESTIMATED EFFECTS OF POTENTIAL DEBRIS FLOW HAZARDS

DEBRIS FLOW		
Magnitude Class	A(3M-7Mm³)	B(1M-3Mm³)
Return Period Mitigated Fan Zone	2,450 - 10,000	930 - 2,450
Ⓐ	Forest cover and all structures destroyed topography changed. V-7 T=5 W=1-1.5	Complete destruction possible in part of corridor, complete change of drainage pattern. V=4 T=4 W-0.7-1.0
Ⓑ	Less rapid but still very destructive debris flow, deposits of variable thickness, preferential flow along open corridors. V=4 T=3.5 W=0.7-1.5	Most forest stands and structures not destroyed, some concentrated destruction. V=3 T=2.5 W=0.5-0.7
Ⓒ	Forest and structures surrounded but not destroyed. V=3 T=2 W=0.5-1.0	Deposits controlled by topographic details and obstructions. Structural damage minor, erosion by water flow in new channels. V=2 T=1 W=0.2-0.5
Ⓓ	Deposits strongly controled by topographic details and obstructions. Structural damage minor, erosion by water flow in new channels. V=2 T=1 W=0.4	Most damage due to water flow, deposition of sediment (gravel), erosion and sediment ponding. V=1 T=0.5 W=0.2

Maximum Parameters: V=Velocity in m/s, T=Thickness of deposits in m, W=Width of damage corridors in kilometres.

Note:　　1) Hazard zone boundaries are transitional. Any site located within approximately 200m of a boundary could have some of the characteristics of the adjacent zone. Such sites should be reassessed by means of a site specific investigation, if the distinction is important.

2) Effects of unmitigated fan zones as shown on Table 8.1.

TABLE 9.1

1/LOTUS/TAB-93/MAR/T91-1525.wk1

PROPOSED MUNICIPAL REGULATORY STRATEGY FOR FAN DEVELOPMENT

Zone #	OCP Designation	Zoning	Development Permit	Approvals Requirements	Special Considerations For Existing Uses (without mitigation)
1	Designate only for uses that involve no significant habitation. Silviculture, outdoor recreation (requiring no significant improvements): resource extraction are examples of appropriate uses. Include alluvial fan flood-proofing policies.	Consistent with OCP designation, provided that zoning allows some economic use.	Not likely necessary, although may be needed if the allowable uses require minor, ancillary improvements.	There are no existing structures, so there will be little need for special requirements or procedures. Any permits (e.g., for uses or structures ancillary to allowable uses) should have requirements for geotechnical analysis, covenants, siting controls, protective works, and floodproofing as appropriate.	Highway and utility corridors exist in this zone. The agencies responsible should be expected to be fully responsible for decisions regarding continuation versus relocation. The Municipal landfill and reservoir require site-specific analysis of advantages and disadvantages of alternatives (e.g., relocation, protection, do-nothing).
2	Similar to Zone 1, but because of less destructive effects policy could allow more intensive forms of outdoor recreation, such as golf course, without residential facilities, particularly if the probability of death approach indicates acceptable risk. No habitable uses. Include alluvial fan flood-proofing policies.	Consistent with OCP designation, provided that zoning allows some economic use.	Should be development permit area for any uses which require structures.	Any permits for new uses or subdivision approvals should require geotechnical analysis, covenants, siting controls, protective works, and floodproofing as needed. Because there are a few existing habitable uses, the Municipality should have a specific policy for these. The minimum requirement should be the use of covenants to protect the Municipality, even for minor repairs. Geotechnical analysis, siting controls, and/or works may be necessary on specific sites.	As for Zone 1 for transportation and facility uses. As well, the few existing houses require special consideration. Policy should balance protection/ liability against burden on individual homeowners.
3	Designations should reflect existing uses and should allow limited infill, but large tracts of vacant land should be designated as for Zone 2. Include alluvial fan flood-proofing policies.	Existing uses should be zoned accordingly (i.e. not made nonconforming). Infill sites should be zoned for appropriate use. Large tracts of vacant land should be zoned consistent with the OCP designations, provided that zoning allows some economic use.	All of this zone should be a Development Permit area to allow detailed regulation of siting, design, tree cover and other aspects of development.	This area has exposure to significant debris flows, debris floods, and river flooding. While the severity is not as great as in Zones 1 and 2, the probability of some hazard is relatively high. Therefore, the regulatory approach should allow existing uses to remain and limited infill to occur, with adequate measures, but should not allow significant new development/ subdivision without complete resolution of liability and hazard issues. All permits or approvals for existing buildings should require covenants and, where needed, floodproofing. New units on existing lots and infill subdivision should require covenants, floodproofing, siting controls and, if necessary, protective works based on geotechnical review. Significant new developments (rezoning, subdivision) should not be allowed until an area-wide mitigation strategy is in effect. This is particularly important because Zone 3 (at present) includes lands that could have increased exposure to hazard in some of the mitigation strategies that emphasize protecting Zone 4.	Municipal facilities (airport, cemetery) require site-specific analysis of advantages and disadvantages of alternatives (e.g. relocation, protection, do-nothing). The existing school, church, and utility facilities also require site-specific evaluation of alternatives.
4	Designations should be determined primarily by general community planning and servicing conditions, because exposure to hazard is not so great as to be the primary determinant of land use. Include alluvial fan flood-proofing policies.	Consistent with OCP designations.	Probably only appropriate for larger sites and significant new development proposals.	This area has exposure to debris flows, debris floods, and flooding, although at considerably less severity than other zones. It would be prudent to require covenants in all permits/approvals (even minor). With so many existing uses, though, it may not be appropriate to be as onerus as in Zone 3. New buildings on existing lots and new infill subdivision should be allowed but should require covenants, floodproofing, and possibly geotechnical analysis if not prohibitive. Major repairs should require covenants, but a policy decision is required to balance protection/ liability concerns against the burden on many existing homeowners. Large new developments (rezoning, subdivision) should not be approved until an overall mitigation strategy is in place and should require geotechnical analysis, covenants, siting controls and protective works as necessary.	The elementary school will require a site-specific analysis of the advantages and disadvantages of alternatives (e.g. relocate, protect, do-nothing).
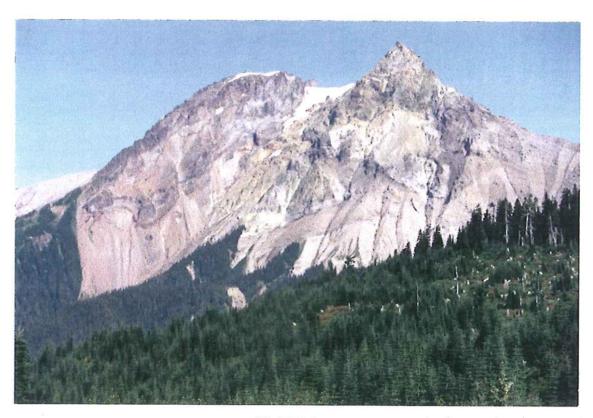
PLATE 1

Dalton Dome and Atwell Peak from Cheekye Ridge.
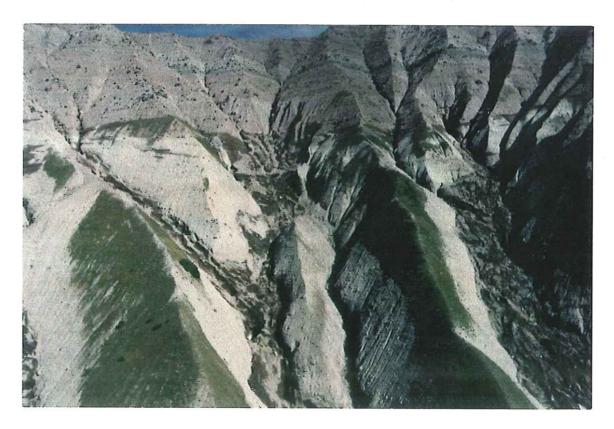
PLATE 2

Pyroclastic breccias in the headwall of Cheekye Valley.

PLATE 3

View of Atwell Peak from Diamond Head, showing Diamond Head
Glacier and the crest of Cheekye Valley.
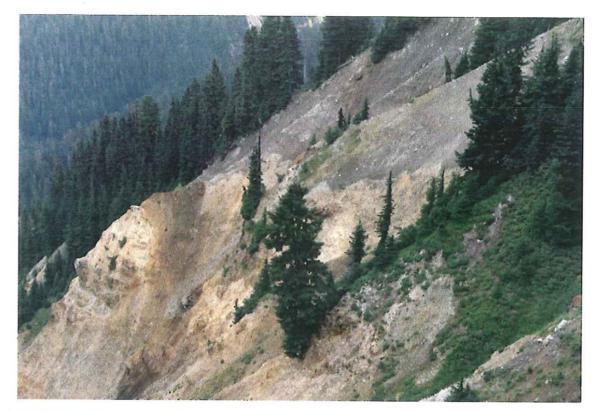
PLATE 4

Pyroclastic breccias between Dalton Dome and Brohm Ridge.

PLATE 5

Dalton Dome volcanic sequence.

PLATE 6

Contact between pyroclastic breccias and altered basement on Cheekye Ridge.

PLATE 7

Micaceous silt gouge in the altered basement rocks near the base of Plate 6.

PLATE 8

Cheekye linears. Overall view looking east.

PLATE 9

Cheekye linears. Brohm Ridge in the distance.

<u>PLATE 10</u>

Minor sag features on Cheekye Ridge, Elevation 1,650 m. The valley is to the left.
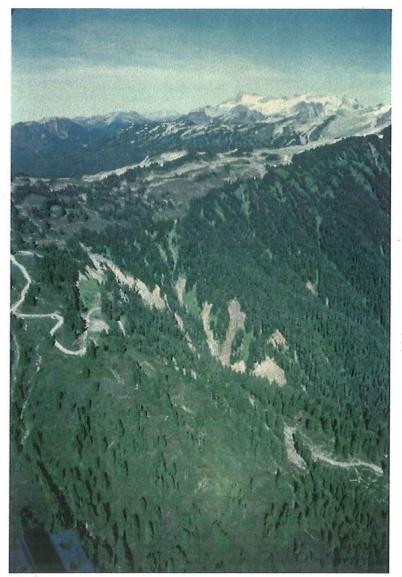
<u>PLATE 11</u>

Disturbed area on Brohm Ridge. Cheekye Valley is to the right.

PLATE 12

East side of Test Pit 91-C-2 on Cheekye Ridge, showing buried peat.

PLATE 13

West side of Test Pit 91-C-2 on Cheekye Ridge, showing steep shear surface.

<u>PLATE 14</u>

Cheekye Gorge, near the apex of the Upper Fan.

<u>PLATE 15</u>

Lower segment of Cheekye Gorge, looking downstream.

PLATE 16

Garbage Dump deposit and a buried log.

PLATE 17

Typical texture of the Garbage Dump deposit.

PLATE 18

Debris flood ("fluvial") deposit near the margin of Cheekye Fan.

PLATE 19

Debris flow deposit (top layer) overlying a fluvial sequence near the
Cheakamus River.

PLATE 20

Test Pit TP92-6, With Surface Diamicton
Unit Overlying Stream Gravel
(2 X 2 m Reference Frame)

PLATE 21

Test Pit TP92-2, With Fluvial Material
(2 X 2 m Reference Frame)

PLATE 22
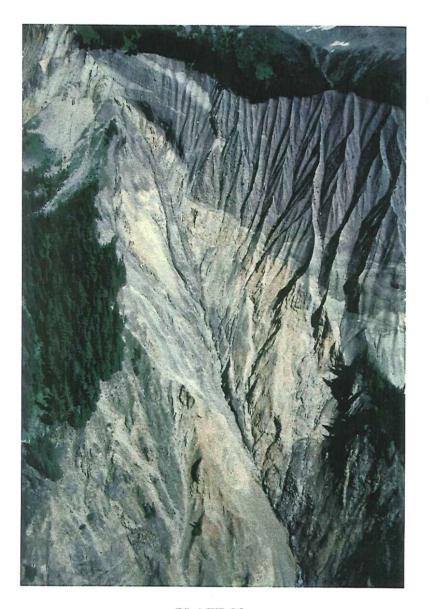
PLATE 23

Source area of the 1984 Mt. Cayley
debris avalanche - debris flow.
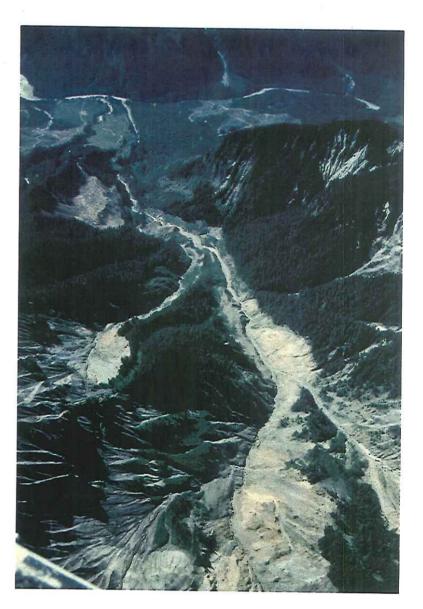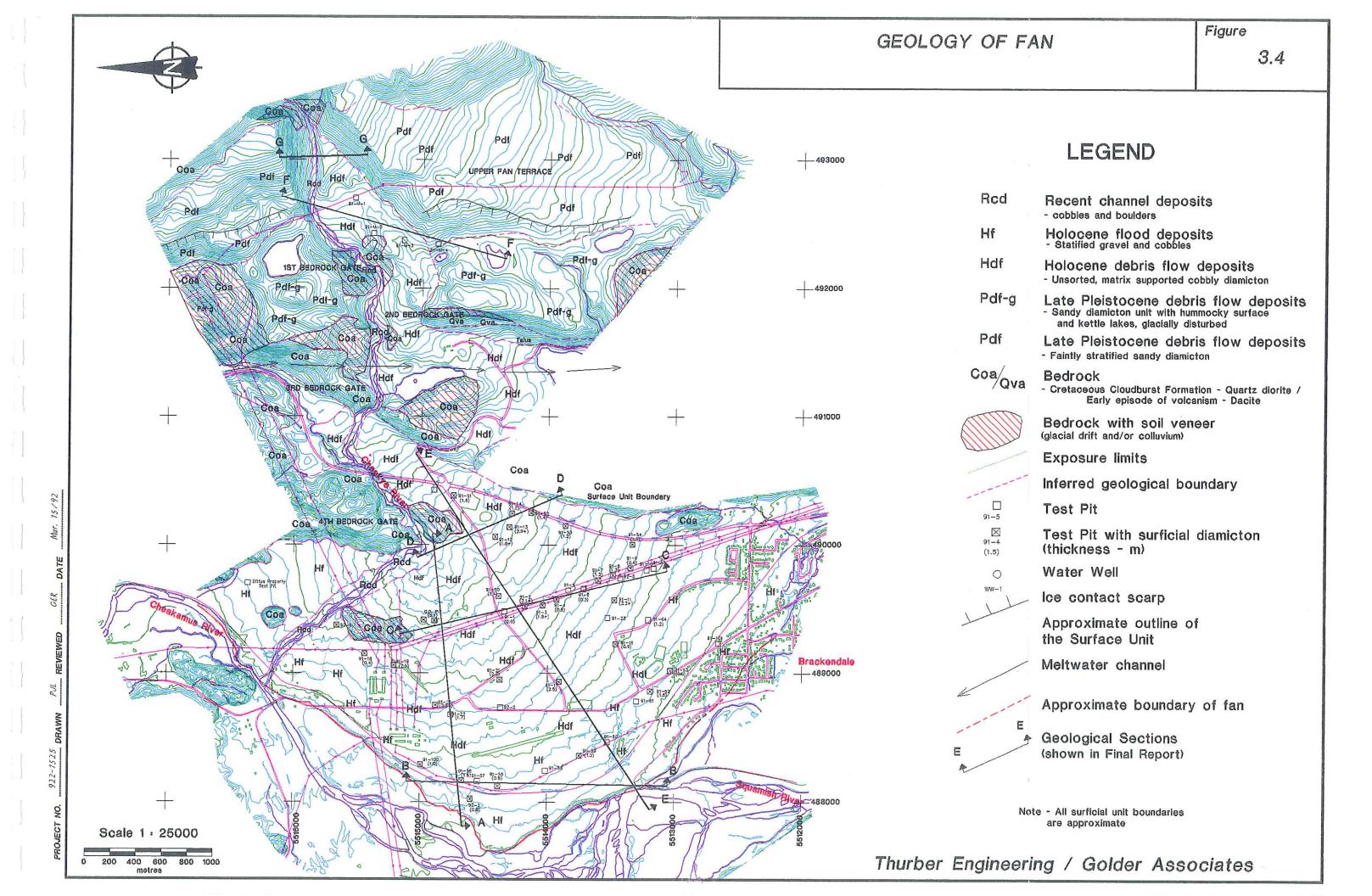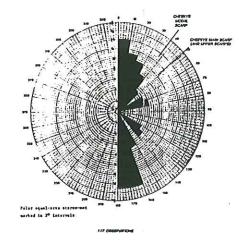
PLATE 24

Path of the 1984 Mt. Cayley
debris avalanche. The right
trimline in the first bend of
the path is 115 m above the channel.

