Squamish River Drainage Basin: (TFL 38) Terrain and Slope Stability Mapping for Forest Management

Prepared for
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by
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EXECUTIVE SUMMARY

Terrain mapping and assessment of slope stability (Classes IV and V) were carried out for the Squamish River drainage basin (T.F.L. 38) at the request of Weldwood of Canada Ltd. (now INTERFOR) in order to provide information for planning of future forestry activities. The results are presented in this report which accompanies a series of 22 terrain and slope stability maps prepared as overlays to 1:15 000 scale orthophotos. Terrain mapping was carried out by air photo interpretation and field checking at terrain survey intensity level B.

The physiography, terrain and climate of the Squamish basin are typical of the southern Coast Mountains. Rugged glaciated mountains rise abruptly from narrow valleys. Forested valleysides are generally steep and commonly precipitous. Gentle slopes and flat land are restricted to the floodplains of the Squamish River and its larger tributaries, and alluvial fans. Some gentle to moderately steep slopes are mantled by glacial drift and colluvium, and pockets of glacial drift are present on steep rocky slopes. Rock slopes are common at all elevations. Most of the area is underlain by intrusive rocks that are strong and resistant to erosion, allowing many very steep but relatively stable rock slopes to persist with little modification since deglaciation. Small areas are underlain by Garibaldi volcanic rocks, and some of these, especially weakly consolidated pyroclastics, can be extremely unstable and have given rise to major debris flows.

Within the context of this rugged landscape, natural slope instability in surficial materials and intrusive rocks appears to be less in the Squamish basin than in some other coastal areas. Nevertheless, thoughtful and innovative forest management will be required to prevent acceleration of slides and erosion as forestry operations move onto ever steeper slopes. The chief types of landslide that are of concern to forestry are debris slides and debris flows. These occur on slopes steeper than about 60% that are underlain by till or colluvium. The chief triggering effects are heavy rainfall onto saturated soil during fall and winter storms, and strong winds.

The maps that accompany this report show that presently unstable terrain (stability Class V) is not widespread in T.F.L. 38. Steep forested slopes that are marginally stable (or potentially unstable) (Class IV) are commonplace however, and will be the focus of much future logging activity. Precautions will be required to avoid destabilization of these slopes and increasing sediment input to streams due to road construction and timber removal. In general, instability appears to be controlled primarily by slope steepness, although on any steep slope, slide initiation sites are determined by the location of wet soils, local slope configuration, and other factors. The local variability of these factors is not shown on the terrain maps, but should be recognized by foresters during ground inspection and layout of roads and cut blocks.

CONTENTS

(1) INTRODUCTION

The objective of this project was to prepare terrain and slope stability maps (stability classes IV and V) for the forested parts of T.F.L. 38, which encompasses the drainage basin of the Squamish River, about 70 000 ha. The maps will be used by International Forest Products Ltd. (formerly Weldwood of Canada Ltd. Coastal Forestry) to prepare an updated Development Plan, as required by the British Columbia Ministry of Forests for the planning of forest management activities.

Terrain mapping and slope stability interpretations were carried out according to provincial standards (Section 3). Terrain mapping was done at a scale of 1:20 000 by air photo interpretation followed by field checking. Terrain maps, with slope stability classes IV and V, were prepared at a scale of 1:15 000 as overlays to orthophotos.

This report augments the information that is shown on the maps. It provides additional information about surficial materials and slope stability of relevance to land use, descriptions of terrain mapping methodology, criteria for slope stability interpretations, and a discussion of terrain map reliability. Implications and recommendations for forest land management that arise out of the terrain analysis are also discussed.

(2) PHYSIOGRAPHIC SETTING

The Squamish River drainage basin lies within the Pacific Ranges of the Coast Mountains (Holland, 1976). Most of the physiographic characteristics of this area (see below) are typical of the Pacific Ranges and similar to areas such as Clowhom and Toba. However, the Squamish basin includes areas of Garibaldi volcanic rocks (2.2), and these can be extremely unstable and hazardous (5.1).

This area experiences a typical west coast mid-latitude climate, with abundant winter precipitation, drier summers, and generally moderate temperatures. Winter precipitation includes rain and snow, with higher elevations dominated by the latter, although rain is not unusual at high altitudes, e.g., as high as 1800 m, during frontal (low pressure) storms. Intense rainfall onto saturated soil during fall and winter storms is the chief trigger of debris slides and debris flows. A combination of intense rainfall and snowmelt during major storms results in maximum stream discharge and overbank flooding along Squamish River and its tributaries. Heavy winter snowfall results in major snow avalanche activity on many steep slopes.

2.1 Relief and Topography

The Squamish basin encompasses rugged, glacially-eroded topography. Deeply incised, steep-sided valleys rise to alpine areas with extensive icefields. Elevations range from about 30 m a.s.l. at the Squamish-Ashlu confluence to 2651 m at the summit of Mt. Boardman near Clendenning Creek. Many summits rise to between

2000 and 2500 m, and much land above 1800 m is ice-covered. Treeline, the upper limit of terrain mapping, is at 1400-1500 m, although non-forested avalanche slopes commonly extend well below this elevation, especially in the higher tributary valleys.

2.2 Bedrock Geology

Most of T.F.L.38 is underlain by rocks of the Coast Plutonic Complex. Small areas in the southeastern part of the basin are underlain by Garibaldi volcanic rocks. The Coast Plutonic Complex evolved during the Mesozoic Era when many discrete masses of molten rock (plutons) pushed upward into older sedimentary and volcanic rocks. Much of the older rock was modified by heat and pressure, and transformed into metamorphic rock. Narrow bands of older, altered rocks (e.g., metavolcanics, gneiss and schist) separate some of the plutons (Fig. 1).

Several different types of plutonic rock have been mapped in the study area: quartz diorite and granodiorite are widespread, and there are small areas of diorite and gabbro (Roddick and Woodsworth, 1979). However, all of these rock types are coarsely crystalline (individual crystals can be seen easily with the naked eye) and their other physical characteristics, such as strength and high resistance to weathering, are similar, and so from now on they will be referred to collectively as "plutonic rocks".

The plutonic rocks typically have great strength and are relatively resistant to weathering and erosion. Planes of weakness (joints) are typically widely spaced, in places as much as several metres apart. This spacing, together with the great strength of unfractured rock, results in the release of very large blocks by weathering processes such as frost shattering and glacial erosion. Thus blocky talus slopes, bouldery glacial deposits, especially till, and bouldery stream gravels are characteristic of this area. Also due to rock strength, talus slopes are of relatively limited extent when compared to other mountain regions such as the Rockies. In places, boulders (rounded edges) and blocks (angular edges) are sufficiently large that they require blasting for removal during road construction. When the coarsely crystalline plutonic rocks are broken down by weathering or glacial abrasion, they disintegrate to a sandy residue. Consequently till matrix is typically quite sandy, and sand is abundant in other glacial and postglacial deposits.

Although the plutonic rocks are usually strong, in places they have been weakened by the intrusion of narrow sheets (dykes) of fine-textured igneous rock, such as basalt and andesite, that are between a few centimetres and a few metres in width. These rocks are more closely jointed and more readily weathered and eroded than the plutonic rocks. It is likely that gullies and open joints (wide cracks) have developed along these dykes, and ground water movement through these more permeable zones may adversely affect slope stability. In some small areas, the plutonic rocks have been altered by subterranean hydrothermal processes to form relatively soft, easily disintegrated material. The altered rocks are more readily eroded and destabilized than unmodified plutonic rock.

Garibaldi volcanic rocks underlie steep slopes along the eastern boundary of the Squamish basin in the vicinity of the old volcanoes Mt. Cayley and Mt. Fee, and flat-lying lavas underlie low-relief terrain along upper Elaho River. Pyroclastic rocks on the slopes of Cayley and Fee consist of weakly consolidated volcanic debris that is commonly unstable and has given rise to major rock avalanches and debris flows (Section 5.1).

2.3 Evolution of the Landscape: Glacial and Postglacial History

Most of the landforms of the Squamish basin are a legacy of the glaciations. Large, erosional features, such as valleys and cirques (valley-head basins), were sculpted during the repeated glaciations of the Pleistocene Epoch, about 2 million to 12 000 years ago. The surficial materials (overburden, engineering soils) date from the last glaciation, about 30 000 to 12 000 years ago, known as Fraser Glaciation in British Columbia, and the postglacial interval.

Landforms in the alpine areas that surround the valleys attest to ice accumulation here during the glaciations. Glaciers headed in the flat-floored, steep-sided cirque basins, and ridges between the glacier-heads were sculpted into knife-edged aretes. On some of the broader interfluves, summit icefields existed. Downvalley, glacial erosion developed typical U-shaped valleys (glacial troughs) with precipitous side-slopes and floors where gentle gradients alternate with rock steps. The major valleys were deepened below their tributaries, which were left hanging. Some tributaries occupy troughs that "hang" by as much as 500 m above the larger valleys, giving rise to difficulties of road access. For example, High Falls Creek, descends more than 500 m in 1.5 km as it approaches the Squamish River. Gorges are common where streams descend from hanging valleys, for example at Ashlu and Elaho canyons, further compounding access problems.