GEOLOGY OF FAN

Figure 3.4

LEGEND

Rcd	**Recent channel deposits** - cobbles and boulders	
Hf	**Holocene flood deposits** - Statified gravel and cobbles	
Hdf	**Holocene debris flow deposits** - Unsorted, matrix supported cobbly diamicton	
Pdf-g	**Late Pleistocene debris flow deposits** - Sandy diamicton unit with hummocky surface and kettle lakes, glacially disturbed	
Pdf	**Late Pleistocene debris flow deposits** - Faintly stratified sandy diamicton	
Coa/Qva	**Bedrock** - Cretaceous Cloudburst Formation - Quartz diorite / Early episode of volcanism - Dacite	

Bedrock with soil veneer (glacial drift and/or colluvium)

Exposure limits

Inferred geological boundary

Test Pit   91-5

Test Pit with surficial diamicton (thickness - m)   91-4 (1.5)

Water Well   WW-1

Ice contact scarp

Approximate outline of the Surface Unit

Meltwater channel

Approximate boundary of fan

Geological Sections (shown in Final Report)

Note - All surficial unit boundaries are approximate

Scale 1 : 25000

0 200 400 600 800 1000
metres

Thurber Engineering / Golder Associates

PROJECT NO. 922-7525 DRAWN P.J.L. REVIEWED GER DATE Mar. 15 / 92

APPROXIMATE OUTCROP OF
QUATERNARY VOLCANICS

PHOTOLINEAMENTS

Polar equal-area stereo-net
marked in 2° intervals

117 OBSERVATIONS

TRENDS OF MAJOR PHOTOLINEAMENTS

0   2000   4000

SCALE - metres

DESIGN	G.R.	Thurber Engineering Ltd./	CHEEKYE RIVER TERRAIN HAZARD STUDY		
DRAWN		Golder Associates Ltd.	PHOTOLINEAMENTS IN PROJECT AREA		
APPROVED	G.R.	PROVINCE OF BRITISH COLUMBIA			
DATE	Dec. 1991	MINISTRY OF ENVIRONMENT, LANDS & PARKS	SCALE 1 : 50 000	PROJECT No. 912-1402	DRAWING No. 3.5

LOCATION PLAN

Figure 1.1

STUDY AREA

BRITISH COLUMBIA

ALBERTA

PACIFIC OCEAN

BRACKENDALE

Cheekye Fan

Squamish River

Cheakamus River

Cheekye River

Brohm Ridge

SQUAMISH

Cheekye Ridge

Mount Garibaldi

Atwell Peak

Diamond Head

Miles 1   0   3 Miles
Metres 1000   0   1000   2000   3000   4000 Mètres
Yards 1000   0   1000   2000   3000   4000 Verges

Thurber Engineering/Golder Associates

Geology by N. Green (1974-75) modified after Mathews
and Roddick and Woodsworth (1975).

Thurber Engineering/Golder Associates

QUATERNARY GEOMORPHOLOGICAL FEATURES, STUDY AREA

Figure 3.3

LEGEND

⬚ (diagonal hatch)	Contemporary Glaciers
⬚ (stippled)	Recent Colluvial and Alluvial Fans
⊘	Roche Moutonée (bedrock knobs)
⬮	Kettle Lakes
→→	Melt Water Channel
⊤⊤⊤	Ice Contact Scarp
■	Kame Deposits
⬚ (dotted)	Pleistocene Colluvial Terrace
⬭	Area Free of Glacial Drift (with all identified erratics)

Thurber Engineering / Golder Associates

North

a) CHeekye Ridge

Valley Slope →

North

Valley Slope ←

b) Brohm Ridge

LOWER HEMISPHERE POLAR EQUAL
AREA PROJECTION

☐ Foliation and Schistosity
+ Joints
△ Faults, Dykes

PROJECT NO. *912-1464* DRAWN *E.A.* REVIEWED *Jn* DATE *March '93*

Thurber Engineering / Golder Associates

PROJECT NO. 912-1464 .... DRAWN G.A. REVIEWED WA DATE March '93 ......

M.I.T. GRAIN SIZE SCALE

LEGEND:
Sample A
Sample B

Size of opening, inches

U.S.S. sieve size, meshes / inch

GRAIN SIZE, mm

PERCENT FINER THAN

BOULDER | COBBLE SIZE | GRAVEL SIZE (coarse | medium | fine) | SAND SIZE (coarse | medium | fine) | SILT SIZE (fine grained) | CLAY SIZE (fine grained)

Grain size distribution, silty gouge in altered basement rocks, location H48

— **Thurber Engineering/Golder Associates** —

LEGEND:
1) Location H48 Cheekye Ridge
2) Test Pit 91-C-2, Cheekye Ridge, Sample C
3) Test Pit 91-C-2, Cheekye Ridge, Sample D
4) Location H, Base of Diamond Head Headwall
5) Location H6, below Dalton Dome
6) Location H8, Top of Brohm Ridge
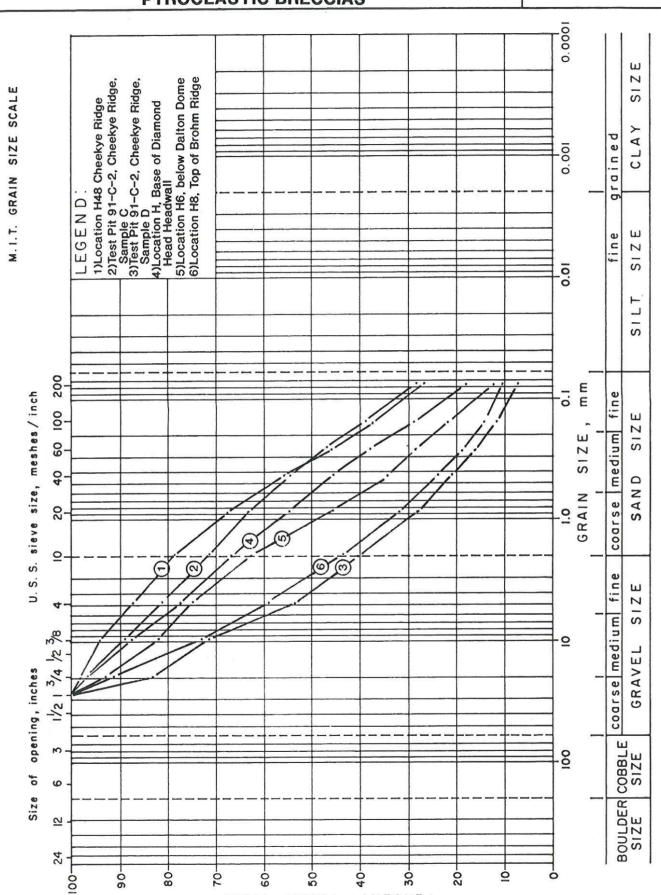
Typical grain size distribution curves, Pyroclastic breccias.

Thurber Engineering / Golder Associates
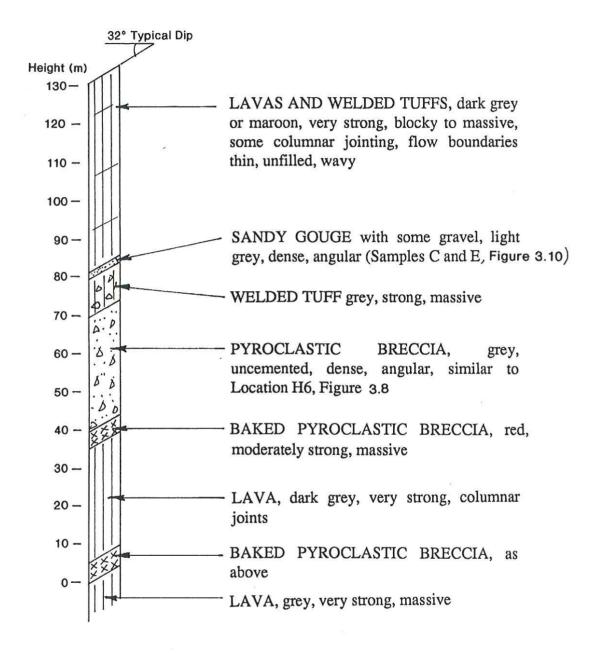
PROJECT NO. 9/2-1464 DRAWN 6.4. REVIEWED W DATE March '93

32° Typical Dip

Height (m)

130 —

120 —

110 —

100 —

90 —

80 —

70 —

60 —

50 —

40 —

30 —

20 —

10 —

0 —

LAVAS AND WELDED TUFFS, dark grey or maroon, very strong, blocky to massive, some columnar jointing, flow boundaries thin, unfilled, wavy

SANDY GOUGE with some gravel, light grey, dense, angular (Samples C and E, Figure 3.10)

WELDED TUFF grey, strong, massive

PYROCLASTIC   BRECCIA,   grey, uncemented, dense, angular, similar to Location H6, Figure 3.8

BAKED PYROCLASTIC BRECCIA, red, moderately strong, massive

LAVA, dark grey, very strong, columnar joints

BAKED PYROCLASTIC BRECCIA, as above

LAVA, grey, very strong, massive

PROJECT NO. 912-1464 DRAWN G.A. REVIEWED DATE March '93

GRAIN SIZE DISTRIBUTION

SANDY GOUGE IN THE DALTON DOME VOLCANICS

Figure **3.10**

M.I.T. GRAIN SIZE SCALE

Size of opening, inches

U.S.S. sieve size, meshes / inch

LEGEND:

Location H3, Sample E

Location H1, Sample C

PERCENT FINER THAN

GRAIN SIZE, mm

BOULDER SIZE	COBBLE SIZE	coarse	medium	fine	coarse	medium	fine	coarse	medium	fine
		GRAVEL SIZE			SAND SIZE			SILT SIZE		CLAY SIZE
									fine grained	

Grain size distribution, sandy gouge in the Dalton Dome volcanic column.

Thurber Engineering/Golder Associates

SCALE 1 : 10 000

LEGEND

Scarp Height in metres

Thurber Engineering / Golder Associates

← —— NW (towards Cheekeye Valley)

35-38°

SILT, grey, loose, with some sand and
gravel (slope wash)

TOPSOIL

PEAT
(C_{14} 3220 years)

DISCONTINUITY, dip 82° at azimuth 290
signs of normal shear displacement

SILTY SAND, light brown, compact, with
some gravel and cobbles (slope wash)

SILTY SAND, GRAVEL AND COBBLES,
brown, dense, angular, slightly fissured
(weathered pyroclastics, Sample C)

SILTY SAND, GRAVEL AND COBBLES,
grey, very dense, angular (unweathered
pyroclastics, Sample D)

SCALE

0   1   2   3   4 metres
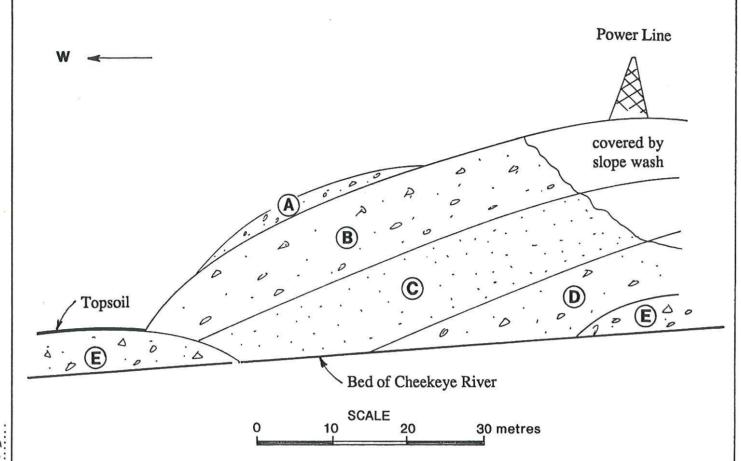
NOTE : Test Pit located at the base of 8.0m high normal scarp near
the centre of the Cheekye Linears

PROJECT NO. 912-1464 DRAWN G.A. REVIEWED J.W. DATE March '93

BROHM RIDGE LINEARS

Figure **3.13**

5,521,000 N

5,520,000 N

495,000 E

SCALE 1 : 10 000

LEGEND

7   Scarp Height in metres

Thurber Engineering/Golder Associates

W ←

Power Line

covered by slope wash

(A)

(B)

(C)

(D)

(E)

Topsoil

(E)

Bed of Cheekeye River

SCALE

0   10   20   30 metres
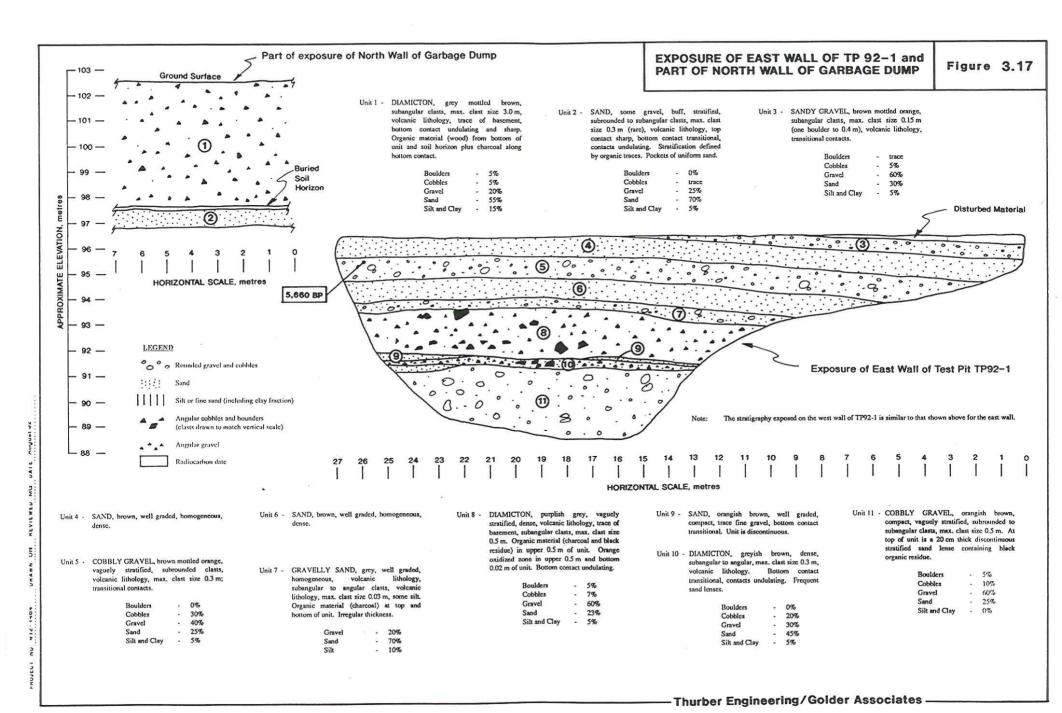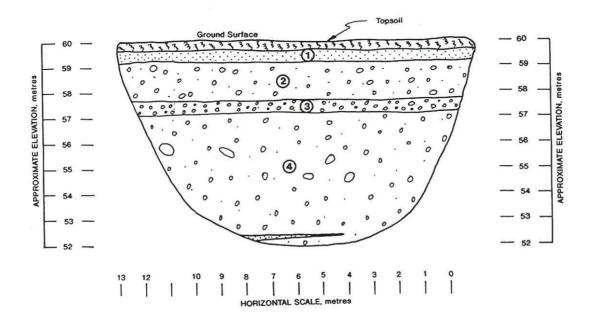
(A) DIAMICTON, tan, dense, angular, faintly stratified, 30% sand and fines, max. clast 1.0 m

(B) DIAMICTON, tan, very dense, angular, faintly stratified, 55% sand and fines, max. clast 1.0 m

(C) DIAMICTON, tan, very dense, angular, homogeneous, 70% sand and fines, max. clast 0.2 m

(D) DIAMICTON, similar to B

(E) TERRACE DIAMICTON (deposited against an erosional scarp cut in Units B-D), grey, compact, angular 40% sand and fines, fragments of tree trunks (recent debris flow deposits)

Thurber Engineering/Golder Associates

Upper Fan Deposit
(diamicton)

Ground Surface
Elevation – m

500
450
400
350

Cheekye River

Exposure
B 89

Ground Surface

Ground Surface
Elevation – m

500
450
400
350

Max. clast 0.7m

% sand & finer +55%

TOPOGRAPHY SCALE 1 : 5,000 (horizontal & vertical)

EXPOSURE SCALE 1 : 200 (vertical)

Thurber Engineering/Golder Associates

SECTION F – F THROUGH MIDDLE FAN | Figure 3.16

Upper Fan Deposit (diamicton)

(14m to East) TP 91-M-1
(7m to West) TP 91-M-2
(5m to West) TP 91-M-3
(1m to West) TP 91-M-4

Ground Surface Elevation – m
400
350
300
250

Cheekye River
Ground Surface
Fawn Lake

Ground Surface Elevation – m
400
350
300
250

TEST PIT SCALE – vertical
0 5 10

TOPOGRAPHY SCALE – horiz. & vert.
0 100 200 300

Maximum Clast. Dia. in Diamicton
2m
1m
0

Maximum Clast. Dia. in Diamicton
2m
1m
0

% Sand & Fines in Diamicton
100
50
0

% Sand & Fines in Diamicton
100
50
0

Thurber Engineering / Golder Associates

EXPOSURE OF EAST WALL OF TP 92-1 and PART OF NORTH WALL OF GARBAGE DUMP

Figure 3.17

Unit 1 - DIAMICTON, grey mottled brown, subangular clasts, max. clast size 3.0 m, volcanic lithology, trace of basement, bottom contact undulating and sharp. Organic material (wood) from bottom of unit and soil horizon plus charcoal along bottom contact.

Boulders	-	5%
Cobbles	-	5%
Gravel	-	20%
Sand	-	55%
Silt and Clay	-	15%

Unit 2 - SAND, some gravel, buff, stratified, subrounded to subangular clasts, max. clast size 0.3 m (rare), volcanic lithology, top contact sharp, bottom contact transitional, contacts undulating. Stratification defined by organic traces. Pockets of uniform sand.

Boulders	-	0%
Cobbles	-	trace
Gravel	-	25%
Sand	-	70%
Silt and Clay	-	5%

Unit 3 - SANDY GRAVEL, brown mottled orange, subangular clasts, max. clast size 0.15 m (one boulder to 0.4 m), volcanic lithology, transitional contacts.

Boulders	-	trace
Cobbles	-	5%
Gravel	-	60%
Sand	-	30%
Silt and Clay	-	5%

LEGEND

- ∘₀∘∘ Rounded gravel and cobbles
- Sand
- Silt or fine sand (including clay fraction)
- ▲▲ Angular cobbles and bounders (clasts drawn to match vertical scale)
- ▴▴ Angular gravel
- ▭ Radiocarbon date

5,660 BP

Note: The stratigraphy exposed on the west wall of TP92-1 is similar to that shown above for the east wall.

Unit 4 - SAND, brown, well graded, homogeneous, dense.

Unit 5 - COBBLY GRAVEL, brown mottled orange, vaguely stratified, subrounded clasts, volcanic lithology, max. clast size 0.3 m; transitional contacts.

Boulders	-	0%
Cobbles	-	30%
Gravel	-	40%
Sand	-	25%
Silt and Clay	-	5%

Unit 6 - SAND, brown, well graded, homogeneous, dense.

Unit 7 - GRAVELLY SAND, grey, well graded, homogeneous, volcanic lithology, subangular to angular clasts, volcanic lithology, max. clast size 0.03 m, some silt. Organic material (charcoal) at top and bottom of unit. Irregular thickness.

Gravel	-	20%
Sand	-	70%
Silt	-	10%

Unit 8 - DIAMICTON, purplish grey, vaguely stratified, dense, volcanic lithology, trace of basement, subangular clasts, max. clast size 0.5 m. Organic material (charcoal and black residue) in upper 0.5 m of unit. Orange oxidized zone in upper 0.5 m and bottom 0.02 m of unit. Bottom contact undulating.

Boulders	-	5%
Cobbles	-	7%
Gravel	-	60%
Sand	-	23%
Silt and Clay	-	5%

Unit 9 - SAND, orangish brown, well graded, compact, trace fine gravel, bottom contact transitional. Unit is discontinuous.

Unit 10 - DIAMICTON, greyish brown, dense, subangular to angular, max. clast size 0.3 m, volcanic lithology. Bottom contact transitional, contacts undulating. Frequent sand lenses.

Boulders	-	0%
Cobbles	-	20%
Gravel	-	30%
Sand	-	45%
Silt and Clay	-	5%

Unit 11 - COBBLY GRAVEL, orangish brown, compact, vaguely stratified, subrounded to subangular clasts, max. clast size 0.5 m. At top of unit is a 20 cm thick discontinuous stratified sand lense containing black organic residue.

Boulders	-	5%
Cobbles	-	10%
Gravel	-	60%
Sand	-	25%
Silt and Clay	-	0%

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EXPOSURE OF EAST WALL
OF TEST PIT TP 92-2

Figure 3.18

LEGEND

○ ○ ○ ○   Rounded gravel and cobbles

Sand

| | | | Silt or fine sand (including clay fraction)

▲ ◣   Angular cobbles and bounders
(clasts drawn to match vertical scale)

▴ ▴ ▴   Angular gravel

Unit 1 - SAND, brown, compact, some rounded gravel and cobbles.

Unit 2 - COBBLY GRAVEL, reddish brown, rounded clasts max. clast size 0.25 m, volcanic lithology. Transitional contacts.

Boulders	-	0%
Cobbles	-	15%
Gravel	-	70%
Sand	-	15%
Silt and Clay	-	0%

Unit 3 - GRAVEL, reddish brown, vaguely horizontally stratified, subrounded, max. clast size 0.1 m, volcanic lithology. Transitional contacts.

Boulders	-	0%
Cobbles	-	2%
Gravel	-	80%
Sand	-	18%
Silt and Clay	-	0%

Unit 4 - GRAVEL AND COBBLES, brown, subrounded, max. clast size 1.5 m, volcanic lithology.

Boulders	-	15%
Cobbles	-	40%
Gravel	-	30%
Sand	-	15%
Silt and Clay	-	0%

Note: The stratigraphy exposed on the west wall of TP92-2 is similar to that shown above for east wall.

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EXPOSURES OF EAST WALL OF TP 92-3 and VERTICAL BACKHOE TRENCH — **Figure 3.19**

LEGEND

- ⬭ ⬭ Rounded gravel and cobbles
- Sand
- Silt or fine sand (including clay fraction)
- ◣ ◆ Angular cobbles and bounders (clasts drawn to match vertical scale)
- ▴ ▴ ▴ Angular gravel
- [ ] Radiocarbon date

VERTICAL BACKHOE TRENCH
(located 15m east of TP92-3)

HORIZONTAL SCALE, metres

NOTE: Stratigraphy exposed in west wall of TP92-3 similar to that shown above for east wall

TP92-3 (EAST WALL)

HORIZONTAL SCALE, metres

Unit 1 - DIAMICTON, grey mottled orange, dense, subangular to angular clasts, max. clast size 0.1 m, volcanic lithology, lower contact sharp and contains 1 cm thick buried soil horizon.

Gravel	55%
Sand	35%
Silt and Clay	10%

Unit 2 - SAND AND GRAVEL, brown, compact, rounded clasts, max. clast size 0.03 m, volcanic lithology.

Gravel	50%
Sand	50%
Silt	trace

Unit 3 - COBBLY GRAVEL, brown mottled orange, subrounded to rounded clasts, max. clast size 0.3 m, volcanic lithology, vague horizontal stratification, contacts transitional.

Boulders	0%
Cobbles	20%
Gravel	45%
Sand	30%
Silt and Clay	5%

Unit 4 - DIAMICTON, purplish grey, dense, subangular clasts, max. clast size 0.25 m, volcanic lithology, inversely graded, irregular thickness, yellowish fibrous residue common around clasts.

Boulders	0%
Cobbles	10%
Gravel	50%
Sand	30%
Silt and Clay	10%

Unit 5 - SAND, greyish brown, compact, vaguely stratified, several organic clayey silt seams (charcoal, plant fibre, leaf impressions).

Unit 6 - DIAMICTON, reddish brown, subangular, max. clast size 0.3 m, volcanic lithology vaguely stratified, top contact transitional, bottom contact sharp.

Boulders	0%
Cobbles	10%
Gravel	60%
Sand	25%
Silt and Clay	5%

Unit 7 - GRAVELLY SAND, grey mottled orange, compact, organic silt lenses common (charcoal, plant fibre), gravel and sand pockets.

Cobbles	2%
Gravel	25%
Sand	50%
Silt	15%
Clay	8%

Unit 8 - DIAMICTON, reddish brown, subangular to angular, max. clast size 0.1 (rare), volcanic lithology, top contact sharp (organic silt lense), bottom contact transitional.

Boulders	0%
Cobbles	0%
Gravel	45%
Sand	50%
Silt and Clay	5%

Unit 9 - COBBLY SAND AND GRAVEL, reddish brown, vaguely stratified subrounded to subangular, max. clast size 0.25 m, volcanic lithology.
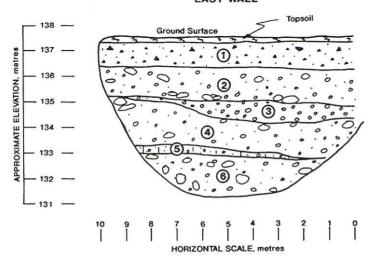
Cobbles	10%
Gravel	40%
Sand	50%
Silt and Clay	0%

Unit 10 - DIAMICTON, reddish brown, subangular to angular clasts, volcanic lithology transitional contacts.

Unit 11 - COBBLY SAND AND GRAVEL, greyish brown, mottled orange, vaguely stratified, rounded clasts, max. clast size 0.5 m (rare), volcanic lithology, occasional cross-bedded sand lenses.

Boulders	trace
Cobbles	20%
Gravel	60%
Sand	20%
Silt and Clay	trace

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EAST WALL

WEST WALL

LEGEND

o ° o ° Rounded gravel and cobbles

: : : : Sand

| | | | | Silt or fine sand (including clay fraction)

▲ ◆ ▲ Angular cobbles and bounders (clasts drawn to match vertical scale)

▲ ▲ ▲ Angular gravel

Unit 1 - SANDY   GRAVEL,   (DIAMICTON), purplish grey, dense, angular, max. clast size 0.2 m, volcanic lithology. Yellowish fibrous residue coating clasts.

Boulders	0%
Cobbles	5%
Gravel	65%
Sand	25%
Silt and Clay	5%
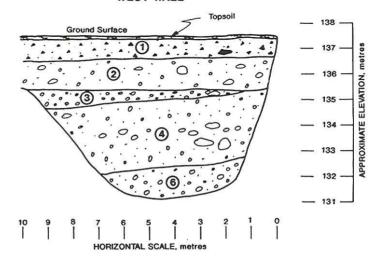
Unit 2 - COBBLY   GRAVEL,   brown,   dense, subangular clasts, max. clast size 0.6 m, volcanic lithology, poorly sorted. Yellowish fibrous residue coating clasts, organics (charcoal and roots) in top 0.2 m of unit, contacts transitional.

Boulders	5%
Cobbles	20%
Gravel	50%
Sand	20%
Silt and Clay	5%

Unit 3 - GRAVEL, grey, compact, subangular clasts, max. clast size 0.2 m, volcanic lithology. Yellowish fibrous residue coating clasts. Irregular thickness.

Boulders	0%
Cobbles	5%
Gravel	75%
Sand	20%
Silt and Clay	0%

Unit 4 - SANDY GRAVEL, purplish grey, compact to dense, vaguely stratified, subangular clasts, max. clast size 0.4 m (rare), volcanic lithology, 10% basement. Some yellowish fibrous residue coating clasts. Contacts transitional.

Boulders	5%
Cobbles	20%
Gravel	45%
Sand	30%
Silt and Clay	trace

Unit 5 - SILTY GRAVEL, brown, angular, max. clast size 0.2 (rare), volcanic lithology, 25% basement, wet. Irregular thickness.

Boulders	0%
Cobbles	5%
Gravel	60%
Sand	25%
Silt and Clay	10%

Unit 6 - COBBLY GRAVEL, brown mottled orange, compact, subrounded clasts, max. clast size 0.5 m, volcanic lithology, trace basement. Top contact transitional.
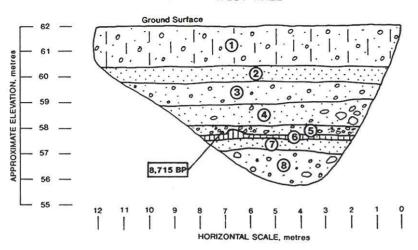
Boulders	5%
Cobbles	20%
Gravel	50%
Sand	25%
Silt and Clay	trace

EXPOSURES OF EAST and WEST WALLS OF TEST PIT TP 92-5

Figure 3.21

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EXPOSURES OF EAST and WEST WALLS OF TEST PIT TP 92-6

Figure 3.22

EAST WALL

WEST WALL

Ground Surface

Ground Surface

APPROXIMATE ELEVATION, metres

HORIZONTAL SCALE, metres

1,665 BP

LEGEND

⊙ ⊙ ⊙ ⊙ Rounded gravel and cobbles

Sand

Silt or fine sand (including clay fraction)

▲ ◆ Angular cobbles and bounders
(clasts drawn to match vertical scale)

▴ ▴ ▴ Angular gravel

Radiocarbon date

Unit 1 - COBBLY SAND AND GRAVEL, brown,
subrounded, compact, volcanic, occasional
boulders. Penetrated by roots.