The sequence of events that occurred during Fraser Glaciation was probably similar to that of earlier glaciations. From regional evidence (Clague, 1981) we know that climate deterioration and growth of mountain glaciers commenced about 30 000 years ago. Icefields, such as those that exist at present on the upland between the Ashlu and Elaho Rivers, gradually thickened and expanded under the influence of increasing winter snowfall until glaciers expanded and advanced down the valleys. By about 20 000 years ago, it is likely that the main valleys were occupied by glaciers more than 1000 m thick, and at the glacial maximum, about 15 000 years ago, ice buried all land below about 2250 m. The Squamish glacier was a minor tributary to the vast Strait of Georgia-Puget Sound ice lobe that extended south to Olympia, Washington.

Shortly after 15 000 years ago, the climate trend reversed abruptly, and rapid glacier melting commenced. In the Squamish basin, the ice surface became lower, peaks and ridges emerged, and the more or less continuous ice sheet was replaced by a system of valley glaciers. Eventually, as the ice continued to get thinner, the glaciers receded back up their valleys. Temporary halts in recession appear to have occurred after tributary glaciers had separated from trunk glaciers in the Squamish and Elaho valleys. The resulting recessional moraines (ridges of bouldery till) (Photo 1) are commonly sites of present day slope instability (Section 4.1). By about 10 000 years ago glaciers were probably no more extensive than they are today.

During deglaciation, meltwater streams flowed along the edges of the decaying glaciers at elevations high above the present valley floors. On moderate slopes, glacial debris was picked up by the meltwater and redeposited as veneers or terraces of glaciofluvial gravels, for example in the vicinity of Shovelnose Creek (Section 4.2). Meltwater streams draining from the snouts of the tributary glaciers deposited gravels alongside the ice, leaving irregular terraces of glaciofluvial sands and gravels (Section 4.2). Small lakes were also impounded by ice in the trunk valley, as indicated by pockets of glaciolacustrine sediments on the valleysides (Section 4.3), although major lake-related landforms are absent.

The melting glaciers uncovered much loose and unstable debris that was rapidly eroded and redistributed downslope in the newly exposed, unvegetated landscape. Basal (subglacial) till had accumulated beneath the moving glaciers, and on many slopes, loose gravelly ablation till that had accumulated on top of the ice was emplaced onto the basal till as the ice melted (see also Section 4.1). Before the landscape was colonized by vegetation, flowing water, debris flows, landslides, and even wind were effective agents of degradation. Much of the material removed from the steeper slopes was redeposited on gentler slopes along the valley floor as colluvium and fluvial sediments. Gully erosion on steep till-covered hillsides was effected by both streams and debris flows, and reworked materials accumulated in colluvial fans. These processes were particularly effective in the vicinity of Mt. Cayley and Mt. Fee, where large volumes of debris were derived from the weak rocks of the Garibaldi volcanics. Stream sediments accumulated in aggrading floodplains along the major rivers, and alluvial fans were constructed at the mouths of tributaries. Many of the above processes continue to modify the present day landscape, although less rapidly than formerly.

After deglaciation, bedrock slopes that had been steepened by glacial erosion were affected by weathering processes such as frost shattering, and by erosion due to debris flows, rockfalls and snow avalanches. Talus slopes and avalanche cones have continued to develop throughout postglacial time. Major rockslides (or rock avalanches) probably occurred during or shortly after deglaciation.

(3) METHODOLOGY

3.1 Terrain Mapping

Terrain mapping followed the standard British Columbia procedures for terrain classification (Howes and Kenk, 1988) and mapping methodology (Ryder, 1994).

Preliminary terrain mapping was done by interpretation of 1:15 000 scale, 1978, black and white air photos. No more recent, large scale photos were available. Difficulties encountered as a result of using relatively old photos are discussed in

Section 3.3. Initially we had attempted to do air photo interpretation using orthophotos with stereomates, but stereoviewing showed great distortion of slope steepness and ground surface morphology, and so this approach was abandoned. Air photo interpretation was carried out by the terrain mappers and checked by J.M.Ryder.

Field work was carried out during June and July 1994. (See Appendix 2 for terrain mappers.) A total of 55 crew days were used for checking, giving an overall rate, for the 70 000 ha basin, of about 1280 ha/crew day. This relatively rapid rate of progress, as compared to usual rates of between 500 and 1000 ha per day, is due to several factors. Large areas of the valley floors and lower slopes have already been logged, so that there was much road access (including deactivated roads that could be easily walked). For the same reason, visibility was good, enabling mappers to check certain conditions, such as rocky slopes, thick vs. thin till, from afar. Also, the area that we mapped, which was generally those areas below treeline, included extensive avalanche slopes with no commercial trees and inoperable areas of steep rock which did not require ground checking, and the broad floodplains of the Squamish and Elaho rivers. Finally, map sheets 92J-042 and -043 were mapped by air photo interpretation with no field checking (terrain survey intensity level E) at the request of INTERFOR staff.

Checking was carried out largely by means of foot and vehicle traverses. Helicopter drop offs and brief overview flights were used for remote areas, particularly in the upper Elaho and Clendenning areas. Attention was focused on relatively steep slopes likely to be designated as stability classes IV and V. All field observation sites are shown on the terrain maps: "ground check sites", which were visited, are distinguished from "visual sites", where notes were made on the basis of viewing from a distance. Formal site descriptions on field forms were recorded for 444 sites, and field data forms are presented in Appendix 4 (separate volume). Soil pits were dug where natural exposures, such as slide scars or tree-throw hollows, were not available for examination. Road cuts were described in cleared areas. Unrecorded checks were made in all polygons that were traversed. Where necessary, terrain mapping on the air photos was corrected on-site.

Following field work, mapping on the air photos was checked for consistency and reviewed for a final time by JMR. Polygon boundaries were then transferred to transparent overlays on 1:15 000 scale orthophotos by hand, using features visible on both the mapped photos and the orthophotos as a guide to the placement of boundary lines. Slope steepness classes were added, based partly on field measurements and partly on determinations from 1:20 000 scale topographic maps (7.5 m contour interval). Soil moisture was not added to the maps because, other than well and rapidly drained areas such as steep rock and talus slopes, moisture conditions are so variable that almost all polygons include a range of at least three moisture classes. Assignment of slope stability ratings to polygons is discussed in Section 3.2.

3.2 Slope Stability Interpretations

Slope stability depends upon numerous factors, of which the most significant are slope steepness, soil moisture and shallow groundwater conditions, material characteristics including texture, thickness, and depth to impermeable layer; slope morphology (irregular vs. smooth; concave vs. convex), and slope position (upper-, mid-, lower-slope). A single set of quantitative definitions for slope stability classes, in terms of slope steepness, soil moisture etc., is not applicable to all coastal areas of British Columbia. This is due partly to variation of criteria from area to area according to local conditions such as precipitation intensity and bedrock types, and partly to insufficient information about slope failure processes.

For interpretation of slope stability in T.F.L.38, we applied criteria that we have used recently for similar assessments in similar terrain in other parts of the southern Coast Mountains (Table 3.1). These criteria were used as guidelines rather than rules. Judgment is applied to modify the guidelines if necessary, for example to take account of soil drainage conditions and slope morphology, as indicated in the two right hand columns of the table. Each polygon was rated individually by the mapper. Only slope stability classes IV and V are shown on the terrain maps.

Table 3.1: Guidelines for Interpretation of Slope Stability Classes

Potential Slope Stability and Surface Erosion Classes	Dominant Slope Class*	Material and Landforms	Dominant Texture	Active Processes	Soil Drainage	Slope Morphology
I	1 and 2 .... 1&2 mixed	F^Gt, F^Gu; Cf; Ff .... Mv, Mb; Cv; R	g; sr, g $s, s; sr	none none	poorly drained and wet soils are relatively susceptible; units with slopes within 3 or 4° of an upper class boundary may be assigned to the next highest class	slopes with irregular or benched topography controlled by bedrock are relatively stable; units with slopes close to a lower class boundary may be assigned to the next lowest class.
II	2 .... 2 and 3	Mv, Mb .... Cf; F^G; R	s$ sr; g;	none none		
III	3 4	Mv, Mb; Cv .... Ca, Ck, R, F^G	$s; sr sr, x; g	none none		
IV	4 and 5 .... 4 and 5	Mv, Mb, Cv, Cb .... Rk, Rs	all	-V, -Rb*		
V	any gradient	all	all	-F, -Rd*, -Rs* **		

* Slope classes are defined as follows: Class 1: 0-3° (0-5%); Class 2: 4-15° (7-27%); Class 3: 16-26° (29-49%); Class 4: 27-35° (51-70%); Class 5: over 35° (70%).

** Refers to the initiation zone of active gullies, rapid mass wasting (mostly debris flows), and slow failure.

3.3 Reliability and Limitations of Mapping

The accuracy of terrain mapping, and hence the reliability of slope stability interpretations, depends on numerous factors, such as skill and experience of mappers, scale and quality of air photos used, type and density of vegetation, field access and length of time spent in the field, quality of base maps, and type and complexity of terrain and surficial materials mapped. The more relevant of these factors are discussed here.

For this project, quality of air photos was excellent, but because the air photos were 16 years old at the time of mapping, many of the present roads and clearcuts are not shown on the photos. Consequently, mappers sometimes had difficulty in pin-pointing their positions along roads or in cut blocks, although it is unlikely that field observations were attributed to the wrong polygon.

All preliminary air photo interpretation was checked and corrected where necessary by an experienced mapper (JMR). Field checking was done by crews with experience of at least several previous projects in similar terrain. In general, field access was good, since roads extend along most valleys and supplementary helicopter drop-offs were used where necessary. Field time (Section 3.1) was judged adequate, especially since road access was good.