Unit 2 - DIAMICTON, brown, dense, angular, max.
clast size 0.5 m, volcanic, trace of basement.
Organic material (soil horizon to 30 mm
thick, rootlets and charcoal) at bottom
contact. Top contact transitional, bottom
contact sharp and dipping between 1° and
5°S in the exposure.

Boulders	-	5%
Cobbles	-	15%
Gravel	-	50%
Sand	-	15%
Silt and Clay	-	15%
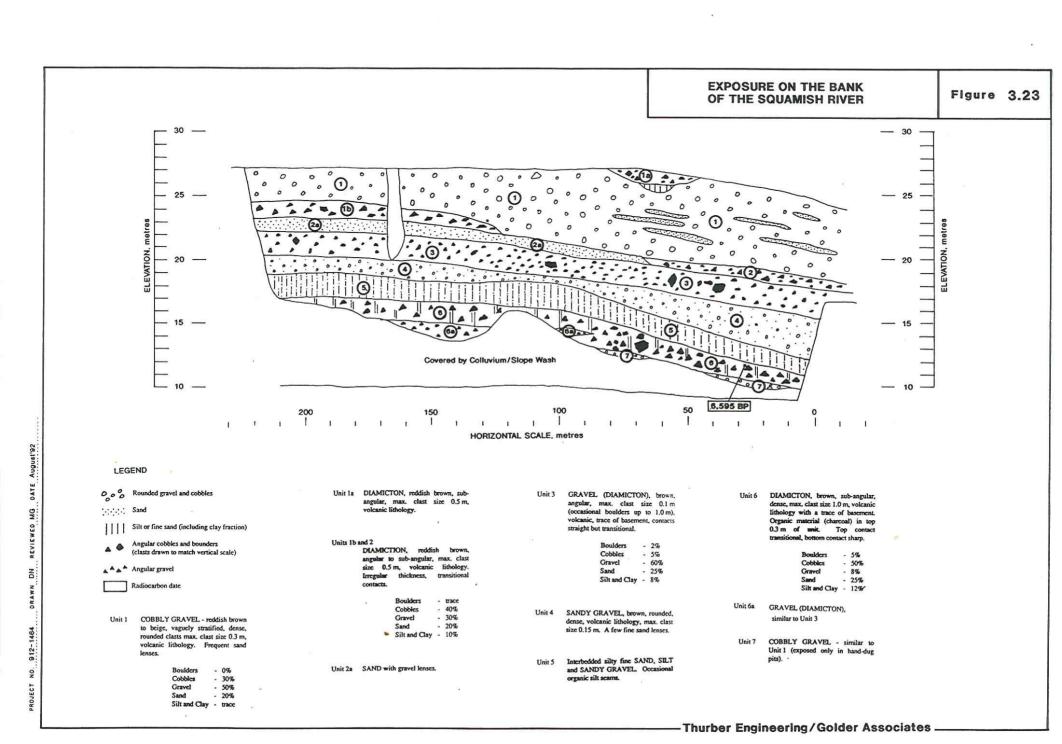
Unit 3 - COBBLY GRAVEL, brownish grey,
vaguely stratified, compact, rounded, max.
clast size 0.9 m volcanic lithology, trace of
basement. Contains sand lenses.
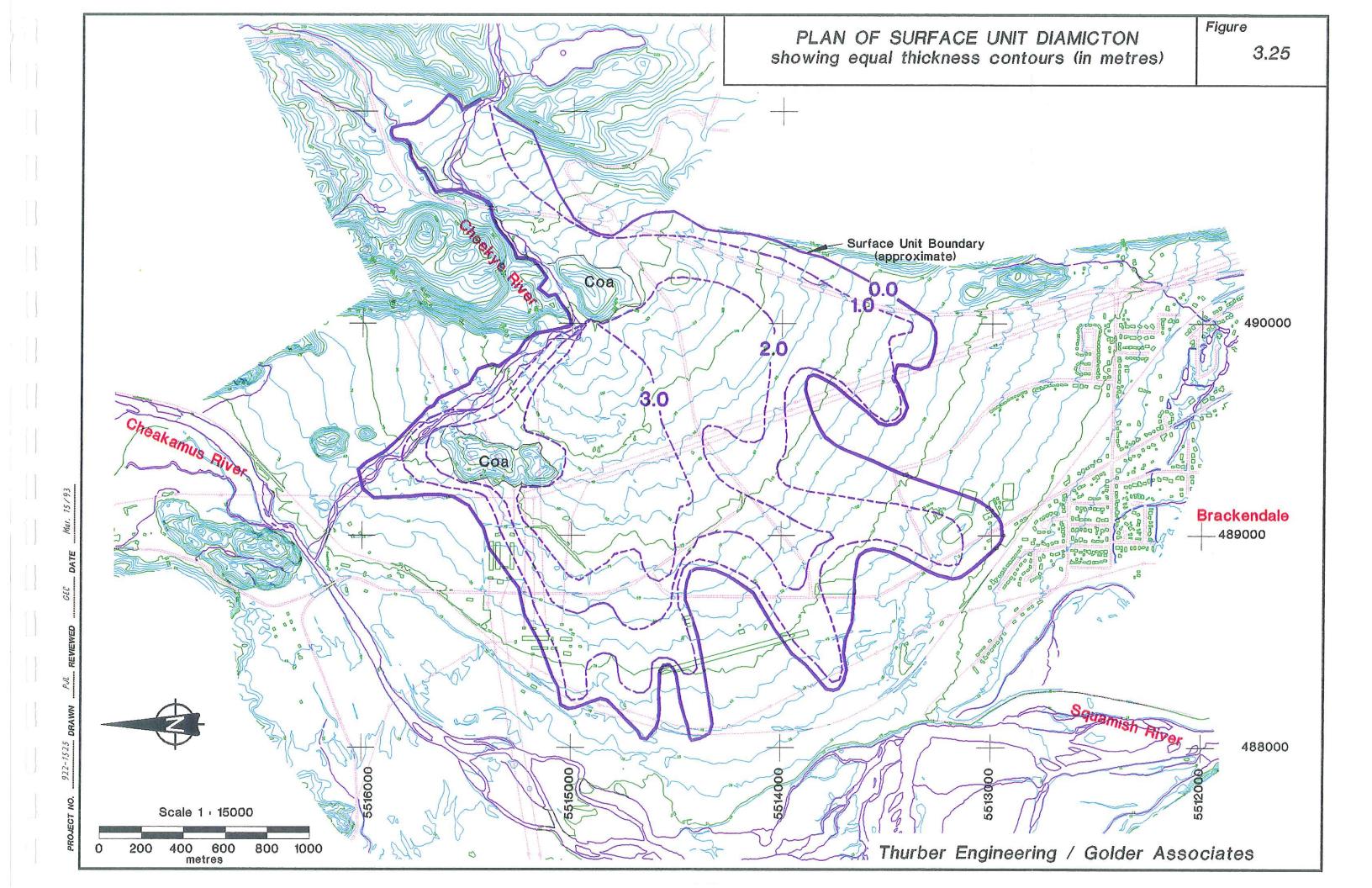
Boulders	-	10%
Cobbles	-	25%
Gravel	-	45%
Sand	-	20%
Silt and Clay	-	0%

Unit 4 - SAND, brown, med. grained, compact.

Gravel	-	5%
Sand	-	80%
Silt and Clay	-	15%

PROJECT NO 912-1464   DRAWN DN   REVIEWED MG   DATE August'92

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EXPOSURE ON THE BANK OF THE SQUAMISH RIVER

Figure 3.23

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DISTRIBUTION OF DIAMICTONS
ISOMETRIC VIEW, CHEEKYE FAN

Figure 3.24

LEGEND

Fan Boundary

Bedrock Knoll

91-1   Test Pit or Exposure
(Depth scale in metres)

Diamicton (Debris Flow)

Fluvial Deposits

Assumed Correlation Line,
Base of Surficial Diamicton

Assumed Correlation,
Squamish River Unit

NOTE: Fan surface slope is not shown

SCHEMATIC ONLY
Not to Scale

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PLAN OF SURFACE UNIT DIAMICTON
showing equal thickness contours (in metres)

Figure
3.25

Surface Unit Boundary
(approximate)

0.0
1.0
2.0
3.0

Coa
Coa

Cheekye River
Cheakamus River
Squamish River

Brackendale
490000
489000
488000

5516000
5515000
5514000
5513000
5512000

Scale 1 : 15000

0   200   400   600   800   1000
metres

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PROJECT NO. 922-1525   DRAWN ..... GEC   REVIEWED ..... PJL   DATE ..... Mar. 15/93

TYPICAL GRAIN SIZE DISTRIBUTION CURVES ON CHEEKYE FAN (from Jordan, 1991 b)

Figure 3.26

M.I.T. GRAIN SIZE SCALE

LEGEND:
1) Fan toe – bottom unit
2) Fan toe – bottom unit
3) Fan toe – top unit at airport pit
4) 1984 debris flow near Hwy 99
5) Undated debris flow near Hwy 99
6) Cheekye River channel gravel
7) Garbage dump debris flow *
8) Test Pit 91-20, surficial diamicton *
9) Test Pit 91-21 *

* This Investigation

NOTE: Samples Truncated to 1" minus Fraction

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GRAIN SIZE HISTOGRAMS

Figure 3.27

NOTES:

1) All percentages by weight.

2) Boulders and cobbles content was estimated usually as % volume, then converted into % weight. Gravel, sand and fines was measured by washed sieve test.

3) % clay noted only where measured by a hydrometer test.

LEGEND:

B – Boulders >300 mm

C – Cobbles 150–300 mm

G – Gravel 2–150 mm

S – Sand 0.076–2 mm

F – Fines <0.076 mm

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Vancouver Island Earthquakes
Jan 1982 – Nov 1991

LATITUDE

LONGITUDE

51° N

47° N

121° W

129° W

See Appendix II for Legend

Produced at the Pacific Geoscience Centre   Sidney BC
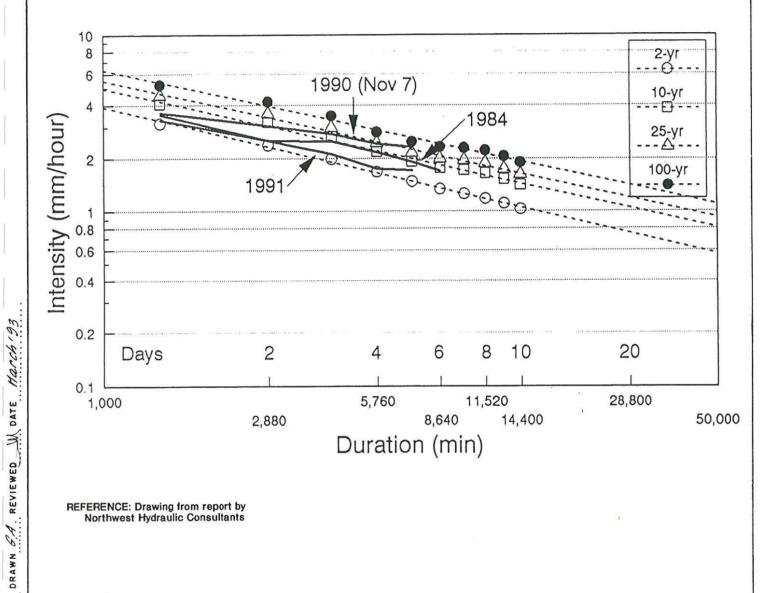
Date: 91/12/03   Time: 13:05:59

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EARTHQUAKES WITHIN PROJECT AREA

Figure 4.2

Jan 1978 - Nov 1991

Mt. Garibaldi

LATITUDE

LONGITUDE

50° N

49° N

122° W

124° W

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LEGEND

● AES PRECIPITATION GAUGE

▲ WSC STREAMFLOW GAUGE

SCALE 1:250,000

REFERENCE: Drawing from report by Northwest Hydraulic Consultants

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SQUAMISH AES STATION
INTENSITY – DURATION – FREQUENCY CURVES

Figure 5.2

REFERENCE: Drawing from report by
Northwest Hydraulic Consultants

Thurber Engineering / Golder Associates

REFERENCE: Drawing from report by
Northwest Hydraulic Consultants

point slopes   a   2.5°
         b   2.5°
         c   2-2.5°
         d   3°
         e   2-2.5°
         f   3.5°
         g   3.5°

mean fan slope 2.7°

apparent area of debris accumulation

bedrock canyon

fan

vertical exaggeration 3.28 x
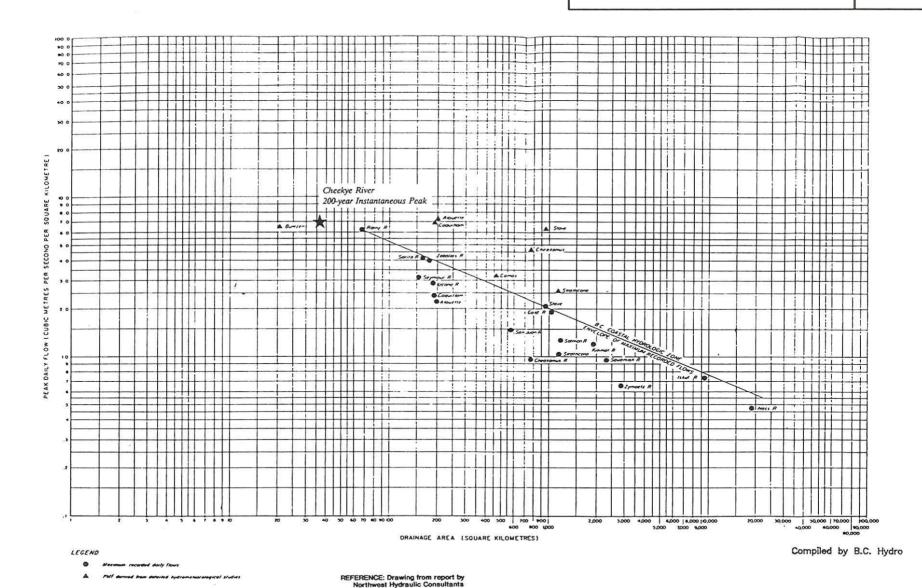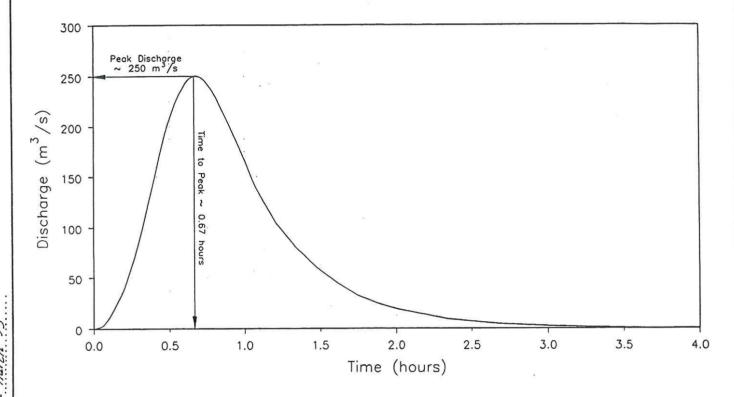
from P. Jordon and Associates (1987)

REFERENCE: Drawing from report by
Northwest Hydraulic Consultants

PEAK DAILY FLOW (CUBIC METRES PER SECOND PER SQUARE KILOMETRE)

Cheekye River
200-year Instantaneous Peak

Bunsen
Alouette
Coquitlam
Rams R
Stave
Cheekamus
Sarita R
Zeballos R
Seymour R
Ucona R
Comox
Coquitlam
Alouette
Stromcona
Stave
Gold R
San Juan R
B.C. COASTAL HYDROLOGIC ZONE
ENVELOPE OF MAXIMUM RECORDED FLOWS
Salmon R
Kitimat R
Stromcona
Cheakamus R
Squamish R
Zymoetz R
Iskut R
Noss R

DRAINAGE AREA (SQUARE KILOMETRES)

LEGEND

● Maximum recorded daily flows

▲ PMF derived from detailed hydrometeorological studies

REFERENCE: Drawing from report by
Northwest Hydraulic Consultants

Compiled by B.C. Hydro

PROJECT NO. 912-1464 DRAWN G.A. REVIEWED .... DATE March '93

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CHEEKYE RIVER
200 – YEAR DESIGN HYDROGRAPH

Figure **5.6**

Peak Discharge ~ 250 m³/s

Time to Peak ~ 0.67 hours

Based on SCS Dimensionless Hydrograph

Note:

The hydrograph is for the Cheekye River upstream of its' confluence with the Brohm River.