Accuracy of transfer of terrain boundary lines to orthophotos benefited from the close comparisons of features that was possible from mapped photo to orthophoto, but very dark shadows on some small parts of the orthophotos precluded accurate placement of lines. In such areas lines were dotted, i.e., shown as "assumed boundaries" to indicate their unreliability.

One of the chief difficulties encountered in terrain mapping on steep mountainsides in the Coast Mountains is the distinction of mantles and veneers of colluvium (Cw, Cv) from those consisting of till (Mw, Mv). Natural exposures of these materials are not common, and they cannot be easily separated by observations based on soil pits (which were dug at most sites) because materials at shallow depths have been modified by weathering. Also, the locally-derived till on steep mountainsides is very similar to colluvium, and both materials commonly occur in the same polygons. Thus Mw and Mv terrain may well include a fair amount of Cw and Cv, and vice versa. This mapping problem is not a serious constraint on stability interpretations because on steep slopes, Mw, Mv, Cw and Cv are grouped together (Table 3.1).

Map users should bear in mind that the smallest polygons delimited on the air photos were between 1 and 2.25 cm^2, or between about 1.5 and 3.5 ha. Thus local variations in terrain conditions over distances of less than about 100 m were not mapped. Within-polygon variations in slope steepness, material characteristics and soil moisture, and local inclusions of materials other than those that were mapped, must be recognized and taken into consideration by map users. The chief implication of this for forest management is that detailed planning, e.g., of road alignments, block boundaries, will require ground checking in order to discover and flag sites that may be particularly sensitive to disturbance.

In some polygons where variability of slope stability class is due to variable slope steepness, we have indicated two stability classes (e.g., II, III), of which the former is the most extensive. (If only one stability class is allowed, e.g., for data entry into GIS, then the higher class should be used, regardless of its relative extent.) It must also be assumed, however, that there will be local variability of slope stability due to variations in soil drainage, till texture, slope morphology, and other factors. Thus in any polygon mapped as Stability Class III for example, there will invariably be some small areas of Class IV, and possibly some small areas of Class II. For the same reason, it is likely that small areas of Class IV terrain occur within polygons mapped as Class V. Attention is drawn to some types of local variability in Sections 4 and 5.

The information and analyses contained in this report are based on observations of land-surface conditions and current understanding of slope processes. However, because slope stability is strongly influenced by subsurface conditions that are not apparent from surface observations or air photo interpretation (e.g., characteristics of subsurface materials, subsurface hydrologic conditions), by events whose time of occurrence cannot be predicted (e.g., extreme storms, earthquakes), and by land management practices, the results and recommendations provided in this report cannot guarantee that no landslides will occur in areas affected by forestry activities. Appropriate use of terrain information and implementation of recommendations will, however, reduce the risk of landslides and erosion.

(4) SURFICIAL MATERIALS

4.1 Till (M, M')

Till (M, morainal material) is defined as material deposited directly from glacier ice. Both basal and ablation tills may be highly variable, with gradations in characteristics such as texture and consolidation over short distances. Basal till was deposited subglacially by melting of ice at the sole of a glacier. Typically, it is massive (non-stratified), poorly-sorted material, with clasts (particles > 2mm) supported in a fine-grained matrix of sand, silt and clay. It is usually the most highly consolidated (densest) and strongest of all the surficial materials; and it is highly cohesive. The permeability of basal till is generally low.

Ablation (supraglacial) till (M') consists of debris that melted out on top of a glacier when the ice surface melted downward during deglaciation. It is relatively gravelly with little silt and no clay. Typically, it is non-consolidated, non-cohesive, gravelly, and of rapid permeability. Characteristics such as clast size vary markedly over short distances. Ablation till commonly contains pockets of till that flowed off the glacier when saturated (flow till), glaciofluvial sand and gravel, and fine-textured (fine sand, silt, clay) glaciolacustrine sediments.

In general, in the Squamish basin, basal till is the most widespread surficial material. It was described at 203 of our 444 observation sites. It forms a widespread and continuous cover (Mb, Mv, Mw) on many gentle to moderate slopes

at all elevations (Photo 2), including those of the alpine zone . On steeper slopes, till is discontinuous, thin (Mv, Mw), and commonly buried by a veneer of colluvium derived from rock outcrops upslope. On irregular slopes, till fills depressions between rocky protuberances (Mw), and small pockets of till survive even on precipitous slopes in such situations. Till thickness can vary greatly over short distances. On slopes mapped as till blanket (Mb), till is thicker than 1 or 2 m, whereas till is thinner than 1 to 2 m on slopes mapped as till veneer (Mv). Mantle of variable thickness (Mw) is shown on slopes where till fills depressions in an irregular bedrock surface; till thickness varies continuously from 0 to several metres, and rock outcrops may be common.

Most till in the Squamish basin shows characteristics that are typical of basal till throughout the southern Coast Mountains -- characteristics that reflect its derivation from the underlying coarse textured crystalline rocks (Photos 3 and 4). Till matrix is a uniform silty fine sand (ṡs), but the proportion of clasts (= particles > 2 mm) varies locally (i.e., within polygons), ranging between about 30 and 70% by volume. Clasts in till are chiefly subangular and subrounded pebbles and cobbles, although boulders are common and may be so large that blasting is required for their removal during road construction. On the terrain maps, the texture symbol is omitted from till polygons where texture conforms to the description in this paragraph.

During postglacial time, weathering and soil-forming (pedogenic) processes have transformed the upper 1 to 2 m of the till into relatively loose sandy material with properties that are dissimilar to those of unmodified till (Photo 4). The weathered till is highly permeable, so that water from rain and snowmelt moves rapidly down through the soil until it reaches the upper surface of the unweathered till. A perched water table tends to develop here, and within this saturated zone, water seeps downslope through the lower part of the soil. This process is highly significant because most debris slides are triggered by loss of cohesion related to the high pore water pressure that develops at the base of the soil zone when the water table rises during intense rainstorms (Section 5.1). The contact between weathered (soil) and unweathered till is commonly a sharp weathering front, and this becomes the slip-plane along which detachment occurs. Where unweathered till is overlain by a thin layer of colluvium, e.g., in "Cv over Mb" terrain units, the colluvium/till contact functions similarly to that between weathered and unweathered till.

Unweathered basal till is highly consolidated (i.e., dense), relatively strong and cohesive (for a surficial material), and will support steep slopes. Sloughing of till occurs in road cuts that intersect the weathering front seepage zone (Photo 4). Basal till is also frost-susceptible: on frosty nights, ice needles grow just below the till surface. This results in surface sloughing on road cuts and heaving and softening of roads where till is used as ballast.

The permeability of basal till is slow, and soils are commonly relatively wet on gentle slopes, concavities, and toe-slopes. Surface runoff results in gully erosion (Photo 2).

Ablation till in the Squamish basin displays the typical characteristics noted above (Photo 5). Some relatively large areas of ablation till were mapped in the same areas as extensive glaciofluvial deposits, that is, in the vicinity of Shovelnose Creek and along the east side of the upper Squamish River. Ablation till was also mapped adjacent to the glaciolacustrine deposits near the Elaho-Sims confluence. Other, smaller areas of ablation till are scattered throughout the area mapped, and include recessional moraines at the mouths of tributaries, such as Limelite Creek (92J-013).

Slopes underlain by ablation till are typically unstable where they are steeper than about 70%. Road cuts tend to ravel, and falling rocks create a local hazard (Photo 5).

4.2 Glaciofluvial Materials (F^G)

Glaciofluvial sediments were deposited by glacial meltwater streams. Glaciofluvial ice-contact deposits (e.g., F^Gu, F^Gh, F^Gb) accumulated against or on top of melting glacier ice, and commonly overlie till. Proglacial deposits were laid down in outwash plains (F^Gp), deltas (F^Gt) and fans(F^Gf) downstream from the glacier. Postglacial streams may have cut down thorough outwash plains and fans, transforming them into terraces (F^Gt). Glaciofluvial outwash deposits consist of sand and gravel with little finer material. Sorting and bedding characteristics are variable, depending on the mode and site of deposition. Sorting ranges from poor (well graded) to good (poorly graded), and bedding (stratification) ranges from well defined to absent. Ice contact deposits may display distorted bedding, slump structures, and faults as a result of settling and collapse due to melt of supporting ice. Foreset beds (beds deposited on the frontal slope of the delta and inclined at 10-20^{o}) are typical of former deltas. Large, ice-rafted boulders are common in glaciofluvial deposits. Ice-contact glaciofluvial materials may contain pockets of silt and clay that were deposited in small ice-marginal ponds, and pockets of till that slid or flowed from adjacent ice. Like till, ice-contact materials are highly variable with regard to characteristics such as texture.

Glaciofluvial sands and gravels are highly porous and permeable, and thus they form relatively dry and well drained sites. The material is non-cohesive, and so tends to ravel when exposed in steep stream banks and road cuts. Where glaciofluvial material consists entirely of well drained gravel and sand, it is relatively stable. Where lenses of finer materials (e.g., silt) are present, the resulting perched watertables may lead to instability resulting in debris slides and gully erosion. Also, where thin glaciofluvial materials overlie impermeable bedrock, till, or glaciolacustrine sediments, impeded drainage can lead to slope failure. Glaciofluvial materials are potential sources of aggregate and fill.

In the Squamish basin, the largest areas of glaciofluvial materials are found in map areas 92J-013E (Camp No. 3) and 92J-024 (Upper Squamish) along the east side of Squamish River, and west of the river near Dipper Creek. The gravels blanket a moderately sloping hillside. As seen in road cuts, they are coarse and bouldery, and they range in thickness from about 2 to over 5 m. They consist chiefly of plutonic rock types, such as granodiorite, and they overlie basal till. Similar bouldery

glaciofluvial gravels are also extensive on the eastern slopes of Squamish valley in the vicinity of Shovelnose and Turbid Creeks where they are associated with a variety of landforms, including fans, hummocks and blankets. Glaciofluvial terraces were also mapped along Elaho River, in the valley of High Falls Creek, and at widely scattered sites elsewhere (Photo 6).

4.3 Glaciolacustrine Materials (L^G)

Glaciolacustrine (= glacial lake) sediments consist of fine sand, silt, and clay carried by meltwater streams and deposited in temporary, ice-dammed lakes. Typically, these sediments are thinly bedded or laminated (= beds thinner than 1 cm), and layers of coarser and finer texture alternate (Photo 7). Glaciolacustrine sediments that contain even a modest proportion of silt and clay are only slowly permeable, or effectively impermeable, and so the presence of even a thin layer of this material is sufficient to cause impeded drainage, perched watertables, and surface seepage. All these conditions promote instability. These fine materials, especially sand and coarse silt, are also susceptible to surface erosion by running water. These sensitive materials have created many headaches for forest managers.

In the Squamish basin, glaciolacustrine sediments were mapped in only two areas, although lenses of silty sediments were noted at several other sites. In Sims Creek valley (map sheet 92J-022), silty lake sediments underlying till and glaciofluvial gravels are the chief cause of unstable river banks and scarps. Between 1 and 2 km northeast of the Elaho-Sims confluence (map sheet 92J-023), glaciolacustrine sediments, overlain in places by glaciofluvial gravels, were mapped in four polygons (Photo 8). Small lenses and pockets of glaciolacustrine sediments in till and glaciofluvial materials were noted at several sites, e.g., BW7, 9, 24, 28 and PF66. These lenses probably extend from a few metres to a few tens of metres, and are a few centimetres to 1 or 2 m in thickness. They were found by mappers only where they are exposed in roadcuts or stream banks. Such lenses are probably common in till, especially ablation till, and glaciofluvial gravels, and they undoubtedly contribute to slope instability.

4.4 Colluvium (C)

Colluvium is material that has moved downslope due to a variety of gravitational processes, including rockfall, debris flows, and snow avalanches. The characteristics of colluvium and colluvial landforms are dependent upon source material (bedrock or glacial drift) and the process whereby it was moved. Thus the texture of colluvium varies widely.

In the mapped area, colluvial veneers, blankets and mantles (Cv, Cb, Cw) are the most common forms of colluvium. These features are mapped where loosened and weathered rock has moved downslope, either by slow processes such as soil creep, or by catastrophic events, such as debris flows or rockfall. The colluvial material typically consists of loosely packed rubble or blocks with interstitial silty sand (Photo 9).

Rockfall colluvium is widespread at the foot of cliffs. Talus slopes (e.g., aCk, arCk) flank open cliffs, and talus cones (e.g., xCc, srCc) have formed where rock fall is funneled down gullies. Talus material derived from plutonic rocks consists of large angular blocks (>25.6 cm) and rubble (Photo 10). It is loosely packed and non-cohesive, well drained and relatively dry. Blocky talus slopes and cones are usually not prone to debris slides (stability class III). Talus derived from the Garibaldi volcanics is much finer textured (rCk, srCc) and prone to debris flows when water from the cliffs above is funneled onto the upper part of a slope during intense rainstorms. Avalanche cones (Cc-A) are similar to talus cones, but transportation of rocky debris by sliding snow results in slopes that are less steep more concave than the typical 70% talus slope.

Blocky talus provides relative stable substrate for roads, although there may be a potential hazard from rockfall, and surface raveling and upslope recession of road cuts may occur. Fallen blocks are commonly used as rip rap to control river bank erosion.

Rockslides and rock avalanches from steep mountainsides have also given rise to blocky and rubbly colluvium. Such landslide deposits form areas of hummocky or undulating terrain (aCh, rCrh, etc.).

Debris flow fans and cones (e.g., sbgCf, ‡srCf-Rd, Cc-Rd) are present at the lower ends of most gullies and steep (> 25%) creeks in the study area (Photo 11). The fans have accumulated as a result of repeated debris flows throughout postglacial time. Particularly large fans have developed at the ends of channels that drain from Garibaldi volcanic rocks in the vicinity of Turbid Creek; debris flows are a recurrent problem for road maintenance here. Debris flows should be expected on any colluvial fan, even though there may be no visible evidence of a recent event: all fans should be viewed as hazardous sites.

4.5 Fluvial Materials (F, F^A)

Fluvial deposits have been transported by flowing water. They underlie floodplains, river (fluvial) terraces, alluvial (fluvial) fans and deltas. Fluvial materials consist of loosely packed, non-cohesive gravels, sands, and minor silt. Sands and gravels are porous and highly permeable. Typically, they provide sites that are dry and well drained unless the watertable lies close to the ground surface, as in the case of floodplains and the lower parts of fans.

In the study area, broad floodplains flank the Squamish and Elaho Rivers (Photo 12), and smaller, discontinuous floodplains, some of which are too narrow to map, extend along many tributaries. Floodplains commonly consist of a gravelly active channel zone (sgF^Ap) bordered by a forested floodplain with overbank sediments (sFv over gF^Ap) that is inundated during major floods. Alluvial (fluvial) fans (Ff, Ff-B)

are present at the mouths of tributary valleys. Fluvial materials along steep tributary creeks and in the alluvial fans are coarse and bouldery.

River terraces (Ft) are relatively rare in the Squamish area, probably because the main streams are tending to build up their beds, rather than degrade them, as a result of plentiful sediment supply. Fluvial terraces are restricted to a few tributary valleys. Fluvial terraces are dry, well drained, and stable (unless underlain by moist till or glaciolacustrine sediments). They are good sites for roads and industrial activities. Fluvial sands and gravels can be used for aggregate and fill, although fluvial terrace cappings may be only a metre or two thick over glacial materials or bedrock (Photo 13).

4.6 Organic Materials (O)

Organic materials include peat and organic soil horizons thicker than about 40 cm. In the study area, small patches of thick organic soil are common where soils are relatively moist on gentler slopes and in shallow gullies and concavities. In such locations, the presence of a thick organic soil horizon is an easily recognized indicator of wet soil conditions. Organic soils that are sufficiently extensive to map (e.g., Ov over Mv) were recorded in a few subalpine areas where heavy precipitation, cool temperatures and gentle slopes combine to cause very moist soil conditions. They were also mapped in a few places where wet valley-floors have resulted from partial blockage of a valley by fan development.

Organic soils are non-consolidated and highly susceptible to compaction, puddling and destruction due to repeated passage of equipment and even foot traffic.

4.7 Bedrock (R)

Bedrock is mapped where it outcrops and where it is overlain by only a few centimetres of weathered rock or soil. Different types of bedrock present in the study area are indicated on Figure 1 and described in Section 2.2.

(5) ACTIVE GEOMORPHOLOGICAL PROCESSES

5.1 Unstable Bedrock Types

Rock types that are susceptible to slope failure are indicated on the terrain maps by the use of superscripts. The Garibaldi volcanic rocks (R^V) include weakly consolidated pyroclastic rocks (partly cemented masses of volcanic debris) that are highly prone to raveling and mass failure, giving rise to abundant rockfall and rock avalanches, and masses of volcanic debris are commonly transformed into major debris flows during heavy rain (Jordan, 1987). The great volume of sediment that is yielded by these rock types is indicated by the large size of the colluvial fans that have accumulated at the foot of the channels that descend from unstable slopes in the vicinity of Mts. Cayley and Fee, such as Turbid Creek. (See Fig. 1).

Foliated rocks (schist) (R^F) also appear to be relatively unstable, giving rise to gully-wall failures and failures in sidecast materials consisting largely of weathered foliated rocks (e.g., at Site BW 10). (See also Fig. 1.)

The following sections pertain to slope processes on other rock types.

5.2 Debris Slides and Debris Flows (-R, -R", -R"d, -R"s)

Debris slides are a variety of small landslide. They occur when a mass of glacial drift or weathered bedrock becomes detached from a hillside and moves rapidly downslope by sliding along a shear plane. (Debris avalanches, which are not differentiated in this report, are similar, but in this case the detached material tumbles and falls downslope.) If the sliding (or avalanching) debris is saturated, or if debris falls into a stream and becomes saturated, it will be transformed into a debris flow. A debris flow is the rapid flow of a mass of viscous material, consisting of mud, sand, stones, and organic debris.

As noted in Section 4.1, debris slides are initiated on steep hillsides by sliding of weathered till and/or colluvium along a shear plane that coincides with the contact between weathered and unweathered till, or between colluvium and till, or between either till or colluvium and bedrock. Slides are triggered by heavy rain onto ground that is already saturated, and result from loss of soil strength due to high pore water pressure. During wet conditions, slides are also triggered by wind stress on trees, tree throw, impact of falling rocks from upslope, and vibrations due to earthquakes or human activity. In logged areas, debris slides that occur several years after logging may be due to the loss of soil strength that results from root decay. Slides downslope from roads are commonly triggered by diverted drainage.