REFERENCE: Drawing from report by Northwest Hydraulic Consultants
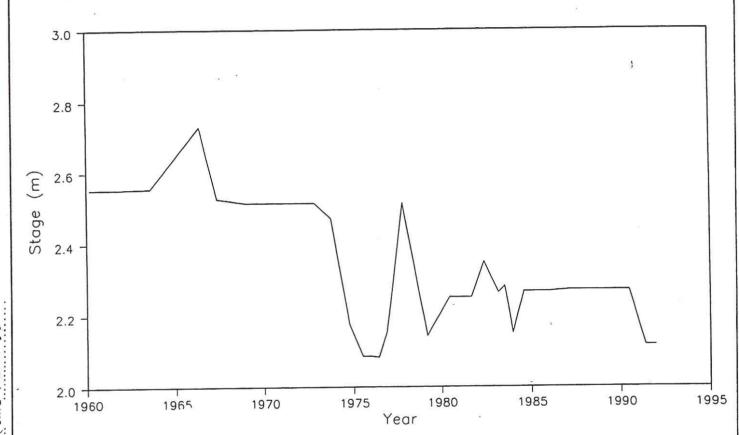
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Airphoto BC5007:12

Airphoto BC2350:1

REFERENCE: Drawing from report by
Northwest Hydraulic Consultants

PROJECT NO. *912-1964* DRAWN *G.A.* REVIEWED *J.N.* DATE *March '93*
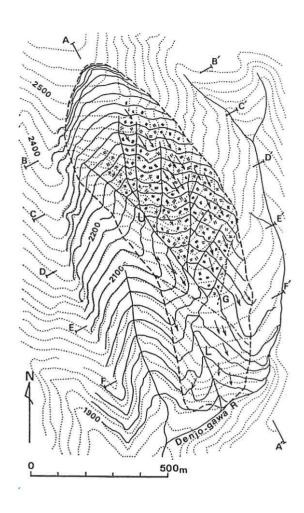
Thurber Engineering/Golder Associates

REFERENCE: Drawing from report by
Northwest Hydraulic Consultants
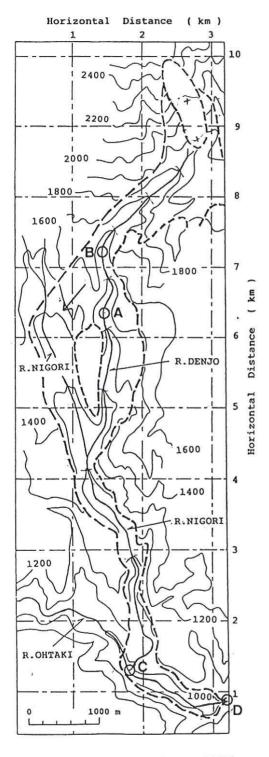
REFERENCE: Drawing from report by
Northwest Hydraulic Consultants

Solid line: contour of post-failure, Dotted line: contour
of pre-failure, Broken line: boundary of source area,
Arrows: direction of striation, Hatched area: out crop of
Senbonmatsu pumice layer, U:upper valley, L:lower valley,

(from Inokuchi, 1985)
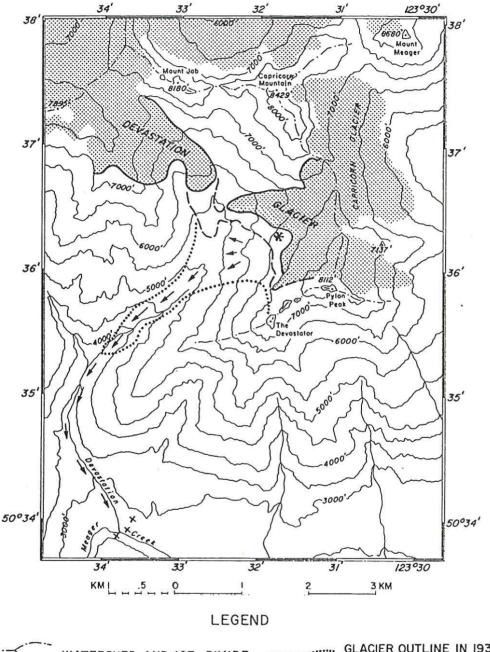
a) Source Area
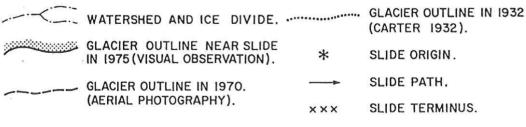
(from Sassa, 1987)

b) Flow Path

(from Hardy et al.,1978)

LEGEND

POSSIBLE OUTLINE OF THE 1855 SLIDE SCAR

UPPER BOUNDARIES OF THE 1855 DEBRIS FLOW

POST-1855 ALLUVIAL DEPOSITS

BOUNDARIES OF MAJOR DEPOSITION OF 1855 AND POST-1855 DEPOSITION IN RUBBLE CREEK

BOUNDARIES OF VOLCANIC ROCK IN THE VICINITY OF THE BARRIER

BOUNDARY OF 1855 AND POST-1855 DEPOSITIONAL FEATURES IN THE CHEAKAMUS VALLEY

BOUNDARY OF PRE-1855 RUBBLE CREEK DEBRIS

GEOLOGIC SECTION

TURNING POINT OF SECTION

LEGEND

—·—·— WATERSHED AND ICE DIVIDE.	·········· GLACIER OUTLINE IN 1932 (CARTER 1932).
GLACIER OUTLINE NEAR SLIDE IN 1975 (VISUAL OBSERVATION).	✳ SLIDE ORIGIN.
— — — GLACIER OUTLINE IN 1970. (AERIAL PHOTOGRAPHY).	→ SLIDE PATH.
	××× SLIDE TERMINUS.

(from Mokievski-Zubok)
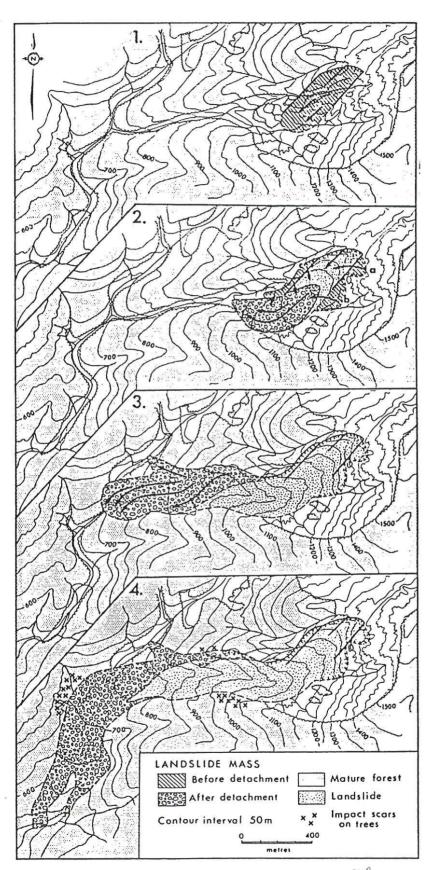
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1.

2.

3.

4.

LANDSLIDE MASS

Before detachment   Mature forest

After detachment   Landslide

Contour interval 50m   Impact scars on trees

0   400

metres
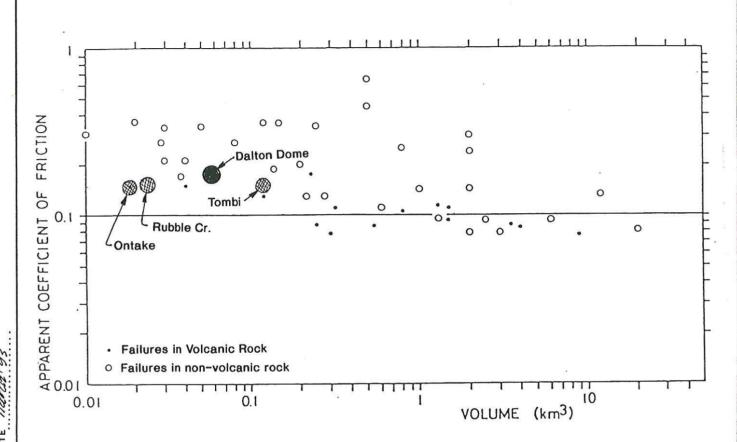
(from Clayne and Souther, 1982)

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NOTE : • Dalton Dome data refers to estimated runout of a potential large avalanche.
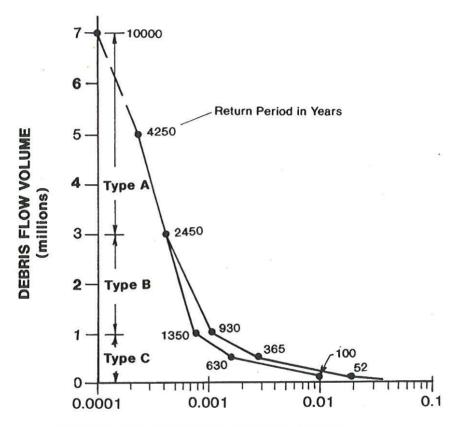
NOTES : Dalton Dome data refers to the predicted runout of a large
rock avalanche, estimated by other means.

ANALYSIS OF DEEP SEATED SLUMPING MECHANISM

Figure 7.1

Main Scarp Circle
$F_s = 2.03$
$a_c = 0.42$ g

Pyroclastics

Piezometric Surface

"Critical Circle
$F_s = 1.89$

$\sigma_c = 100$ Mpa
"Good Quality" (unaltered)
Rock Mass

Critical Circles
for Weaker Rocks

A

B

D

C

Altered Zone

Fresh Rock

DISTANCE (m)

Y

ELEVATION (m)

45° Rotation

Pyroclastics

Altered Zone

Basement Rock

500m

500m   500m

PROJECT NO. *912-1464*   DRAWN *O.A.*   REVIEWED .... DATE *March '93*

(log scale on x-axis, normal scale on y-axis)

NOTE: The two curves for debris flow volume <3Mm^3 represent different interpretations regarding percentage of total fan assigned as debris flow deposits.

ASSUMED STRENGTH ENVELOPES FOR SHEARING THROUGH ROCK MASS (after Hoek & Brown, 1980)

Figure 7.3

a) Poor Quality Rock

b) Fair Quality Rock

c) Good Quality Rock
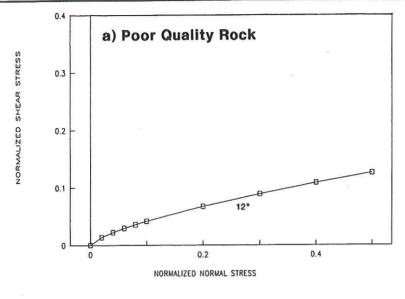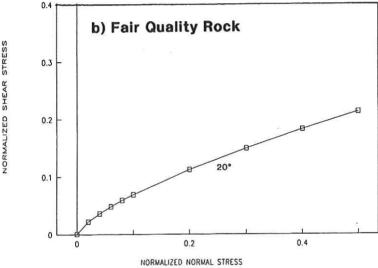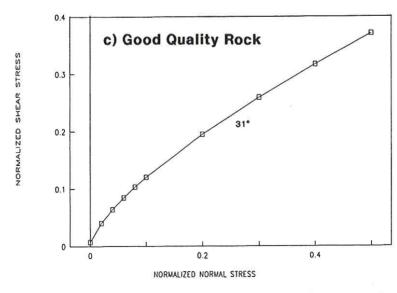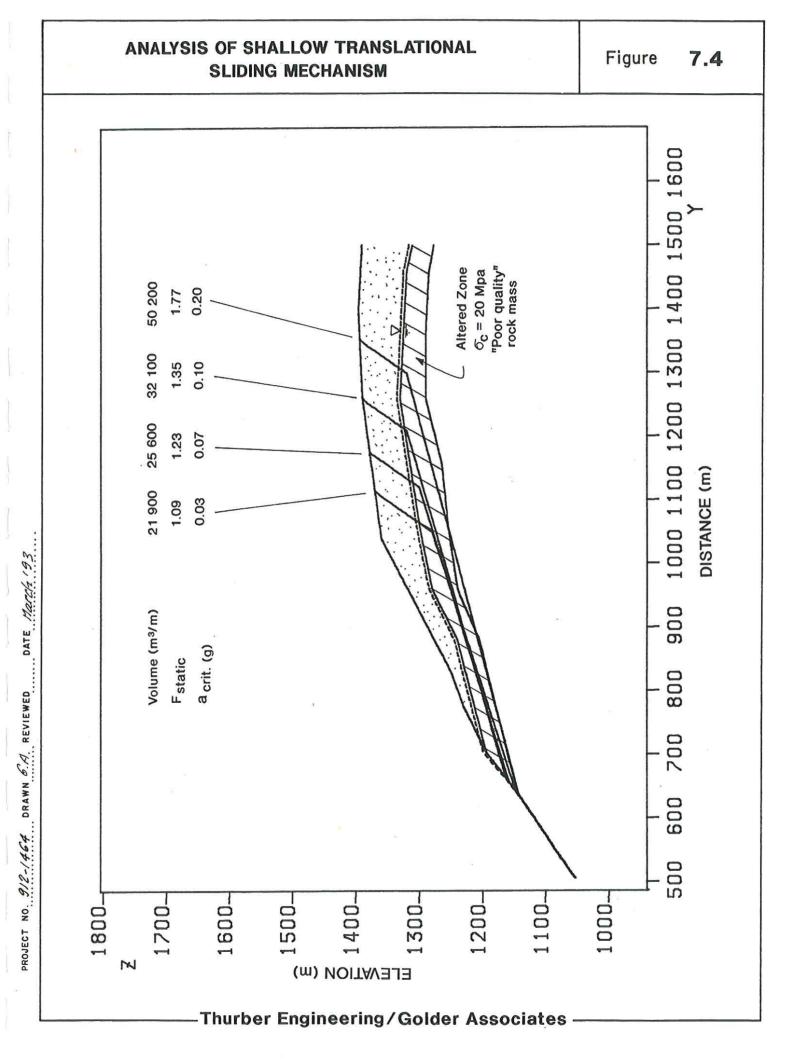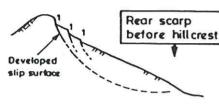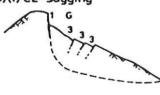
NOTE : Shear stresses are normalized by dividing by the uniaxial compressive strength of intact rock.