Where debris slides occur high up on steep slopes and where flows enter stream channels, a debris flow may move down slope for several hundred metres or more before it is arrested by gentler terrain or by draining, or it may enter a stream.. Debris flows are also effective agents of erosion, and so the volume of material in a flow commonly increases downslope. Thus debris slides and flows are a significant potential source of stream sediment (Jordan, 1987) and also a hazard to activities or structures (roads, culverts) located downslope. As noted above (Section 4.4), debris flow (colluvial) fans are particularly hazardous sites. Erosion by debris flows results in loss of soil and vegetation cover, and the development and enlargement of gullies. Where erosion has (re)commenced due to a recent flow, rehabilitation of active gullies, either by natural regeneration or by artificial means such as grass seeding, is a long-term process.

In the Squamish valley, debris slides and debris flows are the most common types of slope failure (Photos 12, 14, 15, and 16) in forested terrain. Natural slides and flows appear to be less common here than in coastal areas of heavier precipitation, but we have no quantitative data to back up this casual observation.

On the terrain map symbols such as Mv/Rs-R"d and Mv/Rs-R"s are used to indicate terrain polygons that include the initiation sites of debris flows and debris slides. Symbols such as Cv-Rd are used for downslope areas affected by debris flows from above. These downslope areas are not unstable, but debris flows from upslope are a potential hazard.

5.3 Rockfall (-Rb, -R"b)

This process involves the release of relatively small masses of rock (e.g., a single block or a few cubic metres) and movement downslope by free fall, rolling and bouncing. Given the steep slopes and extensive cliffs of the Squamish valley, rockfall is relatively minor. Many talus slopes are stable and covered by vegetation (including lichen on "bare" slopes), fresh rockfall scars on cliffs of plutonic rock are uncommon. Slope stability in this context can be attributed to the strength of the plutonic rocks which underlie most of the study area. Metamorphic rocks (Fig. 1) are less stable, and rockfall is more common in areas where these rocks are exposed. Talus slopes are the most obvious evidence of rockfall, and most talus slopes are potentially hazardous sites.

Active rockfall is shown on the terrain map where fresh scars on cliffs or freshly deposited rocks on talus slopes indicate recent activity. It is also shown where, unexpectedly, we found recently fallen rocks in some forested areas where evidence for rockfall is not apparent on the air photos. In some places, rocks had fallen from steep cliffs in the next terrain polygon upslope, but elsewhere, rocks were falling from steep rocky bluffs in forested terrain. In these latter areas, falling rock could be especially hazardous to forest workers because ground disturbance due to falling and yarding will loosen more rocks and cause unstable blocks to move rapidly downslope. Loss of cohesion due to root rot could also lead to further rockfall three to five years after logging.

On the terrain map symbols such as Rs-R"b are used to indicate source areas for rock fall. Symbols such as Ck-Rb are used for downslope areas affected by rockfall from above, where rockfall is a potential hazard..

5.4 Snow Avalanches (-A, $-A^1$, $-A^2$, $-A^0$)

Snow avalanche tracks are abundant and widely distributed throughout the map area, indicating that avalanches are common during winter and early spring. Tracks are clearly distinguished by the absence of mature forest. Snow avalanches are a natural process, although removal of timber from steep, high slopes that receive heavy snowfall could possibly result in extension of natural initiation zones. More certain, is that removal of forest adjacent to the runout zone of an avalanche track can result in extension of the runout distance. In other words, if protection from avalanches is required for either structures or for natural resources such as lakes, belts of protective forest should be retained.

Although an active process, snow avalanches are not a factor in the assessment of slope stability. They are a hazard to winter activities, however, and accumulated avalanche snow can delay opening of roads in the spring. On the terrain maps, avalanche tracks were subdivided according to their extent in a terrain polygon. "Major" avalanche tracks (e.g., Mb-A^1) are broader than the height of adjacent mature forest and occupy more than about 20% of the polygon area. "Minor" avalanche tracks (e.g., Mb-A^2)are narrow and occupy less than about 20% of a polygon. Many tracks appear to be undergoing recolonization at present: air photos show immature conifers that do not appear to have been recently swept by avalanches. This trend may reflect a long-term climate change; avalanches would certainly have been more frequent than now during the Little Ice Age of the Eighteenth and Nineteenth Centuries. These old avalanche tracks are distinguished on the terrain map, (e.g., Mb-A^o).

5.5 Gully Erosion (-V)

Gullies are small ravines with V-shaped cross section formed in drift and bedrock. The symbol is usually applied to terrain polygons where more than one gully is present. Gullies are formed by the erosive effects of debris flows, small streams, snow avalanches, and rockfall, as already noted. The presence of gullies on drift-covered hillsides (e.g., Mb-V) indicates that the underlying material is susceptible to erosion and/or instability. Consequently, gullied terrain is commonly rated as unstable or marginally unstable (stability class V or IV) because gully side-slopes and headwalls are commonly unstable (Section 3.2) (Photos 2 and 14).

5.6 River Behaviour (-B, -J, -I)

Process symbols that describe stream behaviour are attached to terrain symbols for floodplains and fans. Braided streams (e.g., F^Ap-B) have multiple channels that split and rejoin around gravel bars. In the Squamish area, some reaches of the Squamish and Elaho Rivers and some streams on alluvial fans are braided. In general braiding develops where a stream is transporting much bedload (sand, gravel), and where great variations in stream discharge occur during the year. During storm runoff and snow melt, the entire active channel zone may be covered by rapidly flowing water. The behaviour of braided streams is typified by such floods, and by abrupt changes in channel position (avulsions) during floods. Aggradation (accumulation of gravel, raising the stream bed) is common on braided streams, and also results in frequent changes of channel position and undercutting of stream banks. Accordingly, braided streams may be hard to control and difficult to bridge.

A few reaches of the Squamish and Elaho Rivers were mapped as anastamosing (e.g., F^Ap-J). Here, the river channel pattern is similar to that of a braided stream, except the channels split around forested islands, rather than bare bars. Islands are more stable than the bars of a braided stream, although avulsions are still possible.

Most streams on floodplains and fans in the Squamish area have "irregularly sinuous channels" (e.g., F^Ap-I). The active channel zones of these streams are narrower

than those of they braided streams, and although they are subject to similar floods, channel shifts are less common.

Where gravelly materials are introduced to a stream as a result of debris flows and erosion, coarse sediment accumulates along the channel, and the streams show an increasing tendency to braiding and related behaviour (cf., Jordan, 1987). Sediment buildup diverts the stream to the edge of the active channel zone, thus encouraging bank erosion which in turn puts more sediment into the stream. If trees fall into the channel from undercut banks, they trap more sediment, and more gravel accumulation occurs. Thus the process is self-perpetuating.

5.7 Other Processes (-F, -H, -U)

Other process symbols used in only a few places on the terrain map include the following:

Failing (-F"): Refers to slope failures where movement occurs slowly (imperceptibly) and/or where the displaced material moves only short distance downslope. Small slumps and slides in till along gully sidewalls, and unstable bedrock with tension cracks are included in this category.

Kettled (-H): Refers to glacial deposits with depressions resulting from melting of buried ice. This differs from other processes shown on the map in that it is not an active process, but it is mentioned here for the sake of completeness.

Inundation (-U): Refers to areas that are seasonally inundated due to changes in lake and river levels.

(6) DISCUSSION AND RECOMMENDATIONS FOR MANAGEMENT

6.1 Slope Stability

Our mapping suggests that debris slides and debris flows are moderately common in T.F.L.38. Debris slides and debris flows do not appear to be as abundant here as in other Coast Mountain areas, although topography and surficial materials are similar. This could be related to the relatively great distance of the Squamish basin, particularly the upper Squamish and Elaho areas, from the coast, and hence a different precipitation regime. However, although we observed the distribution of slides and flows (see on-site symbols on air photos), we did not carry out a specific inventory. Natural slides are fairly common in forested areas. There have been small slides on logged slopes and there are sidecast failures. It is apparent that most of the latter are related to old roads.

The interpretations for slope (in)stability that are indicated on the terrain map (see also Section 3.2) show that Class V polygons are not widespread in the Squamish area, although small areas of unstable terrain are scattered across the region.

instability appears to be controlled primarily by slope steepness, although given a steep slope, slide initiation sites are determined by the location of wet soils and by local slope configuration (concavities, gullies, foot of rock outcrops). Scarp slopes cut into thick drift (till, glaciofluvial and glaciolacustrine sediments) and colluvium as a result of stream undercutting or road construction are commonly unstable or likely to be destabilized by any form of disturbance. Other factors that may influence slope stability and that are hard to assess include slope aspect (=direction the slope is facing) and exposure to intense rain.

6.2 Blocky and Bouldery Substrate

In the Squamish area, blocky and bouldery materials present special problems for regeneration and planting. Even where forested, these rocky substrates usually have only thin soil, typically a covering of grit (weathered rock) and moss, or small pockets of soil lodged in the narrow spaces between adjacent boulders. Removal of the forest cover results in destruction of the moss cover due to desiccation, and the unprotected soil is washed down into cavities in the coarse substrate. Consequently, it may be very difficult, if not impossible, to restock such sites by regeneration or replanting (e.g., Photo 10). For this reason, we were requested to map bouldery and blocky substrates.