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ANALYSIS OF SHALLOW TRANSLATIONAL
SLIDING MECHANISM

Figure **7.4**

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C1. (a) R - sagging

Developed slip surface

Rear scarp before hill crest

Undeveloped slip surface

Rear scarp behind hill crest

(b)(i) CL - sagging

G = graben

(b)(ii) CB - sagging

PROJECT NO. 912-1464 DRAWN G.A. REVIEWED ... DATE March '93
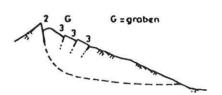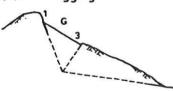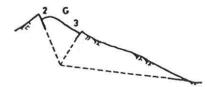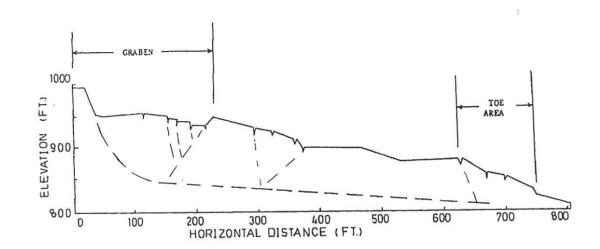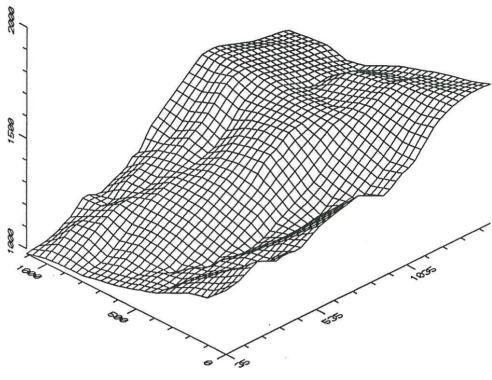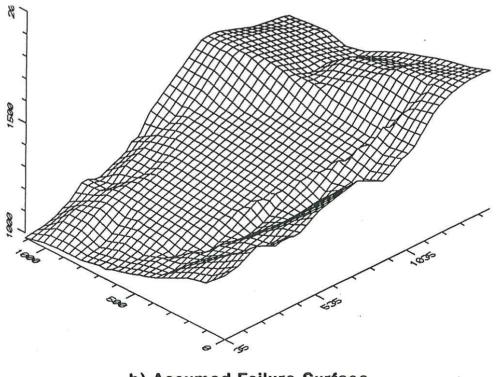
(Edgerton Slide, surface profile from Tweedie,1979)
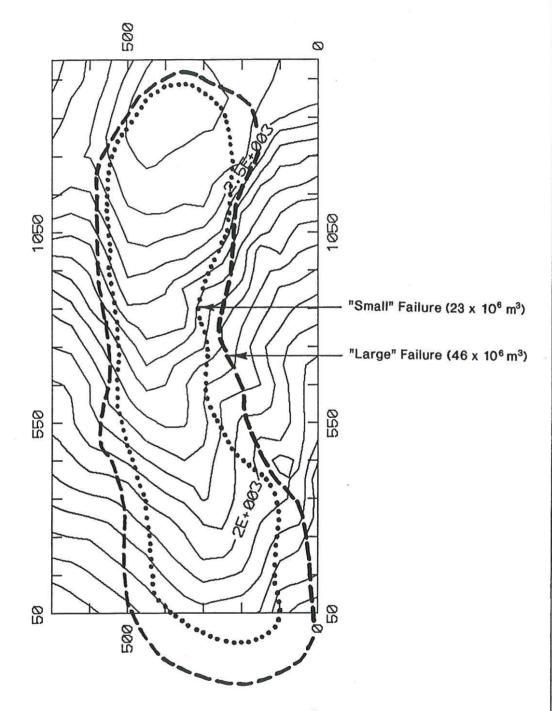
a) Ground Surface

b) Assumed Failure Surface

Thurber Engineering / Golder Associates
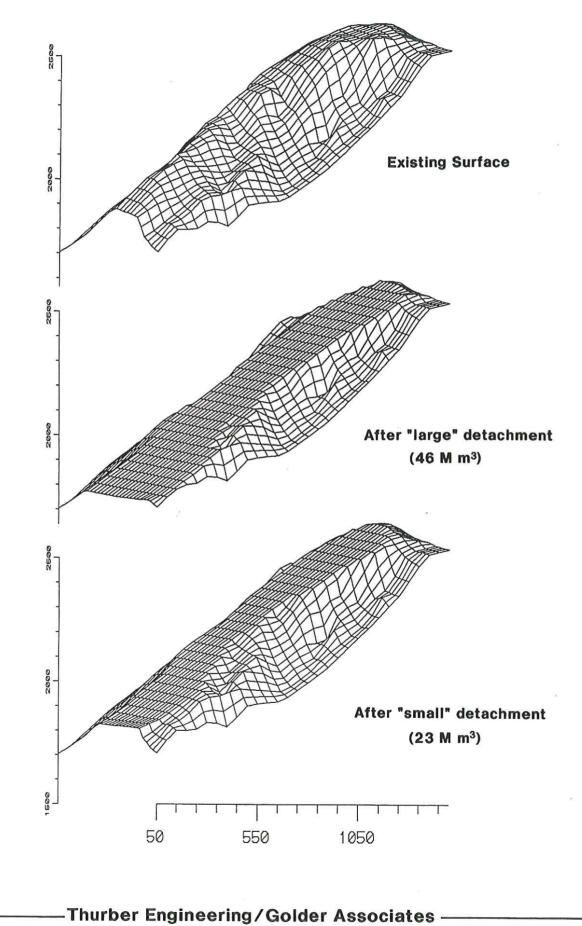
"Small" Failure (23 x 10^6 m^3)

"Large" Failure (46 x 10^6 m^3)

(Scale in metres).

Existing Surface

After "large" detachment
(46 M m^3)

After "small" detachment
(23 M m^3)
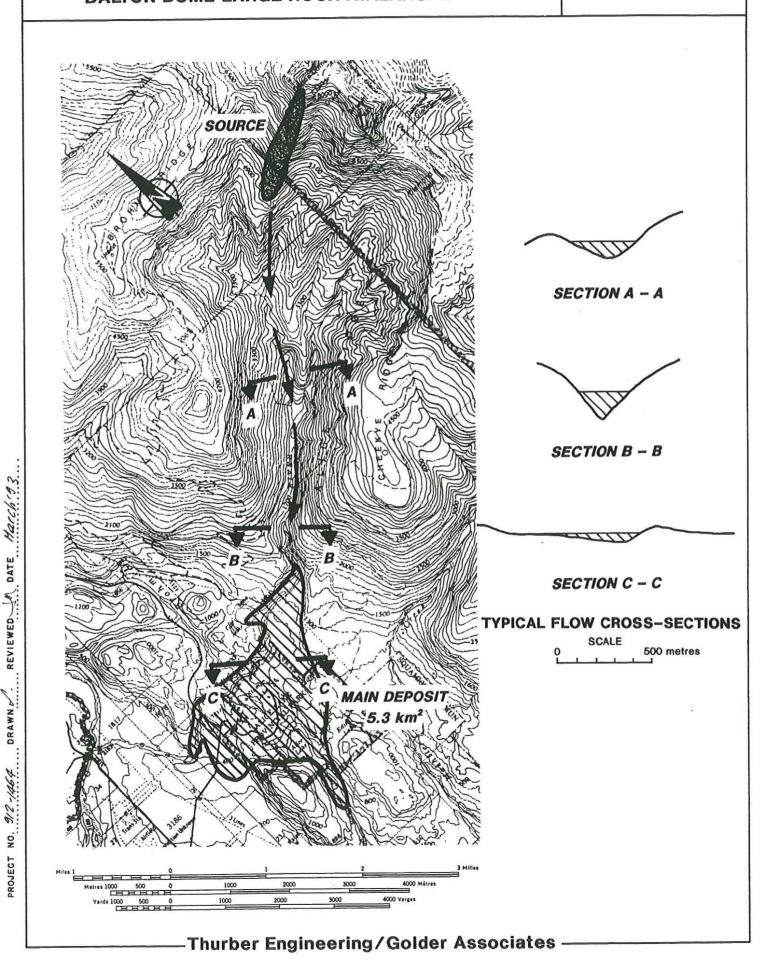
No.	Name	No.	Name
1.	Frank	27.	Vaiont
2.	Elm	28.	Rockslide Pass
3.	Gros Ventre	29.	Avalanche Lake, South Lobe
4.	Madison Canyon	33.	Rubble Creek
5.	Little Tahoma Peak	34.	Kennedy River
6.	Sherman Glacier	36.	Maligne Lake
7.	Hope	37.	Martinez Mountain
8.	Huascaran, 1970	40.	Antelao
9.	Huascaran, 1966	42.	Bec Rouge
10.	Mayunmarca	44.	Clavans
11.	Blackhawk	46.	Disentis (Muster)
12.	North Nahanni	47.	Dobratsch
13.	Beaver Flats	49.	Lago di Alleghe
14.	Brazeau Lake	50.	Lavini di Marco
16.	Goldau	52.	Mottec
17.	Diablerets	53.	Motto d'Arbino
18.	Granier	57.	Mt. Ontake
22.	Valtellina		
23.	Lake of the Woods		
26.	Pandemonium Creek		

NOTES : • Numbers 5,6,8 and 9 all involve travel over glacier ice.

• Mt.Ontake is a strongly channelized event.

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SCHEMATIC PLAN
DALTON DOME LARGE ROCK AVALANCHE

Figure **7.11**

SOURCE

SECTION A – A

SECTION B – B

SECTION C – C

TYPICAL FLOW CROSS–SECTIONS

SCALE

0   500 metres

A

A

B

B

C

C   *MAIN DEPOSIT*
5.3 km²

Miles 1   0   1   2   3 Miles

Metres 1000 500 0   1000 2000 3000 4000 Mètres

Yards 1000 500 0   1000 2000 3000 4000 Verges

Thurber Engineering / Golder Associates

PROJECT NO. 912-1464   DRAWN   REVIEWED   DATE March/93
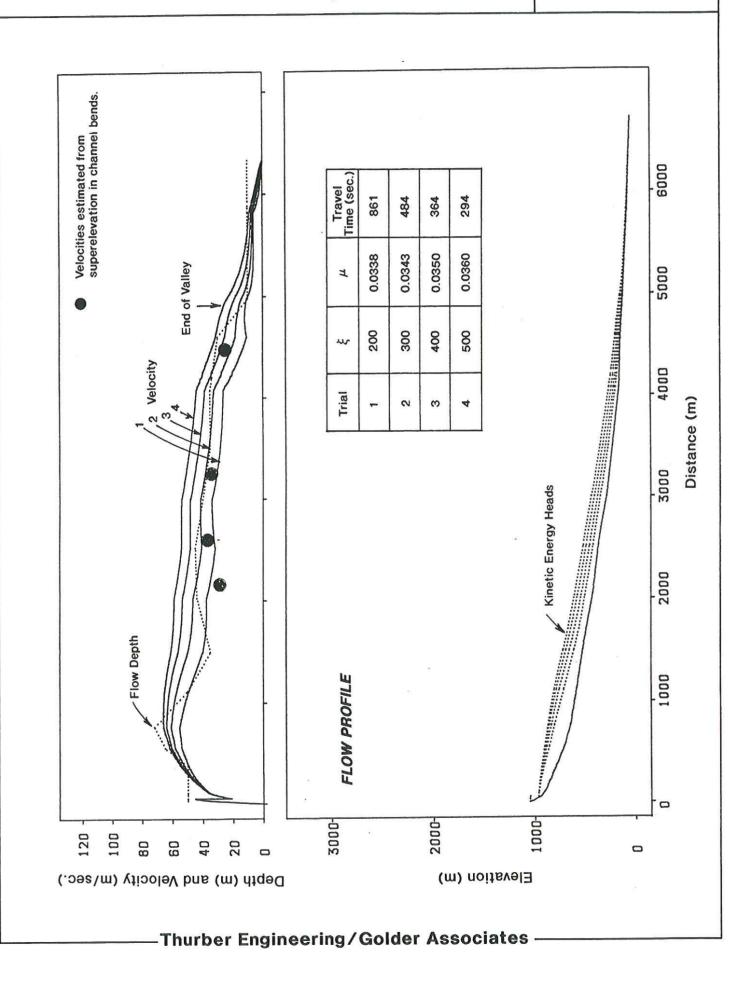
NOTES : • Case identification numbers are given in Fig. 7.10
   • Dalton Dome (data refers to potential large rock avalanche.

DYNAMIC ANALYSIS OF RUBBLE CREEK (1855) ROCK AVALANCHE (see Hardy et al. 1978)

Figure **7.13**

Velocities estimated from superelevation in channel bends.

Trial	ξ	μ	Travel Time (sec.)
1	200	0.0338	861
2	300	0.0343	484
3	400	0.0350	364
4	500	0.0360	294

End of Valley

Velocity

Flow Depth

Depth (m) and Velocity (m/sec.)

FLOW PROFILE

Kinetic Energy Heads

Distance (m)

Elevation (m)

Thurber Engineering / Golder Associates
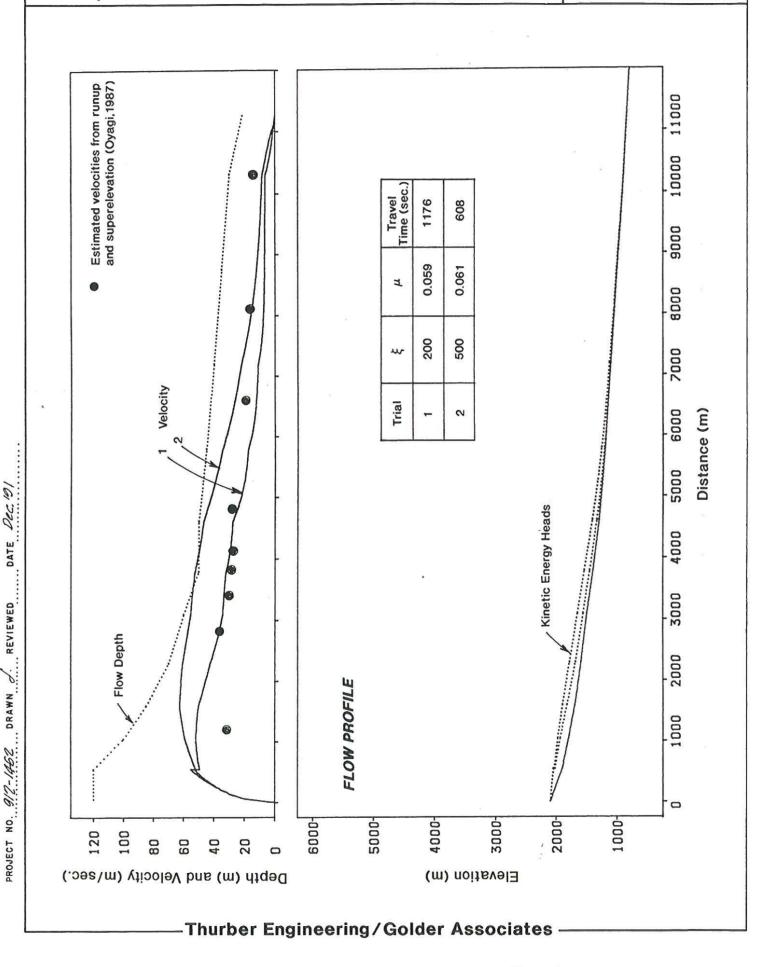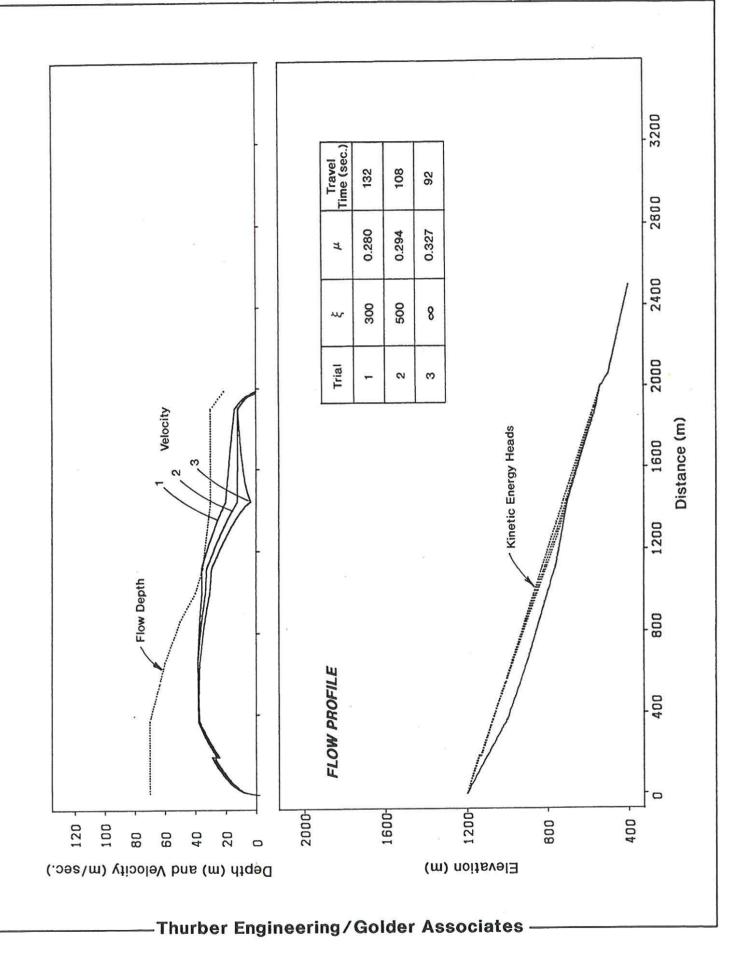
DYNAMIC ANALYSIS OF Mt.ONTAKE ROCK AVALANCHE OF 1984,
(See Moriwaki et al.(1985) and Oyagi (1987)