Blocky and bouldery materials are common in the Squamish basin as a result of the predominantly plutonic bedrock (Section 2.2). Bouldery materials (rounded or subrounded particles with diameter more than about 25 cm) are common in fluvial terrain (floodplains and fans) associated with steep creeks. Blocky materials (angular or subangular fragments with diameter more than about 25 cm) are found in talus slopes, other colluvial landforms, and colluvial veneers.

Blocky and bouldery materials are indicated on the terrain maps by texture symbols: "a", blocks; "x", angular fragments (including blocks); and "b", boulders. Typical terrain symbols for bouldery and blocky substrate are: aCc, aCk, raCk, arCc, raCb, aCv, bFf, bgFf, bgF^{A}f.

6.3 General Recommendations

Although unstable terrain (class V) is of relatively limited extent in the T.F.L., potentially unstable (or marginally stable) terrain (Class IV) is widespread, and much future harvesting will take place on these slopes. General recommendations for the management of terrain in stability classes IV and V are provided in Table 6.1. These management implications are keyed to wet, coastal conditions.

As noted in Section 3.3, conditions that influence slope stability, such as slope steepness, slope configuration, and soil moisture, vary locally over distances of a few metres to several tens of metres. Such variations are not shown on the terrain maps, and it is up to forest engineers to recognize and take account of particularly sensitive areas during ground layout of cut blocks and roads.

Table 6.1

Stability Class	Stability Condition	Management Implications
IV	Marginally stable terrain; high potential for induced instability, especially along roads.	A field review by terrain specialist or geotechnical engineer is required prior to finalization of logging plans. Harvesting should consider the use of full suspension systems. Road length should be minimized; road construction and maintenance methods should be appropriate for steep terrain.
V	Unstable terrain; active or recurrent slope failures present.	Slope stability and erosion concerns take precedence over timber harvesting. Detailed stability analysis by terrain specialist or geotechnical engineer required prior to any decision on timber harvesting.

6.4 Specific Recommendations for T.F.L. 38

During field work and air photo interpretation, we made numerous casual observations of road conditions and other aspects of land use. Although not the main objective of our study, we offer the following recommendations. We realize that some of the following practices are already in effect, and that some problems that we noted date from practices that are no longer current, (e.g., for road construction). Nevertheless, we offer the following as a contribution to reducing degradation of slopes and streams due to slope instability.

Roads:

(1) Old roads on all slopes steeper than 60% and in all areas underlain by glaciolacustrine materials require regular inspection and maintenance, probably at least once a year following winter rains and snowmelt. Dependent upon road condition and use, appropriate actions (current MoF guidelines) should be taken to minimize sidecast failures and erosion, and consequent input of sediment to streams. Unused and little-used roads should be deactivated and stabilized.

(2) In the vicinity of gullies, road construction and maintenance practices should be selected so as to ensure: (a) that road materials or disturbed soil do not enter the gully either directly during road construction or as a result of later failure of road material, (b) that gully crossings are designed to prevent erosion (or either road or gully sidewalls) by any floods or debris flows that may descend the gully.

(3) Construction of roads on steep slopes (>65%) should be minimized, but where they are essential, all appropriate measures should be used to avoid soil and site degradation (full bench, excess materials endhauled, no diversion of natural drainage paths.)

(4) Road construction in Class IV terrain should be avoided during wet weather. If necessary, ongoing construction should be temporarily halted during intense rain onto saturated ground.

(5) Seeding: Grass (or other) seeding should be used to stabilize bare soil surfaces such as road cuts, road edges, ditches, debris slide/flow scars and tracks in clearcuts, and any other areas of bare or disturbed soil.

(6) Yarding Systems: Yarding systems that minimize ground disturbance (tower, skyline, helicopter) and road length should be used on Class IV slopes.

Implementation of effective practices and techniques to minimize instability, soil erosion and site loss will be of increasing importance in the future as forest operations move onto steeper slopes with thinner soils.

The information and analyses contained in this report are based on observations of land-surface conditions and current understanding of slope processes. However, because slope stability is strongly influenced by subsurface conditions that are not apparent from surface observations or air photo interpretation (e.g., characteristics of subsurface materials, subsurface hydrologic conditions), by events whose time of occurrence cannot be predicted (e.g., extreme storms, earthquakes), and by land management practices, the results and recommendations provided in this report cannot guarantee that no landslides will occur in areas affected by forestry activities. Appropriate use of terrain information and implementation of recommendations will, however, reduce the risk of landslides and erosion.

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APPENDIX 1

ANNOTATED PHOTOGRAPHS

Photo 1: Recessional moraine (M') in Sims valley near Sims-Elaho confluence
Steep side slopes on such moraines are commonly unstable when
undercut by creeks or roads. (Photo: A.Collett)

Photo 2: Elaho valley near Jarvis Creek (mile 59, E-main). Typical lower slopes covered by basal till. Note rock outcrops that indicate the variable thickness of the till, and note gullies (between road cuts) that indicate the erodible nature of this material. (Photo: S.Tsang)

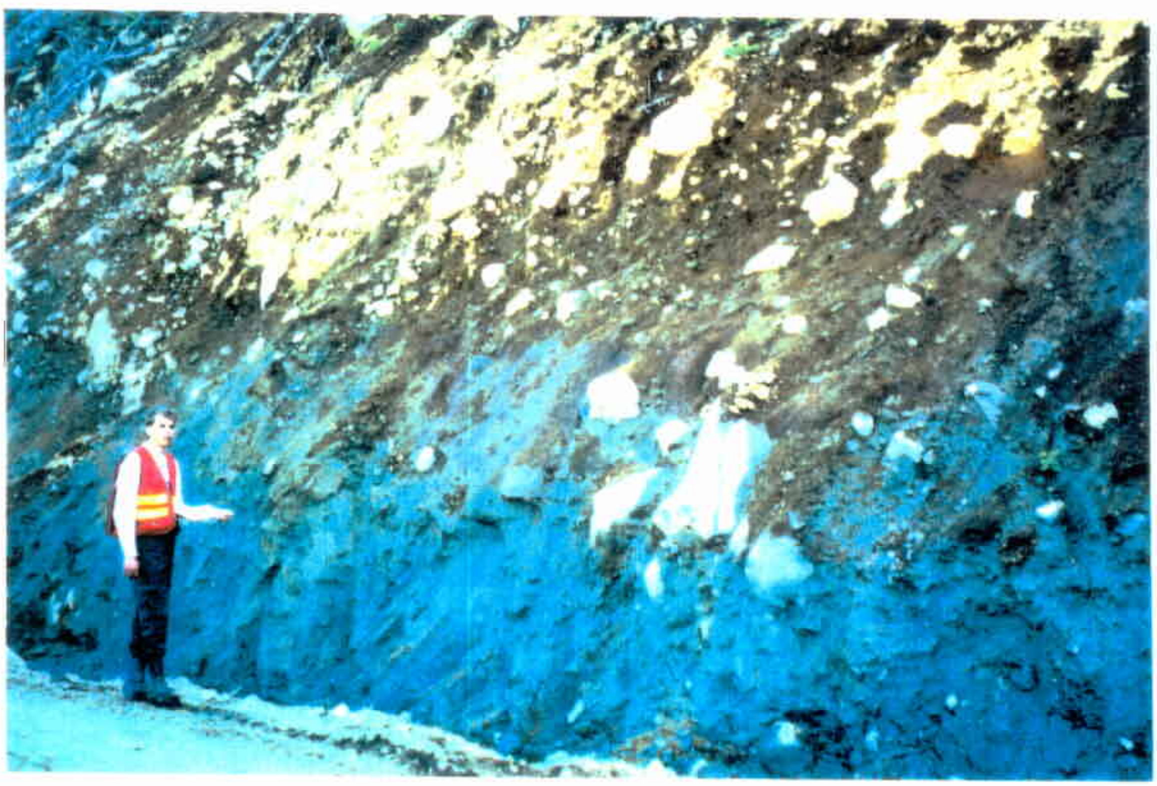

Photo 3: Typical basal till exposed in road cut, Elaho valley. Note blue-grey colour of unweathered till, and subangular clasts (pebbles, cobbles and boulders) set in a fine grained (silty sand) matrix. (Photo: A. Gallotti)

Photo 4: Thick, highly consolidated till with few boulders in road cut at Site ST25. Note sharp contact between weathered (soil) and unweathered till (arrow). This contact is usually the lower limit of the rooting zone, as shown here. (Photo S.Tsang)

Photo 5: Thick ablation till exposed in roadcuts in Elaho valley (E-600, Site AC37). Material has a much higher proportion of clasts (stones) and less fines than basal till. It is relatively loose and subject to raveling in road cuts. (Photo A. Collett)

Photo 6: Glaciofluvial gravels overlying till at lower Blakery Creek; (arrow marks gravel/till contact). Note crude stratification in the coarse bouldery gravels. (Photo S.Tsang)

Photo 7: Close up of typical glaciolacustrine sediments (thinly bedded silt and fine sand), upper Squamish area (Site BW 7). (Photo: B.Waddington)

Photo 8: Glaciolacustrine sediments underlying steep slope with post logging failures, Elaho valley near Sims Creek (Site AC67). Slides were probably cause by water seeping from a perched watertable at the contact of the fine textured glaciolacustrine material and overlying glaciofluvial gravels. (Photo: A.Collett)