Figure **7.14**

- Estimated velocities from runup and superelevation (Oyagi.1987)

Trial	ξ	μ	Travel Time (sec.)
1	200	0.059	1176
2	500	0.061	608

Velocity

Flow Depth

Depth (m) and Velocity (m/sec.)

FLOW PROFILE

Kinetic Energy Heads

Elevation (m)

Distance (m)

Thurber Engineering / Golder Associates
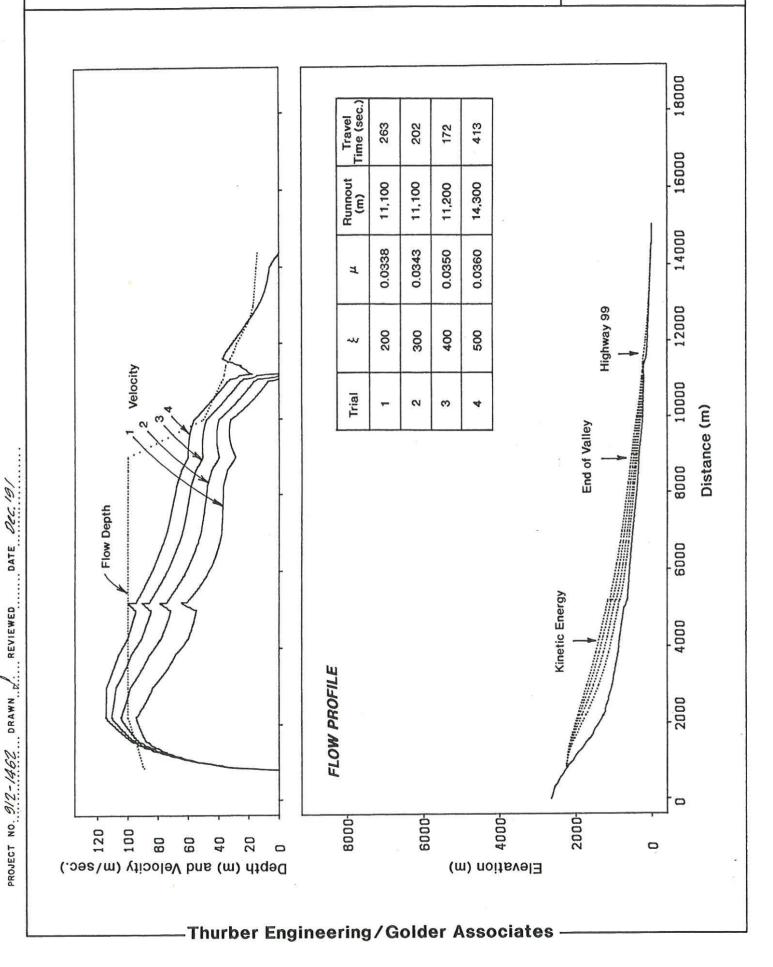
DYNAMIC ANALYSIS OF
DUSTY CREEK DEBRIS AVALANCHE (1963)
(See Clague and Souther, 1982)

Figure **7.15**

Trial	ξ	μ	Travel Time (sec.)
1	300	0.280	132
2	500	0.294	108
3	∞	0.327	92

Velocity

1

2

3

Flow Depth

FLOW PROFILE

Kinetic Energy Heads

Depth (m) and Velocity (m/sec.)

120 100 80 60 40 20 0

Elevation (m)

2000 1600 1200 800 400

Distance (m)

400 800 1200 1600 2000 2400 2800 3200

DYNAMIC ANALYSIS OF "LARGE" POTENTIAL ROCK AVALANCHE FROM DALTON DOME

Figure **7.16**

Trial	ξ	μ	Runout (m)	Travel Time (sec.)
1	200	0.0338	11,100	263
2	300	0.0343	11,100	202
3	400	0.0350	11,200	172
4	500	0.0360	14,300	413

FLOW PROFILE

Depth (m) and Velocity (m/sec.)

Flow Depth

Velocity

Kinetic Energy

End of Valley

Highway 99

Elevation (m)

Distance (m)
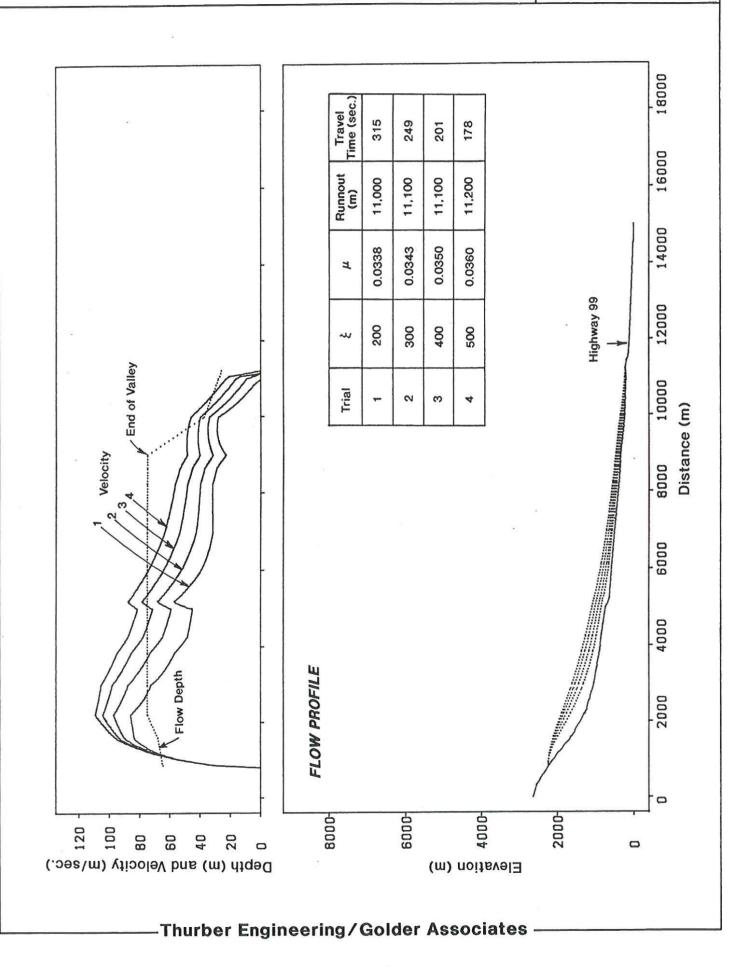
DYNAMIC ANALYSIS OF "SMALL" POTENTIAL ROCK AVALANCHE FROM DALTON

Figure **7.17**

Trial	ξ	μ	Runnout (m)	Travel Time (sec.)
1	200	0.0338	11,000	315
2	300	0.0343	11,100	249
3	400	0.0350	11,100	201
4	500	0.0360	11,200	178

PROJECT NO. *912-1462*   DRAWN ....   REVIEWED ....   DATE *Dec. '91*

Depth (m) and Velocity (m/sec.)

Velocity

End of Valley

Flow Depth

1 2 3 4

FLOW PROFILE

Elevation (m)

Highway 99

Distance (m)

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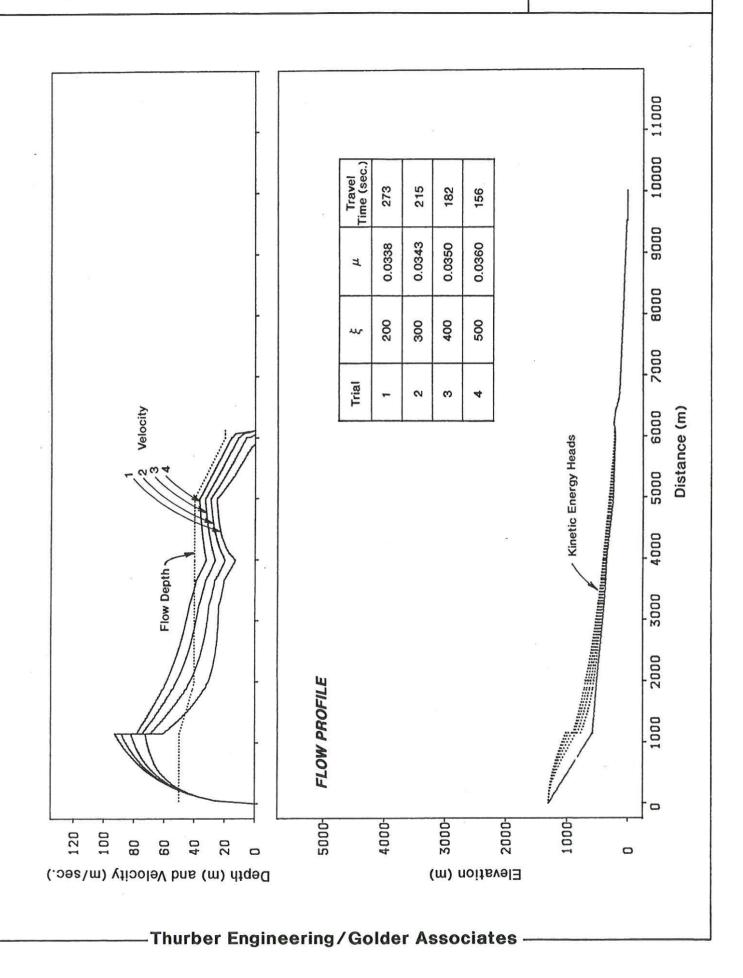
DYNAMIC ANALYSIS OF LARGE SCALE POTENTIAL FAILURE OF THE CHEEKYE RIDGE

Figure **7.18**

Trial	ξ	μ	Travel Time (sec.)
1	200	0.0338	273
2	300	0.0343	215
3	400	0.0350	182
4	500	0.0360	156

FLOW PROFILE

Velocity

Flow Depth

1 2 3 4

Kinetic Energy Heads

Depth (m) and Velocity (m/sec.)

Elevation (m)

Distance (m)
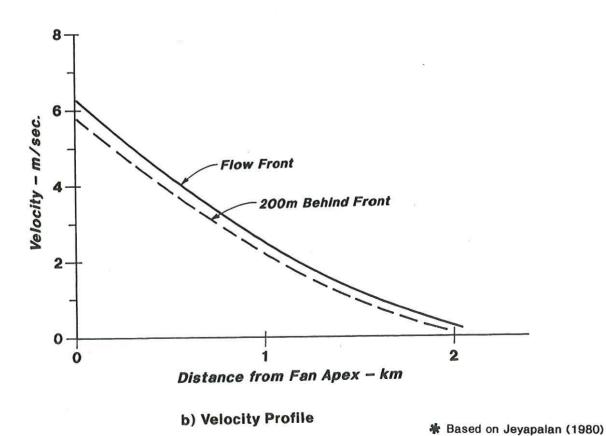
Thurber Engineering/Golder Associates

a) Distribution of Deposits

b) Velocity Profile

✱ Based on Jeyapalan (1980)
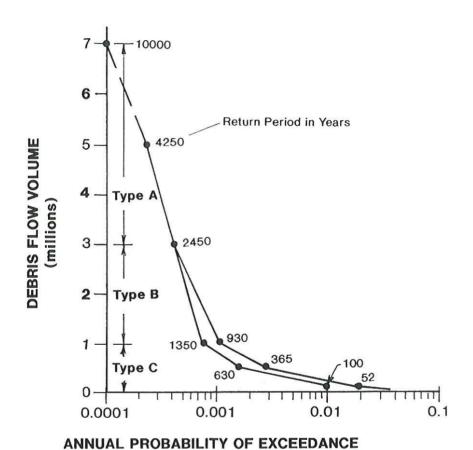
Thurber Engineering / Golder Associates

(log scale on x–axis, normal scale on y–axis)

NOTE: The two curves for debris flow volume <3Mm^3 represent different interpretations regarding percentage of total fan assigned as debris flow deposits.
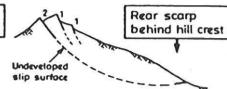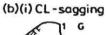
TABLE 8.1

EXPLANATION OF ZONING ON FIGURES 8.1, 8.6, 8.7, 9.1, 9.2 AND 9.3: ESTIMATED EFFECTS OF POTENTIAL DEBRIS FLOW HAZARDS

	DEBRIS FLOW		
Magnitude Class	A(3M-7Mm³)	B(1M-3Mm³)	C(100,000 - 1Mm³)
Return Period **Fan Zone**	2,450 - 10,000	930 - 2,450	52 - 930
1	Forest cover and all structures destroyed, topography changed. V=7m/s T=5m W=1-1.5m	Complete destruction possible in a part of corridor; complete change of drainage pattern. V=4m/s T=4m W=-.7-1.0m	Destructive debris flow surges along and close in the existing Cheekye river channel. Partial destruction elsewhere. V=3m/s T=3m W=0.2-0.7m
2	Less rapid but still very destructive debris flow; deposits of variable thickness; preferential flow along open corridors. V=4m/s T=3.5m W=0.7-1.5m	Most forest stands and structures not destroyed, some concentrated destruction V=3m/s T=2.5m W=0.5-0.07m	Forest and structures near open corridors surrounded by debris. V=2m/s T=2m W=0.2-0.5m
3	Forest and structures surrounded but not destroyed. Very non-uniform damage. Damage minor, erosion by water flow in new channels. V=3m/s T=2m W=0.5-1.0m	Deposits controlled by topographic details and obstructions. Structural damage minor. Erosion by water flow in new channels. V=2m/s T=1m W=0.2-0.5m	Flooding damage, sediment deposition (gravel) erosion by flow in new channels. V=1m/s T=0.5m W=0.2m
4	Deposits strongly controlled by topographic details and obstructions. Structural damage minor, erosion by water flow in new channels. V=2m/s T=1m W=0.4m	Most damage due to water flow, deposition of sediment (gravel), erosion and sediment ponding V=1m/s T=0.5m W=0.2m	Minor flooding damage (gravel deposition, erosion). Water and sediment ponding in low areas. V=1m/s T=0.2m W=0.2m
5	Debris filling the plain in some locations, possible temporary landslide dam several metres high, erosion of fan margin scarp.	Possible temporary dam at the location of present Cheekye River mouth. Change of flow patterns in Cheakamus/ Squamish.	Possible temporary dam at the mouth of the Cheekye River. Moderate flow pattern changes downstream.
6	No direct impact of debris. River flooding possible due to landslide dam, rapid erosion of the right river bank.	Possible flooding due to landslide dam at Cheekye mouth. Possible erosion else-where.	Possible flooding due to dam at Cheekye mouth.

Maximum Parameters: V=Velocity in m/s, T=Thickness of deposits in m, W=Width of damage corridor in kilometres.

Note: 1) Hazard zone boundaries are transitional. Any site located within approximately 200m of a boundary could have some of the characteristics of the adjacent zone. Such sites should be reassessed by means of a site specific investigation, if the distinction is important.

FAN ZONING - EXISTING CONDITIONS

Figure 8.1

LEGEND

3 - Fan zone designation (see Tables 8.1, 9.1)

— - Assigned zone boundary

Cheekye River

Cheakamus River

Squamish River

Brackendale

AREA PROTECTED BY EXISTING FLOOD DYKES. PONDING POSSIBLE BELOW EL. 15 m (approx.)

Scale 1 : 15000

0 200 400 600 800 1000
metres

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490000
489000
488000

5516000
5515000
5514000
5513000
5512000

SUMMARY OF RISK ACCEPTANCE CRITERIA — Figure 8.2

Source # (see Table 8.1)

A

Range of probabilities of a disaster involving a number of casualties (P_D)

Probability of hazard

Source # (see Table 8.1)

B
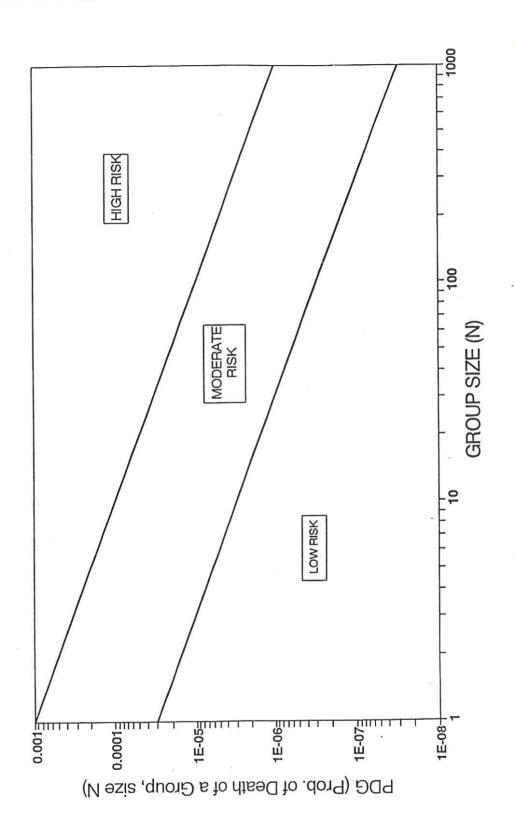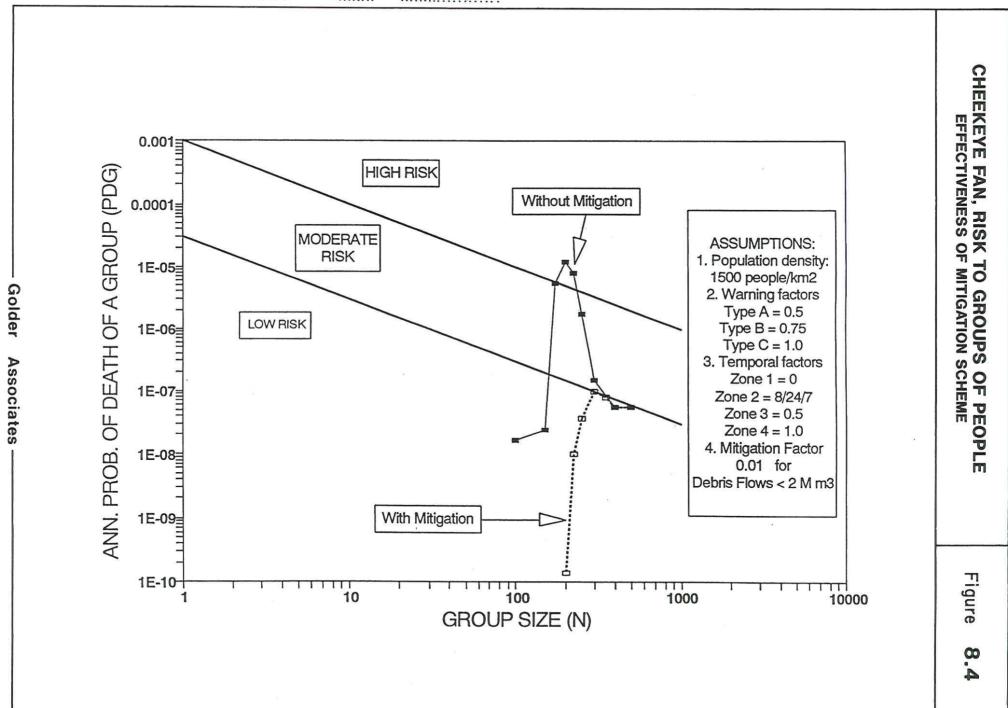
Probability of a death of an individual (P.D.I.)

Background risks: (Morgan, 1992)

Range of Involuntary risks

Range of voluntary risks

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Y-axis: PDG (Prob. of Death of a Group, size N) — 0.001, 0.0001, 1E-05, 1E-06, 1E-07, 1E-08

X-axis: GROUP SIZE (N) — 1, 10, 100, 1000

HIGH RISK

MODERATE RISK

LOW RISK

Golder Associates

CHEEKEYE FAN, RISK TO GROUPS OF PEOPLE
EFFECTIVENESS OF MITIGATION SCHEME

Figure 8.4

ASSUMPTIONS:
1. Population density:
   1500 people/km2
2. Warning factors
   Type A = 0.5
   Type B = 0.75
   Type C = 1.0
3. Temporal factors
   Zone 1 = 0
   Zone 2 = 8/24/7
   Zone 3 = 0.5
   Zone 4 = 1.0
4. Mitigation Factor
   0.01   for
Debris Flows < 2 M m3

θ

V

Fan Slope 2.9°

Approach
Angle, θ

90°
60°
45°
30°

* Height, (design) – m

8

6

4

2

0

0   2   4   6   8   10

Velocity – m/sec.

* *Height of dyke at centreline, Incorporates a factor
of safety of 1.2, Assumed flow depth is 3m.*

(based on Hungr et al., 1984)

FAN ZONING WITH LARGE DYKES
SCENARIO 1

Figure
8.6

LEGEND

3 - Fan zone designation
    (see Table 8.1)

— - Assigned zone boundary

[7.0] - Dyke height in metres

Dyke A

Dyke B

Dyke C

Dyke D

Dyke E

Minimal Hazard

Cheekye River

Cheakamus River

Squamish River

Brackendale

AREA PROTECTED BY
EXISTING FLOOD DYKES.
PONDING POSSIBLE
BELOW EL. 15 m (approx.)

Scale 1 : 15000

0   200   400   600   800   1000
            metres

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FAN ZONING WITH LARGE DYKES
SCENARIO 2

Figure
8.7

LEGEND

3 – Fan zone designation
(see Table 8.1)

– Assigned zone boundary

7.0 – Dyke height in metres

Cheekye River

Cheakamus River

Dyke B

Minimal Hazard

4.0

Dyke A

4.0

6.0

Dyke A

4.0

Brackendale

489000

490000

AREA PROTECTED BY
EXISTING FLOOD DYKES.
PONDING POSSIBLE
BELOW EL. 15 m (approx.)

Squamish River

488000

Scale 1 : 15000

0   200   400   600   800   1000
metres

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TABLE 8.10
EXPLANATION OF ZONING ON FIGURE 8.8:
ESTIMATED EFFECTS OF POTENTIAL DEBRIS FLOW HAZARDS

DEBRIS FLOW		
Magnitude Class	A(3M-7Mm³)	B(1M-3Mm³)
Return Period Mitigated Fan Zone	2,450 - 10,000	930 - 2,450
Ⓐ	Forest cover and all structures destroyed topography changed. V-7 T=5 W=1-1.5	Complete destruction possible in part of corridor, complete change of drainage pattern. V=4 T=4 W-0.7-1.0
Ⓑ	Less rapid but still very destructive debris flow, deposits of variable thickness, preferential flow along open corridors. V=4 T=3.5 W=0.7-1.5	Most forest stands and structures not destroyed, some concentrated destruction. V=3 T=2.5 W=0.5-0.7
Ⓒ	Forest and structures surrounded but not destroyed. V=3 T=2 W=0.5-1.0	Deposits controlled by topographic details and obstructions. Structural damage minor, erosion by water flow in new channels. V=2 T=1 W=0.2-0.5
Ⓓ	Deposits strongly controled by topographic details and obstructions. Structural damage minor, erosion by water flow in new channels. V=2 T=1 W=0.4	Most damage due to water flow, deposition of sediment (gravel), erosion and sediment ponding. V=1 T=0.5 W=0.2

Maximum Parameters: V=Velocity in m/s, T=Thickness of deposits in m, W=Width of damage corridors in kilometres.

Note: 1) Hazard zone boundaries are transitional. Any site located within approximately 200m of a boundary could have some of the characteristics of the adjacent zone.   Such sites should be reassessed by means of a site specific investigation, if the distinction is important.

2) Effects of unmitigated fan zones as shown on Table 8.1.

FAN ZONING WITH SMALL DYKES
SCENARIO 3

Figure 8.8

LEGEND

3 - Fan zone designation
(see Table 8.1)

Ⓐ - Mitigated fan zone designation
(see Table 8.10)

▬ - Assigned zone boundary

[7.0] - Dyke height in metres

Dyke A

Dyke B

Dyke C

Excavated Basin

Cheekye River

Cheakamus River

Squamish River

Brackendale

AREA PROTECTED BY EXISTING FLOOD DYKES. PONDING POSSIBLE BELOW EL. 15 m (approx.)

Scale 1 : 15000

0 200 400 600 800 1000
metres

Thurber Engineering / Golder Associates

EXISTING LAND USE / EXISTING HAZARD CONDITIONS

Figure 9.1

EXISTING LAND USE KEY

A - PREDOMINANTLY RESIDENTIAL
B - SCHOOL
C - CHURCH
D - CEMETERY
E - MUNICIPAL LANDFILL / WATER STORAGE
F - COMMERCIAL RECREATION
G - PARK
H - AIRPORT
I - QUARRY
J - WOODWASTE DUMP
K - B.C. HYDRO SUB-STATION
L - INDUSTRIAL (MILL)
M - TANTALUS SUBDIVISION (UNDEVELOPED)

ROADS
RAILWAY
B.C. HYDRO POWER LINE RIGHT OF WAY
MAJOR FACILITIES

HAZARD LEGEND

3 - Fan zone designation (see Table 8.1)

— - Assigned zone boundary

ALICE LAKE PROV. PARK

DISTRICT OF SQUAMISH QUARRY

DRYDEN CREEK RESORT

490000

489000

Brackendale

DISTRICT OF SQUAMISH SANITARY LANDFILL

DISTRICT OF SQUAMISH RESERVOIR

Cheekye River

Cheakamus River

CHEEKYE STABLES

FERGIE LODGE

B.C. HYDRO CHEEKYE SUB-STATION

MILL

DISTRICT OF SQUAMISH AIRPORT

DIST. OF SQUAMISH CEMETERY

CHURCH

SECONDARY SCHOOL

ELEMENTARY SCHOOL

STUMP DUMP

Squamish River

AREA PROTECTED BY EXISTING FLOOD DYKES. PONDING POSSIBLE BELOW EL. 15 m (approx.)

488000

5516000 5515000 5514000 5513000 5512000

Scale 1 : 15000

0   200   400   600   800   1000
              metres

Mar. 15/93   DATE

GER   REVIEWED

P.R.   DRAWN

922-7525   PROJECT NO.

Thurber Engineering / Golder Associates

LAND OWNERSHIP KEY

NON CROWN PROVINCIAL LAND:
A – INDIAN RESERVES
B – DISTRICT OF SQUAMISH
C – B.C. HYDRO
D – HOWE SOUND SCHOOL DISTRICT
E – PRIVATE LAND (except for municipal roads and parks)

CROWN PROVINCIAL LAND BY STATUS:
F – LEASE OR LICENCE OF OCCUPATION
G – U.R.E.P. (RECREATION RESERVE)
H – ALICE LAKE PROVINCIAL PARK (PARK RESERVE)
I – SAND and GRAVEL RESERVE
J – ECOLOGICAL RESERVE
K – FOREST TENURE and ADMINISTRATION AREAS
L – FOREST
M – OTHER CROWN LAND

SOURCE – MINISTRY OF ENVIRONMENT, LAND AND PARKS NOVEMBER 1991

HAZARD LEGEND

3 – Fan zone designation (see Table 8.1)
— Assigned zone boundary

ALICE LAKE PROV. PARK

DISTRICT OF SQUAMISH QUARRY

DRYDEN CREEK RESORT

Cheekye River

CHEEKYE STABLES

DISTRICT OF SQUAMISH SANITARY LANDFILL

DISTRICT OF SQUAMISH RESERVOIR

Cheakamus River

BC HYDRO POWER LINE

CHURCH

ELEMENTARY SCHOOL

SECONDARY SCHOOL

Brackendale

FERGIE'S LODGE

B.C. HYDRO CHEEKYE SUB-STATION

DIST. OF SQUAMISH CEMETERY

GOVERNMENT ROAD

MILL

DISTRICT OF SQUAMISH AIRPORT

STUMP DUMP

AREA PROTECTED BY EXISTING FLOOD DYKES. PONDING POSSIBLE BELOW EL. 15 m (approx.)

Squamish River

Scale 1 : 15000

0 200 400 600 800 1000 metres

490000
489000
488000
5516000
5515000
5514000
5513000
5512000

PROJECT NO. 922-7525 DRAWN PJL REVIEWED GER DATE Mar. 15/93

Thurber Engineering / Golder Associates

PLANNING AREAS BASED ON HAZARD EXPOSURE

Figure 9.3

HAZARD LEGEND

3 — Fan zone designation (see Table 8.1)

—— Assigned zone boundary

Cheekye River

Cheakamus River

Brackendale

AREA PROTECTED BY EXISTING FLOOD DYKES. PONDING POSSIBLE BELOW EL. 15 m (approx.)

Squamish River

Scale 1 : 15000

0 200 400 600 800 1000
metres

Thurber Engineering / Golder Associates

PROJECT NO. 922-1525 DRAWN PJL REVIEWED GEC DATE Mar. 15/93

490000
489000
488000
5516000
5515000
5514000
5513000
5512000