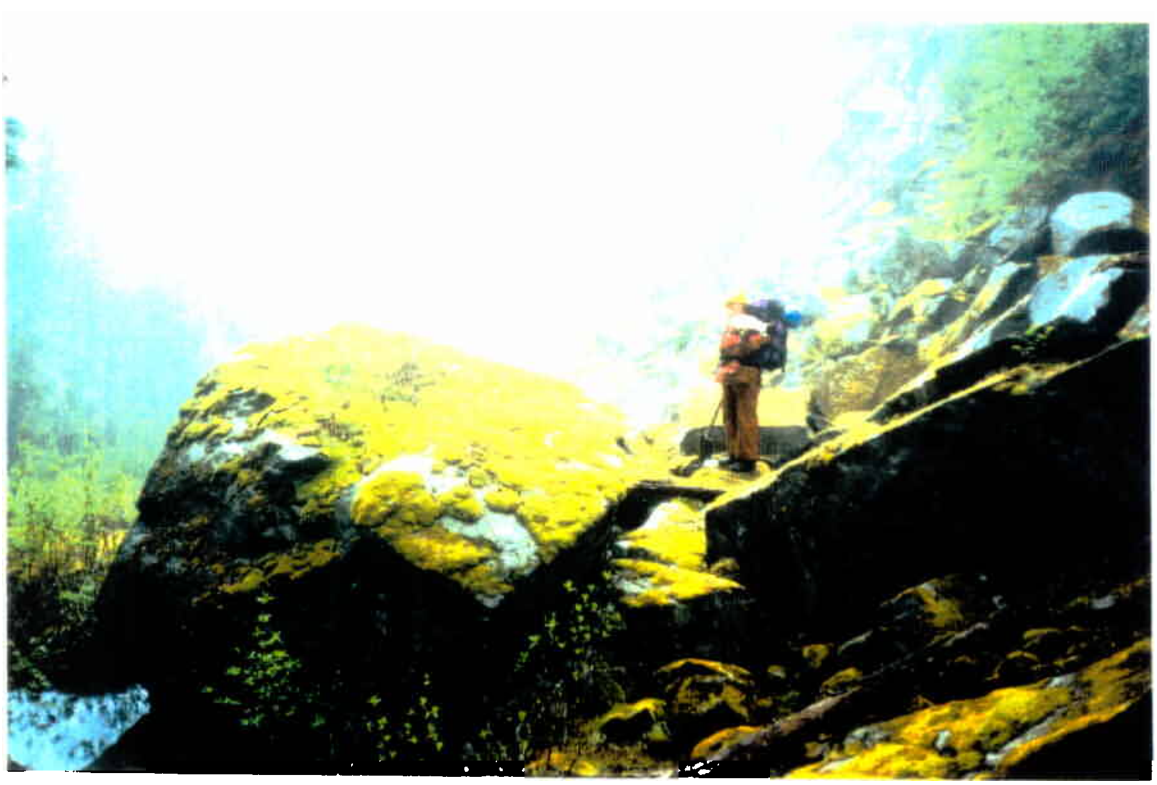

Photo 10: Blocky colluvium, typical of areas underlain by plutonic rocks. This site has not yet been colonized by forest, although vegetation is gaining a foothold on the moss-covered blocks in the foreground. Where forested sites on this kind of substrate are disturbed by logging, they can revert to unproductive, rocky land. (Photo: S.Tsang)

Photo 9: Colluvium exposed in soil pit: Note angular fragments of plutonic rock and sandy matrix. (Photo S.Tsang)

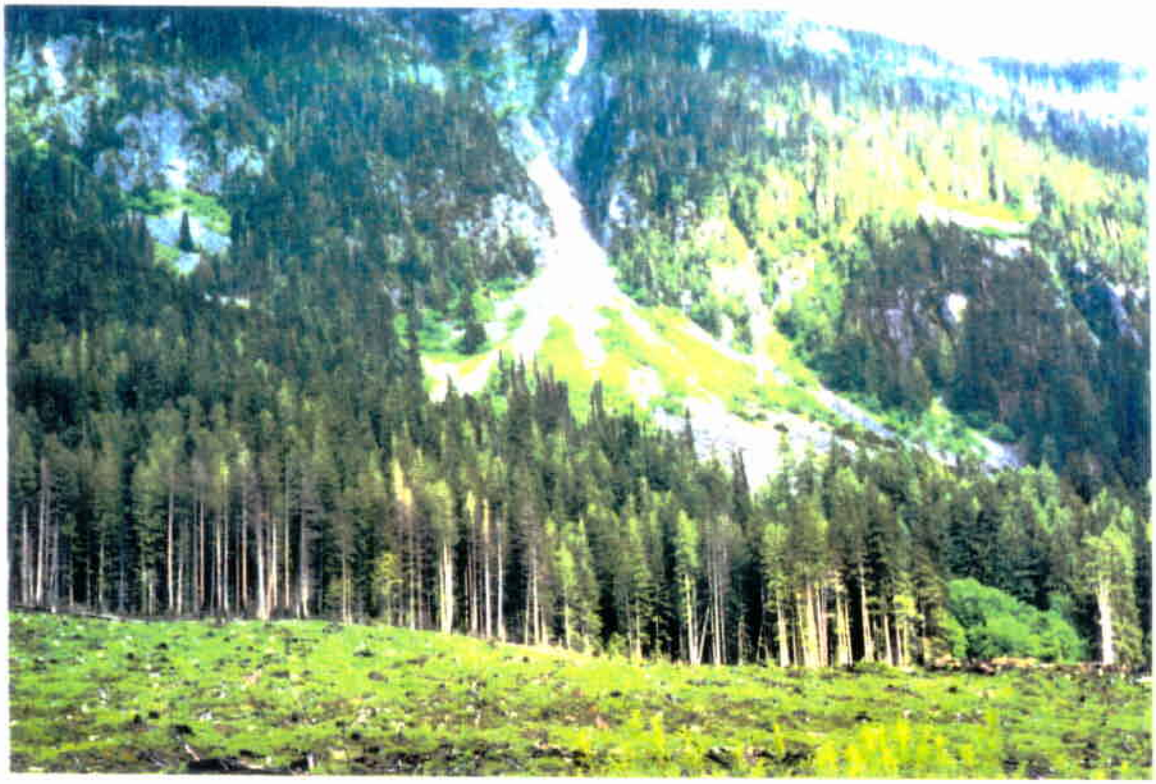

Photo 11: Colluvial cone formed by rockfall, debris flows and snow avalanches. Note fresh debris-flow deposits overlying vegetated surface. Cones with less-active processes are forested. (See also caption to Photo 10). (Photo: S.Tsang)

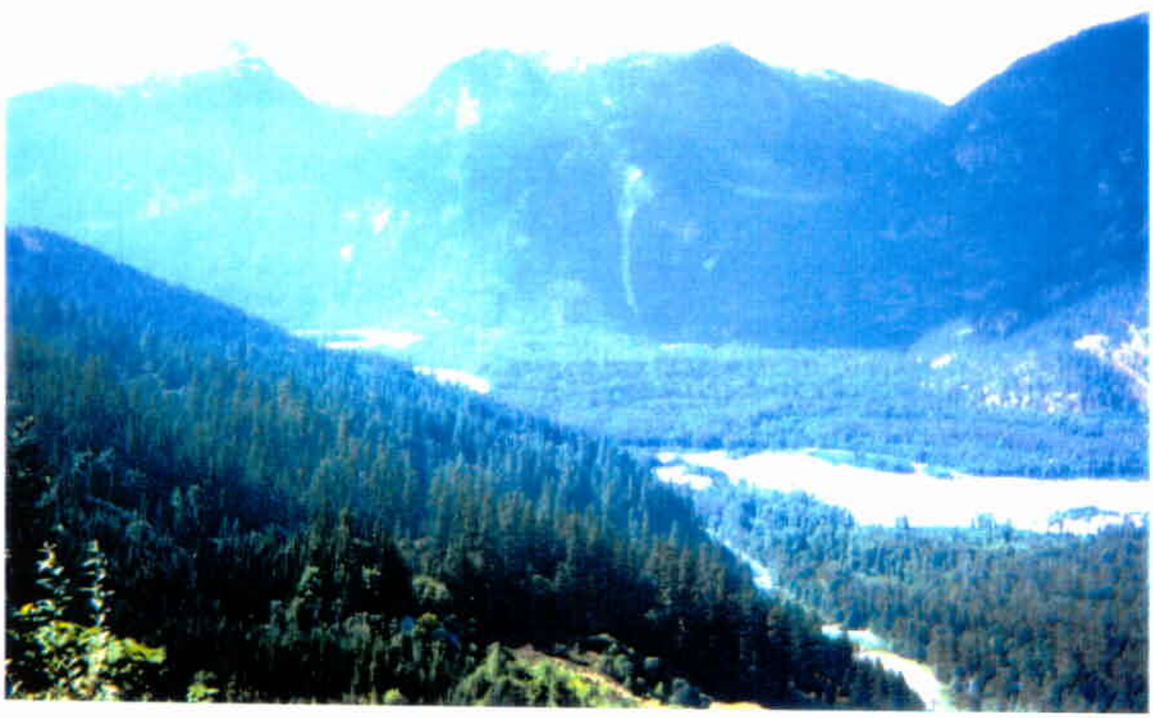

Photo 12: View of Elaho River floodplain. A sandy fluvial veneer overlies fluvial gravels beneath the forested part of the floodplain. Note debris slide/flow on distant hillside at centre photo. (Photo: P.Stokes)

[illegible] Glaciofluvial [illegible] material [illegible] thick [illegible] terrace [illegible] fill near Lava Creek. Note [illegible] stratified gravels and bouldery [illegible] deposit (boulders [illegible] particles [illegible]). (Photo S. Tsang)

Photo 15. Natural debris slide-flow track on slope undisturbed by logging. Revegetation of scar by deciduous vegetation suggests that the event occurred about a decade ago. (Photo A. Collett)

Photo 14: Gullies formed as a result of small debris slides on steep erosional slope in thick till (Ms). Slides appear to have followed logging, and probably resulted from loss of root strength or soil disturbance by yarding. After the slide scar (track) is formed by the initial event, surface erosion by running water continues to enlarge the gullies, a process that is hard to control. (Photo: B.Waddington).

Photo 16: View down a debris flow that resulted from natural slope failure in till. Subsequent erosion by running water has formed a small gully (foreground). (Photo: A.Collett)

APPENDIX 2

Map sheet responsibilities.

Map Sheet #	Map Name	Terrain Mapper
92G-093	Ashlu	J.Dunkley and J.M.Ryder
92G-094	High Falls Creek	J.Dunkley and P.Friele
92J-003	Upper Ashlu	P.Stokes
92J-004	Squamish	P.Friele
92J-013	Lower Elaho	P.Friele
92J-014	Camp No.2	B.Waddington
92J-022	Sims Creek	A.Collett, S.Tsang
92J-023	Elaho and Sims Junction	A.Collett
92J-024	Upper Squamish	B.Waddington
92J-032	Clendenning	S.Tsang
92J-033	Upper Elaho	S.Tsang
92J-042	Upper Clendenning	S.Tsang
92J-043	Cesna Creek	S.Tsang

APPENDIX 3

STANDARD TERRAIN MAP LEGEND

(1) TERRAIN UNIT SYMBOLS

Simple Terrain Units: e.g., gFt-A

texture → g; surficial material → F; surface expression → t; process → A

Note: Two letters may be used to describe any characteristic other than surficial material, or letters may be omitted if information is lacking.

Composite Units: Two or three groups of letters are use to indicate that two or three kinds of terrain are present within a map unit.

e.g., Mm·Rr indicates that "Mm" and "Rr" are of roughly equal extent

Mm/Rr indicates that "Mm" is more extensive than "Rr" (about 2/1 or 3/2)

/Mv over Rr indicates that Rr is partially buried by Mv

Stratigraphic Units: Groups of letters are arranged one above the other where one or more kinds of surficial material overlie a different material or bedrock:

e.g., Mv over Rr means that "Mv" overlies "Rr".

(2) MATERIALS

A	Anthropogenic materials	Artificial materials, and materials modified by human actions such that their original physical appearance and properties have been drastically altered.
C	Colluvium	Products of gravitational slope movements; materials derived from local bedrock and major deposits derived from drift; includes talus and landslide deposits.
D	Weathered bedrock	Bedrock modified *in situ* by mechanical and chemical weathering.
E	Eolian sediments	Sand and silt transported and deposited by wind; includes loess.
F	Fluvial sediments	Sands and gravels transported and deposited by streams and rivers; floodplains, terraces and alluvial fans.
F^A	"Active" fluvial sediments	Active deposition zone on modern floodplains and fans; active channel zone.
F^G	Glaciofluvial sediments	Sands and gravels transported and deposited by meltwater streams; includes kames, eskers and outwash plains.
I	Ice	Permanent snow and ice; glaciers.
L	Lacustrine sediments	Fine sand, silt and clay deposited in lakes.
L^G	Glaciolacustrine sediments	Fine sand, silt and clay deposited in ice-dammed lakes.
M	Till	Material deposited by glaciers without modification by flowing water. Typically consists of a mixture of pebbles, cobbles and boulders in a matrix of sand, silt and clay; diamicton.
O	Organic sediments	Material resulting from the accumulation of decaying vegetative matter; includes peat and organic soils.
R	Bedrock	Outcrops, and bedrock within a few centimetres of the surface.
U	Undifferentiated materials	Different surficial materials in such close proximity that they cannot be separated at the scale of the mapping.
V	Volcanic materials	Unconsolidated pyroclastic sediments.
W	Marine sediments	Sediments deposited by settling and gravity flows in brackish or marine waters, and beach sands and gravels.
W^G	Glaciomarine sediments	Sediments laid down in marine waters in close proximity to glacier ice.

(3) TEXTURE

Specific Clastic Terms

c	clay	< 4μm
$	silt	62.5 - 4μm
s	sand	2 mm - 62.5μm
p	pebbles	2 - 64 mm
k	cobbles	64 - 256 mm
b	boulders	> 256 mm
a	blocks	angular boulders

Common Clastic Terms

f	fines	any or all of c, $, and fine s
d	mixed fragments	pebbles and larger clasts in a matrix of fines
g	gravel	any or both of p and k
r	rubble	angular gravel
x	angular fragments	mix of both r and a
m	mud	mix of both c and $
y	shells	shell or shell fragments

Organic Terms

e	fibric
u	mesic
h	humic

(4) SURFACE EXPRESSION

a	moderate slope(s)	predominantly planar slopes; 16-26°
b	blanket	material > 1-2m thick with topography derived from underlying bedrock (which may not be mapped) or surficial material
c	cone	a fan-shaped surface that is a sector of a cone; slopes 15° and steeper
d	depression	enclosed depressions
f	fan	a fan-shaped surface that is a sector of a cone; slopes 3 - 15°
h	hummocky	steep-sided hillocks and hollows; many slopes 15° and steeper
j	gentle slope(s)	predominantly planar slopes; 4-15°
k	moderately steep slope	predominantly planar slopes; 27-35°
m	rolling topography	linear rises and depressions; < 15°
p	plain	0-3°
r	ridges	linear rises and depressions with many slopes 15° and steeper
s	steep slope(s)	slopes steeper than 35°
t	terrace(s)	stepped topography and benchlands
u	undulating topography	hillocks and hollows; slopes predominantly < 15°
v	veneer	material < 1-2m thick with topography derived from underlying bedrock (may not be mapped) or surficial material; may include outcrops of underlying material

(5) GEOLOGICAL PROCESSES

A	Avalanches	slopes modified by frequent snow avalanches
B	Braiding channel	channel zone with many diverging and rejoining channels; channels laterally unstable
C	Cryoturbation	heaving and churning of soil and surficial materials due to frost action
D	Deflation	removal of sand and silt particles by wind action
E	Glacial meltwater channels	areas crossed by meltwater channels that are too small or too numerous to map individually
F	Failing	slope experiencing slow mass movement, such as sliding or slumping
H	Kettled	area includes numerous small depressions and/or lakes where buried blocks of ice melted
I	Irregularly sinuous channel	channel displays irregular turns and bends
J	Anastamosing channel	channels diverge and converge around semi-permanent islands
K	Karst processes	solution of carbonates (limestone, dolomite) resulting in development of collapse and subsidence features
M	Meandering channel	channel characterized by regular turns and bends
N	Nivation	surface modified by hollows developed around semi-permanent snowbanks
P	Piping	subsurface erosion of silty sediments by flowing water resulting in the formation of underground conduits
R	Rapid mass movement	slope or parts of slope affected by processes such as debris flows, debris slides and avalanches, and rockfall
S	Solifluction	slope modified by slow downslope movement of seasonally unfrozen regolith
U	Inundated	areas submerged in standing water from a seasonally high watertable
V	Gullying	slope affected by gully erosion
W	Washing	winnowing of fines by flowing water resulting in development of lag deposits
X	Permafrost processes	processes related to the presence of permafrost; permafrost aggradation and degradation
Z	Periglacial processes	solifluction, nivation and cryoturbation occurring together in a single terrain unit

Mass Movement Sub-Classes

-F	slow mass movement
-Fc	soil creep
-Fg	rock creep
-Fk	tension cracks
-Fp	lateral spread in bedrock
-Fj	lateral spread in surficial materials
-Fe	earthflow
-Fm	slump in bedrock
-Fu	slump in surficial material
-Fx	slump-earthflow
-R	rapid mass movement
-Rf	debris fall
-Rb	rock fall
-Rs	debris slide
-Rr	rockslide
-Rd	debris flow
-Rt	debris torrent
-R"	rapid mass movement initiation zone

(6) SOIL DRAINAGE CLASSES

r	rapidly drained
w	well drained
m	moderately well drained
i	imperfectly drained
p	poorly drained
v	very poorly drained

Where two drainage classes are shown, e.g., "wi", then no intermediate classes are present; if the symbols are separated by a dash, e.g., "w-i", then all intermediate classes are present.

(7) ON-SITE SYMBOLS AND BOUNDARY LINES

Ice flow direction indicators:

crag and tail

drumlins

striations

grooves

lineations

Scarps: escarpments; bluffs

in Quaternary materials

in bedrock

Mass Movement and Erosion Features:

scar of recent small slide

scar of recent larger slide

scar of old landslide

recent debris flow

Cirque

Glacial meltwater channels (small, large)

Eskers (known, unknown)

Observation/sample site: ⊙S10

Terrain Unit Boundary Lines:

definite boundary

indefinite, approximate or gradational boundary

assumed or arbitrary boundary

APPENDIX 4: FIELD DATA FORMS

See separate volume (ring binder)